processes

MDPI

Article

Features of Ash and Slag Formation During Incomplete Combustion of Coal from the Karazhyra Deposit in Small- and Medium-Scale Power Plants

Natalya Seraya [1], Vadim Litvinov [2], Gulzhan Daumova [3,*], Maksat Shaikhov [4], Raigul Ramazanova [1] and Roza Aubakirova [5]

[1] International School of Engineering, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk 070001, Kazakhstan; nseraya@edu.ektu.kz (N.S.); rramazanova@edu.ektu.kz (R.R.)
[2] Proektno-Ekologicheskoe Bjuro LLP, Ust-Kamenogorsk 070001, Kazakhstan; litvinov_vadim@mail.ru
[3] School of Earth Sciences, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk 070000, Kazakhstan
[4] Vostokenergo LLP, Ust-Kamenogorsk 070001, Kazakhstan; maksat.shaikhov@kazminerals.com
[5] Higher School of IT and Natural Sciences, S. Amanzholov East Kazakhstan University, Ust-Kamenogorsk 070001, Kazakhstan; roza.aubakirova@bk.ru
* Correspondence: gdaumova@edu.ektu.kz

Abstract

The study presents a comprehensive assessment of the combustion efficiency of low-grade coal from the Karazhyra deposit in small- and medium-capacity boiler units of the energy workshops operated by Vostokenergo LLP (East Kazakhstan Region, Kazakhstan). It was found that the average annual thermal energy output amounts to 2,387,348.85 GJ with a coal consumption of 164,328.5 tons. Based on operational data from 2016 to 2017, the average thermal efficiency (boiler efficiency) was 66.03%, with a maximum value of 75% recorded at the Zhezkent energy workshop. The average lower heating value (LHV) of the coal was 19.41 MJ/kg, which is below the design value of 20.52 MJ/kg, indicating the use of coal with reduced energy characteristics and elevated ash content (21.4%). The unburned carbon content in the ash and slag waste (ASW) was determined to be between 14 and 35%, indicating incomplete combustion. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses revealed the presence of microspheres, porous granules, and coal residues, with silicon and aluminum oxides dominating the composition (up to 70.49%). Differences in the pollutant potential of ash from different boiler units were identified. Recommendations were substantiated regarding the adjustment of the air–fuel regime, modernization of combustion control systems, and utilization of ASW. The results may be used to develop measures aimed at improving the energy efficiency and environmental safety of coal-fired boiler plants.

Keywords: low-grade solid fuel; coal; underburning; ash; ash and slag waste

check for updates

Academic Editor: Cherng-Yuan Lin

Received: 1 July 2025
Revised: 21 July 2025
Accepted: 29 July 2025
Published: 4 August 2025

Citation: Seraya, N.; Litvinov, V.; Daumova, G.; Shaikhov, M.; Ramazanova, R.; Aubakirova, R. Features of Ash and Slag Formation During Incomplete Combustion of Coal from the Karazhyra Deposit in Small- and Medium-Scale Power Plants. *Processes* **2025**, *13*, 2467. https://doi.org/10.3390/pr13082467

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

To address the challenges of the energy sector and reduce atmospheric emissions, the Republic of Kazakhstan (RK) is implementing a Concept for the Transition to a "Green" Economy, aimed at developing more environmentally friendly energy production systems, including the use of renewable energy sources (RESs) such as wind, solar, and hydropower [1]. In recent years, the share of electricity generated from RESs has shown

steady growth—from 2.80% in 2020 to 5.82% in 2023 [1]. According to the national strategy, the targets are 6% by 2025, 15% by 2030, and at least 50% by 2050 [2].

Despite the declared shift toward a carbon-neutral economy, coal remains the dominant energy resource in Kazakhstan, accounting for 49.6% of primary energy consumption [1]. This is due to its availability, well-developed infrastructure, and relatively low cost [3]. Global statistics confirm coal's stable role in electricity production, contributing around 40% [4]. Kazakhstan holds significant reserves—34 billion tons, or approximately 4% of global reserves [5]. However, widespread use of low-grade coal presents several technical and environmental challenges. Such coal is characterized by high ash content, low calorific value, and a tendency toward incomplete combustion, which reduces the efficiency of energy systems and increases the volume of ash and slag waste (ASW). In small- and medium-capacity boiler houses, particularly in regions lacking centralized gas or fuel oil supply, its use remains economically justified.

There are about 2500 boiler facilities operating in Kazakhstan, most of which burn local coal and are characterized by low energy efficiency (efficiency levels of 40–55%) [6,7]. The outdated condition of equipment and the absence of modern combustion control systems result in significant underburning and, as a result, an increase in the content of unburned carbon in ash and slag waste (ASW). It should be noted that the total volume of ash is determined primarily by the mineral composition of the source coal and the geology of the deposit, rather than by operational features. Estimates indicate that up to 19 million tons of ash and slag are generated annually in Kazakhstan, with cumulative waste exceeding 300 million tons [8,9].

ASW poses a serious environmental threat, including dust emissions, the release of toxic substances (CO, NO_x, SO_x), acid rain, and secondary contamination of soil and water. A critical risk factor is the presence of heavy metals and radioactive components in the waste [10].

Coal combustion efficiency is closely linked to fuel characteristics and combustion conditions. Key indicators of combustion losses include unburned carbon content and ash parameters. Techniques such as laser-induced breakdown spectroscopy (LIBS) [11] and elemental analysis [12] have demonstrated potential for real-time monitoring of fuel and combustion product composition. Factors contributing to incomplete combustion include coal heterogeneity, the presence of inert and initially oxidized compounds, and suboptimal combustion regimes.

This study focuses on coal from the Karazhyra deposit, used in boiler units in the East Kazakhstan Region. It is the largest deposit of grade D bituminous coal, located on the territory of the former Semipalatinsk nuclear test site. The deposit is being developed by Karazhyra JSC (formerly Semey Komirleri LLP, FPG Semey JSC, and Semey-Komir JSC). The average ash content of the coal is 15.7%, with values ranging from 10.5% to 19.0%. In the raw coal mass, ash content reaches up to 25.7% (ranging from 18.7% to 30.2%). The average lower heating value of the as-received fuel is 17.16 MJ/kg. According to GOST 25543-88 [13], the coal from this deposit is classified as hard coal of grade D (long-flame), with the following typical composition in its organic part: carbon—75–80%, hydrogen—2.5–5.7%, nitrogen—1–3%, and oxygen—1.5–15%.

Several studies have been dedicated to a detailed examination of the qualitative composition of coal from the Karazhyra deposit. For example, in ref. [14], comprehensive research was carried out using the Labsys Evo analyzer, employing differential thermal analysis (DTA) and thermogravimetric analysis (TGA) to assess the mass changes of coal samples with temperature. This analysis determined the key physicochemical characteristics of Karazhyra coal. The results provided accurate data on the coal's thermal stability, combustion behavior, and the composition of carbonaceous and volatile compounds—factors

that play a critical role in evaluating its energy efficiency and environmental safety during combustion [14].

According to official data from Daman Group LLP for 2020 [15], Karazhyra coal intended for pulverized combustion demonstrates similar characteristics, with emphasis on moisture content, ash content, volatile matter, sulfur and carbon content, as well as other chemical elements such as hydrogen, nitrogen, and oxygen.

In ref. [16], which focused on the physicochemical analysis of coal from the Karazhyra deposit, a comprehensive assessment was conducted, including the determination of sulfur, carbon, hydrogen, nitrogen, and oxygen content. Special attention was also given to the coal's heat capacity, morphology, and particle size. Scanning electron microscopy (SEM), a highly effective technique, was used to examine particle morphology and structure, enabling precise evaluation of particle shape, size, and surface texture. The study demonstrated that Karazhyra coal possesses a relatively high calorific value, indicating good energy characteristics. Moreover, the coal is characterized by low ash and moisture content, making it more efficient and environmentally friendly for combustion. These parameters are especially important when assessing the potential use of this coal in various sectors, including the energy industry and manufacturing, where both economic and environmental considerations are critical.

According to the test results conducted in 2021 by "SOZUGOL," the official dealer of Karazhyra JSC in Russia [17], the high quality of Karazhyra coal was confirmed, including key parameters such as ash content, moisture, sulfur content, volatile matter yield, and lower heating value. These parameters are essential for assessing the coal's energy value and its suitability for use in the energy sector. All test results confirmed that Grade D coal exhibits favorable characteristics that meet the requirements for application in various industrial and energy processes.

Additionally, these findings were supported by other sources, including Karazhyra LTD LLC [18], where Grade D coal underwent detailed analysis confirming similar quality indicators. This study paid particular attention to the chemical element composition and its influence on coal's performance characteristics. The research showed that coal from the Karazhyra deposit demonstrates stable and high-quality parameters, making it a sought-after resource in the market and suitable for a wide range of applications.

