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Article

CIRCULAR ECONOMY IN MATERIAL ECODESIGN: BRICK PRODUCTION FROM MINE WASTE

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ABSTRACT

The construction materials industry increasingly faces difficulties in securing high-quality raw materials for ceramic products such as bricks. In Bulgaria, natural clay resources are limited, while growing demand for building materials and the transition toward a circular economy require alternative raw materials. This study examines the potential for utilizing accumulated mining waste from the Pernik coal basin as a substitute for natural clay in brick production. Laboratory analyses, including X-ray diffraction (XRD), chemical composition, and grain-size distribution were conducted to determine the mineralogical and technological properties of the material. The results show that the mining waste contains significant clay minerals, with kaolinite contents of up to 30% and a plasticity index of 22.3, confirming its suitability for ceramic production. A techno-ecological-economic analysis indicates that up to 60% of conventional clay raw materials can be replaced without compromising product quality. The economic evaluation demonstrates positive net present values for all analyzed production capacities. The results confirm the potential of mining waste as a secondary raw material supporting circular economy practices.

Keywords: *circular economy; material eco-design; mining waste; utilization; bricks*

INTRODUCTION

Coal mining residues are widely recognized as a significant environmental concern due to their large volumes and potential impact on soil, water, and air quality. Haibin and Zhenling [1] identify coal mining waste as a serious environmental threat and emphasize that higher-value use represents one of the most effective approaches for reducing its negative environmental impact while improving resource efficiency. Consequently, the valorization of industrial solid waste, particularly coal mining residues, has become an important research field in recent years [2-4].

Recent studies highlight the potential of recycling and cascading utilization of industrial by-products as key elements of circular and green economy strategies. In this context, mining waste has attracted considerable attention as a potential alternative raw material in the ceramic

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industry [2,5–8]. Research conducted by Lemeshev et al. (2004) demonstrates that coal mining residues can be successfully used in the production of ceramic and construction materials due to their suitable physical and mechanical properties. Furthermore, the wet co-grinding of clay and coal mining waste has been shown to improve the physical and mechanical characteristics of ceramic products.

In many countries, including Bulgaria, the extraction of natural clay resources for ceramic production is associated with increasing environmental pressure and the gradual depletion of high-quality deposits. At the same time, large quantities of mining waste have accumulated in coal mining regions such as the Pernik coal basin. These deposits represent both an environmental challenge and a potential source of secondary raw materials for the construction materials industry.

Within the framework of circular economy principles and material eco-design approaches, the utilization of mining waste in brick production offers opportunities to reduce the extraction of natural resources, minimize waste accumulation, and improve resource efficiency in the construction sector.

The aim of this study is to examine the potential for utilizing accumulated mining waste from the Pernik coal basin in Bulgaria as an alternative raw material in brick production through a techno-ecological-economic assessment within a circular economy framework.

MATERIALS AND METHODS

Based on a review of the characteristics of coal provinces and their basins in Bulgaria, the Pernik Basin within the Pernik Coal Province was selected as the most promising source of clay materials derived from mining waste that could substitute natural raw materials [9]. In this basin, coal-forming processes occurred relatively late, from the middle–late Oligocene to the late Oligocene–early Miocene [10, 11]. The clay content varies, with unweathered marls containing about 52.0% physical clay and weathered marls about 66.4%. Among the primary minerals [12], quartz and feldspars dominate, while montmorillonite, hydromicas, and kaolinite prevail among the secondary minerals [13-15].

To assess the suitability of existing mining waste from the Pernik coal basin, samples were collected from landfills formed in different parts of the basin and at different times. After analyzing the formation periods, extraction methods, and disposal practices of mining waste in the Pernik Basin, five composite samples were collected from different landfills according to the criterion of generation period, in order to evaluate the influence of atmospheric conditions on the deposited mining waste [16, 17].

According to the ÖNORM S 2123-3 standard [18], the number of individual samples was set at 50, with a minimum composite sample weight of 2 kg. Larger quantities were collected to ensure sufficient material for both laboratory and semi-industrial studies on waste utilization.

Table 1: Information on sampling points in the Pernik Coal Basin (PB).

Sample	Altitude, m	Year of generation	Sample weight,
Sample 1	743	2012	29.250
Sample 2	738	2010	34.425
Sample 3	724	1990	32.575
Sample 4	739	2000	32.575
Sample 5	759	1965	37.550

The locations of the sampling points are presented in Figure 1.

Figure 1. Location of sampling points in the Pernik coal basin area

The samples were analyzed to determine the elemental and mineral composition of the mining waste. Elemental composition in the samples was determined in accordance with BDS EN 13657, using ICP–Atomic Emission Spectroscopy (ICP-AES) with an inductively coupled plasma excitation source operating at a temperature of 8000 K.

An additional X-ray Fluorescence (XRF) analysis was performed following the BDS EN 15309:2007 standard to determine the oxides of the main rock-forming elements in the samples.

