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New technology for hydrogen and geopolymer composites production from post-mining waste

Deliverable 6.2

Economic aspects of hydrogen and geopolymer composites production from waste dumps

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1. Introduction

The legal basis for the work entitled: “New technology for hydrogen and geopolymer composites production from post-mining waste” (acronym H2GEO) is a grant agreement No: 101112386 (RFCS-2022). H2GEO project consortium is composed of seven partners: KOMAG Institute of Mining Technology (KOMAG), Poland; GIG National Research Institute (GIG), Poland; Institute of Construction and Architecture Slovak Academy of Sciences (USTARCH), Slovakia; Institute of Energy and Fuel Processing Technology (ITPE), Poland; VSB - Technical University of Ostrava (VSB), Czech Republic; Wrocław University of Technology (PWR), Poland, and Haldex S.A. (HDX), Poland.

2. Goal of the work

The objective of Deliverable 6.2 is to evaluate the economic feasibility of integrated hydrogen production and geopolymer composite manufacturing using materials recovered from mining waste dumps. The analysis aims to identify the key cost factors, investment requirements, operational expenditures, and potential economic benefits associated with the proposed technology. Particular attention is given to the valorisation of mining waste as a secondary raw material, the reduction of disposal costs, and the creation of additional revenue streams through the production of high-value construction materials and hydrogen.

3. Estimation of the potential mineral resources possible to obtain from waste

As part of the H2GEO project, comprehensive studies were carried out on the potential for recovering mineral resources from waste and on the economic assessment of the effects of reclaiming post-mining areas.

Within the scope of this report, the analysis included:

- estimation of the quantity of potential mineral resources that can be obtained from waste, which forms the basis for determining the potential for increasing the domestic mineral resource base,
- determination of land volume and the decrease or increase in the value of the reclaimed area compared to its original value, enabling the assessment of the economic effects of reclamation and redevelopment of post-mining areas.

The first of the analysed aspects, related to resource potential, concerns the evaluation of the quantity and quality of mineral fractions that can be recovered from spoil heaps. The analysis includes identification of the share and value of coal fractions and mineral fractions. Coal fractions may be used for energy purposes, while mineral fractions are suitable for use in geopolymerisation processes and in the construction materials industry. The analyses consider granulometric structure, mineral composition, and the share of glassy and clay phases determining the suitability of the waste as a secondary raw material. The results of these analyses make it possible to determine the mass of waste that can be technologically utilized and the potential market value of the recovered materials.

The second aspect, concerning the determination of land value after reclamation, focuses on assessing changes in the economic value of land resulting from its transformation from degraded areas into areas with economic potential. Reclamation of spoil heaps, carried out in parallel with the recovery of mineral fractions, leads to a reduction in their volume, improvement in geotechnical stability, and limitation of dust and pollutant emissions. As a result, reclaimed areas can be reintroduced into use, which is assumed to translate into an increase in their economic value as well as social and environmental benefits.

Thus, the study analyses not only resource potential but also the spatial and economic balance resulting from reclamation. Both aspects are interrelated – the greater the share of mineral fraction that can be utilized, the greater the economic benefits and the smaller the volume of waste requiring disposal. Ultimately, this leads to reduced costs of maintaining spoil heaps and increased value of post-mining areas, aligning with the objectives of the circular economy and the strategy of sustainable transformation of post-mining regions.

The task therefore provides data necessary for the development of an economic and spatial assessment of the implementation of the technology developed in WP6, serving as a bridge between technological aspects (T6.1) and the assessment of the economic and environmental potential of the entire process.

3.1. Objective of the study

The objective of the study carried out under task T6.2 is to quantitatively and qualitatively estimate the resource potential and changes in the economic value of land following the reclamation of post-mining spoil heaps in the context of hydrogen production technology and geopolymer composites developed in WP6.

The analysis aims, among others, to identify mineral fractions which, after appropriate processing (screening, classification, and cleaning), may constitute a valuable raw material for geopolymerisation processes or other industrial applications.

The results of the estimations will allow determination of:

- the mass share of the mineral fraction in the total waste mass,
- the potential volume of recovered mineral resources, expressed in Mg and as a percentage of the total waste mass,
- the approximate market value of these resources based on current prices of mineral materials with similar properties.

The analysis also includes the assessment of land value after reclamation, including determining whether the waste processing and resource recovery process contributes to an increase or decrease in the economic value of land.

The analysis includes:

- comparison of the economic value of land in its original state and after reclamation,
- identification of factors affecting the market value of reclaimed land.

The goal of the task is to determine the balance of economic benefits resulting from combining mineral resource recovery processes with the reclamation of post-mining areas. Such an approach enables an integrated assessment of the effectiveness of the proposed technology in economic, spatial, and environmental dimensions, taking into account the principles of the circular economy and the transformation of post-industrial areas.

The obtained results will constitute the basis for further economic analyses of the project (Deliverable D6.2), as well as a reference point for developing recommendations regarding the implementation of the technology under industrial conditions, including the selection of pilot locations and forecasting potential socio-economic benefits for post-mining regions.

3.2. Scope of research and analyses

The scope of research and analyses conducted under task T6.2 includes the quantitative and qualitative assessment of post-mining waste in terms of its resource potential and its impact on the economic value of land after reclamation. The research aims to determine to what extent the processing of spoil heaps may contribute to increasing mineral resource reserves while simultaneously improving the value of degraded land.

Analyses concerning the quantity of potential mineral resources include:

- review of literature on the deposition of post-mining materials, including granulometric and mineral composition of waste, with particular emphasis on mineral fractions suitable for industrial use,
- determination of the mass share of the mineral fraction in the total waste mass and estimation of the amount of recoverable raw material.

The second research area concerns the assessment of spatial and economic effects related to the reclamation of spoil heaps after processing their contents. The scope includes:

- determination of unit land value (PLN/m²) before and after the reclamation process,
- comparison of the economic value of land before and after reclamation based on available market data,
- determination of the potential value of coal and mineral fractions.

3.3. Characteristics of the selected post-mining spoil heap

The object of the analysis is CSOG in Knurów, located at ul. Szybowa 44, 44-190 Knurów (Śląskie Voivodeship, Gliwice County). The site was selected due to its large area and the lack of prior reclamation activities. The geographical coordinates of the site are approximately 50°12′07″N, 18°40′58″E. The area is owned by Jastrzębska Spółka Węglowa S.A. (Budryk coal mine in Ornontowice)[1].

The landfill area is approximately 16.5 ha, making CSOG one of the larger facilities of this type in the Upper Silesian Coal Basin. The facility has been in operation since the 1960s (initially storing waste from, among others, Szczygłowice mine, and since 1988 also from Sośnica mine). Over the decades, tens of millions of Mg of mining waste have been accumulated there[1].

According to data (as of the end of 2018), the total capacity of the landfill was approximately 77×10^6 m³, with remaining capacity of approximately 40.85×10^6 m³. The mass

[1] Marszałek Województwa Śląskiego. *Plan gospodarki odpadami dla województwa śląskiego na lata 2023–2028, Załącznik II. Wykaz instalacji z sektora gospodarczego*; Urząd Marszałkowski Województwa Śląskiego: Katowice, Polska, 2024

of waste deposited so far is estimated at several tens of millions of Mg - for example, by the end of 2018 approximately 28.83 million Mg of waste had been deposited. In recent years, the annual increase in mass has been on the order of several million Mg: in the years 2015–2017, approximately 11.28 million Mg were deposited in total (on average approximately 3.76 million t/year).

The landfill is an active facility (in the operational phase) and continues to receive mining waste. It holds a valid operating permit until 23 March 2032 and an approved Mining Waste Management Program (decision No. 675/OS/2012). It also has a water permit for the discharge of industrial wastewater (decision No. 3489/OS/2016). CSOG is classified as a “non-hazardous” mining waste facility (other than Category A), which implies lower safety requirements compared to the highest-risk facilities.

The main waste streams originate from mines operated by Jastrzębska Spółka Węglowa. In the years 2015–2017, 66.3% of deposited mass came from the Budryk mine (7,477.4 thousand tonnes), and 33.7% from the Knurów operation (Knurów-Szczygłowice mine, 3,798.7 thousand tonnes). Historically, significant suppliers also included the Szczygłowice mine (in the early period) and Sośnica mine (after 1988).

The waste deposited at CSOG in Knurów consists of typical mining waste classified as non-hazardous. According to the waste catalogue, three main codes are accepted:

01 01 02 – waste from the extraction of minerals other than metal ores (mainly waste rock from coal seam extraction),

01 04 12 – waste from washing and cleaning of minerals (coal processing waste, so-called slurries),

01 04 81 – waste from flotation processing of coal (post-flotation waste).

The deposited materials are a mixture of waste rock (mainly sandstones, mudstones, and clay shales) and processing waste. Waste rock consists of coarser fractions of clays and sands, while processing (mechanical beneficiation) produces coal slurries and flotation concentrates (flotation waste) with fine grain size. Lithologically, approximately 80% of the waste mass consists of claystones, with smaller amounts of mudstones and sandstones. The high content of organic matter (coal) in slurries and flotation concentrates results in a loss on ignition of approximately 15–25%.

3.4. Methodology

This chapter presents the input data necessary to conduct a quantitative analysis of mineral resources contained in waste deposited at the Central Mining Waste Disposal Facility (CSOG) in Knurów (Fig. 1). These data include the quantitative characteristics of the facility, the chemical and mineral composition of the waste, its physical properties, and estimates of the potential resources of coal and mineral fractions that can be recovered in industrial or reclamation processes.

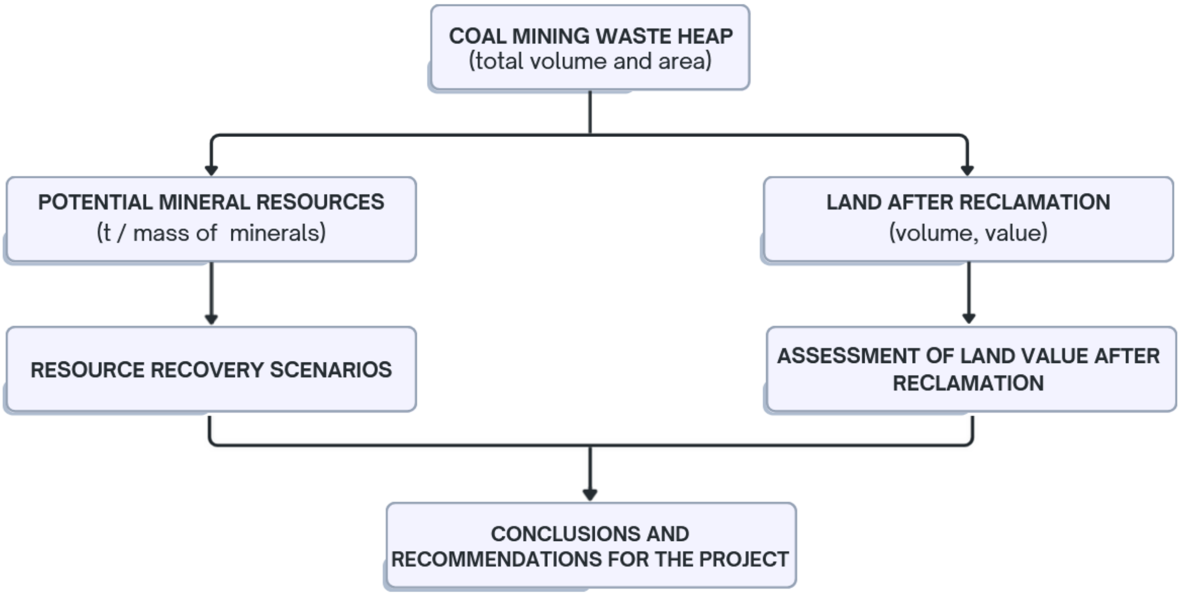

Fig. 1. Methodology for analysing selected economic aspects related to spoil heap management.

3.5. Input data with quantitative analysis of mineral resources

The dominant part of the landfill volume consists of waste rock, and to a lesser extent—slurries and post-flotation waste originating from coal beneficiation processes. The mining waste deposited at the Knurów heap is a heterogeneous material, comprising a mixture of mineral and organic fractions. Its chemical composition is characterized by a predominance of aluminosilicates and the presence of associated elements such as iron and sulphur. Quality parameters are presented in table below.