In ref. [19], the key physicochemical properties of coal from the Karazhyra deposit were established, with particular focus on the behavior of the mineral fraction during combustion. Specifically, attention was given to the temperature regimes at which the primary combustion reactions occur and the duration of fuel exposure to high temperatures. These studies helped identify critical parameters affecting combustion efficiency and pollutant emissions. It was found that Karazhyra coal exhibits good operational properties during combustion, which can be used to optimize combustion technologies and improve energy efficiency in power generation facilities.

Scientific publications [14–19] confirm significant variability in the composition of coal depending on the mining site and preparation technology (Table 1). To justify the conditions for efficient combustion, it is important to consider not only the elemental composition but also the coal's morphological, thermal, and granulometric characteristics.

Table 1. Comparison of the elemental composition of Karazhyra coal according to various sources.

Source	Moisture, %	Ash, %	Volatile Matter, %	Sulfur, %	C, %	H, %	N, %	O, %	P, %	Lower Heating Value, MJ/kg
[14,16]	14.00	19.8	47.0	0.40	75.5	5.30	1.70	16.80	0.040	—
[15]	14.00	18.0	47.0	0.45	74.4	5.58	1.51	18.00	0.028	—
[17]	10.98	11.9 [1]	48.3 [2]	0.30	—	—	—	—	—	22.73
[18]	14.00	18.0	47.0	0.40	73.3	5.70	1.41	19.40	0.020	21.34
[19]	13.00	19.4	—	0.26	50.0	3.68	0.92	12.74	—	19.05

[1] Ash content for dry fuel. [2] Volatile matter for dry ash-free fuel.

The analysis of literature data on coal from the Karazhyra deposit (Table 1) shows that its quality characteristics fall within acceptable limits but vary across sources. The average ash content ranges from 18% to 19.8%, the calorific value from 19.05 to 22.73 MJ/kg, and sulfur content remains below 0.5%. These indicators generally meet the requirements for fuel used in small-scale energy generation. However, the high variability of these parameters necessitates the adaptation of combustion regimes and design calculations for specific coal batches. This instability in fuel properties directly affects combustion conditions, the completeness of fuel burnout, and the formation of ash and slag waste, ultimately influencing the technical, economic, and environmental performance of boiler operations.

Therefore, the efficient utilization of such fuel requires a comprehensive approach aimed at adapting operating parameters to the actual characteristics of the coal.

Improving energy efficiency and reducing the environmental impact of heat generation requires addressing the following priority tasks [20,21]:

- Optimization of boiler and furnace operation modes based on the characteristics of the coal used;
- Reduction in slagging and fouling on heat exchange surfaces;
- Reduction in harmful atmospheric emissions;
- Intensification of heat transfer processes during combustion of low-grade fuels;
- Rational use of fuel resources and improvement of the overall efficiency of boiler systems.

The implementation of these directions is impossible without a detailed analysis of fuel properties, combustion conditions, and the characteristics of ash and slag formation. In this regard, the study of coal used in small-scale heat generation systems, such as that from the Karazhyra deposit—known for its unstable composition and elevated ash content—is of particular relevance.

Given the high variability in coal properties, especially in terms of ash content, volatile matter, and calorific value, a key aspect becomes the control of combustion completeness under real operating conditions. The most direct indicator of this is the content of unburned carbon in ash and fly ash, which reflects both the efficiency of the combustion process and the proper functioning of the equipment.

In this regard, monitoring the unburned carbon content in fly ash and ash–slag waste (ASW) represents an important indicator of coal combustion conditions. Regular control of this parameter is essential to ensure the optimal operation of coal-fired boilers and to properly adjust operating modes in small- and medium-capacity power centers.

In view of the above, the objective of this study is to perform a comprehensive assessment of the efficiency of Karazhyra coal utilization in small- and medium-capacity boilers, using the example of the power centers operated by Vostokenergo LLC, with a focus on identifying the causes of incomplete combustion and the formation of ash and slag waste.

To achieve this objective, the following tasks were completed:

- Determination of the thermal efficiency (coefficient of performance) of boiler operations based on actual production data;
- Analysis of the physicochemical characteristics of the coal and ash–slag waste, including composition and degree of underburning;
- Investigation of the microstructure and chemical composition of ash–slag waste;
- Calculation of slagging and contamination indices for ash.

Thus, the present study is aimed at substantiating approaches to improving the energy efficiency of small- and medium-capacity coal-fired boilers operating on low-grade fuel, based on the analysis of actual operational indicators and the properties of ash–slag waste.

The novelty of this study is a comprehensive assessment of the degree of underburning of Karazhyra coal in the operating conditions of small- and medium-sized boiler houses in East Kazakhstan. Unlike most works that focus solely on the characterization of coal as a fuel, this work covers not only the properties of coal itself, but also ash residues, including an analysis of morphology, elemental composition, and the degree of fuel loss. This approach makes it possible to identify specific technological problems of low-grade fuel combustion and suggest ways to increase energy efficiency and reduce the environmental burden.

2. Materials and Methods

2.1. Objects of Study

Vostokenergo LLP is a source of heat supply for settlements in the East Kazakhstan Region, Republic of Kazakhstan: Shemonaikha, Ust-Talovka, Belousovka, Altaysky, and Zhezkent, as well as industrial enterprises in the region. Structurally, the enterprise is divided into three power plants:

(1) Belousovsky power plant (PP).

Belousovka village:

Site No. 1—the central industrial boiler house—is located on the territory of the main industrial site of Vostoktsvetmet LLC. It is designed to provide heat to the working premises of the outdoor facilities of the Belousovsky mine, the Belousovskaya enrichment plant, buildings of auxiliary enterprises, and the administration and residential areas of Belousovka village.

Altai village:

Site No. 1 is an industrial boiler house on the territory of the main industrial site, intended for heating the administrative and domestic complex, as well as the production and auxiliary buildings and structures of the Irtysh mine.

(2) Zhezkent power plant (Zhezkent village).

Site No. 1 is an industrial boiler house, designed to provide thermal energy to the production and administrative premises of the enterprise, as well as the residential area of Zhezkent village.

(3) Ust-Talovsky power plant (Ust-Talovka village, Shemonaikha city).

Site No. 1—an industrial boiler house—is a centralized source of heat and steam supply for the following facilities: Shemonaikha, Ust-Talovka, the Nikolaevskaya enrichment plant, the industrial site of Nikolaev quarry, and the passenger transport workshop.

Site No. 2—treatment facilities of the city of Shemonaikha for the treatment of domestic wastewater. The boiler house is intended for heating the administrative and domestic building and all auxiliary buildings of the treatment facilities.

Coal from the Karazhyra deposit (135 km southwest of the city of Semey, in the Zhana-Semeysky district of the East Kazakhstan Region of the Republic of Kazakhstan) is used as the main solid fuel in the power plants of Vostokenergo LLC. To determine the main

problems of solid fuel combustion in low-power boilers operated by the power centers of Vostokenergo LLC, coal and ash samples were obtained and analyzed from all power plants of Vostokenergo LLC. The basic parameters characterizing the content of residual substances after the combustion of solid fuel (coal) are the physicochemical properties of ash and slag spillage collected from boiler bunkers on the studied boiler units. The samples were collected during coal combustion in furnaces with the most typical operating mode for each boiler. Samples of ash and slag waste were collected manually from the lower bunkers of ash collection units (electrostatic precipitators and ash collectors) of the boiler units of the studied power plants. Sampling was carried out in accordance with the requirements of the standard ST RK ISO 18283-2016 [22] and adapted to the characteristics of solid waste from fuel combustion. Samples of ash and slag waste were collected from different levels and zones of the bunkers to ensure representativeness. The obtained samples were combined, thoroughly mixed, and subjected to quartz treatment and crushing to a fraction of less than 0.2 mm for subsequent analysis. The averaged samples were sent for visual, mineralogical, and physicochemical analysis of the composition and structure of boiler waste.