The mineralogical composition was investigated by X-ray diffraction (XRD), with phase identification conducted using the American reference database JCPDS, containing approximately 145,000 reference patterns of minerals and chemical compounds. Quantitative determinations were made using the Peter and Kalman method, applying pre-established calibration coefficients (corundum numbers) for the individual mineral phases.

In addition, the clay fraction was preliminarily separated from the waste using water-based separation. Its physical characteristics were examined and compared with the applicable standards for the production of bricks and tiles according to BDS 14175:1986 [19].

To perform a techno-ecological-economic analysis of the proposed options for the utilization of mining waste, the "Pollution, Protection, Payment" approach, also known as the "3P analysis," was applied.

The essence of this approach lies in the ecological assessment of each stage of the production process, including a techno-ecological-economic evaluation of the equipment used for its implementation. The ecological analysis is based on the material balance of the process and includes the interpretation of the technical and economic level indicator T (2) and the ecological-economic level indicator EC (1) during the operation of a solid waste processing plant [20; 21].

Equations applied in the "3P – Pollute, Protect, Pay" approach are as follows:

$$EC = T \,.\, ATC \tag{1}$$

$$T = M \,.\, C.\, E.\, PI \tag{2}$$

$$M = M1 : M2 \tag{3}$$

$$C = \Sigma C\,1 : \Sigma C2 \tag{4}$$

$$E = \Sigma C3 : \Sigma C4 \tag{5}$$

$$D = \Sigma C5 : \Sigma C6 \tag{6}$$

where: M – coefficient of utilization of the production capacity; M_1 – annual actual capacity of the installation, thousand t; M_2 – annual practical capacity of the installation, thousand t; C – coefficient of utilization of the input waste; C_1 – mass flow rate of the obtained products, t/h or kg/h; C_2 – mass flow rate of the input waste, t/h or kg/h; E – efficiency coefficient of the purification (treatment) equipment; C_3 – mass flow rate of waste substances captured by the purification equipment, t/h or kg/h; C_4 – mass flow rate of waste substances, t/h or kg/h; PI – degree of environmental pollution; C_5 – maximum permissible concentration (MPC) of the waste substance, kg/Nm^3 or kg/h (t/h); C_6 – mass flow rate of waste substances not captured by the purification equipment, t/h or kg/h; ATC – cost of producing one unit of product from conventional raw materials relative to the price of the product obtained from waste, lv./lv. product. When implementing an eco-technology, according to Equations (3)–(6), the coefficients M, C, E, and D should be approximately equal to 1, without exceeding this value. This is because an optimal technological process is achieved when:

- the production capacity of the installation is close to its actual operating capacity;
  - the input waste materials are completely utilized during the process;
  - the efficiency coefficient of the purification equipment approaches its maximum value, i.e., also tends toward 1;
  - the waste substances released into the environment during the implementation of the solid waste processing technology occur at concentrations corresponding to a low level of environmental pollution.

Under the optimal implementation of the eco-technology, the coefficients I and T should also tend toward 1 [21].

For the analysis of investments in the current study are used commonly implemented methodologies for investments analysis which are the following:

- Annual Cash Flows (CF) analysis. The cash flows are estimated using the formula below:

$$CF = (TR - TC)0.9 + D \quad (7)$$

where TR represents total revenues from brick sales; TC denotes total annual operating costs of the brick production facility; and D is annual depreciation calculated using the straight-line method. The coefficient 0.9 reflects the share of net profit after corporate tax deduction, considering the flat corporate tax rate of 10% in Bulgaria.

- Annual discounted cash flows (PV, present value) were estimated as a 25-year annuity. This period corresponds to the minimum depreciation period for buildings and similar assets under Bulgarian corporate tax law.

$$PV = CF\frac{1-\frac{1}{(1+r)^{25}}}{r} \quad (8)$$

where PV represents the total present value of discounted cash flows, r is the discount rate, and 25 denotes the investment lifespan in years.

- Net present value (NPV) (NPV) is applied as a general indicator for assessing the efficiency of alternative investment options under different production scales.

$$NPV = PV - I_i \quad (9)$$

RESULTS AND DISCUSSION

The results of the conducted chemical analyses indicate that, with regard to the pH of the mining waste in the individual samples that had been exposed to outdoor conditions for different periods, no significant changes in the pH values of the solid waste were observed. The mining waste exhibits a neutral to slightly alkaline reaction, which does not undergo substantial variations regardless of the year in which the mining waste was generated.

The total sulfur content varies from 0.47 mg/kg to below 0.01 mg/kg, while the sulfide sulfur content in the solid mining waste in all samples remains at levels up to 0.10 mg/kg. The results obtained from the testing of the mining waste are presented in tabular form for all analyzed samples (Table 2).

Table 2. Chemical element content in mining waste samples – Pernik Coal Basin.