Table 1. Quality parameters of mining waste from the Knurów spoil heap (indicative values).

Component	Average value
Organic carbon content, %	6.7
Calorific value, kJ/kg	22,662
Sulphur content, %	0.80
Ash content, %	20.24

Based on available data for CSOG in Knurów and literature data on spoil heap morphology, the following characteristics of the landfill were assumed.

The main minerals present in the waste include quartz, kaolinite, illite, calcite, dolomite, gypsum, pyrite, and amorphous matter representing dispersed carbon. Trace amounts of metallic elements are also present, including rare earth elements, indicating potential as a secondary raw material[2].

The waste is characterized by a heterogeneous structure:

- waste rock, which contains mainly grains >1 mm accounting for 93.8%[3],
- post-flotation waste consists of more than 70% dust-clay fraction (<0.05 mm)[3].

Physical properties:

- bulk density of the soil skeleton: approximately 1.7 g/cm³ [4],
- porosity: approximately 45%[5],
- filtration coefficient: 2.7×10^{-5} m/s[6].

Compaction parameters:

- optimum moisture content w_{opt}: 12%[7],

[2] Szlugaj, J. *Charakterystyka mineralogiczno-petrograficzna odpadów wydobywczych z wybranych kopalń węgla kamiennego w aspekcie ich wykorzystania do produkcji kruszyw mineralnych*; Instytut Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk: Kraków, Polska, 2020. (*Studia, Rozprawy, Monografie*, 214).
[3] https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.jsw.pl%2Fraportroczny-2022%2Fmedia%2Fe73262dc682b0bc6b4db3db59fe3cede.xlsx&wdOrigin=BROWSELINK, access: 13.11.2025
[4] Góralczyk, S.; Baic, I. Odpady z górnictwa węgla kamiennego i możliwości ich gospodarczego wykorzystania. *Polityka Energetyczna* 2009, *12*(2/2), 215–226. ISSN 1429-6675.
[5] Kadela, M.; Gwóźdź-Lasoń, M.; Dudko-Pawłowska, I. Parametry geotechniczne wybranych odpadów kopalnianych i hutniczych. *Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk* 2016, *94*, 229–242.
[6] https://ekotrans-bogdanka.pl/images/Prezentacja_Bogdanka_2020.pdf, access: 12.11.2025
[7] Borys, M.; Filipowicz, P. Charakterystyka odpadów pogórniczych i energetycznych dla ich zastosowania do budowy i modernizacji nasypów hydrotechnicznych. Zesz. Probl. Postęp. Nauk Rol. 2005, 506, 77–84.

- maximum dry density of the soil skeleton ρ_{ds}: 1.91–2.06 g/cm³ [8].

Analyses showed that the organic carbon content ranges from 2.3–13.5%, with an average value for the entire deposit of approximately 6.7%, while the calorific value of the waste ranges from 17,764–26,466 kJ/kg, with an average of 22,662 kJ/kg. The presence of carbon and pyrite results in the risk of self-heating and spontaneous combustion, which is confirmed by thermographic monitoring conducted at the site.

Based on the accumulated waste mass of 28,829,236.88 Mg and an average carbon content of approximately 6.7%, the estimated amount of recoverable coal is 1,931,558.87 Mg

The remaining mineral fraction, accounting for over 90% of the waste mass, contains aluminosilicate (SiO_2, Al_2O_3) and carbonate ($CaCO_3$, $MgCO_3$) raw materials, which can be used for the production of geopolymers, aggregates, or reclamation materials.

Table 2. Estimated resource balance of the Knurów spoil heap [9, 10, 11, 12]

Fraction	Share [% of dry mass]	Mass [Mg]	Typical minerals / rocks
Aluminosilicate fraction (total)	approx. 73	21,045,342.92	kaolinite, illite, quartz, locally muscovite; rocks: coal shale, claystone, mudstone, fine-grained sandstone
– including coal shale	approx. 25	7,207,309.22	kaolinite, illite, quartz with dispersed coal particles
– including claystone	approx. 24	6,919,016.85	kaolinite, illite, fine-grained quartz; sometimes admixtures of gypsum and fine carbonates
– remaining aluminosilicates	approx. 24	6,919,016.85	quartz, mixture of clay minerals, feldspars
Coal fraction	approx. 6.7	1,931,558.87	organic matter of hard coal (macerals: vitrinite, inertinite, etc.), amorphous carbon phase
Carbonate fraction	approx. 10	2,882,923.69	calcite, dolomite

[8] Zydroń, T.; Zawisza, E.; Macałka, A.; Jantos, P. Badania parametrów zagęszczalności gruboziarnistego kruszywa z żużla wielkopiecowego. Górn. Geoinż. 2008, 32, 381–392.
[9] Smołka-Danielowska, D.; Walencik-Łata, A. The Occurrence of Selected Radionuclides and Rare Earth Elements in Waste at the Mine Heap from the Polish Mining Group. Minerals 2021, 11, 504.
[10] Marcisz, M.; Adamczyk, Z.; Gawor, Ł.; Nowińska, K. The Impact of Depositing Waste from Coal Mining and Power Engineering on Soils on the Example of a Central Mining Waste Dump. Gospod. Surowcami Miner. Miner. Resour. Manag. 2021, 37, 179–192.
[11] Sybilski, D.; Kraszewski, C.; Wileński, P.; et al. Ocena i badania wybranych odpadów przemysłowych do wykorzystania w konstrukcjach drogowych; Instytut Badawczy Dróg i Mostów: Warszawa, Poland, 2004.
12 Pyssa, J. Extractive Waste from Hard Coal Mining in Poland—Balance, Status of Management and Environmental Aspects. E3S Web Conf. 2017, 14, 02024.

Fraction	Share [% of dry mass]	Mass [Mg]	Typical minerals / rocks
Iron-sulphide fraction	approx. 9	2,594,631.32	pyrite as the dominant phase; possible: marcasite, secondary iron minerals (goethite, hematite) and iron sulphates (jarosite)
Trace elements	approx. 1	288,292.37	rare earth elements (e.g., La, Ce, Nd, Y), heavy metals (Zn, Pb, Cu, Ni, Co, Cr) associated with clay, iron-sulphide, or carbonate phases

The slight difference in totals results from rounding of individual fraction shares, which is typical for approximate mass balances and does not affect the interpretation of results.

3.6. Valuation of the potential value of the spoil heap

In this subsection, the quantitative characteristics of waste deposited at the Central Mining Waste Disposal Facility in Knurów, presented in Section 2.1, have been translated into estimates of the potential economic value of the main material fractions. The starting point is the total waste mass estimated at approximately 28.83 million Mg and an average combustible content of 6.7%, which allows the separation of a coal fraction with significant energy potential and a mass-dominant mineral fraction that may serve as a raw material for further processing.

The objective of the analyses presented in Sections 2.2.1 and 2.2.2 is to determine the order of magnitude of the market value of these fractions under the assumption of their utilization in selected technological scenarios. In the first stage (2.2.1), the potential value of the coal fraction was estimated both for its direct use as a solid fuel and for its conversion into hydrogen through gasification processes. In the second stage (2.2.2), the value of the remaining mineral fractions was analysed, taking into account their possible use as aggregates, components of geopolymer composites, or reclamation materials. The objective of Section 2.2.3 is to determine changes in land value depending on the method of surface development.

The results obtained are indicative and based on approximate market prices and quality parameters typical for waste from hard coal mines in the Upper Silesian Coal Basin. They form the basis for further assessment of the economic feasibility of spoil heap management and for linking resource potential with the analysis of land value changes after reclamation in subsequent sections of the report.

3.6.1. Potential value of the coal fraction

The coal fraction deposited in the Knurów waste heap is a key component determining the energy potential of the analysed site and its suitability as a source of feedstock for hydrogen production within the technology developed under WP6. Based on the total mass of waste, amounting to approximately 28,829,236.88 Mg, and the average organic carbon content of approximately 6.7%, the potential quantity of recoverable coal was estimated at approximately 1,931,558.87 Mg. Assuming an average calorific value of the waste of 22,662 kJ/kg, the total chemical energy potential amounts to 43,750 TJ.

The first approach assumed the use of recovered coal as an energy fuel. In this scenario, the coal fraction, after being separated from the waste mixture through mechanical beneficiation processes, including screening, hydraulic classification and gravity separation, is treated as a low- or medium-grade fuel intended for combustion in utility or industrial boilers. To obtain parameters comparable to those of commercially available coal fuels, the ash and moisture contents would have to be reduced to levels acceptable in terms of applicable emission standards and end-user requirements. Based on the recovered coal fraction of 1,931,558.87 Mg and its effective calorific value of 22,662 kJ/kg, the total energy potential can be estimated at 43,750 TJ. Assuming an electricity generation efficiency of 35%, this corresponds to the production of approximately 4.25 TWh of electricity. The economic value of this scenario may be determined by reference to the market price of coal fuels with comparable properties, assumed for estimation purposes at PLN 1,000/Mg, resulting in a total value of approximately PLN 1.93 billion.

The second approach assumes the use of the coal fraction as feedstock for hydrogen production. In this scenario, the coal recovered from the waste heap is not treated as a final energy fuel but as a feedstock component in plasma gasification processes resulting in the production of synthesis gas. Following the removal of particulate matter, sulphur compounds and chlorine compounds from the gas, and the subsequent water-gas shift reaction, it is possible to obtain a hydrogen stream meeting the requirements of further technological stages, such as compression, storage, use in fuel cells or application in chemical processes.

Assuming a hydrogen production yield corresponding to the conversion of 13.2% of the coal feedstock into hydrogen, as reported in Deliverable D4.1 for the Steam/Fuel Ratio variant of 1.3 kg/kg and a feed rate of 20 kg/h, the coal remaining in the waste heap, with an estimated mass of 1,931,558.87 Mg, could theoretically yield approximately 254,969.73 Mg of H_2. In energy terms, this corresponds to approximately 8.49 TWh, based on the lower heating value of hydrogen of approximately 33.3 kWh/kg.

The economic value of the hydrogen production scenario was estimated using several alternative market price levels. It should be emphasised that hydrogen produced from the coal fraction deposited in the waste heap cannot be classified as green hydrogen, as the input material is of fossil origin. Therefore, the green hydrogen price of EUR 6.61/kg H_2 was adopted solely as an upper reference point for the potential value of the product and not as a basis for classifying the analysed hydrogen. At this price and using the average EUR/PLN exchange rate for 2025 of PLN 4.2402/EUR, the value of the potentially produced hydrogen would amount to approximately PLN 7.15 billion. For comparison, assuming a grey hydrogen price of EUR 3.76/kg H_2, the corresponding value would be approximately PLN 4.06 billion, while at a price of EUR 1/kg H_2 it would amount to approximately PLN 1.08 billion. This demonstrates that the economic result is strongly dependent on the adopted hydrogen reference price. Consequently, the presented values should be regarded as a scenario analysis rather than as a definitive market forecast.

A comparison of the results indicates that, although the use of the coal fraction as an energy fuel involves simpler technology, lower investment requirements and the possibility of relatively rapid implementation using existing energy infrastructure, its economic and energy potential remains limited to approximately 4.25 TWh of electricity and a market value of approximately PLN 1.93 billion.

By contrast, the gasification and conversion of the coal fraction into hydrogen, despite its considerably greater process complexity, higher energy consumption and the need to construct a plasma gasification plant and synthesis gas treatment systems, offers a higher energy output, corresponding to approximately 8.49 TWh of chemical energy contained in hydrogen, and, when compared with the upper reference-price scenario, a value higher by approximately PLN 5.22 billion. The gasification of the coal fraction and subsequent conversion of synthesis gas into hydrogen also make it possible to obtain a product with a higher unit value and potentially broader applications in the hydrogen economy than those offered by the direct combustion of the fraction as a solid fuel.

However, the resulting product should not be regarded as green hydrogen because it is produced from a coal fraction of fossil origin. Any potential classification of this hydrogen as low-carbon hydrogen would require a separate life-cycle greenhouse gas emissions assessment covering, among other factors, energy consumption in the gasification process, process-related emissions, the method used for synthesis gas purification, and the possibility of capturing or utilising the generated CO_2. In the present analysis, the hydrogen scenario should therefore be considered an alternative method of managing the recovered coal fraction rather than a green hydrogen production pathway.