2.2. Methods

To determine the unburned carbon in the analyzed ash and slag samples, the following method was used [23]. A sample of ash (a) weighing about 1 g, calculated on a dry matter basis, was placed in a beaker and treated with 300–400 cm^3 of 10% solution of HCl, heated in a sand bath for 3–4 h to transfer soluble compounds, including iron compounds, into the solution. Heating was carried out until the smell of hydrogen sulfide disappeared, while the amount of solution was reduced to 100–150 cm^3. After heating was completed, the precipitate that did not dissolve in the HCl was filtered through an ashless paper filter, thoroughly washed with hot water until the reaction to chloride ions disappeared by $AgNO_3$. The residue on the filter was dried at 105 °C to a constant weight, and its weight was determined (P_1). Knowing the weight of the original sample and the residue after treatment with hydrochloric acid, the amount of dissolved substances (%) was determined in relation to the original sample:

$$R = \frac{(a - P_1)}{a} \cdot 100\%, \quad (1)$$

where R is the amount of dissolved substances; a is the weight of the original sample; and P_1 is the weight of the sample after the treatment by HCl. The residue with the filter was placed in a crucible and calcined in a muffle furnace, and the weight of the remaining ash was determined (P_2). Then, the soluble residue (%) in the remaining ash was calculated in relation to the initial weight of dry matter:

$$K = \frac{P_2}{a} \cdot 100\%, \quad (2)$$

where K is the soluble residue; a is the weight of the original sample; and P_2 is the weight of the sample after calcination. Summing up the values K and R, we obtained the total ash content of the original material:

$$A^C = K + R, \quad (3)$$

where A^C is the total ash content. The content of unburned carbon (%) in the initial ash was determined by the formula:

$$C_2 = \left(100 - A^C\right), \quad (4)$$

The elemental composition of the samples was determined in the analytical research laboratory of the VERITAS Excellence Center of the D. Serikbayev East Kazakhstan Technical University (EKTU, Ust-Kamenogorsk, East Kazakhstan Region, Republic of Kazakhstan). The samples were tested using a JSM-6390LV scanning electron microscope (SEM) (JEOL Ltd. (Tokyo, Japan)). Ash and slag sampling were carried out from several technologically and geographically different facilities (power plants) of Vostokenergo LLP. At least 5 independent samples representing different batches of products or places of ash and slag accumulation were collected for each object. Each sample was subjected to a triple repeat analysis to assess the intraprobe variability and statistical reliability of the results. All samples were dried to a constant mass at a temperature of 105 °C before analysis and screened through a sieve with 0.071 mm cells to standardize the fraction. Sampling for analysis was carried out randomly from the prepared powder. The samples were placed on a conductive carbon film and examined on a scanning electron microscope with an energy-dispersion element microanalysis device at the following settings:

Accelerating voltage: 15 kV is optimal for obtaining high-quality images and elemental analysis without damaging samples.

- Working distance: 10 mm—to ensure sufficient depth of field and good signal quality.
- Operating mode: low vacuum at a pressure of 50 Pa—to minimize charging of non-metallic samples.

Energy dispersion analysis (EDX) was performed using standardized calibration samples that ensure the accuracy of element determination within ±1%. For each sample, a detailed analysis was performed on two to four randomly selected areas at high magnifications with microanalysis of 3–7 spectra.

Mineralogical analysis of ash and slag samples was performed by X-ray phase analysis (XRD) on a Bruker D8 Advance diffractometer. The following device settings were used:

- Angle range 2θ: 5–70°, which makes it possible to identify most mineral phases in ash and slag.
- Scanning step: 0.02°, providing high-angle resolution and high-quality diffraction profile.
- Exposure time: 1 s/point, providing optimal signal-to-noise ratio.
- Quality control was performed using standard silicon (Si) and α-aluminum (Al) samples, with the analysis repeated at least three times to assess reproducibility.
- Internal software tools for calibration and automatic data processing (EVA, PDF-2) were used.

The method allowed the determination of both the qualitative and quantitative mineral composition of the ash, including the content of the main oxides—SiO_2, Al_2O_3, Fe_2O_3, etc.

During all stages of the analysis, the accuracy and repeatability of measurements were monitored. Statistical methods of processing repeated data were used to assess reproducibility in terms of elemental and mineralogical composition. If significant deviations were detected, the samples were re-measured and the causes of the deviations analyzed. These measures have made it possible to increase the reliability and reproducibility of the results, which meet modern requirements for analytical research in the field of carbon chemistry and materials science.

The slagging factor (R_s) of the studied ash and slag samples was calculated taking into account the value of the acid-base ratio—the ratio of the sum of the main components of the ash (Fe_2O_3, CaO, MgO, K_2O, Na_2O) to the sum of the acidic components of the ash (SiO_2; Al_2O_3; TiO_2) according to the empirical formula [24]:

$$R_s = \frac{(Fe_2O_3 + CaO + MgO + K_2O + Na_2O) \cdot S}{(SiO_2 + Al_2O_3 + TiO_2)}, \quad (5)$$

where Fe_2O_3, CaO, MgO, K_2O, Na_2O, SiO_2, Al_2O_3, TiO_2 is the content of oxides in coal ash, %; and S is the sulfur content in coal, %.

The contamination factor (R_f) of the studied ash and slag samples for deposits at $(CaO + MgO) < Fe_2O_3$ was calculated using a formula that considers the total content of sodium and potassium oxides [24]:

$$R_f = \frac{(Fe_2O_3 + CaO + MgO + K_2O + Na_2O) \cdot (K_2O + Na_2O)}{(SiO_2 + Al_2O_3 + TiO_2)}, \quad (6)$$

3. Results and Discussion

To assess the volume of ash and slag waste generated during the operation of the power plants of Vostokenergo LLC, as well as the amount of unburned fuel particles (underburning) at the Testing Center of Centergeolanalit LLC (Karaganda, Karaganda Region, Republic of Kazakhstan), a technical analysis of coal samples from the Karazhyra deposit used by the power plants was carried out (Table 2).

Table 2. Results of mixed testing of coal samples from the Karazhyra deposit consumed by the power plants of Vostokenergo LLP.

No.	Parameter and Units of Measurement	Design Values [25]	Experimental Values					
			Name of the Power Plant					
			Belousovsky		Zhezkentsky	Ust-Talovsky		
			Boiler House in the Belousovka Village	Boiler House in the Altaysky Village	Boiler House in the Zhezkent Village	Boiler House in the Ust-Talovka Village	Boiler House of the Treatment Facilities of the City of Shemonaikha	Average Value
1	Working moisture, W_t^r, %	14.0	13.1	18.3	10.9	14.4	12.5	13.84
2	Ash content, A^d, %	15.9	21.0	21.8	20.3	20.3	23.6	21.40
3	Total sulfur, S^r %	0.45	0.55	0.46	0.39	0.48	0.39	0.45
4	Lower calorific value of thefuel in working condition, Q_i^r, MJ/kg	20.52	19.93	18.13	20.43	19.68	18.88	19.41
5	Total carbon, C^r, %	74.40	50.96	46.71	51.87	50.64	49.66	49.97
6	Total hydrogen, H^r, %	5.70	3.97	3.41	4.17	3.99	4.02	3.91
7	Total nitrogen, N^r, %	1.41	1.02	0.92	1.02	0.96	0.98	0.98
8	Total oxygen, O^r, %	19.4	12.10	12.44	13.58	12.10	11.77	12.4

During coal combustion, not only is energy generated, but the organic part also forms volatile compounds in the form of smoke and steam, and the non-combustible mineral part is released in the form of solid focal residues, forming a dust-like mass (ash), as well as lump slags—ash and slag waste. Therefore, the chemical composition, physical properties, and amount of ash and ash and slag mixtures depend on the type of coal and the conditions of its combustion. In this paper, when studying coal samples from the Karazhyra deposit, collected at the PP of Vostokenergo LLP, the average chemical qualitative composition was established as follows (%): carbon—49.97; hydrogen—3.91; nitrogen—0.98; oxygen—12.4; and sulfur—0.45 (Table 2).

For low-grade metamorphic coals (grade D), which includes coal from the Karazhyra deposit, the minimum values of total moisture in the product, without thermal drying of the coal, are 13–15%. This is due to the high values of internal "bound" moisture in these

coals, the amount of which is determined by the chemical nature of the coal, petrographic composition, degree of carbonization, and granulometric composition. Based on the results of the studies, the average value of working moisture for the coal samples was determined, which is within the normal range and is 13.84% (Table 2).

Sulfur in coals is a harmful impurity. In small-scale power engineering, sulfur is the main factor limiting the minimum thermal loads of boilers, since at low temperatures of exhaust gases, condensate falls out on the tail surfaces, and sulfur dioxide from the combustion products, combining with the condensate, forms sulfuric acid, which destroys the metal of the boilers. Coals of East Kazakhstan are characterized by low sulfur content; the average sulfur content (S^r %) in the studied coal samples from the Karazhyra deposit is 0.45% (Table 2).

The combustion heat is the most important indicator for assessing the consumer value of coals, especially those used in thermal power engineering. The lower combustion heat (Q_i^r, MJ/kg) characterizes the fuel in its natural state, i.e., at specific values of moisture and ash content per working mass. This indicator was used in this study to determine the quality of coal. The nature of the change in the average combustion heat depends on the degree of metamorphism (grade composition of coals). It was found that the average and lower combustion heat (19.41 MJ/kg) per working state of fuel (Table 2) for the samples under study is below the permissible value declared by the manufacturer, Karazhyra JSC (20.52 MJ/kg).