№	Name of the metric	Unit of measurement	Test results				
			Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
1	V	mg/kg	106	107	107	91	110
2	Cr	mg/kg	56	47	60	43	55
3	Co	mg/kg	24	21	24	21	21
4	Ni	mg/kg	40	36	42	35	39
5	Cu	mg/kg	74	75	73	60	71
6	Zn	mg/kg	72	78	85	64	88
7	As	mg/kg	10	60	52	8	45
8	Mo	mg/kg	3	4	<3	<3	3
9	Cd	mg/kg	1.0	1.0	1.0	1.0	1.0
10	Ba	mg/kg	338	1229	1211	367	981
11	Pb	mg/kg	30	37	36	29	34
12	Hg	mg/kg	<0.20	<0.20	<0.20	<0.20	0.34
12	Fe_2O_3	%	6.85	7.32	7.54	6.69	6.26
13	MnO	%	0.11	0.12	0.13	0.12	0.08
14	TiO_2	%	0.77	0.64	0.76	0.67	0.81
15	CaO	%	6.89	11.38	8.42	9.21	4.04
16	K_2O	%	1.19	0.44	1.27	0.82	1.28
17	P_2O_5	%	0.05	0.09	0.05	0.05	0.02
18	SiO_2	%	55.33	46.23	54.94	55.09	50.83
19	Al_2O_3	%	15.45	13.10	15.62	15.67	14.03
20	MgO	%	0.23	0.21	0.36	0.30	0.10
21	Na_2O	%	0.12	0.12	0.11	0.16	0.10
22	S	%	0.11	0.47	<0.01	0.010	0.28
23	S^{2-}	%	<0.10	0.10	<0.10	<0.10	<0.10
24	loss on ignition	%	12.68	20.08	10.50	10.30	24.63
25	pH	pH	8.58	7.83	8.51	8.53	7.79

The mineral composition of each sample was analyzed using X-ray diffraction (XRD) and the results are presented in Figure 2 [22].

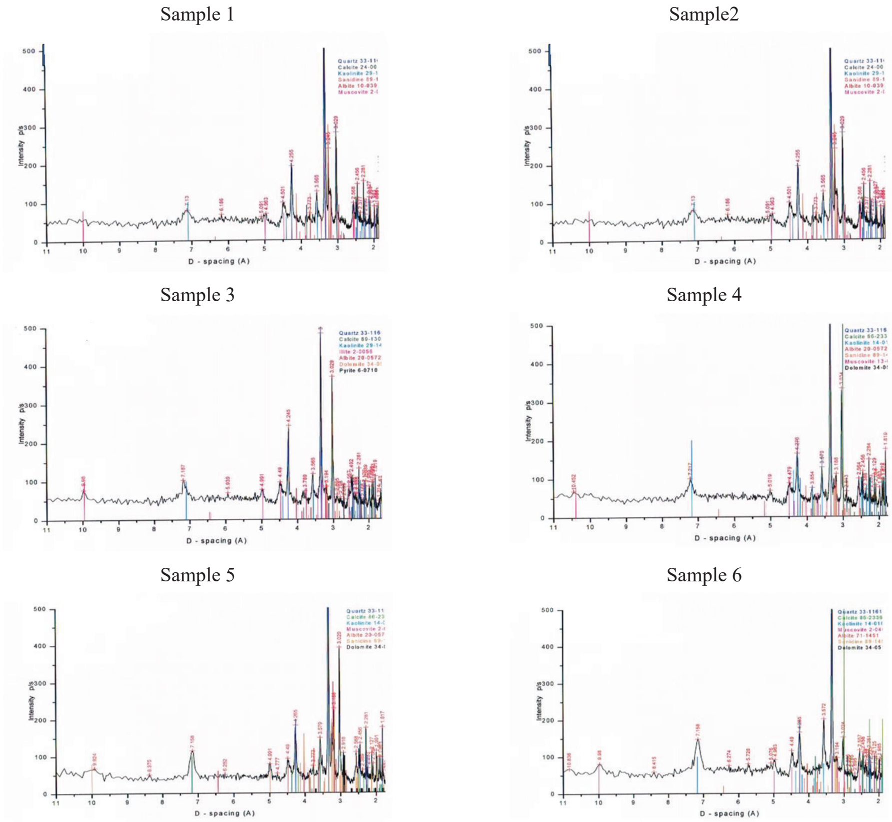

Figure 2. X-ray diffraction analysis of samples from the experimental site

Based on the results of the X-ray diffraction analysis of samples from the Pernik coal basin, the mineral composition and its variations were determined. No significant changes in mineral composition were observed over time. Kaolinite is present in considerable amounts, reaching up to 31%. These findings confirm previous studies conducted in the Pernik basin, which identify quartz, kaolinite, illite, and siderite as the main minerals, and pyrite, marcasite, and calcite as secondary minerals [23].

To separate the fine fraction, expected to contain mainly clay minerals, water separation was performed on five mining waste samples [24]. The obtained fine fraction was analyzed according to BDS EN ISO 17892-4:2017 (Geotechnical investigation and testing – Laboratory testing of soil – Part 4: Determination of particle size distribution) [25]. The grain-size composition of the sample was determined, and the results are presented in Table 3.