3.6.2. Value of the mineral fraction

After separating the coal fraction, which accounts for an average of 6.7% of the total mass of the deposited material, the main volume of the central heap in Knurów consists of mineral fractions of an aluminosilicate and carbonate nature. Due to their physical and granulometric properties, these materials can be used as low- and medium-quality aggregates in road construction, earthworks, and reclamation activities.

The aluminosilicate fraction includes mainly sandstones, mudstones, and claystones, which, after processing, can serve as aggregates used in road sub-bases and soil stabilization. The carbonate fraction, represented by rocks containing calcite and dolomite, exhibits properties comparable to shale aggregates used in earthworks. Market prices for such materials, in raw and unprocessed form, typically range from 12–23.37 PLN/t [13,14,15], while a conservative reference value of 18 PLN/t was adopted for this study.

The total mass of material deposited in the heap is 28,829,236.88 Mg, of which 93.3% is the mineral fraction, corresponding to an estimated 26,897,678 Mg of raw material potentially usable as aggregate. Applying the indicated unit price, the total economic value of the remaining mineral fractions amounts to approximately 484.2 million PLN.

The potential use of the recovered mineral fraction as a raw material for geopolymer production was also considered. Preliminary estimates (based on available geopolymer market data) indicate that the cost of geopolymer mortar is approximately 43 PLN/kg[16] [17]. Geopolymer production currently involves costs often 30–40% higher than those of traditional cement, mainly due to the cost of alkaline activators and limited commercial scale. These materials can compete with conventional cement only at sufficiently large production scales and with low raw material

[13] https://www.nowiny.pl/wiadomosci/126758-sprawdzamy-kto-moze-zarobic-na-rozbiorce-haldy-raport.html, access: 18.11.2025
[14] https://www.haldex.com.pl/sprzedaz/kruszywa/, access: 18.11.2025
[15] https://www.stefpol.pl/cennik.html, access: 18.11.2025
[16] https://www.scribd.com/document/751668147/Optimization-of-Geopolymer-Cement-Production-Technology-2022, access: 10.12.12
[17] kensington-green.pl/product/cienkowarstwowa-zaprawa-geopolimerowa, access: 10.12.12

costs, which further supports the rationale for using spoil heap material as filler and aggregate. Despite higher initial costs, geopolymers represent a sustainable construction material with reduced carbon footprint and high chemical resistance, making them an attractive alternative in the context of the circular economy and environmentally friendly solutions[18].

The estimated value confirms the significant economic potential of mineral material, which—if appropriately managed—may constitute an important component of a business model related to spoil heap reclamation and secondary use of post-mining waste. In further stages of the study, this value will be compared with the energy potential of the coal fraction, enabling a comprehensive economic assessment of the analysed facility.

3.7. Change in the value of spoil heap land after reclamation

The change in the land use of the area beneath the central spoil heap in Knurów, combined with full technical and biological reclamation, leads not only to a reduction in the environmental impact of the facility but also to a fundamental change in its market value. For the purposes of this study, the current value of degraded land burdened by a mining waste heap was assumed as the starting point, estimated at 10 PLN/m² [19]. With an area of 16.5 ha, this corresponds to a total value of approximately 1.65 million PLN. The justification for the adopted prices, based on market analysis for individual variants, is presented below.

In its current state, the land beneath the spoil heap has the character of a typical post-mining area: it is burdened by the need to incur reclamation costs, generates negative environmental impacts, including emissions to water and air and the risk of fires, and practically cannot be used for economic activity. These factors cause a market investor to value such land significantly lower than standard construction or industrial plots within the city. As part of the analysis, a variant assessment was carried out for the value of the same land after full reclamation, assuming different directions of its final use. In each case, it was assumed that reclamation allows the removal of limitations resulting from the presence of a mining waste disposal facility and the integration of the area into the local functional and spatial system of the city. The analysis covers five variants, differing both in their target purpose and in the scale of increase in the unit land value.

[18] https://www.marketdataforecast.com/market-reports/europe-geopolymer-market, access: 10.12.12
[19] https://szybko.pl/l/na-sprzedaz/nieruchomosci/%C5%9Bl%C4%85skie-Knur%C3%B3w, access: 10.12.12

The forest-agricultural variant is the most conservative transformation direction, assuming the conversion of the reclaimed area into land dominated by trees, with the possibility of limited agricultural use. In this scenario, a target value of 35 PLN/m² was adopted [20], which for an area of 16.5 ha corresponds to a total value of approximately 5.78 million PLN. This means an increase in value of approximately 250% relative to the initial state of 10 PLN/m². This variant is consistent with the practice of reclaiming many mining spoil heaps in Poland, where post-industrial land, after slope shaping and stabilization, is allocated for environmental purposes with a limited scope of technical intervention. The adopted value of 35 PLN/m² fits within the prices of forested and wooded land located within the administrative boundaries of cities in Silesia, which have potential for conversion to recreational use or serve as a green buffer. Although average prices of agricultural and forest land in the Silesian Voivodeship amount to 6–10 PLN/m², in urban locations such as Knurów these lands are valued significantly higher due to the so-called location rent and the potential to restore use after reclamation. This value also corresponds to the lower limits of prices for recreational, non-construction plots in Gliwice County. The calculated increase in value of approximately 250% relative to the initial state is therefore justified by the improvement of the biogeochemical capacity of the land and its ecological functionality, while maintaining a conservative approach to development.

The green-recreational variant assumes the transformation of the area into an urban park, walking areas, or non-building recreational space. Assuming that after reclamation the area will be equipped with basic recreational infrastructure, including pedestrian routes, small architecture, and arranged greenery, the land value was estimated at 50 PLN/m² [21], giving a total of approximately 8.25 million PLN. In this variant, the increase in value relative to the initial value is approximately 400%. At the same time, it should be emphasized that in this development direction, non-financial benefits play a significant role: improvement in residents' quality of life, increased attractiveness of neighbouring properties, and improvement of the city's image. Near Knurów, prices of land for commercial recreation or allotment gardens on the free market fluctuate within the range of 40–70 PLN/m². The increase in value compared to the forest variant, from 35 to 50 PLN/m², results from assigning the area a usable function and introducing infrastructure, which increases its commercialization potential and attractiveness for private investors who may lease the land for temporary events or services.

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[20] https://www.gov.pl/web/arimr/srednie-ceny-gruntow-wg-gus, access: 10.12.12
[21] https://srk.com.pl/oferta/oferty-nieruchomosci, access: 10.12.12

The variant intended for renewable energy sources, namely photovoltaic installations, combines an environmental function with electricity generation. After full reclamation and appropriate shaping of the terrain, the land may be used for a PV farm, which, due to the growing demand for such locations, significantly increases its market value. The analysis adopted a target value of 80 PLN/m², corresponding to a total amount of approximately 13.20 million PLN for the plot under consideration. This represents an approximately 700% increase compared to the initial value. This variant is consistent with current energy transition trends and constitutes an attractive alternative to conventional industrial development. The value of 80 PLN/m² results from the dynamic situation on the market for land intended for photovoltaic farms. Analysis of market trends in 2024 and 2025 indicates that prices of investment land dedicated to renewable energy sources in Silesia, with grid connection potential, as post-mining areas often benefit from proximity to high-voltage energy infrastructure, range from 15,000 to 25,000 PLN of annual lease per hectare, which, when capitalized to the market value of land, corresponds to levels of 65–110 PLN/m² [22]. The adopted amount of 80 PLN/m² is an averaged value, taking into account the need to incur additional expenditure on specific foundation solutions for structures on embankment ground and necessary geotechnical investigations. This variant combines an environmental function with electricity generation and represents an attractive alternative to conventional industrial development, in line with current energy transition trends in the European Union.

The next two variants concern industrial development, which, from a purely economic point of view, generates the highest increase in land value. In the industrial variant with restrictions, it is assumed that the reclaimed area is suitable for warehouse and production development, but with certain restrictions resulting from the history of the site, such as requirements concerning building foundations, subsoil monitoring, and height limitations. In this scenario, the unit value of the plot was adopted at 120 PLN/m², which for 16.5 ha gives approximately 19.80 million PLN. This represents an approximately 1,100% increase in value compared to the initial state. The valuation at 120 PLN/m² is supported by secondary market data, where plots of varying standards, including land requiring investment expenditure, reach prices of approximately 116–133 PLN/m² [23] [24].

[22] https://blog.ongeo.pl/news-dzierzawa-gruntow-pod-farmy-fotowoltaiczne-w-2025-roku, access: 10.12.12
[23] https://www.otodom.pl/pl/oferta/duza-dzialka-w-spokojnej-okolicy-blisko-centrum-ID4iqFH, access: 10.12.12
[24] https://www.otodom.pl/pl/oferta/dzialka-budowlano-rolna-w-spokojnej-czesci-knurowa-ID4wU2u, access: 10.12.12

In the industrial variant with full use of potential, it is assumed that reclamation will be carried out in a manner enabling the land to be treated as functionally equivalent to new, uncontaminated industrial land. After meeting technical requirements, including subsoil stabilization, water management, and full removal of structural limitations, and after appropriate integration of the plot into the city's transport system, the unit land value can be estimated at 200 PLN/m². For the analysed area of 16.5 ha, this corresponds to a value of approximately 33.00 million PLN, i.e. an increase of approximately 1,900% relative to the baseline value of 10 PLN/m². The value of 200 PLN/m² corresponds to prices of investment land in the high-class segment in the Katowice Special Economic Zone (KSSE) and in key transport nodes of Silesia. Analysis of the industrial land market in the Silesian Voivodeship indicates that the average sale price is approximately 227 PLN/m² [25] for fully serviced and investment-ready plots. Knurów, thanks to direct access to the A1 motorway, has significant logistical potential, which justifies adopting a value close to the regional average.

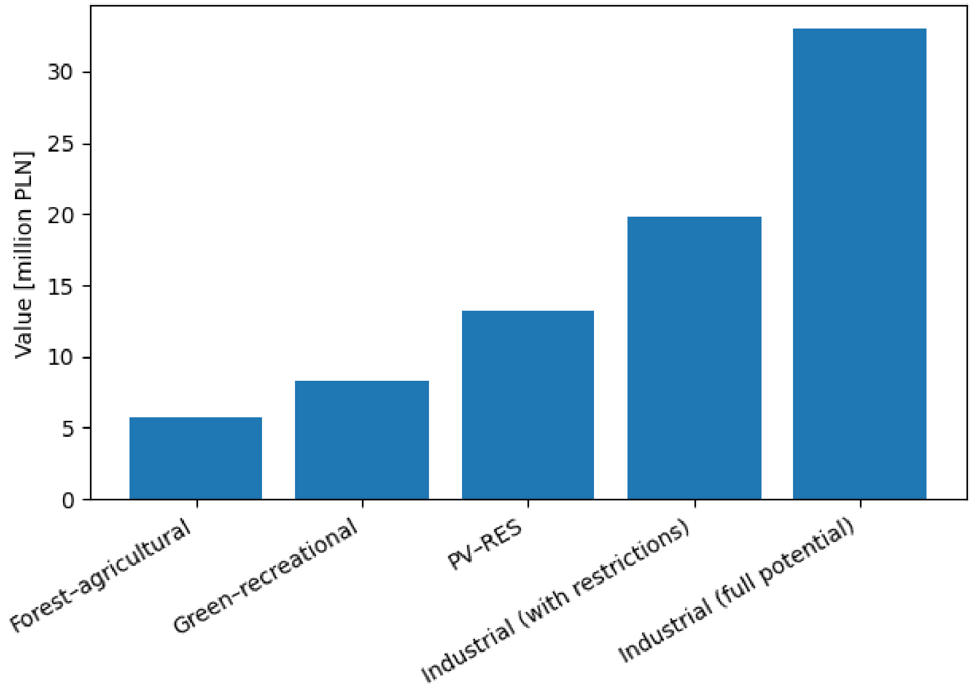

Fig. 2 Land value after reclamation for different development variants.

[25] https://gratka.pl/nieruchomosci/dzialki-grunty/przemyslowa/slaskie, access: 10.12.12

Table 3 Land value after reclamation for different development variants.