In this study, to assess the quality of the coal used from the Karazhyra deposit, the ash content indicator was used—related to absolutely dry fuel (A^d, %), the average value of which is 21.4% (Table 2). This is inconsistent with the declared technical characteristics in accordance with the requirements for the quality of coal in the open pit and the current Organization Standard ST RK 1816-2014 "Coals of the Karazhyra Deposit. General Specifications". Thus, the analysis of the obtained data allowed establishing that the coal used in the power plants of Vostokenergo LLP belongs to non-design coal of the Karazhyra deposit (does not meet the quality requirements established for grade D fuel, has insufficiently high heat release, and contains a large number of impurities) due to a lower carbon content and a higher ash content, with a lower heat of combustion of the fuel than that of the design one.

To conduct the analysis in this study, actual data on the production activities of Vostokenergo LLC were used [26], according to which the average volume of thermal energy generation was 2,387,348.85 GJ, and the average coal consumption was 164,328.5 tons (Table 3).

To determine the average efficiency of fuel energy use for the years 2016–2017—specifically, the thermal efficiency (coefficient of performance) of the heating boiler—the ratio of the volume of fuel consumed to the amount of heat generated was used. The lower heating value of coal, taken as 19.47 MJ/kg based on available quality certificates, was used as the baseline parameter. Based on these data, the calculated coal demand was determined, and the efficiency of the boiler installations was assessed.

Based on a comparative analysis of the actual average values of coal consumption and heat energy production for the period 2016–2017 (Table 3), it was established that the average fuel energy utilization efficiency across Vostokenergo LLC is 66.03%. The fuel energy utilization efficiency coefficients for each power plant were calculated using actual production data from Vostokenergo LLC (Table 4). According to these data, the most efficient coal combustion process (75%) is observed in the boilers of the Zhezkent power plant (Figure 1), which is attributed to the applied technology.

Table 3. Key performance indicators of Vostokenergo LLP.

Indicator	Belousovsky PP	Ust-Talovsky PP	Zhezkent PP	TOTAL Vostokenergo LLP
Thermal energy production in 2016, GJ	498,031.09	1,102,165.51	762,741.08	2,362,937.67
Thermal energy production in 2017, GJ	551,571.65	1,056,602.66	803,585.70	2,411,760.01
Average value of thermal energy production for 2016–2017, GJ	524,801.37	1,079,384.29	783,163.18	2,387,348.85
Average coal consumption in 2016, t	36,802.0	79,688.0	49,282.0	165,772.0
Average coal consumption in 2017, t	38,182.0	73,432.0	49,227.0	160,841.0
Average coal consumption for 2016–2017, t	37,492.0	76,560.0	50,276.5	164,328.5

Table 4. Fuel energy efficiency coefficient for power plants of Vostokenergo LLC.

Indicator	Belousovsky PP	Ust-Talovsky PP	Zhezkent PP	Total of Vostokenergo LLP
Average value of thermal energy production, GJ	524,801.37	1,079,384.29	783,163.18	2,387,348.85
Average coal consumption, t	37,492.0	76,560.0	50,276.5	164,328.5
Annual coal requirement with a net calorific value of coal of 19.47 MJ/kg, t	26,963.0	55,455.0	40,237.0	122,655.0
Fuel energy efficiency, %	60.9%	61.9%	75.0%	66.0%

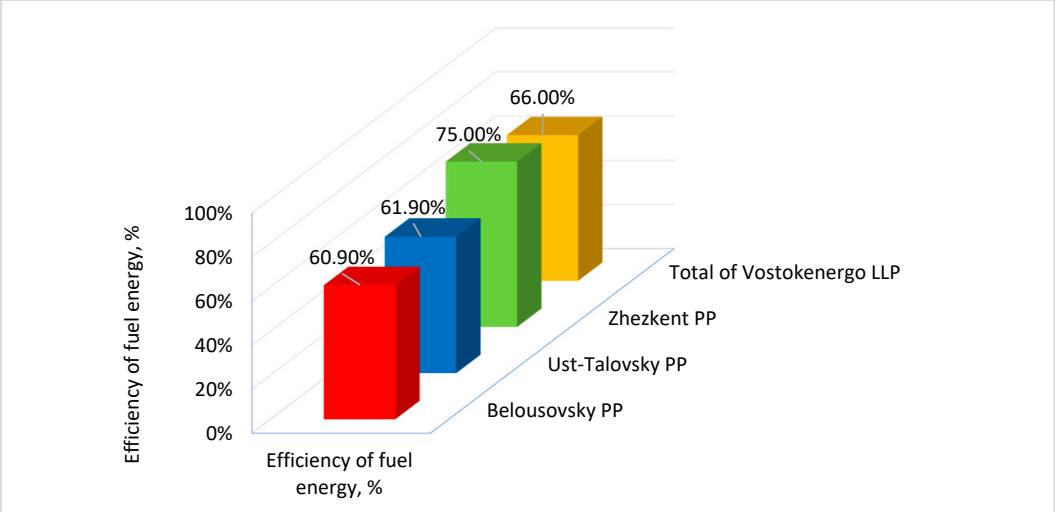


Figure 1. Efficiency of fuel energy use by power plants of Vostokenergo LLC.

Data on the efficiency of boiler installations were provided directly by Vostokenergo LLP's power plants and represent average values based on internal monitoring of equipment operation. It should be noted that the initial data with detailed variability and repeated measurements were not available in this study, which limits the possibility of conducting a statistical assessment of the significance of the identified differences in efficiency between power plants (for example, 66.03% versus 75%). To more accurately determine the factors influencing the variability of efficiency, it is necessary to systematically collect experimental data, followed by the use of methods of variance analysis (ANOVA) or Student's t-test. In the future, it is planned to organize such studies, which will make it possible to distinguish the influence of the technical condition of the equipment and the random variability of indicators. In the current study, differences in efficiency are considered as preliminary indicators demonstrating the variability in the efficiency of boiler installations at various facilities of Vostokenergo LLP.

The analysis of the obtained data indicates high levels of unburned fuel under actual operating conditions of the power centers, where part of the unburned fuel is carried away with the flue gases from the boilers, and part settles with the slag.

Samples of ash and slag waste generated at the power centers of Vostokenergo LLC were analyzed at the accredited testing laboratory of AltaiTehEnergo LLC (Ust-Kamenogorsk, East Kazakhstan Region, Republic of Kazakhstan). In accordance with the approved methodology, an experimental analysis was conducted, resulting in the determination of unburned carbon content (an indicator of incomplete combustion) in the ash and slag samples (Figure 2).

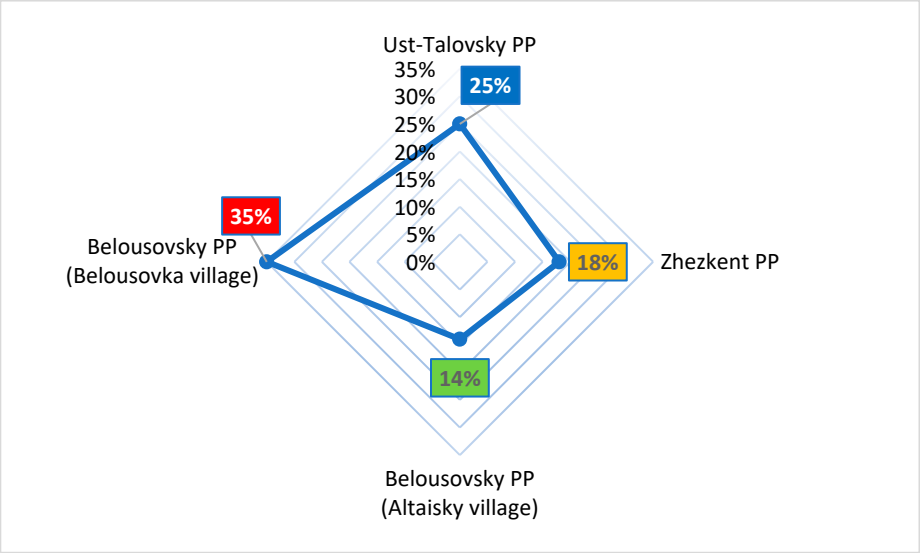


Figure 2. Unburned carbon (underburnt) content in samples of ash and slag from the PPs of Vostokenergo LLP.

Based on the results of the experimental studies, the unburned carbon content (an indicator of mechanical underburning of fuel) was determined in ash and slag samples collected from various power plants within the structure of Vostokenergo LLC. The obtained values were as follows (%): Ust-Talovsky power plant—25; Zhezkent power plant—18; Belousovsky power plant (Altaysky village)—14; and Belousovsky power plant (Belousovka village)—35 (Figure 2). The identified underburning levels indicate significant losses of combustible material, particularly at certain sites, pointing to inefficient fuel combustion regimes and potential design or operational deficiencies of the boiler equipment. The highest unburned carbon content was recorded at the Belousovsky power plant in Belousovka village (35%), which necessitates a separate analysis of the causes and the development

of measures to reduce underburning. The obtained data confirm the need to optimize combustion processes to enhance fuel efficiency and reduce the volume of ash and slag waste generation.