Table 3. Particle size distribution of the sub-sieved fraction of mining waste

Faction	mm	%
Gravel	>2.0	-
Sand	2.0-0.1	13
Silt	0.1-0.005	57
Clay	<0.005	30

Water separation significantly increased the silt and clay fractions in the samples, with the clay content reaching up to 30%.

Clay is the main raw material used in the production of ceramic bricks. Studies indicate that suitable brick clay should exhibit low shrinkage and swelling, appropriate firing color, relatively low firing temperature, and the ability to produce dry and fire-resistant bricks [26].

In Bulgaria, the production of bricks and tiles from clay raw materials is regulated by BDS 14175:1986 [19]. According to this standard, clay raw materials are evaluated based on mineralogical-petrographic characteristics, chemical composition, grain-size distribution, and technological properties. The chemical composition is assessed through the content of major oxides, expressed as mass percentages. The sum of alkaline-earth carbonates ($CaO + MgO$) must not exceed 25%.

Analyses of samples from the Pernik coal basin show compliance with this requirement, with MgO content of 0.36% and CaO content of 11.38%, resulting in a combined value below the 25% limit.

To assess the suitability of clay materials for brick and tile production, technological properties such as natural moisture, plasticity, harmful impurities, shrinkage, and sintering are also evaluated according to BDS 14175:1986 [19]. The results are presented in Table 4.

Table 4. Results of laboratory testing of an average sample of sub-sieved fraction of mining waste from the Pernik coal province

Moisture content Wn, %	20.93
Liquid limit (W_L) %	42.8
Plastic limit Wp, %	20.5
Plasticity index lp, %	22.3
Consistency index lc	0.98

According to BDS 14175:1986, the plasticity index of clay used for brick and tile production should not be lower than 7, while the analyzed samples show a value of 22.3%, indicating high suitability for ceramic production. This suggests that clay-rich mining waste may serve as a potential alternative to natural clays, reducing the need for additional extraction.

The evaluation of clay raw materials under BDS 14175:1986 includes mineralogical–petrographic characteristics, chemical composition, grain-size distribution, and technological properties. In this study, the assessment focuses on mining waste dumps from the Pernik coal basin rather than a natural deposit, aiming to explore its potential end-of-waste utilization.

According to available data (EIA, 2010), the design capacity of the selected brick production facility is 600 t/day (198,000 t/year), while the actual capacity is 530 t/day (174,900 t/year). The required raw materials include 154,296 t/year of clay, 25,704 t/year of coal slurry, and 35,000 t/year of water, with electricity consumption of approximately 8.1 GWh/year.

Analyses show that the fraction below 0.045 mm from Pernik mining waste, composed mainly of dust and clay particles, is classified under BDS 676-85 as dust clay. With a plasticity index of 22.3%, the material is suitable as an alternative clay raw material for brick and tile production. In addition, the presence of residual coal particles may reduce the need for additional coal slurry during firing.

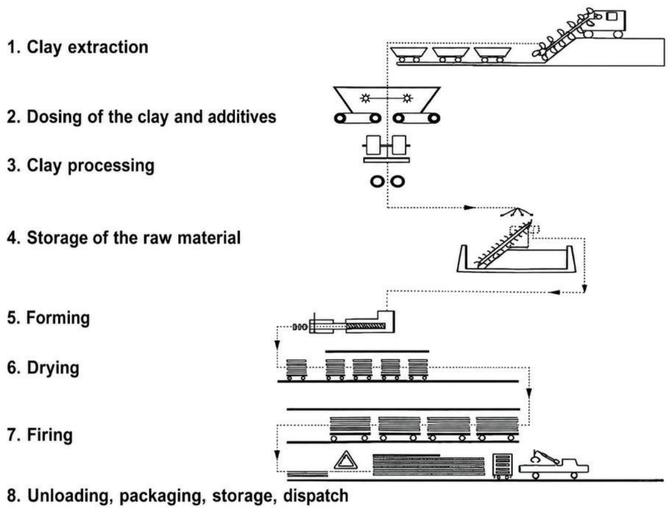

Figure 3. Technological scheme for brick production (EIA, 2010).

Air pollution is expected from both organized and unorganized sources. Unorganized emissions mainly result from transport operations, while organized emissions arise primarily from combustion processes, generating pollutants such as CO_2, SO_2, NO_x, and particulate matter.

The gas flow rate is 150,000 Nm³/h at an approximate temperature of 50°C, and no additional flue gas treatment systems are planned. The expected emissions from organized sources are presented in Table 5.

Due to the specific characteristics of the production process, no wastewater is generated, but solid waste is produced. This typically consists of defective bricks or fragments, classified under waste code 10 12 08 according to the Bulgarian Waste Classification Regulation. These materials are reused in the production process or for internal road maintenance, representing on-site waste recovery. The quantity of such waste is estimated at approximately 1% of the input materials (clay and coal slurry).