Development variant [-]	Estimated unit land price [PLN/m²]	Estimated land value [million PLN]	Increase in value [%]
Forest-agricultural	35	5.78	250
Green-recreational	50	8.25	400
PV-RES	80	13.20	700
Industrial (with restrictions)	120	19.80	1100
Industrial (full potential)	200	33.00	1900

The target unit land values adopted in the analysis, ranging from 35 to 200 PLN/m², are not arbitrary values, but result from a comparative analysis of transaction and offer prices of real estate in Knurów and the Upper Silesian Agglomeration, taking into account the specificity of post-industrial land. The comparison of the above variants shows that the potential increase in the value of the land beneath the central spoil heap in Knurów ranges from approximately 4.1 million PLN in the forest-agricultural variant to approximately 31.4 million PLN in the industrial variant with full potential, calculated as the difference between the value after reclamation and the value of the current degraded state. In further parts of the study, these variants may constitute the basis for assessing the economic feasibility of reclamation, taking into account the costs of necessary technical and biological measures as well as additional environmental and social effects.

4. Economic analysis

4.1. CAPEX estimation

The capital cost estimate was conducted in accordance with the Cost Estimate Classification System presented by AACE International (Association for the Advancement of Cost Engineering), and capital cost calculations were performed to AACE Class 4 accuracy. All costs presented in the report are net costs. The cost estimation methodology included determining bare erected cost (BEC), engineering, procurement, and construction cost (EPCC), total plant cost (TPC), and total overnight cost (TOC).

Table 4 AACE International Cost Estimation Accuracy Classification.

Accuracy class	Project implementation level [%]	Typical Estimation Goal	Expected accuracy range [%]
Class 5	0% do 2%	Project concept	L: -20% do -50%, H: +30% do +100%
Class 4	1% do 15%	Feasibility study	L: -15% do -30%, H: +20% do +50%
Class 3	10% do 40%	Budget, Permits and Control	L: -10% do -20%, H: +10% do +30%

Accuracy class	Project implementation level [%]	Typical Estimation Goal	Expected accuracy range [%]
Class 2	30% do 75%	Control, bidding	L: -5% do -15%, H: +5% do +20%
Class 1	65% do 100%	Checking the estimate, making offers	L: -3% do -10%, H: +3% do +15%

The calculations were based on data obtained through consultations with external companies, as well as our own knowledge and experience. Estimates were made based on the adopted expenditure structure, which included the following items:

1. Bare erected cos (BEC) – these include the costs of equipment and devices, as well as the costs of construction, assembly, and installation of equipment, along with other costs directly related to the construction of the installation. Equipment cost estimates are frequently developed for each plant or plant component using in-house database and conceptual estimating models for specific technologies
2. Engineering, procurement, and construction cost (EPCC) – these include bare erected cost plus items such as design costs, project management costs, site preparation, and other indirect costs.
3. Total plant costs (TPC) – these include EPCC costs plus items such as process contingency and project contingency.
4. Total overnight cost (TOC) – these are the total construction costs plus pre-production costs, spare parts costs, and other investor costs (legal costs, studies, investor engineering costs, management reserve, etc.).

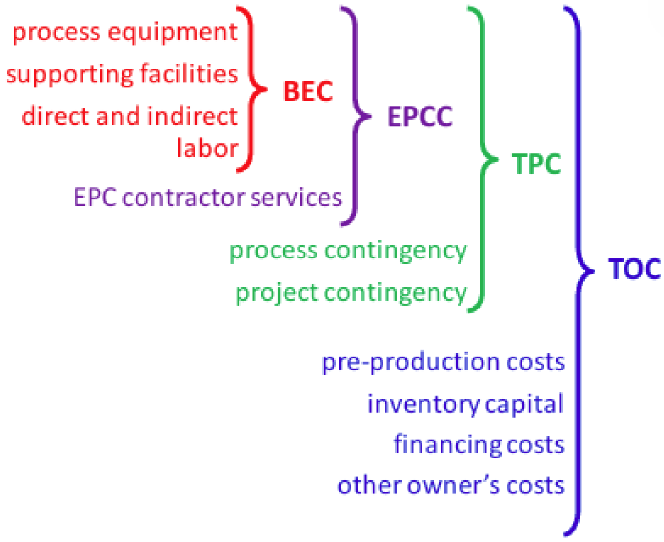

Fig. 3 Capital cost levels and their elements.

4.1.1. Waste separation and classification system

Bare erected cost

Bare erected cost estimation was conducted for an integrated system comprising a waste separation unit and a mineral fraction separation unit. Adopting a common approach stems from the direct technological link between both units and the shared support infrastructure, mobile equipment, technical support, and maintenance. Separate estimation of these costs could lead to artificially inflated capital and operating expenditures, as some resources are used simultaneously by both components of the installation.

Main equipment cost

Equipment cost for main systems was presented in the Table below.

Table 5 Equipment cost – waste separation system.

No.	Equipment	Qty, pcs	Power, kW	Price, EUR
1	Grizzly screen 80 (100) mm, fixed screen + hydraulics + vibrator	2	11.0	66 035
2	Steel feed hopper with a capacity of 20 m³. The bunker discharge is equipped with a control flap with a feeder, with feeder speed controlled by a frequency inverter. Additionally equipped with a vibrator, manually controlled.	2	25.0	207 537
3	Belt conveyor B-1000, length 20 m, inclination angle approx. 15–20 degrees. Speed 0.8 m/s, capacity up to 350 Mg/h	2	22.0	141 503
4	Magnetic separator for conveyor B-800	2	22,0	99 052

No.	Equipment	Qty, pcs	Power, kW	Price, EUR
5	Double-deck classification screen equipped with spray bars on both decks. Upper deck with square apertures of 35 mm, lower deck with slot apertures of 2 mm. Screen capacity up to 200 Mg/h	4	88.0	471 676
6	Belt conveyor B-600, length 15 m, inclination angle approx. 15–20 degrees. Speed 1.6 m/s, capacity up to 150 Mg/h	4	30.0	122 636
7	Separator S-100	4	88.0	1 415 028
8	Dewatering screen for concentrate. Capacity up to 20 Mg/h	4	60,0	283 006
9	Belt conveyor B-600, length 15 m, inclination angle approx. 15–20 degrees. Speed 1.0 m/s, capacity up to 40 Mg/h	4	30.0	122 636
10	Dewatering screen for tailings. Capacity up to 100 Mg/h	4	73.6	358 474
11	Belt conveyor B-600, length 15 m, inclination angle approx. 15–20 degrees. Speed 1.6 m/s, capacity up to 150 Mg/h	4	30.0	122 636
12	Dewatering screen for undersize. Capacity up to 8 Mg/h	1	15.0	70 751
13	Belt conveyor B-600, length 15 m, inclination angle approx. 15–20 degrees. Speed 0.5 m/s, capacity up to 10 Mg/h	1	5.5	30 659
14	Feed preparation sump, min. 40 m³, for TBS feed preparation	1	0.0	18 867
15	Classification hydrocyclone	6	0.0	176 878
16	Teetered bed separator (TBS)	3	45.0	566 011
17	Dewatering arc screen for TBS concentrate	3	0.0	91 977
18	Dewatering screen for TBS concentrate. Capacity up to 8 Mg/h	3	45.0	212 254
19	Belt conveyor B-600, length 15 m, inclination angle approx. 15–20 degrees. Speed 0.5 m/s, capacity up to 10 Mg/h	3	16.5	91 977
20	Dewatering screen for TBS tailings. Capacity up to 50 Mg/h	3	55.2	254 705
21	Belt conveyor B-600, length 15 m, inclination angle approx. 15–20 degrees. Speed 1.0 m/s, capacity up to 50 Mg/h	3	22.5	91 977
22	Dorr-type radial thickener, Ø10 m, capacity up to 450 m³	4	22.0	358 474
23	Filter press PFK570N	4	160.0	2 358 379
24	Belt conveyor B-600, length 15 m, inclination angle approx. 15–20 degrees. Speed 0.5 m/s, capacity up to 10 Mg/h	4	22.0	122 636
25	Water tank with a capacity of min. 2000 m³	1	0.0	660 346
26	Emergency water tank with a capacity of min. 2000 m³	1	0.0	660 346
27	Clean water pump with a capacity of 450 m³/h, γ = 1.01 g/cm³, head H=20 m	4	180.0	160 370
28	Clean water pump from well, capacity 150 m³/h, head H=20–24 m	2	37.0	37 734
29	Slurry pump for thickener underflow (Dorr), capacity 100 m³/h, solids concentration up to 600 g/L, head H=5 m	4	120.0	89 618
30	Slurry pump from feed sump to hydrocyclone, capacity 250 m³/h, solids concentration up to 250 g/L, head H=25 m	3	111.0	122 636
	SUM		**1336.3**	**9 586 812**

Table 6 Equipment cost – Mineral fraction classification and production of natural aggregates.

No.	Equipment	Qty, pcs	Power, kW	Price, PLN
1	Steel storage hopper with a capacity of 10 m³, equipped with a feeder and a vibrator	4	50.0	339 607
2	UPK 1000×700 crusher	1	100.0	169 803
3	Belt conveyor B-600, length 15 m	10	75.0	305 589
4	PWP1 1,2x4 screen	2	12.0	141 503
5	Double-deck classification screen PWP2 1,8x5,25	1	22.0	117 919
6	NAEL 3A centrifuge	3	139.5	141 503
7	Clean water pump EMM INDUSTRY 200-150 EFI-FDS-EMR2	1	45.0	40 092
	SUM		**443.5**	**1 257 016**

Mobile equipment

The number and parameters of the transport vehicles were determined based on the assumed installation capacity of approximately 682 Mg/h and the adopted work organization (220 days/year, 20 hours/day). Unit prices were determined based on approximate market prices for new industrial-grade machines intended for continuous operation in processing and mining plants.

Table 7 Mobile equipment cost.

No.	Equipment	Qty, pcs	Unit price, mln EUR	Price, mln EUR
1	Wheel loader 5–6 m³	4	0.6–0.8	2.4–3.3
2	Hauler/technology truck 25–30 Mg	3	0.5–0.7	1.4–2.1
3	Crawler excavator 25–35 t	2	0.4–0.7	0.8–1.3
4	Forklift / Telehandler	1	0.1–0.2	0.1–0.2
5	Service/technical vehicle	1	0.06–0.12	0.06–0.12
	SUM			**4.78–7.05**

For further economic analyses, the value assumed was approximately EUR 5.9 million.

Civil works and supporting infrastructure

The costs of technical support and infrastructure were estimated using the indicator method based on the assumed areas, the scope of infrastructure and the unit costs of implementing typical industrial facilities and processing plants.

Table 8 Civil works and supporting infrastructure.

No.	Position	Qty	Unit price	Price, mln EUR
1	Technological and manoeuvring areas	15 000 m²	42–71 EUR/m²	0.64–1.06
2	Raw material and product storage yards	20 000 m²	28–52 EUR/m²	0.57–1.04
3	Internal roads	16 000 m²	59–94 EUR/m²	0.94–1.51
4	Drainage of squares and roads	set	—	0.28–0.59
5	Foundations for devices	ok. 1000 m³ of concrete	425–660 EUR/m³	0.42–0.66
6	Supporting structures and viaducts	ok. 250 Mg of steel	3 302– 4 717 EUR/Mg	0.83–1.18
7	Power connection, switchboard, transformer	ok. 2–2,5 MVA	—	0.47–0.94
8	Control room / dispatch room	ok. 250 m²	1 415–2 005 EUR/m²	0.35–0.5
9	Automation, I&C, monitoring, traffic control system	set	—	0.47–0.94
10	Maintenance workshop	ok. 600 m²	1 061–1 651 EUR/m²	0.64–0.99
11	Spare parts warehouse	ok. 300 m²	825–1 297 EUR/m²	0.26–0.40
12	Parking / machine parking area	ok. 3000 m²	35–59 EUR/m²	0.11–0.18
13	Refuelling point + fuel tank	set	—	0.19–0.35
14	Social and health and safety facilities	ok. 400 m²	1 179–1 769 EUR/m²	0.47–0.71
15	Lighting, fencing, external monitoring	set	—	0.24–0.47
16	Project reserve / contingencies	ok. 10%	—	0.71–1.18
	Total facilities and infrastructure			**7.55–12.66**

For further analysis average price of 10.14 mln EUR was assumed.

Bare erected cost calculation

Bare erected cost was estimated based on the presented data.

Table 9 Estimated amounts for bare erected cost.