It should be noted that the underburning values determined in this study are based solely on the analysis of unburned fuel particles present in ash and slag waste. However, this approach does not account for the additional portion of unburned fuel carried away with the flue gases from the furnace units, which undoubtedly leads to an underestimation of the total mechanical losses. Therefore, the actual level of incomplete fuel combustion may be significantly higher than the values established during the analysis.

To determine the material composition of the ash and slag samples, their mineral composition and geochemical characteristics were studied. A comprehensive analysis was carried out using scanning electron microscopy and physicochemical investigation methods. As a result of the microscopic analysis, surface morphology images of the examined ash and slag waste were obtained and are presented in Figure 3. The physicochemical analysis data of the ash and slag composition from the boiler facilities of Vostokenergo LLC are shown in Supplementary Materials (Tables S1 and S2).

Scanning electron microscopy (SEM) combined with localized energy-dispersive microanalysis offers high information content when studying the mineral phases present in ash and slag waste. This method enables detailed examination of the morphological and elemental features of mineral particles at the microstructural level.

The results of the conducted studies revealed that the ash and slag samples represent polydisperse systems composed of dust-like particles varying in morphology, size, and chemical composition. Both amorphous and crystalline structures were observed, differing in structure and degree of aggregation, which reflects the complex nature of ash and slag formation processes during fuel combustion.

Despite the visual similarities among the analyzed samples, pronounced differences were observed, attributed to the specific operational characteristics of boilers at different power centers. For instance, samples collected from the Zhezkent power plant and the boiler plant in Altaysky village were characterized by gray to light gray coloration, whereas samples from other sites displayed darker, even black coloration. This indicates a higher content of unburned carbonaceous fractions in those samples, which was confirmed in subsequent stages of physicochemical analysis.

All analyzed samples exhibit distinct morphological similarities among the components of ash and slag waste. Regardless of the sampling location, the following typical structural elements were identified in their composition:

- Spherical particles (microspheres);
- Irregularly shaped granules with a distinct porous structure;
- Conglomerates with partially fused areas and carbon-containing inclusions;
- Fragments of unburned fuel (coal particles).

These morphological features indicate typical thermal processing conditions in boiler installations and confirm the polydisperse and heterogeneous nature of ash and slag waste.

Microspheres are characteristic morphological elements regularly present in ash and slag waste. Their quantity directly depends on the fuel combustion conditions and the degree of oxidation completeness. The highest microsphere content is observed in ash and slag waste from boilers operating under optimal temperature conditions, where a high degree of fuel burnout is achieved. Under such conditions, the share of spherical particles can reach up to 25–30% in fly ash and 8–10% in total ash and slag waste. Microsphere formation is associated with the impact of high temperatures on the mineral components of coal, primarily quartz and aluminosilicates, which, under vitrification conditions, transform into hollow, semi-transparent spherical structures containing air (Figure 3i). Due to

their structure, they possess low density and high mobility. Conversely, when combustion regimes are violated, temperatures are insufficient, or oxidation is incomplete, the microsphere content drops sharply—to 1% or less, as confirmed by microscopic analysis of samples from the Zhezkent and Belousovsky power plants (Figure 3).

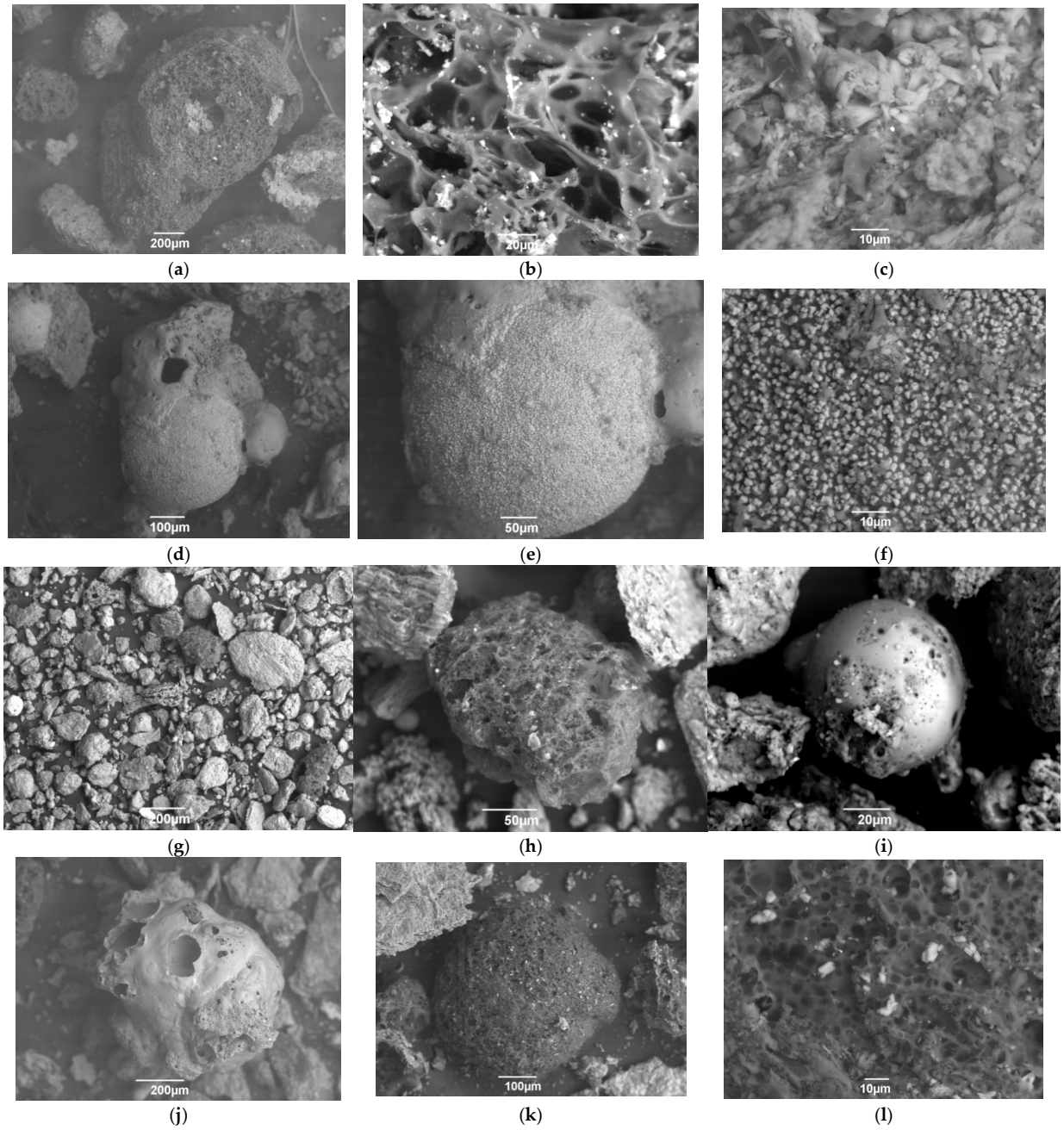


Figure 3. Microstructure of ash and slag waste. (**a**) Belousovsky Energy Center (Belousovka village), 60× magnification; (**b**) Belousovsky Energy Center (Belousovka village), 750× magnification; (**c**) Belousovsky Energy Center (Belousovka village), 1500× magnification; (**d**) Belousovsky Energy Center (Altaysky village), 130× magnification; (**e**) Belousovsky Energy Center (Altaysky village), 270× magnification; (**f**) Belousovsky Energy Center (Altaysky village), 1500× magnification; (**g**) Zhezkent Energy Center, 80× magnification; (**h**) Zhezkent Energy Center, 400× magnification; (**i**) Zhezkent Energy Center, 850× magnification; (**j**) Ust-Talovsky Energy Center, 95× magnification; (**k**) Ust-Talovsky Energy Center, 160× magnification; (**l**) Ust-Talovsky Energy Center, 1000× magnification.

The main portion of the total ash and slag waste volume consists of irregularly shaped granules with a wide variety of sizes and morphological features. These particles form during the fuel combustion process and are typically free structures lacking a clearly defined geometry. A significant feature of these granules is the presence of porous inclusions formed because of the thermal transformation of carbon components that have not been fully separated from the mineral portion of the fuel. The appearance of such porous structures is primarily due to coal preparation characteristics, including the degree of fuel grinding, as well as combustion parameters, particularly the temperature regime and air supply intensity. With finer coal grinding, the proportion of free granules with compact structure increases (Figure 3f). At the same time, under suboptimal fuel preparation or unstable combustion conditions, the content of porous inclusions increases, formed by partial charring of the organic phase retained within the ballast particles (Figure 3j,l). This structural heterogeneity highlights the significant influence of combustion parameters on the morphology of ash and slag formations and must be considered when evaluating fuel feed efficiency and the degree of complete fuel burnout.