Table 5. Sources of organized emissions in brick production.

No.	Source name	Height (m)	Diameter (mm)	T (°C)	Flow rate (Nm³/h)	Pollutant	ELV (mg/Nm³)	Emission (mg/Nm³)
1	Kiln stack	16	1000	250	88,000	Dust/PM	40	40
						(NOx)	500	500
						(SOx)	750	750
						Total organic carbon	20	20
2	Dryer stack	11	1400/1700	50	150,000	Dust/PM	40	40
						(NOx)	80	80
						(SOx)	100	100
						Total organic carbon	20	20
3	Dust collector stack	11	400	–	7,600	Dust/PM	40	40

In order to maintain the quality of the resulting product, based on literature data [5] we replace 60% of the clay and coal slurry used with mine waste. The exact amount of replacement of conventional raw materials, so as not to compromise the quality, can be determined experimentally or through simulation models. The obtained data for the input raw materials are given in Table 6, and a material balance diagram in Figure 4.

Table 6. Quantities of substances required for the production of bricks by utilizing coal mining waste

Material	Quantity (t/year)
Waste	108,000
Water	35,000
Clay	61,718
Coal slurry	10,282
Total input	**215,000**

Technical aspect. Mining waste from the Pernik coal basin can be utilized for brick production due to its high content of fine clay particles (about 60% clay dust). According to available data, the designed production capacity of the installation is 600 t of bricks per day, equivalent to 198,000 t per year. The actual operating capacity is 530 t per day, resulting in an annual production of approximately 174,900 t of bricks.

Environmental aspect. Environmental impact assessment considers emissions from both organized and unorganized air pollution sources. The impact coefficient for unorganized emissions is 0.70, while no pollution from organized sources is expected (coefficient 1.0). The dust collection system returns all captured particles to the production mixture, preventing waste generation. No wastewater is discharged, and all solid residues are reused in the process. According to the methodology of Todorova and Dombalov (2005), the calculated overall environmental pollution coefficient, based on the average impact of liquid, solid, and gaseous emissions, is 0.92.

Economic aspect. The economic evaluation uses the following reference prices for raw materials and energy:

1. Water – 0.86 EUR/m^3
2. Diesel fuel (21.02.2015) – 1.12 EUR/L
3. Electricity for industrial consumers – 0.09 EUR/kWh
4. Clay – 357.91 EUR/t
5. Coal slurry – 40.91 EUR/t

The price of mining waste is estimated based on its clay content (about 60%), resulting in a calculated value of 214.74 EUR/t. A comparison between the costs of brick production from conventional raw materials and those incorporating mining waste indicates a cost ratio of 1.23 EUR per EUR of product.

The economic viability of brick production from mining waste should be considered in a strategic, long-term context. The application of such technology should demonstrate economic benefits for investors over a period exceeding five years. Profitability may arise both from the establishment of a new production facility and from the integration of the technology into an existing enterprise.

In this context, the cost–benefit analysis is mainly influenced by the following parameters:

- Investment costs, depending on the production capacity of the installation. Based on the currently available data, which allow only a preliminary assessment of the feasibility of such installations, capital costs represent one of the key determinants of investment efficiency.
- Discount rate applied to future cash flows. The determination of this rate remains largely conditional, as the expected return from similar investments depends on comparable scales of capital expenditure and associated risks. At present, there is no officially published information or study recommending a specific discount rate for such projects. In this study, a baseline discount rate of 5.8% is applied, consistent with commonly used ranges for long-term industrial investments, reflecting both the time value of money and project-related risk [28]. To ensure robustness of the results, a sensitivity analysis is conducted by increasing the discount rate by 10%, in line with recommended practices in the evaluation of sustainable and circular economy projects [27].

The capital costs for establishing a new production facility are substantial, ranging from EUR 0.5 million to EUR 10 million, depending on the production capacity. Table 4 presents the possible investment cost ranges for the construction of a brick production installation.

Table 4. Investment parameters of brick production installations

Type of producer	Actual capacity (bricks/day)	Annual actual capacity (bricks/year)	Annual actual capacity (tons, ~3 kg/brick)	Investment cost for equipment (EUR million)*
Small to medium-sized enterprise	80,000 – 150,000	≈ 24–45 million	≈ 72,000 – 135,000	1.5–7.0
Large automated installations	200,000 – 350,000+	≈ 60–105 million	≈ 180,000 – 315,000	≥ 20.0

***Source: Startup**

The table indicates that investment projects for the utilization of mining waste can operate at different scales of production, resulting in significantly different financial plan parameters. For the purposes of this study, several scenarios are analysed and modelled based on a reference technology with a capacity of 198,000 t/year.

The data used are averaged values derived from multiple information sources and should be considered indicative, as the prices of these inputs are typically subject to individual contractual agreements. Electricity and water prices represent national average levels for 2025, while wage values are based on average values from the Eurostat Structural Business Statistics. The results are presented in Tables 5 and 6.