Cost item	Value [mln EUR]
Waste Separation System	9.59
Mineral fraction classification and production of natural aggregates	1.26
Mobile equipment	5.9
Technical facilities and infrastructure	10.14
Bare erected costs (BEC)	**26.88**

Engineering, procurement and construction cost (EPCC)

Based on NETL guidelines, EPCM contractor services were estimated at 20 percent of BEC. These costs consist of all home office engineering and procurement services as well as field construction management costs.

Total plant cost (TPC)

Total construction costs (TPC) were estimated based on the following assumptions and findings:

- Process risk costs were estimated based on the AACE guidelines, which present the following process risk ranges:

Table 10 AACE Process Risk Guidelines.

Technology status	Process Contingency
New concept with limited data	40+
Concept with bench-scale data	30-70
Small pilot plant data	20-35
Full-sized modules have been operated	5-20
Process is used commercially	0-10

Because all equipment and planned work are being implemented commercially, the process contingency was assumed to be 5% of EPCC.

Based on AACE guidelines, the cost of project contingency for accuracy class 4 was assumed to be 15% of EPCC.

Total overnight cost (TOC)

Total overnight costs were calculated based on the NETL and AACE guidelines, as well as own knowledge and experience. Specific assumptions are presented below:

- For pre-production costs, based on the NETL guidelines, it consists of 6 months operating labour, 1 month of OPEX accounting for maintenance, materials, consumables etc. and 2% of TPC for other costs,
- For Inventory capital costs, 0.5% of TPC was assumed for spare parts and 2 months supply of consumables on-site,

- For other owner's costs 15% of TPC was assumed for costs such as preliminary studies, permitting costs, legal fees, site improvements outside of the facility boundaries, owner's engineering, owner's contingencies etc.

Calculation of Total Overnight cost (TOC)

Based on the presented expenditure structure and the adopted assumptions, the total investment expenditure (TOC) was determined, and the results are presented in the table below.

Table 11 Total overnight costs – waste separation and classification system.

Outlay structure	Cost, mln EUR
Waste Separation System	9.59
Mineral fraction classification and production of natural aggregates	1.26
Mobile equipment	5.90
Technical facilities and infrastructure	10.14
Bare erected cost (BEC)	**26.88**
Contracting Strategy and EPC Contractor Services	5.38
Engineering, procurement and construction cost (EPCC)	**32.26**
Process Contingency	1.61
Project Contingency	4.84
Total plant cost (TPC)	**38.71**
Preproduction (Start-Up) Costs	2.58
Inventory Capital	0.59
Other Owner's Costs	5.81
Total overnight cost (TOC)	**47.69**

4.1.2. Geopolymer production system using calcined mineral fraction

Bare erected cost

Bare erected cost for geopolymer concrete production system was calculated for different cost components: main equipment, civil works and supporting infrastructure.

Main equipment cost

Mineral feedstock handling and preparation (7.52 mln PLN) – this system is responsible for milling, drying and feeding mineral fraction for further processes. It includes feed hoppers and belt conveyors for raw material handling, pre-drying installation, grinding mill, classification system with dust collection, fine material storage and feeding system for BFB reactor.

BFB calcination unit (8.27 mln PLN) – in this system, in an oxidizing atmosphere (500–800°C), residual organic carbon is combusted, and sulphide minerals are oxidized, improving chemical purity and reducing the risk of undesirable reactions. A critical stage is the decomposition of carbonates (mainly $CaCO_3$ and $MgCO_3$) in the range of 650–900°C, which leads to CO_2 release and formation of reactive oxides (CaO, MgO). These phases can influence the geopolymerisation mechanism, promoting the formation of additional binding phases such as C-(A)-S-H.

Heat exchanger system (7.33 mln PLN) - An integral element of the installation is a waste heat recovery system for waste heat from process exhaust gases and the hot solid product. The high-temperature streams leaving the reactor constitute a significant source of reusable energy. It consists of exhaust Gas – Oxidizer Heat Exchanger, Exhaust Gas – Water Heat Exchanger and Calcined Product Cooler.

Civil works and supporting infrastructure

This position was calculated using indicators presented in the Table below. Calculations were based on the methodology and data presented for waste separation system.

Table 12 Civil works and supporting infrastructure.

No.	Position	Qty	Unit price	Price, mln EUR
1	Technological and manoeuvring areas	2 000 m²	42–71 EUR/m²	0.11
2	Internal roads	1 000 m²	59–94 EUR/m²	0.08
3	Drainage of areas and roads	set	—	0.03
4	Foundations for equipment	ok. 1500 m³ of concrete	425–660 EUR/m³	0.81
5	Supporting structures and viaducts	ok. 400 Mg of steel	3 302– 4 717 EUR/Mg	1.60
6	Power connections, distribution boards, transformers	0,5 MVA	—	0.35
7	Control/dispatch rooms	ok. 125 m²	1 415–2 005 EUR/m²	0.21
8	Automation, I&C, monitoring, traffic control systems	set	—	0.28
9	Maintenance workshop	ok. 200 m²	1 061–1 651 EUR/m²	0.28
10	Spare parts warehouse	ok. 100 m²	825–1 297 EUR/m²	0.11
11	Social and occupational health and safety facilities	ok. 200 m²	1 179-1769 EUR/m²	0.29
12	Lighting, fencing, external monitoring	set	—	0.18

No.	Position	Qty	Unit price	Price, mln EUR
13	Project reserve/contingency	ok. 10%	—	0.43
	Total facilities and infrastructure			**4.77**

Bare erected cost estimation

Bare erected cost was estimated based on the data obtained from equipment providers, previous project of similar scope and own experience and data.

Table 13 Estimated amount for bare erected cost.

Cost item	Value [mln EUR]
Mineral feedstock handling and preparation	1.77
BFB calcination unit	1.95
Heat exchanger system	1.73
Civil works and supporting infrastructure	4.77
Bare erected cost (BEC)	**10.23**

Other cost components included Engineering, procurement, and construction costs (EPCC) and Total construction costs (TPC) were calculated with similar assumptions to the calculation of Waste separation and classification system.

Total overnight costs (TOC)

Total overnight costs were calculated based on the NETL and AACE guidelines, as well as own knowledge and experience. Specific assumptions are presented below:

- For pre-production costs, based on the NETL guidelines, it is 2% of TPC for other costs,
- For Inventory capital costs, 0.5% of TPC was assumed for spare parts,
- For other owner's costs 15% of TPC was assumed for costs such as preliminary studies, permitting costs, legal fees, site improvements outside of the facility boundaries, owner's engineering, owner's contingencies etc.

Calculation of Total capital expenditure (TOC)

Based on the presented expenditure structure and the adopted assumptions, the total investment expenditure (TOC) was determined, and the results are presented in the table below.

Table 14 Total overnight costs – Geopolymer production system using calcined mineral fraction.

Outlay structure	Cost, mln EUR
Mineral feedstock handling and preparation	1.77
BFB calcination unit	1.95
Heat exchanger system	1.73
Civil works and supporting infrastructure	4.77
Bare erected cost (BEC)	**10.23**
Contracting Strategy and EPC Contractor Services	1.53
Engineering, procurement, and construction cost (EPCC)	**11.76**
Process Contingency	0.59
Project Contingency	1.76
Total plant cost (TPC)	**14.11**
Preproduction (Start-Up) Costs	1.24
Inventory Capital	0.68
Other Owner's Costs	2.12
Total overnight cost (TOC)	**18.15**

4.1.3. Geopolymer concrete production system

Bare erected cost

Bare erected cost for geopolymer concrete production system was calculated for different cost components: main equipment, mobile equipment, civil works and supporting infrastructure.

Main equipment cost

Main equipment cost consists of:

- Storage and Dosing of Process Raw Materials (EUR 0.47 million): This section is responsible for the input stability of the entire process. Expenditures include the construction of a battery of silos for fly ash (the precursor) and the mineral fraction of mining waste (the filler). A key element is an advanced strain gauge weighing system, which ensures the maintenance of rigorous proportions of bulk ingredients. Additionally, this cost includes a complete liquid chemical dosing system, including tanks with heating systems for water glass and NaOH solution. The precision of this system is essential to ensure that each batch of material achieves the appropriate quality of the geopolymer matrix, which directly translates into the strength results of the final product.
- Main Process Line (EUR 2.12 million): This is the most important budget item, encompassing the heart of the installation – an MDV-16 intensive counter-rotating mixer,

along with the necessary supporting infrastructure. This device was selected to function as a hybrid process unit, capable of both homogenizing dense concrete masses and dynamically granulating aggregates within a single working chamber. The cost also includes belt conveyors equipped with under-belt scales, which allow for continuous monitoring of line performance and precise transfer of finished product to the curing section. The use of such an advanced machine allows for a significant simplification of the process flow while maintaining the highest mechanical parameters of the material.

- Dust Extraction System (EUR 0.17 million): This expenditure is intended for the construction of an environmental protection and occupational health and safety system within the production hall. This includes pulse jet filters, exhaust fans, and a network of ducts connecting the points most exposed to dust emissions (mixer, chutes, scales). The system is designed to enable the recovery of captured dust and its reintroduction into the process, which eliminates the generation of secondary waste and is in line with the principles of a closed-loop economy.

Mobile equipment cost

The number and parameters of the transport vehicles were determined based on the assumed installation capacity of approximately 445 Mg/h and the adopted work organization (220 days/year, 20 hours/day). Unit prices were determined based on approximate market prices for new industrial-grade machines intended for continuous operation in processing and mining plants.

Table 15 Mobile equipment cost.

No.	Equipment	Qty, pcs	Unit price, mln EUR	Price, mln EUR
1	Wheel loader 5–6 m³	3	0.59–0.83	1.77–2.48
2	Hauler/technology truck 25–30 Mg	2	0.47–0.71	0.09–0.19
3	Crawler excavator 25–35 t	2	0.42–0.66	0.85–1.32
4	Forklift / Telehandler	1	0.09–0.19	0.09–0.19
5	Service/technical vehicle	1	0.06–0.12	0.06–0.12
	SUM			**3.73-5.52**

For further economic analyses, the value assumed was approximately EUR 4.62 million.

Civil works and supporting infrastructure

This position was calculated using indicators presented in the Table below. Calculations were based on the methodology and data presented for waste separation system.

Table 16 Civil works and supporting infrastructure.

No.	Position	Qty	Unit price	Price, mln EUR
1	Processing and manoeuvring areas	10 000 m²	42–71 EUR/m²	0.57
2	Raw material and product storage areas	10 000 m²	28–52 EUR/m²	0.4
3	Internal roads	8 000 m²	59–94 EUR /m²	0.61
4	Drainage of areas and roads	set	—	0.24
5	Foundations for equipment	ok. 300 m³ of concrete	425–660 EUR/m³	0.16
6	Supporting structures and viaducts	ok. 100 Mg of steel	3 302– 4 717 EUR/Mg	0.4
7	Power connection, switchboard, transformer	ok. 7,5-8,5 MVA	—	1.46
8	Control/dispatch room	ok. 125 m²	1 415–2 005 EUR/m²	0.21
9	Automation, I&C, monitoring, traffic control system	set	—	0.28
10	Maintenance workshop	ok. 200 m²	1 061–1 651 EUR/m²	0.11
11	Spare parts warehouse	ok. 100 m²	825–1 297 EUR/m²	0.14
12	Parking/machine parking area	ok. 3000 m²	35–59 EUR/m²	0,28
14	Social and health and safety facilities	ok. 200 m²	1 179–1 769 EUR/m²	0.29
15	Lighting, fencing, external monitoring	set	—	0.35
16	Design reserve/contingency	ok. 10%	—	0.55
	Total facilities and infrastructure			**6.06**

<u>Bare erected cost calculation</u>

Bare erected cost was estimated based on the data obtained from equipment providers, previous project of similar scope and own experience and data.

Table 17 Estimated amount for bare erected cost.

Cost item	Value [mln EUR]
Storage and dosing system for technological raw materials	0.47
Main technological line	2.12
Mobile equipment	4.62
Node dust removal installation	0.17
Civil works and supporting infrastructure	6.06
Bare erected cost (BEC)	**13.44**

Other cost components included Engineering, procurement, and construction costs (EPCC) and Total construction costs (TPC) were calculated with similar assumptions to the calculation of Waste separation and classification system.