The presence of conglomerates with partially fused elements and coal inclusions in the ash and slag samples is a characteristic sign of unstable combustion conditions, often observed in boiler units with irregular fuel and oxidizer supply. The formation of such structural elements is primarily due to the heterogeneity of the initial fuel's particle size distribution and the lack of precise air supply regulation in the combustion zone. A wide range of coal particle sizes, including insufficiently ground fractions, hinders uniform oxidation processes, leading to local overheating or, conversely, low-temperature zones in the furnace. This promotes the formation of conglomerates—aggregates with fused surfaces often containing unreacted carbon inclusions. The absence of metered oxygen supply exacerbates the process, increasing both the number of such conglomerates and the share of unburned fuel. Their presence in ash and slag waste can serve as an indicator of deviations from optimal boiler operation. In cases of pronounced technological violations, the number of fused and carbon-containing inclusions in the ash and slag waste significantly increases, as confirmed by morphological and chemical analyses.

Like most mineral resources, coal contains a wide range of chemical elements, including nearly all naturally occurring ones. However, the majority of these elements are present in trace concentrations. Special attention in composition analysis is given to toxic and environmentally hazardous impurities, including arsenic, mercury, beryllium, lead, vanadium, selenium, cobalt, fluorine, manganese, chromium, nickel, and others.

According to the physicochemical analysis of samples from the structural subdivisions of Vostokenergo LLC, the titanium content in ash and slag waste was found to be as follows (%): Belousovsky power plant (Belousovka village)—0.97; Belousovsky power plant (Altaysky village)—3.55; Zhezkent power plant—4.12; and Ust-Talovsky power plant—2.30 (Tables S1 and S2). In the ash from the Belousovsky power plant (Belousovka village), tungsten was also detected at a level of 2.59%, which may be associated with the geochemical characteristics of the original coal fuel. All analyzed samples revealed a significant iron content—ranging from 14.23% to 46.74%—which is typical for ash resulting from the combustion of coal with high pyrite and other iron-containing mineral content.

Additionally, the following values were determined for specific toxic elements: in the ash from the Belousovsky power plant (Altaysky village), the vanadium content was 0.31%, while the ash from the Zhezkent power plant showed a minor presence of manganese (0.33%).

The sulfur content in ash and slag waste also varied widely: Belousovsky power plant (Belousovka village)—5.37%; Belousovsky power plant (Altaysky village)—2.92%; Zhezkent power plant—0.36%; and Ust-Talovsky power plant—2.39% (Tables S1 and S2).

The presence of sulfur and its compounds requires particular attention in the context of assessing potential environmental impact.

The conducted research did not reveal the presence of radioactive elements in the ash and slag waste of the studied samples. This can be explained by the fact that pure coal generally does not contain naturally occurring radionuclides in significant concentrations. The potential presence of carbonaceous rocks with elevated radioactivity in interlayers has little influence on the overall radiation background, as such rocks are present in trace amounts and typically are not involved in the main combustion process. Nevertheless, the potential risk of coal sourced from oxidation zones or geochemically anomalous areas—where radioactivity levels, particularly in ash, may exceed established sanitary and environmental standards—should be taken into account. Therefore, periodic radiological monitoring of ash samples is recommended when the coal source or mining conditions change.

The chemical and mineral composition of the inorganic fraction of the ash and slag waste was determined based on the results of a comprehensive analysis of ash samples obtained from the combustion of coal from the "Karazhyra" deposit, which is used as the primary fuel source for the power centers of LLP "Vostokenergo" (Table 5).

Table 5. Results of mixed mineralogical analysis of coal ash samples from the Karazhyra deposit consumed by the power plants of Vostokenergo LLP.

No.	Content of Oxides in Coal Ash, %	Name of the Power Plant				
		Belousovsky		Zhezkentsky	Ust-Talovsky	
		Boiler House in the Belousovka Village	Boiler House in the Altai Village	Boiler House in the Zhezkent Village	Boiler House in the Ust-Talovka Village	Boiler House of the Treatment Facilities of the City of Shemonaikha
1	SiO_2	42.11	44.96	47.02	32.90	45.87
2	Al_2O_3	21.67	20.69	21.35	16.99	2
3	Fe_2O	4.98	5.25	10.51	3.73	6.50
4	CaO	2.56	2.91	3.74	2.65	3.65
5	MgO	1.26	0.88	1.44	1.04	1.13
6	K_2O	1.00	0.85	1.08	0.85	1.10
7	Na_2O	1.40	1.00	1.35	1.65	1.40
8	TiO_2	0.89	0.89	0.91	0.75	0.92
9	P_2O_5	42.11	44.96	47.02	32.90	45.87
10	Mn_3O_4	21.67	20.69	21.35	16.99	24.62
11	SO_3	1.10	1.34	1.54	1.54	0.79
12	LOI	23.12	21.04	10.81	37.85	13.27

The mineral (ash) component of coal can exhibit a diverse composition, influenced both by peat accumulation conditions and the lithological–geochemical characteristics of the surrounding rock formations. The main components of coal ash typically include the oxides of silicon (SiO_2), aluminum (Al_2O_3), iron (FeO and Fe_2O_3), calcium (CaO), magnesium (MgO), as well as alkali elements such as potassium and sodium (K_2O, Na_2O).

According to the comprehensive mineralogical and chemical analysis of ash obtained from the combustion of coal from the Karazhyra deposit (Table 5), which is used as the main fuel at the power plants of Vostokenergo LLC, the chemical composition of the ash and slag waste is dominated by oxides, predominantly found in loosely bound forms with

various elements. The major components include silicon dioxide and aluminum oxide: SiO_2 content ranges from 32.9% to 47.02%, and Al_2O_3 from 16.99% to 24.62%, with their combined share reaching 49.89–70.49%. Iron oxides are also present in notable quantities (ranging from 3.73% to 10.51%). The mineralogical composition of the ash and slag includes amorphous glassy aluminosilicates, crystalline quartz, mullite, hematite, magnetite, and fragments of unburned coal.

At all modern thermal power plants (TPPs), during coal combustion, the organic portion of the fuel undergoes complete oxidation, while the mineral impurities in the coal are partially amorphized under high temperatures and transformed into fine-dispersed fractions. These combustion products are captured in two primary forms of ash and slag waste: fly ash (a fine powder with a creamy or gray hue) and bottom ash or slag waste (of porous or dense structure).

The composition and morphology of the resulting ash and slag waste are significantly influenced by the characteristics of the original coal, the type of boiler unit used, and the combustion temperature and aerodynamics. An important quality indicator is the presence of residual unburned fuel in the ash products, which is evaluated by the loss on ignition (LOI)—an indicator that reflects the mass fraction of volatile and carbon-containing components not fully combusted. LOI values in ash vary widely—from 2% to 25% by mass—depending on combustion efficiency. In the analyzed ash samples obtained from Vostokenergo LLC power plants, LOI values ranged from 10.81% (Zhezkent power plant) to 37.85% (Ust-Talovsky power plant, Ust-Talovka village), indicating significant differences in the completeness of fuel combustion across different facilities (Table 5).

Ash is an inert mineral impurity associated with the organic part of coal; however, its composition significantly affects the technological properties and efficiency of coal-based thermal power processes. Primarily, the ash's chemical and mineralogical composition determines its slagging tendency and potential to contaminate heat exchange surfaces. During coal combustion in boilers, thermal transformation of mineral impurities leads to the formation of ash components distributed as follows: approximately 20% forms coarse particles that settle at the furnace bottom, while around 80% becomes fine-dispersed fly ash fractions, carried away with flue gases and captured in gas cleaning systems.

One of the negative technological phenomena during coal combustion is slagging—the process of ash melting at high temperatures, followed by its accumulation and interaction with unburned fuel residues. Slagging begins in the lower section of the furnace and may extend to the convective sections of the steam generator, particularly in zones unprotected from intense radiant heat. Whether slagging occurs is primarily determined by the ash's chemical composition—namely, the content of silicon, aluminum, calcium, magnesium, and alkali metal oxides—and their relative proportions, which define the melting point of ash components. Therefore, understanding ash composition and accounting for it in boiler equipment design and operation is a critical factor in ensuring the efficient and safe performance of thermal energy systems.

For all analyzed ash and slag waste samples obtained from the power plants of Vostokenergo LLC, technological indices were calculated and assessed, including slagging and contamination factors. Based on the chemical composition of the ash, indicators of slag formation propensity and potential contamination behavior of ash particles on boiler heat exchange surfaces were determined. The results of these calculations are presented in Tables 6 and 7, respectively.

Table 6. Slagging factor of coal ash samples from the Karazhyra deposit consumed by the power plants of Vostokenergo LLP.