Table 5. The operational costs per unit of ptoduction

Raw material	Unit price	Price unit	Consumption	Quantity unit
Clay	350	EUR/t	61,718	t
Coal slurry	136.47	EUR/t	10,181	t
Waste	89.41	EUR/t	108,000	t
Water	0.256	EUR/m³	35,000	m³
Electricity	0.0085	EUR/kWh	8,100,000	kWh

Table 6. Operational annual costs for each capacity level

Capacity	Material Costs	Workers	Labour Costs	Total costs	Unit Costs	Revenues at Capacity
72000	11899924.03	40.00	469186.31	12369110.33	171.79	15552000
198000	32724791.07	90.00	1055669.19	33780460.26	170.61	42768000
315000	52062167.61	165.00	1935393.51	53997561.12	171.42	68040000

The results with the estimated NPVs through the models (7)-(9) and the data from tables 5 and 6 are presented in the next Table 7

Table 7. NPS of the investments in the conventional technology and the proposed in the current research

Capacity	NPV-new, EUR	NPV-conventional, EUR
72000	4068951.559	3596121.014
198000	6178390.836	4878106.838
315000	18046050.09	15977416.46

The results presented in Tables 4–6 indicate that the utilization of mining waste in brick production can be economically feasible across different production scales. As production capacity increases, both total operational costs and revenues grow proportionally, while unit production costs remain relatively stable at around 170–172 EUR per ton, indicating the presence of economies of scale and cost stability in the production process. The cost structure is dominated by material costs, which represent the largest share of operational expenditures, while labor costs remain comparatively moderate even at higher capacities due to the increasing level of automation. The investment analysis further confirms the economic potential of the technology: the Net Present Value (NPV) is positive in all analyzed scenarios and consistently higher for the technology incorporating mining waste compared to conventional production. This suggests that the proposed approach not only improves resource utilization but also enhances the financial attractiveness of brick production projects, particularly at larger production capacities where the economic benefits become more pronounced.

In order to evaluate the robustness of the investment results and to assess the impact of key economic parameters on project viability, a sensitivity analysis was conducted. The analysis examines the effect of a 10% increase in three critical variables—cash flows (CF), discount rate (r), and investment costs (I)—on the resulting Net Present Value (NPV) of the investment project. The assessment was performed for the three analyzed production capacity scenarios: 72,000 t/year, 198,000 t/year, and 315,000 t/year. The results of the sensitivity analysis, expressed as the relative change in NPV, are presented in Table 8.

Table 8. Sensitivity analysis of NPV to a 10% change in key parameters

Parameter change	72,000 t/year	198,000 t/year	315,000 t/year
+10% CF	12%	42%	21%
+10% r	-64%	-223%	-111%
+10% I	-2%	-84%	-11%
Average effect	-18%	-88%	-34%

A sensitivity analysis was performed in order to evaluate the robustness of the investment results with respect to changes in key economic parameters. The analysis examines the effect of a 10% increase in cash flows (CF), discount rate (r), and investment costs (I) on the resulting Net Present Value (NPV) for the three analyzed production capacities (72,000 t/year, 198,000 t/year, and 315,000 t/year).

The results indicate that the NPV is highly sensitive to changes in the discount rate, particularly for the medium-capacity scenario (198,000 t/year), where a 10% increase in the discount rate leads to a 223% reduction in NPV. This reflects the strong dependence of long-term investment projects on the assumed cost of capital.

Changes in cash flows show a positive influence on the investment performance, with NPV increasing by 12%, 42%, and 21% for the three analyzed capacity levels, respectively. This confirms that improvements in operational performance or product prices can significantly enhance the economic attractiveness of the project.

The sensitivity to investment costs is comparatively lower, particularly for the smallest capacity scenario, where a 10% increase in capital expenditures reduces NPV by only 2%. However, for the medium-capacity scenario the impact becomes more pronounced, reaching

84%, indicating that investment efficiency becomes increasingly important at larger project scales.

Overall, the results suggest that financial parameters related to the cost of capital and operational cash flows represent the most critical determinants of project viability, while moderate variations in capital expenditures have a comparatively smaller impact on the economic performance of the proposed technology.

CONCLUSIONS

The conducted investigations suggest that the mineral composition of mining waste deposited in open dumps does not undergo significant changes over time, regardless of the duration of exposure to atmospheric conditions. The analyzed samples show similar mineralogical characteristics, with kaolinite present in considerable quantities reaching up to 30%. These findings confirm earlier studies conducted in the Pernik coal basin, which identify quartz, kaolinite, illite, and siderite as the dominant minerals, while pyrite, marcasite, and calcite occur as secondary components.

The obtained results indicate that mining waste contains significant amounts of clay minerals, which can serve as an alternative raw material for ceramic production. In order to improve the usability of these materials, preliminary treatment through water separation was applied. This process enabled the isolation of a fine fraction enriched in clay minerals, which can be effectively incorporated into the raw material mixture for brick production.