Total overnight cost (TOC)

Total overnight cost is calculated based on the NETL and AACE guidelines, as well as own knowledge and experience. Specific assumptions are presented below:

- For pre-production costs, based on the NETL guidelines, it is 2% of TPC for other costs,
- For Inventory capital costs, 0.5% of TPC was assumed for spare parts,
- For other owner's costs 15% of TPC was assumed for costs such as preliminary studies, permitting costs, legal fees, site improvements outside of the facility boundaries, owner's engineering, owner's contingencies etc.

Calculation of Total overnight cost (TOC)

Based on the presented expenditure structure and the adopted assumptions, the total overnight cost (TOC) was determined, and the results are presented in the table below.

Table 18 Total overnight costs – Geopolymer concrete production system.

Outlay structure	**Cost, mln EUR**
Technological devices	2.76
Mobile equipment	5.9
Facilities and supporting infrastructure	5.76
Bare erected cost (BEC)	**14.41**
Contracting Strategy and EPC Contractor Services	2.88
Engineering, procurement, and construction costs (EPCC)	**17.30**
Process Contingency	0.87
Project Contingency	2.59
Total plant costs (TPC)	**20.76**
Preproduction (Start-Up) Costs	0.42
Inventory Capital	0.1
Other Owner's Costs	3.11
Total overnight cost (TOC)	**24.39**

4.1.5. Synthetic aggregates production system

Bare erected cost

Bare erected cost for geopolymer concrete production system was calculated for different cost components: main equipment, mobile equipment, civil works and supporting infrastructure.

Main equipment cost

Main equipment cost consists of:

- Storage and Dosing of Process Raw Materials (EUR 258.7 million): This section is responsible for the input stability of the entire process. The expenditure includes the construction of a battery of silos for fly ash (the precursor) and the mineral fraction of mining waste (the filler). A key element is an advanced strain gauge weighing system, which ensures the maintenance of rigorous proportions of bulk ingredients. Additionally, this amount includes a complete liquid chemical dosing system, including tanks with heating systems for water glass and NaOH solution. The precision of this system is essential to ensure that each batch of material achieves the appropriate quality of the geopolymer matrix, which directly translates into the strength results of the final product.
- Main Process Line (EUR 0.54 million): This is the most important budget item, encompassing the heart of the installation – an MDV-16 intensive counter-rotating mixer, along with the necessary supporting infrastructure. This device was selected to function as a hybrid process unit, capable of both homogenizing dense concrete masses and dynamically granulating aggregates within a single working chamber. The cost also includes belt conveyors equipped with under-belt scales, which allow for continuous monitoring of line performance and precise transfer of the finished product to the curing section. Using such an advanced machine allows for a significant simplification of the process flow while maintaining the highest mechanical parameters of the material.
- Dust extraction system (EUR 0.08 million): This investment is intended to construct an environmental protection and occupational health and safety system within the production hall. This includes pulse jet filters, exhaust fans, and a network of ducts connecting the points most susceptible to dust emissions (mixer, chutes, scales). The system is designed to enable the recovery of captured dust and its reintroduction into the process, eliminating secondary waste and aligning with the principles of a circular economy.

Mobile equipment cost

The number and parameters of the transport vehicles were determined based on the assumed installation capacity of approximately 17 Mg/h and the adopted work organization (8000 hours/year). Unit prices were determined based on approximate market prices for new industrial-grade machines intended for continuous operation in processing and mining plants.

Table 19 Mobile equipment cost.

No.	Equipment	Qty, pcs	Unit price, mln EUR	Price, mln EUR
1	Wheel loader 5–6 m³	1	0.59–0.83	0.59–0.83
2	Hauler/technology truck 25–30 Mg	1	0.47–0.71	0.47–0.71
3	Forklift / Telehandler	1	0.09–0.19	0.09–0.19
	SUM			**1.16-1.72**

For further economic analyses, the value assumed was approximately EUR 1.44 million.

Civil works and supporting infrastructure

This position was calculated using indicators presented in the Table below. Calculations were based on the methodology and data presented for waste separation system.

Table 20 Civil works and supporting infrastructure.

No.	Position	Qty	Unit price	Price, mln EUR
1	Technological and manoeuvring areas	1 500 m²	42–71 EUR/m²	0.08
2	Raw material and product storage yards	2 000 m²	28–52 EUR/m²	0.08
3	Internal roads	500 m²	59–94 EUR/m²	0.04
4	Drainage of yards and roads	set	—	0.04
5	Foundations for equipment	ok. 150 m³ of concrete	425–660 EUR/m³	0.08
6	Supporting structures and viaducts	ok. 50 Mg of steel	3 302– 4 717 EUR/Mg	0.20
7	Power connection, switchboard, transformer	0,6 MVA	—	0.39
8	Control room/dispatch room	ok. 75 m²	1415–2005 EUR/m²	0.13
9	Automation, I&C, monitoring, traffic control system	set	—	0.16
10	Maintenance workshop	ok. 100 m²	1061–1651 EUR/m²	0.14
11	Spare parts warehouse	ok. 50 m²	825–1297 EUR/m²	0.05
12	Parking lot/machine parking yard	ok. 500 m²	35–59 EUR/m²	0.02
14	Social and health and safety facilities	ok. 100 m²	1179–1769 EUR/m²	0.15
15	Lighting, fencing, external monitoring	set	—	0.11
16	Design reserve/contingency	ok. 10%	—	0.15
	Total facilities and infrastructure			**1.66**

Bare erected cost calculation

Bare erected cost was estimated based on the data obtained from equipment providers, previous project of similar scope and own experience and data.

Table 21 Estimated amount for bare erected cost.

Cost item	Value [mln EUR]
Storage and dosing system for technological raw materials	0.26
Main technological line	0.54
Mobile equipment	1.44
Node dust removal installation	0.08
Civil works and supporting infrastructure	1.81
Bare erected cost (BEC)	**4.12**

Other cost components included Engineering, procurement, and construction costs (EPCC) and Total construction costs (TPC) were calculated with similar assumptions to the calculation of Waste separation and classification system.

Total overnight costs (TOC)

Total overnight costs were calculated based on the NETL and AACE guidelines, as well as own knowledge and experience. Specific assumptions are presented below:

- For pre-production costs, based on the NETL guidelines, it consists of 6 months operating labour and 2% of TPC for other costs,
- For Inventory capital costs, 0.5% of TPC was assumed for spare parts,
- For other owner's costs 15% of TPC was assumed for costs such as preliminary studies, permitting costs, legal fees, site improvements outside of the facility boundaries, owner's engineering, owner's contingencies etc.

Calculation of Total capital expenditure (TOC)

Based on the presented expenditure structure and the adopted assumptions, the total investment expenditure (TOC) was determined, and the results are presented in the table below.

Table 22 Total overnight costs – Synthetis aggregates production system.

Outlay structure	Cost, mln EUR
Technological devices	0.87
Mobile equipment	1.44
Facilities and supporting infrastructure	1.81
Bare erected cost (BEC)	**4.12**
Contracting Strategy and EPC Contractor Services	0.62
Engineering, procurement, and construction cost (EPCC)	**4.74**
Process Contingency	0.24
Project Contingency	0.71
Total plant cost (TPC)	**5.59**
Preproduction (Start-Up) Costs	0.95
Inventory Capital	0.03
Other Owner's Costs	0.85
Total overnight cost (TOC)	**7.52**

4.1.6. CBF gasification system

Total equipment cost (TEC)

Total equipment cost estimation was conducted based on DOE/NETL study presented in document „Comparison of commercial state-of-the-art., fossil-based hydrogen production technologies", for Case 4. Due to differences in the gasification technology presented in the DOE/NETL analysis (Shell entrained pressurized gasifier) and technology adopted in our study (fluidised bed gasification), cost data was assumed based on the own experience and data from previous projects for coal gasification.

The total equipment cost calculations were conducted using an exponential investment assessment and price growth index method. The exponential investment assessment method is based on the following function:

$$C_1 = C_0 \left(\frac{S_1}{S_0}\right)^f$$

where C_1 is the calculated investment for the system component, C_0 is the reference investment cost, S_1 is the scale of the system component, S_0 is the base scale parameter and f is the scaling exponent.

The next step of determining the cost of specific equipment in the plant is converting its value from the base year to the current year of implementation. The price growth index method used is characterized by the following equation:

$$C_2 = C_1\left(\frac{I_2}{I_1}\right)$$

where C_2 is the calculated investment cost for the current year, C_1 is the reference investment cost for the base year, I_2 is the price growth index value for current year and I_1 is the price growth index value for the base year. Capital expenditures specified for the base year were calculated for the current year using CEPCI.

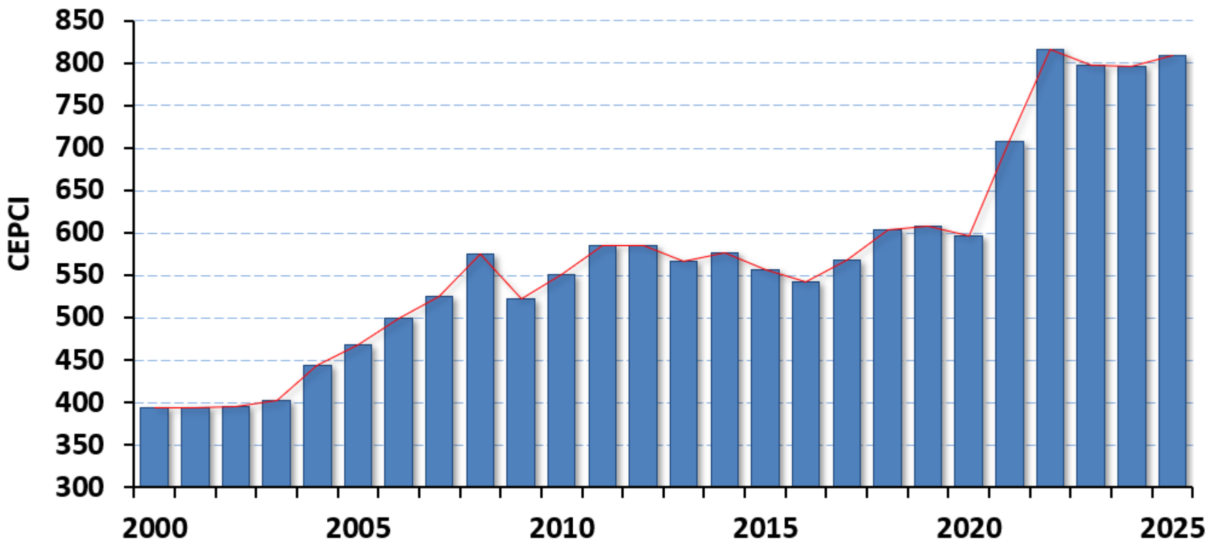

Fig. 4 Price growth index change for years 2000-2025 - CEPCI

Main equipment data used for total equipment cost estimation was presented in the table below.

Table 23 Main equipment data – CBF gasification plant.

Plant component	Scaling parameter S0	S0	Unit	f	C0 [mln USD]	Base year	CEPCI	S1	C2 [mln EUR]
CBF handling, preparation, feed	CBF feed	211967	kg/h	0.75	58.62	2018	603.1	36566	18.62
Gasification island	Thermal input	522.6	MW	0.67	81.05	2017	567.5	250.0	62.37
Air Separation Unit	Oxygen production	167670	kg/h	0.67	126.74	2018	603.1	25242	42.30
Water Gas Shift unit	Syngas stream	569529	kg/h	0.67	133.06	2018	603.1	92823	46.84
Acid Gas Removal Unit	Sulphur product	5280	kg/h	0.67	58.05	2018	603.1	172.0	6.95

Pressure Swing Adsorption Unit	Hydrogen production	27498	kg/h	0.67	41.32	2018	603.1	3090	11.34
Gas Fired Boiler Unit	Thermal input	179	MW	0.67	4.25	2018	603.1	71.5	2.73
Steam Turbine Unit	Gross electric power	89	MW	0.67	28.96	2018	603.1	33.0	17.67

Total equipment cost for CBF gasification unit is estimated at 208,82 mln PLN.

Bare erected cost (BEC)

Calculation of the other cost components of the installation necessary for the bare erected cost calculation was carried out using cost factor method, based on Peters and Timmerhaus methodology. In this methodology, cost factors for different components are calculated as percentage of the total equipment cost. Factors were calculated using DOE/NETL calculation for Case 4. These include the costs of construction, assembly, and installation of equipment, along with other costs directly related to the construction of the installation. Calculated factors are presented in the table below.