No.	Content, %	Name of the Power Plant				
		Belousovsky		Zhezkentsky	Ust-Talovsky	
		Boiler House in the Belousovka Village	Boiler House in the Altai Village	Boiler House in the Zhezkent Village	Boiler House in the Ust-Talovka Village	Boiler House of the Treatment Facilities of the City of Shemonaikha
1	$(Fe_2O_3 + CaO + MgO + K_2O + Na_2O)$	11.2	10.89	18.12	9.92	13.78
2	S_{total}, in coal	0.55	0.46	0.39	0.48	0.39
3	$(SiO_2 + Al_2O_3 + TiO_2)$	64.67	66.54	69.28	50.64	71.41
4	R_s	0.095	0.075	0.102	0.094	0.075

Table 7. Contamination factor of coal ash samples from the Karazhyra deposit consumed by the power plants of Vostokenergo LLP.

No.	Content, %	Name of the Power Plant				
		Belousovsky		Zhezkentsky	Ust-Talovsky	
		Belousovka Village	Altai Village	Zhezkent Village	Ust-Talovka Village	The City of Shemonaikha
1	$(Fe_2O_3 + CaO + MgO + K_2O + Na_2O)$	11.2	10.89	18.12	9.92	13.78
2	$K_2O + Na_2O$	2.4	1.85	2.43	2.5	2.5
3	$(SiO_2 + Al_2O_3 + TiO_2)$	64.67	66.54	69.28	50.64	71.41
4	R_f	0.42	0.30	0.64	0.49	0.48

The ash tendency to slag formation was assessed based on the calculation of the ash slagging factor (R_s), which is the ratio between the content of low-melting and high-melting components in the ash. According to the classification criteria, the value $R_s \leq 0.6$ indicates a low degree of slagging, values in the range $0.6 < R_s \leq 2.0$ indicate a medium degree, $2.0 < R_s \leq 2.6$ indicate a high degree, and at $R_s > 2.6$ the ash is characterized as prone to an ultra-high degree of slagging. Based on the results of the analysis, it was found that the R_s values for all the studied ash samples from the power plants of Vostokenergo LLC do not exceed the threshold of 0.6, which indicates that they belong to the category of ash with a low degree of slagging (Table 6).

The contamination potential of ash refers to its tendency to form deposits (contaminant layers) on the surfaces of heat exchange elements, which leads to reduced heat transfer and, consequently, a decrease in the thermal efficiency (coefficient of performance) of boiler units. The main factor determining ash contamination potential is the content of volatile compounds of alkali metals, primarily potassium (K_2O) and sodium (Na_2O) oxides. A high concentration of these components promotes intensive deposit formation due to the low melting temperatures of their compounds, which is particularly problematic during long-term equipment operation. Table 7 presents the contamination potential factor values for the analyzed samples, characterizing the possible impact of ash and slag waste on the performance of thermal power systems.

When the content of alkali metal oxides (K_2O and Na_2O) in ash exceeds 3%, the coal requires additional investigation to adjust combustion parameters and prevent deposit formation. In all studied samples, the content of K_2O and Na_2O ranges from 0.85% to

1.65%, which does not exceed the critical threshold. To evaluate the contamination potential of ash, the contamination index (R_f) is used. According to classification criteria, $R_f < 0.2$ indicates low contamination tendency, $0.2 \leq R_f < 0.5$—moderate contamination tendency, $0.5 \leq R_f < 1.0$—high contamination tendency, $R_f > 1.0$—very high contamination tendency. Based on the obtained data (Table 7), the ash from the Belousovsky power plant (Belousovka and Altaysky villages), as well as from the Ust-Talovsky power plant (Ust-Talovka village and the city of Shemonaikha), falls within the moderate contamination tendency category. In contrast, the ash from the Zhezkent power plant is characterized by a high contamination tendency, which requires attention during the operation of the associated boiler units.

4. Conclusions

The conducted study enabled a comprehensive assessment of the combustion efficiency of coal from the Karazhyra deposit in the boiler units of Vostokenergo LLP and revealed the impact of fuel characteristics on energy and environmental performance. The average thermal efficiency (boiler efficiency) was found to be 66.03%, with a maximum value of 75% recorded at the Zhezkent energy facility, indicating varying equipment performance across different sites.

It was established that the actual coal properties deviate from design values: lower heating value (LHV) of 19.41 MJ/kg, elevated ash content (21.4%), and relatively low sulfur content (0.45%). While these properties indicate low energy potential, they contribute to reduced sulfur-containing emissions. The ash and slag waste (ASW) generated during operation is characterized by high unburned carbon content (14–35%) and a variety of morphological forms. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses revealed both amorphous and crystalline phases, microspheres, and porous carbonaceous granules. The ash color (ranging from black to light gray) was found to correlate with the degree of incomplete combustion.

Technological indices were calculated: the slagging factor ($R_s \leq 0.6$) indicates low slagging tendency, while the fouling factor (R_f) shows that ash from the Zhezkent energy facility has a high tendency to form deposits on heat exchange surfaces, necessitating specific operational strategies. The variability in the physicochemical properties of coal and ash among the facilities justifies the need for a differentiated approach to combustion regimes, maintenance practices, and waste utilization.

To increase the efficiency of burning coal with high ash content (21.4%) at Vostokenergo LLP's power plants, it is advisable to implement differentiated strategies for adjusting the air–fuel regime using quantitative indicators. The optimal oxygen content in the flue gases should be maintained within 3.5–4.5%, which corresponds to an excess air ratio of about 1.15–1.25. This mode ensures stable combustion, promotes complete afterburning of volatile and solid residues, reduces the proportion of unburned carbon, and minimizes heat losses with exhaust gases. For coals with a high ash content, it is advisable to use a stepwise air supply mode and local temperature control in the flare zone, which reduces the risk of slag formation and deposits on heating surfaces. The proposed parameters can be refined based on operational observations and adapted to the specifics of specific equipment and operating modes.

The following practical recommendations are proposed:

- Adjustment of the air–fuel ratio based on actual coal properties;
- Implementation of automated monitoring systems for flue gas temperature and composition;
- Regular monitoring of ash composition as an indicator of combustion completeness.

The development of waste disposal programs with a high content of SiO_2 and Al_2O_3 (up to 65–75%) should take into account the potential of these wastes as secondary mineral

raw materials. Promising areas are the use of ash as pozzolan additives to cement [27], components for geopolymers [28], technical ceramics [29], gypsum compositions [30], thermal insulation products [31], as well as for the production of aerated concrete [32] and non-autoclaved cellular concrete [33]. Studies show that the substitution of up to 30% of Portland cement with highly reactive ashes does not reduce the strength characteristics of cement composites [34].

The results obtained can be used to improve the energy efficiency and environmental safety of small- and medium-scale boiler systems, as well as to support the development of standards and modernization programs for heat generation facilities in the coal energy sector.

The established fact of a low sulfur content in the coal of the Karazhyra deposit (0.45%) helps to reduce SO_x emissions, but it is accompanied by a high level of unburned carbon in ash and slag waste (14–35%), which reduces energy efficiency and makes it difficult to dispose of them. Such a compromise between environmental and energy characteristics requires a systematic life cycle assessment (LCA), including full consideration of CO_2 and SO_x emissions, energy consumption for re-incineration or ash disposal, as well as environmental effects from the use of waste in building materials. Conducting an in-depth LCA analysis seems to be a promising area for further research and will allow balancing the strategy of operating boiler installations, taking into account the cumulative environmental impact.

It should be noted that the study is based on data collected in 2016–2017, which limits the possibility of identifying long-term trends in changes in the efficiency of power plants and the quality of fuel burned. Possible seasonal variability (for example, fluctuations in the moisture content of coal in winter and summer), changes in the composition of the supplied coal, as well as technical updates or degradation of equipment over time, can have an impact on energy and environmental performance. Therefore, the presented results should be interpreted as a moment slice reflecting typical working conditions in the time interval under study. To assess the dynamics and sustainability of the identified patterns, continued monitoring is required with an expanded time range and the inclusion of new operational data.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr13082467/s1. Table S1: Results of the physicochemical analysis of ash and slag waste from boiler units of the energy centers of Vostokenergo LLP; Table S2: Results of microanalysis of ash and slag waste from energy centers, wt.%.