Laboratory analyses demonstrate that the obtained clay-rich fraction complies with the requirements specified in BDS 14175:1986 for clay raw materials used in brick manufacturing. The measured technological properties, including plasticity index, grain-size distribution, and chemical composition, confirm the suitability of the material for ceramic production and support its potential substitution of natural clay resources.

The techno-ecological-economic analysis further demonstrates that the proposed utilization approach can generate simultaneous environmental and economic benefits. The incorporation of mining waste into brick production reduces the demand for natural clay extraction and contributes to the reduction of mining waste deposits and land occupation. From an environmental perspective, the proposed production scheme is characterized by limited emissions, absence of wastewater generation, and internal recycling of solid residues, resulting in a relatively low environmental impact.

The economic evaluation indicates that brick production based on mining waste is financially viable across different production scales. The investment analysis shows positive Net

Present Values (NPV) for all analyzed scenarios, while the proposed technology demonstrates higher NPVs compared to conventional brick production. The results also reveal that unit production costs remain relatively stable across different capacity levels, suggesting the presence of economies of scale and cost stability in the production process.

The sensitivity analysis confirms the robustness of the economic results while also highlighting the key factors influencing investment performance. The analysis shows that NPV is particularly sensitive to changes in the discount rate, especially for the medium-capacity scenario (198,000 t/year), where a 10% increase in the discount rate leads to a substantial reduction in NPV. This indicates the strong dependence of long-term industrial investments on financing conditions and the cost of capital.

At the same time, increases in operational cash flows have a positive impact on project viability, demonstrating that improvements in operational efficiency or product market prices can significantly enhance the financial attractiveness of the investment. In contrast, the sensitivity to investment costs appears to be comparatively lower, particularly for smaller production capacities.

It should be noted that the present study is subject to certain limitations, including the limited number of analyzed samples, the site-specific nature of the investigated material from the Pernik coal basin, and the reliance on laboratory-scale experiments and model-based economic assumptions. These factors may influence the broader applicability of the results and should be considered in future large-scale or industrial validations.

Overall, the results suggest that mining waste from the Pernik coal basin represents a promising secondary raw material for the ceramic industry. The proposed technological approach supports the implementation of circular economy principles, resource efficiency, and sustainable waste management, while maintaining technological feasibility and economic viability for brick production.

AUTHOR CONTRIBUTIONS

Conceptualization, Aleksandrina Kostadinova, Ekaterina Todorova and Nikolay Neykov; methodology, Aleksandrina Kostadinova and Nikolay Neykov.; software Nikolay Neykov.; validation Ekaterina Todorova and Nikolay Neykov; formal analysis, Aleksandrina Kostadinova and Nikolay Neykov; investigation Aleksandrina Kostadinova and Nikolay Neykov; resources, Ekaterina Todorova; data curation, Aleksandrina Kostadinova and Nikolay Neykov; writing—original draft preparation, Aleksandrina Kostadinova and Nikolay Neykov; writing—review and editing, Ekaterina Todorova; visualization, Aleksandrina Kostadinova and

Nikolay Neykov; supervision, Ekaterina Todorova; project administration, Ekaterina Todorov. All authors have read and agreed to the published version of the manuscript.”

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

[1] Haibin, L., & Zhenling, L. **2010** Recycling utilization patterns of coal mining waste in China. *Resources, Conservation and Recycling, 54*(12), 1331–1340.

[2] Yassine, T., Benzaazoua, M., Hakkou, R., & Mansori, M. **2017** Coal mine wastes recycling for coal recovery and eco-friendly bricks production. *Minerals Engineering, 107*, 123–138. https://doi.org/10.1016/j.mineng.2016.09.001

[3] Fecko, P., Tora, B., & Tod, M. **2013** Coal waste: Handling, pollution impacts and utilization. In *The coal handbook: Towards cleaner production* (pp. 63–84). Woodhead Publishing.

[4] Peng, X., Jiang, Y., Chen, Z., Osman, A. I., Farghali, M., Rooney, D. W., & Yap, P. S. **2023** Recycling municipal, agricultural and industrial waste into energy, fertilizers, food and construction materials, and economic feasibility: A review. *Environmental Chemistry Letters, 21*(2), 765–801.

[5] Lemeshev, V. G., Gabin, K., Sevel'ev, Y. A., Tumanov, D. V., & Lemeshev, D. O. **2004** Utilization of coal-mining waste in the production of building ceramic materials. *Glass and Ceramics, 61*(9–10), 308–311.

[6] Menezes, R. R., Santana, L. N. S., Neves, G. A., & Ferreira, H. C. **2012** Recycling of mine wastes as ceramic raw materials: An alternative to avoid environmental contamination. In *Environmental contamination* (pp. 200–220).

[7] Yang, M., Guo, Z., Deng, Y., Xing, X., Qiu, K., Long, J., & Li, J. **2012** Preparation of CaO–Al2O3–SiO2 glass ceramics from coal gangue. *International Journal of Mineral Processing, 102–103*, 112–115.