Table 24 Bare erected cost – CBF gasification system.

Outlay structure	Cost, mln EUR
Equipment	100%
Installation	45.9%
Electrical installations	6.1%
Instrumentation and Control Systems (I&C) installations	3.0%
Auxiliary installations	37.1%
Land development	3.4%
Buildings and structures	2.2%
Bare erected cost (BEC)	**197.7%**

Engineering, procurement, and construction cost (EPCC)

Engineering, procurement, and construction cost include bare erected cost plus items such as design costs, project management costs, site preparation, and other indirect costs. Calculated cost factor for EPC based on the DOE/NETL Case 4 calculation was estimated at 13,7% of BEC, which corresponds with 15% assumed for other systems.

Total plant cost (TPC)

Total plant cost includes EPCC cost plus items such as process contingency and project contingency. Calculated cost factor for project and process contingencies based on the

DOE/NETL Case 4 calculation were estimated at 6,1% of EPCC for process contingency and 16,5% of EPCC for project contingency, which corresponds with 5% and 15% assumed for other systems.

Total overnight cost (TOC)

Total overnight cost includes the total construction costs plus pre-production costs, spare parts costs, and other investor costs (legal costs, studies, investor engineering costs, management reserve, etc.). Calculated cost factor for project and process contingencies based on the DOE/NETL Case 4 calculation were estimated at:

- 3,2% of TPC for pre-production cost,
- 2,6% of TPC for inventory capital,
- 15,7% for other owner's cost.

These assumptions correspond with values assumed for other systems.

Based on the presented expenditure structure and the adopted assumptions, the total overnight cost (TOC) was determined, and the results are presented in the table below.

Table 25 Total overnight cost – CBF gasification system.

Outlay structure	Cost, mln EUR
Equipment	208.82
Installation	95.48
Electrical installations	12.74
Instrumentation and Control Systems (I&C) installations	6.29
Auxiliary installations	77.41
Land development	7.13
Buildings and structures	4.61
Bare erected cost (BEC)	**412.78**
Contracting Strategy and EPC Contractor Services	56.34
Engineering, procurement, and construction cost (EPCC)	**469.12**
Process Contingency	28.53
Project Contingency	77.52
Total plant cost (TPC)	**575.17**
Preproduction (Start-Up) Costs	18.58
Inventory Capital	15.11
Other Owner's Costs	90.17
Total overnight cost (TOC)	**699.03**

4.2. OPEX estimation

OPEX calculation was carried out for 2 categories of operation expenditures – variable and fixed costs. Variable cost included fuel, energy, media and chemicals consumption, while fixed costs included operating & maintenance labour costs. All calculations were carried out based on the results presented in Deliverable 6.1, including electric energy balances of the integrated H2GEO system, as well as mass balances of the specific systems.

Basic assumptions for OPEX calculation were obtained using public databases, own data and consultations with experts. Unit costs for different components are presented in the table below.

Table 26 Summary of basic assumptions for OPEX calculation.

Component Cost	Unit cost
Electricity cost, EUR/MWh	176.88
Equipment operating cost, EUR/Mg of processing	0.47
Process equipment repair and maintenance costs, EUR/Mg of processing	10.24
Process water cost, EUR/m^3	1.88
Labour specific cost, EUR/y	37 026.56
Flocculant cost, EUR/Mg	4716.76
Cost of hard coal, EUR/Mg	353.76
Cost of corrective additive, EUR/Mg	117.92
Cost of solid NaOH, EUR/Mg	471.68
Cost of R-150 solution, EUR/Mg	563.65
Hydrogen cost, EUR/kg	4.13
Activated carbon price, EUR/kg	13.7
MDEA price, EUR/l	0.85
NaOH solution price, EUR/kg	0.68
Claus catalyst price, EUR/m^3	1936.61
PSA adsorbent price, EUR/m^3	6051.88
WGS catalyst price, EUR/m^3	19366.02
Heating oil price, EUR/t	637.99
Industrial wastewater price, EUR/m^3	2
Sulphur price, EUR/t	450
Slag disposal price, EUR/t	40
Spent activated carbon price, EUR/t	91.39
Spent MDEA price, EUR/m^3	105.63
Filter cake disposal price, EUR/t	43.42
Spent Claus catalyst price, EUR/m^3	100.87
Spent WGS catalyst price, EUR/m^3	100.87
Spent PSA adsorbent price, EUR/m^3	60.52
CO_2 emission allowance price, EUR/t	75

Based on the balances, calculations were made of the flows of individual raw materials and media consumed in each system. Individual values are presented below.

Table 27 Calculations of the flows of individual raw materials and media consumed in each of the systems.

Component cost	Stream value	Unit cost, EUR	Annual cost, mln EUR
Waste separation and classification system			
Flocculant cost	14,96 Mg/y	4 716.76	0.07
Electricity cost	6 270 MWh/y	176.88	1.11
Process water cost	176 000 m^3/y	1.18	0.21
Mobile equipment exploitation cost	3 000 000 Mg/y	0.47	1.42
Geopolymer production system using calcined mineral fraction			
Cost of hard coal	3454,4 Mg/y	353.76	1.22
Cost of corrective additive	2700 Mg/y	117.92	0.38
Electricity cost	10 400 MWh/y	176.88	1.84
Geopolymer concrete production system			
Cost of solid NaOH	123 426 Mg/y	471.68	58.22
Cost of R-150 solution	501 184 Mg/y	563.65	282.49
Electricity cost	64 912 MWh/y	176.88	11.48
Process water cost	9 680 m3/y	1.18	0.01
Mobile equipment exploitation cost	1 954 864 Mg/y	0.47	0.92
Synthetic aggregates production system			
Cost of solid NaOH	13966 Mg/y	471.68	6.59
Cost of R-150 solution	41897 Mg/y	563.65	23.61
Electricity cost	4 765 MWh/y	176.88	0.84
Process water cost	15 882 m^3/y	1.18	0.02
Mobile equipment exploitation cost	135 000 Mg/y	0.47	0.06
CBF gasification system			
Cost of Activated carbon	7,9 Mg/y	13.7 EUR/kg	0.11
Cost of MDEA price	22,07 m^3/y	0.85 EUR/dm^3	0.02
Cost of NaOH solution	486 Mg/y	0.85 EUR/kg	0.33
Cost of Claus catalyst	0,59 m^3/y	1936.61 EUR/m^3	0.001
Cost of PSA adsorbent	9,12 m^3/y	6051.88 EUR/m^3	0.05
Cost of WGS catalyst	27,38 m^3/y	19366.02 EUR/m^3	0.53
Cost of Process water	1 027 228 Mg/y	1.18 EUR/Mg	1.21
Cost of Heating oil	570,42 Mg/y	637.99 EUR/t	0.36
Cost of Industrial wastewater	97539 Mg/y	2 EUR/m^3	0.2
Cost of Spent activated carbon	7,93 Mg/y	91.39 EUR/Mg	0.001
Cost of Spent MDEA	22,07 m^3/y	105.63 EUR/m^3	0.002
Cost of disposal filter cake	916,6 Mg/y	43.42 EUR/Mg	0.04
Cost of Spent Claus catalyst	0,59 m^3/y	100.87 EUR/m^3	0.0001
Cost of Spent WGS catalyst	27,38 m^3/y	100.87 EUR/m^3	0.002
Cost of Spent PSA adsorbent	9,12 m^3/y	60.52 EUR/m^3	0.0005
Cost of CO_2 emission allowance	636406 Mg/y	75 EUR/Mg	47.73

Table 28 Estimated labour costs for each system.

Parameter	Unit cost
Waste separation and classification system	
Number of Full-Time Positions	70
Labour cost, mln EUR/y	2.59
Geopolymer production system using calcined mineral fraction	
Number of Full-Time Positions	35
Labour cost, mln EUR/y	1.3
Geopolymer concrete production system	
Number of Full-Time Positions	57
Labour cost, mln EUR/y	2.11
Synthetic aggregates production system	
Number of Full-Time Positions	45
Labour cost, mln EUR/y	1.67
CBF gasification system	
Number of Full-Time Positions	60
Labour cost, mln EUR/y	2.22

Repairs and maintenance of technological equipment

Waste separation and classification system

The costs of repairs and maintenance of technological equipment were assumed at the level of PLN 1/Mg of processed material, taking into account the replacement of fast-wearing parts, working elements, periodic inspections and ongoing repairs of devices included in the technological line.

Geopolymer production system using calcined mineral fraction

The costs of repairs and maintenance of technological equipment were assumed as 3% of the TPC value.

Geopolymer concrete production system

The costs of repairs and maintenance of technological equipment were assumed at the level of PLN 1/Mg of processed material, taking into account the replacement of fast-wearing parts, working elements, periodic inspections and ongoing repairs of devices included in the technological line.

Synthetic aggregates production system

The costs of repairs and maintenance of technological equipment were assumed as 3% of the TPC value.

CBF gasification system

The costs of repairs and maintenance of technological equipment were assumed as 3% of the TPC value.

Table 29 Summary of costs of repairs and maintenance of technological equipment.

Component Cost	Unit cost, mln EUR/y
Waste separation and classification system	0.71
Geopolymer production system using calcined mineral fraction	0.31
Geopolymer concrete production system	0.35
Synthetic aggregates production system	0.17
CBF gasification system	5.75

Table 30 OPEX costs of the entire system.

Component Cost	Unit cost, mln EUR
Waste separation and classification system	
Labour	2.59
Electricity	1.11
Operation of mobile equipment	1.42
Repairs and maintenance of process equipment	0.71
Process water	0.21
Process reagents	0.07
OPEX variable	2.8
OPEX fixed	3.3
OPEX	6.1
Geopolymer production system using calcined mineral fraction	
Labour	1.3
Electricity	1.84
Repairs and maintenance of process equipment	0.31
Process reagents	1.54
OPEX variable	3.38
OPEX fixed	1.6
OPEX	4.98
Geopolymer concrete production system	
Labour	2.11
Electricity	12.83
Operation of mobile equipment	0.92
Repairs and maintenance of process equipment	0.35

Process water	0.01
Process reagents	340.71
OPEX variable	354.50
OPEX fixed	2.46
OPEX	356.96
Synthetic aggregates production system	
Labour	1.67
Electricity	0.84
Operation of mobile equipment	0.06
Repairs and maintenance of process equipment	0.17
Process water	0.02
Process reagents	30.21
OPEX variable	31.13
OPEX fixed	1.84
OPEX	32.97
CBF gasification system	
Labour	2.22
Repairs and maintenance of process equipment	17.25
Raw resources and media	1.93
Waste utilisation	3.33
CO2 emission allowances	47.73
Others	1.21
OPEX variable	52.98
OPEX fixed	20.68
OPEX	73.66
Total OPEX	
Total OPEX variable	444.79
Total OPEX fixed	29.89
Total OPEX	474.68

4.3. Revenue estimation

The main revenue items include:

- Profits from hydrogen sales,
- Profits from aggregate sales,
- Profits from geopolymer concrete sales,
- Profits from synthetic geopolymers sales,
- Profits from fly ash disposal.

Table 31 Summary of basic assumptions for profit estimation.

Type of profit	Price	Source
Hydrogen sales, EUR/kg	4.14	Hydrogen price was estimated based on the public data obtained from https://www.obserwatorfinansowy.pl/bez-kategorii/rotator/perspektywy-zielonego-wodoru-w-europie/ — using the average production cost of grey hydrogen plus a 10% product margin.
Aggregate sales, EUR/Mg	4.72	The price was estimated based on the market consultations.
Geopolymer concrete sales, EUR/Mg	54.95	The price of geopolymer concrete was determined based on https://kb.pl/cenniki/uslugi/cennik-betonu-po-klasach-w-calej-polsce-sprawdz-ceny/, for C25/30 concrete assuming a density of 2.4 Mg/m³.
Synthetic geopolymers sales, EUR/Mg	42.4	The price was estimated based on the market consultations.
Fly ash utilization, EUR/Mg	224.05	Fly ash price was estimated based on cost of utilization of fly ashes classified as waste from hard and brown coal combustion processes (10 01 18* - EUR 306.6 net per Mg 10 01 19 - EUR 141.5 net per Mg). Utilization in geopolymer production eliminates the waste code and allows for a profit on disposal costs.