Author Contributions: Conceptualization, N.S., V.L., G.D. and M.S.; methodology, N.S. and V.L.; software, V.L. and M.S.; formal analysis, N.S., V.L. and G.D.; investigation, N.S., V.L., G.D. and M.S.; data curation, R.A. and R.R.; writing—original draft preparation N.S., V.L. and G.D.; writing—review and editing, N.S., V.L., G.D., M.S., R.A. and R.R.; visualization, N.S. and G.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article. The data presented in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: Vadim Litvinov is employed by Proektno-Ekologicheskoe bjuro LLP, and Maksat Shaikhov is employed by Vostokenergo LLP. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Fuel and Energy Balance of the Republic of Kazakhstan. Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan. 2023. Available online: https://stat.gov.kz/en/industries/business-statistics/stat-energy/publications/205502/ (accessed on 11 July 2025).
2. Analysis of the Wholesale Market of Electric Energy and Capacity for 2023. JSC "Kazakhstan Electricity Grid Management Company" (Kazakhstan Electricity Grid Operating Company) «KEGOC», Department of Market Analysis and Legislative Initiatives, Astana. 2024. Available online: https://www.kegoc.kz/upload/iblock/0d7/tgrsztaci3oypn9po5x1eoxnz448si2t.pdf (accessed on 11 July 2025).
3. Putilova, I.V. Current State of the Coal Ash Handling Problem in Russia and Abroad, Aspects of the Coal Ash Applications in Hydrogen Economy. *Int. J. Hydrogen Energy* **2023**, *48*, 31040–31048. [CrossRef]
4. Nacke, L.; Vinichenko, V.; Cherp, A.; Jakhmola, A.; Jewell, J. Compensating affected parties necessary for rapid coal phase-out but expensive if extended to major emitters. *Nat. Commun.* **2024**, *15*, 3742. [CrossRef]
5. Kopobayeva, A.; Baidauletova, I.; Amangeldikyzy, A.; Askarova, N. Trace Elements Distribution in the k7 Seam of the Karaganda Coal Basin, Kazakhstan. *Geosciences* **2024**, *14*, 143. [CrossRef]
6. Hui, J.; Zhu, S.; Li, Z.; Cao, X.; Lyu, Q. Mechanism of preheating modification on NOx emission reduction during peak shaving of different coal ranks. *Process Saf. Environ. Prot.* **2025**, *193*, 432–445. [CrossRef]
7. Electric Power Industry of Kazakhstan: Key Facts. Kazakhstan Electricity Grid Operating Company "KEGOC". 2024. Available online: https://www.kegoc.kz/ru/electric-power/elektroenergetika-kazakhstana/ (accessed on 11 July 2025).
8. Recycling and Reuse of Waste Ash. Analytical Report of the OIPiUL "Self-Regulatory Organization 'Association of Practicing Ecologists'", Kazakhstan, 2022. Available online: https://ecounion.kz/?p=7555 (accessed on 11 July 2025).
9. Nurpeisova, M.; Estemesov, Z.; Gabbasov, S.; Ashimova, A.; Bek, A. Studying the properties of ash and slag waste for use in the manufacture of construction products. *Min. Miner. Depos.* **2023**, *17*, 102–109. [CrossRef]
10. Straupnik, I.A. An overview of the environmental impact of coal industry waste. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1070*, 012004. [CrossRef]
11. Wang, Z.; Deguchi, Y.; Watanabe, H.; Kurose, R.; Yan, J.; Liu, J. Improvement on Quantitative Measurement of Fly Ash Contents Using Laser-Induced Breakdown Spectroscopy. *J. Flow Control. Meas. Vis.* **2015**, *3*, 10–21. [CrossRef]
12. Yao, S.; Yao, X.; Zhang, L.; Qin, H.; Yu, Z.; Chen, X.; Lu, Z.; Lu, J. Improving the LIBS quantitative analysis of unburned carbon in fly ash based on the optimization of reference value. *Energy Fuels* **2020**, *34*, 6483–6489. [CrossRef]
13. *GOST 25543-88*; Brown Coals, Hard Coals and Anthracites. Classification According to Genetic and Technological Parameters. Moscow, Russia, 1990. Available online: https://meganorm.ru/Data2/1/4294828/4294828906.pdf (accessed on 11 July 2025).
14. Elyubaeva, N.B.; Bayakhmetova, B.B.; Murzagulova, K.B. Physicochemical methods of studying coal from the karazhira deposit. *Forum Young Sci.* **2017**, *4*, 251–257. (In Russian)
15. Available online: https://www.karazhyra.kz/index.php (accessed on 11 July 2025).
16. Dinzhumanova, R.T.; Bayakhmetova, B.B.; Kassenova, N.B.; Klivenko, A.N. Physico-chemical investigation of stone coals of "Karazhyra" field. *Bull. Karaganda Univ. Chem. Ser.* **2019**, *4*, 98–104. [CrossRef]
17. Available online: https://www.ugolpromstroy.ru/goods/64668460-kamenny_ugol_marki_dpk_sortovoy_25_300_mm_kazakhstanski_karazhyra (accessed on 11 July 2025).
18. Available online: https://kase.kz/files/emitters/KZHR/kzhrp_2019_rus.pdf (accessed on 11 July 2025).
19. Khazhidinova, A.R.; Stepanova, O.A.; Ermoolenko, M.V.; Khazhidinova, A.S. To the question of efficient burning of non-design fuel coal from the Karazhyra cut. *Bull. NNC RK* **2023**, *2*, 58–65. (In Russian) [CrossRef]
20. Alimgazin, A.S.; Alimgazina, S.G. Prospects for the application of energy-saving heat pump technologies using alternative energy sources at the Aksu Ferroalloy Plant—A branch of JSC TNC Kazchrome. *Bull. S. Toraighyrov PSU Ser. Power Eng.* **2019**, *4*, 35–38. (In Russian)
21. Khazhidinova, A.; Stepanova, O.; Yermolenko, M.; Kassymov, A.; Aldazhumanov, Z.; Shayakhmetov, Y.; Baybalinova, G.; Nyssanbayeva, S.; Astemessova, K.; Turlybekova, G. Influence of contamination of low-temperature heating surfaces of boiler on the intensity of convective heat exchange during the burning of nondesign fuel. *Heat Transf. Res.* **2022**, *53*, 83–96. [CrossRef]
22. *ST RK ISO 18283-2006*; Hard Coal and Coke-Manual Sampling (IDT). Moscow, Russia, 2013. Available online: https://meganorm.ru/Index/52/52001.htm (accessed on 11 July 2025).
23. *RD 34.09.603-88*; Procedural Guidelines for Organization Monitoring Composition and Properties of Ash and Slag Emitted by Thermal Power Station Consumers. Moscow, Russia, 1988. Available online: https://meganorm.ru/Index2/1/4294816/4294816567.htm (accessed on 11 July 2025).
24. Doherty, M.B. Evaluation of Coal Quality Impacts on Power Plant Operations. *Coal Prep.* **1998**, 7–51.
25. *ST RK 1816-2014*; Coals of the Karazhyra Deposit. General Specifications. Astana, Kazakhstan, 2014. Available online: https://online.zakon.kz/Document/?doc_id=37456225 (accessed on 11 July 2025). (In Russian)

26. Vostokenergo LLP. *Greenhouse Gas Inventory Report, 2016–2017*, Internal Report; Vostokenergo LLP: Ust-Kamenogorsk, Kazakhstan, 2017. (In Russian)
27. Poudel, S.; Menda, S.; Useldinger-Hoefs, J.; Guteta, L.E.; Dockter, B.; Gedafa, D.S. The Use of Ground Coal Bottom Ash/Slag as a Cement Replacement for Sustainable Concrete Infrastructure. *Materials* **2024**, *17*, 2316. [CrossRef]
28. Yatsenko, E.A.; Trofimov, S.V.; Goltsman, B.M.; Li, W.; Smoliy, V.A.; Ryabova, A.V.; Klimova, L.V.; Izvarin, A.I. Study on the Curing and Foaming of Surfactant-Modified Geopolymer Gels Based on Ash and Slag Waste from Coal Combustion. *Gels* **2024**, *10*, 19. [CrossRef] [PubMed]
29. Buravchuk, N.I.; Guryanova, O.V.; Parinov, I.A. Use of technogenic raw materials in ceramic technology. *Open Ceram.* **2024**, *18*, 100578. [CrossRef]
30. Kosivtsov, Y.Y.; Chalov, K.; Sulman, M.G.; Lugovoy, Y.; Novichenkova, T.; Petropavlovskaya, V.; Gadzhiev, S.; Popel, O. Use of Ash and Slag Waste from Thermal Power Plants as an Active Component of Building Materials. *Chem. Eng. Trans.* **2021**, *88*, 337–342. [CrossRef]
31. Abdrakhimov, V.Z. Influence of Ash and Slag on the Characteristics of Heat Insulation Based on Metallurgical Waste. *Coke Chem.* **2023**, *66*, 310–315. [CrossRef]
32. Rudenko, O.V.; Charykov, N.A.; Kulenova, N.A.; Sadenova, M.A.; Anop, D.K.; Kuldeyev, E. Aerated Concrete, Based on the Ash of Thermal Power Plants, Nanostructured with Water-Soluble Fullerenols. *Processes* **2024**, *12*, 2139. [CrossRef]
33. Rudenko, O.; Beisekenov, N.; Sadenova, M.; Galkina, D.; Kulenova, N.; Begentayev, M. Physical–Mechanical and Microstructural Properties of Non-Autoclaved Aerated Concrete with Ash-and-Slag Additives. *Sustainability* **2025**, *17*, 73. [CrossRef]
34. Golewski, G.L. Assessing of water absorption on concrete composites containing fly ash up to 30% in regards to structures completely immersed in water. *Case Stud. Constr. Mater.* **2023**, *19*, e02337. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.