[8] Djobov, I., Karamanova, E., Avdeev, G., & Karamanov, A. **2024** Characterization of clays from "Mines Maritsa Iztok" as raw materials for ceramic industry. *Journal of Chemical Technology and Metallurgy, 59*(6), 1331–1340. https://doi.org/10.59957/jctm.v59.i6.2024.7

[9] Kortenski, Y. **2002** *Coal geology and organic petrology*. Sofia.

[10] Kortenski, Y., & Zdravkov, A. **2011** Petrological-paleogeographical features of the coal basins of the Pernik province. *Journal of the Bulgarian Geological Society, 72*(1–3), 11–25.

[11] Shishkov, G., Kehayova, M., & Stoykova, S. **1985** *Coal and coal basins in Bulgaria*. Sofia University Press.

[12] Kovachev, V., Strashimirov, B., & Petrov, P. **1991** *Non-metallic minerals*. University of Mining and Geology.

[13] Gushevilov Zh **1980** Chemical and physical properties of certain materials forming the embankments in the Pernik coal basin Bulgaria and their suitability for land reclamation. *Agricultural Chemistry* 15(1): 60–66

[14] Gushevilov, Z.; Paskaleva, K. **1977** Clay mineral composition of marly dumps in the Pernik coal basin and their significance for land reclamation. *Pochvoznanie i Agrokhimiia* 2(6): 14–22

[15] Hristov B., T. Shishkov, V. Katchova, E. Atanassova,I. Atanassova Basic Chemical and Physico-Chemicalcharacteristics of Soils and Substrates in the Region of Pernik Coal Mine Basin, Conference: Soil and Agrotechnology In A Changing World. ISBN: 978-619-90560-0-4At: Sofia Volume: 1, DOI: 10.13140/RG.2.1.2362.5045

[16] Stefanova, V., & Petrov, P. **2019** Soil development and properties of microbial biomass succession in reclaimed sites in Bulgaria. *CBU International Conference Proceedings*. https://doi.org/10.12955/cbup.v7.1492

[17] Petrov, P. **2019** Chemical and physicochemical parameters of recultivated embankments of Maritsa-Iztok mine in relation to development of soil formation process. *Journal of Environmental Protection and Ecology, 20*(2), 912–923.

[18] ÖNORM S 2123-3Sampling plans for waste – Part3: Sampling of solid waste out of material streams.

[19] BDS. **1986** *BDS 14175: Raw clays for the production of bricks and roof tiles. Technical tests. Test methods*. Bulgarian Institute for Standardization.

[20] Pelovski, J., I. Dombalov, Ek. Todorova, V. Kyoseva, E. Sokolovski, P. Petrov, G . Kazaldzhiev, Book Title Methods for treatment and utilization of solid household waste, Publisher: BNOCEOOOS, Sofia, **2007**.

[21] Todorova, E., I. Dombalov, Book Title: Manual for exercises on solid waste processing technologies, Publisher: Ekotech Consult-OOD, Sofia, **2005**

[22] BDS EN 15309. (2007). *Characterization of waste and soil: Determination of elemental composition by X-ray fluorescence*. Bulgarian Institute for Standardization.
[23] Kostova, I. **2005** Geochemical characteristics of coals from the East Maritsa, Pernik and Balkan basins and the relationship of elements with pyrite sulfur. *Journal of the Bulgarian Geological Society, 66*(1–3), 43–60.
[24] Kostadinova, A., & Todorova, E. **2015** Preliminary treatment of mining waste for the purposes of their future utilization. *Forestry Ideas, 21*(1), 47–53.
[25] BDS EN ISO 17892-4. (2017). *Geotechnical investigation and testing – Laboratory testing of soil – Part 4: Determination of particle size distribution (ISO 17892-4:2016)*. Bulgarian Institute for Standardization.
[26] Menezes, R. R., L. N.Santana, G. A. Neves and H. C. Ferreira, Recycling of Mine Wastes as Ceramic Raw Materials: An Alternative to Avoid Environmental Contamination, Environmental Contamination, ISBN 978-953-51-0120-8, Brazil, **2012**, 200-220 p.
[27] Tam, V.W.Y., Le, K.N., Illankoon, I.M.C.S., Tran, C.N.N., Rahme, D., Liu, L. **2023** Economic Impacts of Environmentally Friendly Blocks: The Case of Nu-Rock Blocks. In: Duan, W., Zhang, L., Shah, S.P. (eds) *Nanotechnology in Construction for Circular Economy*. NICOM 2022. Lecture Notes in Civil Engineering, vol 356. Springer, Singapore. https://doi.org/10.1007/978-981-99-3330-3_49
[28] Fregonara, E., & Ferrando, D. G. **2023** The Discount Rate in the Evaluation of Project Economic-Environmental Sustainability. *Sustainability*, *15*(3), 2467. https://doi.org/10.3390/su15032467

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