Table 32 Calculations of the flows of individual revenue in each of the systems.

Revenue component	Stream	Unit price	Annual revenue, mln EUR
Waste separation and classification system			
Natural aggregates sale	2 295 000 Mg/y	4.72 EUR/Mg	10.82
Geopolymer concrete production system			
Geopolymer concrete sale	1 954 865 Mg/y	54.95 EUR/Mg	107.42
Fly ash utilization	1 122 053 Mg/y	224.05 EUR/Mg	251.39
Synthetic aggregates production system			
Synthetic aggregates sale	232 759 Mg/y	42.45 EUR/Mg	9.88
Fly ash utilization	41 897 Mg/y	224.05 EUR/Mg	9.39
CBF gasification system			
Hydrogen sale	24 723 Mg/y	4.14 EUR/kg	102.25
Sulphur sale	1 376 Mg/y	449.98 EUR/Mg	0.62
Excess electricity production	18 306 MWh/y	176.88 EUR/MWh	3.24
Total income			
Total revenue			**495.01**

4.4. Economic performance indicators calculation

The calculation of economic efficiency indicators was based on assumptions based on data presented in the NETL guidelines, publicly available macroeconomic data, and our own assumptions.

Table 33 Global economic assumptions.

Assumption	Value	Source
Capital expenditure period	5 years	Based on NETL guidelines
Distribution of TOC over the Capital Expenditure period	10%, 30%, 25%, 20%, 15%	Based on NETL guidelines
Operational period	30 years	Based on NETL guidelines
Income tax rate	19%	Based on average CIT value
Capital depreciation	20 years	Based on NETL assumptions, assumed straight line depreciation
Escalation of costs and revenues	0% real	Based on NETL assumptions
Escalation of labour cost	2 % real	The long-term average annual dynamics of labour cost was adopted in accordance with the guidelines for the use of uniform macroeconomic indicators[26]
Financial structure, debt/equity	50%/50%	Assumed based on own data
Cost of debt	6%	Assuming average value of WIBOR 6M at 4% + 2% margin
Cost of equity	10%	Based on NETL assumptions
r, discount rate	ATWACC	Assumed ATWACC value
Debt repayment period	30 years	Equal to operational period, based on NETL assumptions

4.4.1. ATWACC

Calculation of after-tax weighted average cost of capital was performed using formula:

$$ATWACC = \%Equity * r_{Equity} + \%Debt * r_{Debt} * (1 - ETR)$$

Where:

$\%_{Equity}$, $\%_{Debt}$ – financial structure of the project, assumed 50%/50%

r_{equity} – cost of equity, 10%

[26] https://www.gov.pl/web/finanse/wytyczne-sytuacja-makroekonomiczna, access 29.06.2026

r_{debt} – cost of debt, 6%,

ETR – effective tax rate, assumed CIT value of 19%.

Calculated ATWACC value is 7.43%.

4.4.2. Results of calculations

Based on the results of CAPEX, OPEX and income estimation, economic performance indicators values were calculated.

NPV [EUR] – Net Present Value – The NPV of a project is defined as the value obtained by discounting, at a constant rate and separately for each year, the differences between cash inflows and outflows occurring over the project's entire life. The NPV indicates only positive inflows or positive benefits from the project.

IRR [%] – Internal Rate of Return – The Internal Rate of Return (IRR) is the discount rate at which the present value of cash outflows equals the present value of cash inflows. In other words, it is the discount rate at which the net present value (NPV) of the project equals zero, meaning that the discounted project benefits are equal to the discounted investment costs. IRR can be interpreted as the annual net rate of return on the invested capital or, alternatively, as the maximum annual borrowing cost (after tax) that the project can sustain while remaining economically viable.

SPBT [years] – Simple Payback Time – The payback period, also known as the payback period, is defined as the period required to recoup the initial investment expenditure through a return on the project's cumulative net cash balances. Using SPBT is useful when rapid technological change is expected in a given industry, particularly when the project's technological life cycle is shorter than its technical life cycle. The payback period method focuses primarily on the initial phase of the operational life and does not represent the investment's performance beyond the payback period.

Table 34 Economic performance indicators.

Indicator	Value
NPV, mln EUR	-400.5
IRR, %	0,87
SPBT, years	30

Calculations show that for analysed case production of geopolymers and hydrogen is characterized with low indicators value.

5. Summary

As part of task T. 6.2, a comprehensive set of quantitative and economic analyses was carried out for the Central Mining Waste Disposal Facility in Knurów, selected as a reference model for the entire WP6 package. The scope of work included an assessment of the resource potential of the deposited waste and an analysis of possible reclamation directions, including changes in land value.

Based on the obtained data, a detailed characterization of the selected spoil heap was performed. The location, ownership, and geometric parameters of CSOG (Central Mining Waste Disposal Facility in Knurów) were determined: an area of approximately 16.5 ha and a mass of waste deposited by the end of 2018 amounting to approximately 28.83 million Mg. The main waste streams were identified (Budryk coal mine and Knurów operation of JSW S.A.), along with mining waste codes (01 01 02, 01 04 12, 01 04 81), as well as the typical lithological composition of the heap, dominated by claystones with admixtures of mudstones and sandstones.

The next stage involved preparing input data for the analysis of mineral and energy resources. Available research results on the mineral composition and physical properties of the waste were compiled, and on this basis the main material fractions were distinguished: the aluminosilicate fraction, carbonate fraction, coal fraction, iron-sulphide fraction, and trace element fraction, including rare earth elements and heavy metals. For each fraction, the mass share in the heap and the corresponding absolute mass were determined; for the aluminosilicate and carbonate fractions, dominant minerals were indicated, including quartz, clayey mudstones, calcite, and dolomite, while for the iron-sulphide fraction, pyrite and related secondary iron minerals were identified.

In the quantitative part, the total mass of waste deposited in the analysed heap was estimated at 28,829,236.88 Mg, of which approximately 6.7% is the coal fraction and 93.3% is the mineral fraction. This allows the separation of approximately 1,931,558.87 Mg of coal fraction and approximately 26,897,678 Mg of mineral fraction, potentially suitable for use as aggregate or raw material for geopolymer composites.

On this basis, a detailed economic analysis of the main fractions was conducted. For the coal fraction, the energy potential was estimated using an effective calorific value of 22,662 kJ/kg; this corresponds to total chemical energy of approximately 43,750 TJ, which, assuming an electricity generation efficiency of 35%, enables the production of approximately 4.25 TWh of electricity. In the variant of direct use of the coal fraction as solid fuel, with an adopted reference price of 1,000 PLN/Mg, the potential economic value is approximately 1.93 billion PLN. In the variant involving gasification and conversion of the coal fraction into hydrogen, assuming a conversion chain efficiency of 13.2%, the potential production of approximately 254,969.73 Mg H_2 was identified, which at a price of 6.61 PLN/kg corresponds to a value of approximately 1.69 billion PLN.

In parallel, the economic value of mineral fractions was estimated. After subtracting the coal fraction, the main mass of the heap consists of aluminosilicate and carbonate fractions, which, due to their granulometric and physical properties, can be used as low- and medium-quality aggregates in road construction, earthworks, and reclamation activities. With a reference price of 18 PLN/t and a mineral fraction mass of approximately 26.90 million Mg, the total indicative economic value of the remaining mineral fractions was estimated at approximately 484.2 million PLN. This analysis confirms that the mineral material may constitute an important component of a business model related to spoil heap reclamation and secondary use of post-mining waste.

As part of the task, a variant-based economic analysis of land after reclamation was also performed. The initial value of degraded land beneath the heap was assumed at 10 PLN/m², which for an area of 16.5 ha corresponds to a total value of approximately 1.65 million PLN, with uncertainty scenarios of 5–20 PLN/m² considered. Five target directions of land development were then analysed: the forest-agricultural variant, approximately 35 PLN/m² and 5.78 million PLN; the green-recreational variant, approximately 50 PLN/m² and 8.25 million PLN; the photovoltaic farm variant, 80 PLN/m² and 13.20 million PLN; the industrial variant with restrictions, 120 PLN/m² and 19.80 million PLN; and the industrial variant with full use of potential, 200 PLN/m² and 33.00 million PLN. The total potential increase in land value, calculated as the difference between the post-reclamation state and the current land value, ranges from approximately 4.1 million PLN in the forest-agricultural variant to approximately 31.4 million PLN in the industrial variant with full potential.

The comparison of results concerning resource potential and changes in land value shows that processing the central spoil heap in Knurów may simultaneously contribute to increasing the national mineral resource base, generating significant revenues from the recovery of coal and mineral fractions, and substantially increasing the value of the reclaimed land.

Second part of Deliverable 6.2 includes a financial analysis of the full chain technology concept of mine waste dumps, including: determination of estimated investment expenditure, estimated production costs and determination of the economic performance indicators, such as NPV, IRR.

The analysis covered the full chain technology consisting of the following systems:

- Waste separation and classification system,
- Geopolymer production system using calcined mineral fraction,
- Geopolymer concrete production system,
- Synthetic aggregates production system,
- CBF gasification system.

The presented technology ensures the optimal integration of all the analysed systems and reduces the number of by-products generated by each system.

CAPEX analysis has shown that the CBF gasification system accounts for the highest expenditure. The reason for such a high cost is the high level of complexity of the technologies involved in the process.

Table 35 CAPEX outlay structure for full-chain technology.

Outlay structure	Cost, mln EUR
Waste separation and classification system	
Bare erected cost (BEC)	26.88
Engineering, procurement and construction cost (EPCC)	32.26
Total plant cost (TPC)	38.71
Total overnight cost (TOC)	47.69
Geopolymer production system using calcined mineral fraction	
Bare erected cost (BEC)	10.23
Engineering, procurement and construction cost (EPCC)	11.76
Total plant cost (TPC)	14.11
Total overnight cost (TOC)	18.15
Geopolymer concrete production system	
Bare erected cost (BEC)	14.41
Engineering, procurement and construction cost (EPCC)	17.30
Total plant cost (TPC)	20.76

Total overnight cost (TOC)	24.39
Synthetic aggregates production system	
Bare erected cost (BEC)	4.12
Engineering, procurement and construction cost (EPCC)	4.74
Total plant cost (TPC)	5.59
Total overnight cost (TOC)	7.52
CBF gasification system	
Bare erected cost (BEC)	412.78
Engineering, procurement and construction cost (EPCC)	469.12
Total plant cost (TPC)	575.17
Total overnight cost (TOC)	699.03
Full-chain technology	
Bare erected cost (BEC)	468.42
Engineering, procurement and construction cost (EPCC)	535.18
Total plant cost (TPC)	654.34
Total overnight cost (TOC)	796.78

OPEX and revenue analysis showed that geopolymer concrete production is characterised by the highest costs associated with the purchase of solid NaOH and R-150 water glass, which are essential to the process. However, the use of fly ash – the utilisation cost of which is very high – has shown that the possibility of utilising fly ash from power stations and heating districts fuelled by hard coal and brown coal significantly improves the results.

Table 36 OPEX and revenue analysis for full-chain technology.

Outlay structure	Cost, mln EUR
Waste separation and classification system	
OPEX var	2.8
OPEX fix	3.3
OPEX	6.1
Revenue	10.82
Geopolymer production system using calcined mineral fraction	
OPEX var	3.38
OPEX fix	1.6
OPEX	4.98
Revenue	-
Geopolymer concrete production system	
OPEX var	354.5
OPEX fix	2.46
OPEX	356.96
Revenue	358.81
Synthetic aggregates production system	

OPEX var	31.13
OPEX fix	1.84
OPEX	32.97
Revenue	19.27
CBF gasification system	
OPEX var	52.98
OPEX fix	20.68
OPEX	73.66
Revenue	106.11
Full-chain technology	
OPEX var	444.79
OPEX fix	29.89
OPEX	474.68
Revenue	495.01

The production costs of geopolymer concrete are almost equal to the revenue from its sale, whilst the OPEX for synthetic aggregates is almost twice as high as the revenue, which significantly reduces the profitability of the full-chain technology. An analysis of economic performance indicators has shown that the full-chain technology is characterised by low profitability, mainly due to the high production costs of geopolymer concrete and synthetic aggregates, which are not covered by their sales revenue.

Table 37 Economic performance indicators.

Indicator	Value
NPV, mln EUR	-400.5
IRR, %	0,87
SPBT, years	30

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