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H2GEO

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

Deliverables 1.4

Publishable Report

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Introduction

This publishable report summarises the main results of the H2GEO project, which developed an integrated circular-economy concept for converting post-mining waste into hydrogen and geopolymer-based materials. It consolidates the key findings of Deliverables and selected project Milestones, covering waste characterisation and separation, hydrogen production, mineral-fraction valorisation, the final technology concept, and its economic, environmental, social and legal assessment. Detailed methods and results are provided in the individual source deliverables.

The descriptions of Deliverables D4.1–D5.4 have been generalised due to the confidential nature of the results obtained.

D.1.1. The communication and dissemination plan

Deliverable D1.1 presented the Communication and Dissemination Plan for the H2GEO project. The document was prepared by KOMAG at the initial stage of the project and defined the principles, tools and channels used for internal communication, external dissemination and public visibility of the project and its results. It provided a common framework for coordinating communication activities between consortium partners and for presenting the project to external stakeholders in a coherent manner.

The main purpose of the plan was to ensure effective transfer of information about the H2GEO objectives, activities and results to relevant target groups. The document distinguished between communication, understood as increasing the public visibility of the project, consortium and research programme, and dissemination, focused on making project results available to specific audiences, including the scientific community, public authorities, industry, potential investors and other stakeholders.

D1.1 described the internal communication strategy, based on regular information exchange between project partners through e-mails, telephone calls, online meetings, teleconferences and direct meetings. It also defined the role of the Steering Committee in monitoring project progress, coordinating work packages, analysing risks and supervising milestones and deliverables. Research teams were assigned responsibility for data archiving, progress reporting and identification of potential implementation difficulties.

The external communication and dissemination toolbox included the project logo, website, roll-ups, social media posts, press releases, conference presentations, flyers, document templates and promotional presentations. Dissemination tools included scientific publications, oral and poster presentations, seminars, congresses, potential patent activity, stakeholder meetings and training activities for local governments and entrepreneurs. The main dissemination channels included the H2GEO website, public reviews, annual e-newsletters, social media, print media, scientific publications, conferences and project-related events.

The plan also defined target audiences and key dissemination subjects. The target groups included project partners, academic and research communities, industrial stakeholders, local authorities, enterprises, State Treasury companies, related EU projects and the general public. The key subjects included the H2GEO project itself, the consortium and funding programme, the development of the technology chain for hydrogen and geopolymer composite production from mine waste dumps, and the economic, environmental, social and legal assessment of the proposed technology.

A separate part of D1.1 concerned EU visibility requirements. The document specified that communication and dissemination materials should include the EU emblem, relevant funding statement and required disclaimer concerning responsibility for expressed views and opinions. These rules applied to publications, reports, newsletters, posters, webpages, infographics, event materials and other public project outputs.

D1.1 also documented the first communication and dissemination actions undertaken in the project. These included preparation of the H2GEO project logo, publication of project information on Facebook and presentation of the project on partner websites. Overall, the deliverable established the organisational and procedural basis for communication and dissemination within H2GEO, ensuring stakeholder engagement, visibility of EU funding and consistency of public information throughout project implementation.

D.1.2. Webpage created and initiated

Deliverable D1.2 documented the creation and launch of the H2GEO project webpage. The webpage was established as one of the main communication and dissemination tools of the project, in accordance with the Communication and Dissemination Plan defined in D1.1. Its purpose was to provide public access to basic information on the project, including its objectives, consortium, activities and progress.

The webpage included several main sections. The home page presented the H2GEO project identity, general project information, abstract, main aims and selected news. The "About" section described the project assumptions, objectives, research scope and expected impact, including the use of post-mining waste for hydrogen and geopolymer composite production. A separate section presented the project consortium, including research institutions, universities and industrial partners involved in the project, thereby showing its international and interdisciplinary character.

The webpage also included elements required for project visibility, such as the H2GEO logo, project duration, contact details, links to project partners and the EU funding disclaimer. Overall, D1.2 confirmed that the H2GEO webpage had been created and made available as a central online communication channel supporting dissemination activities and public visibility of the project.

D.1.3. The Comprehensive Public Overview of the Project

Deliverable D1.3 provided a comprehensive public overview of the H2GEO project. The document presented the basic project information, general objective, consortium structure, work plan and main thematic areas covered by the project. Its function was informative and dissemination-oriented, as it explained the project concept in a form accessible to external audiences.

D1.3 described H2GEO as a 36-month RFCS project focused on developing a new technology for hydrogen and geopolymer composite production from post-mining waste. The project was based on a circular economy approach, in which material deposited in mine waste dumps is treated not only as an environmental burden, but also as a potential source of useful raw materials. The main technological assumption was to separate post-mining waste into an energy fraction for hydrogen production through gasification and a mineral fraction for geopolymer composite production with fly ash.

The deliverable highlighted the environmental relevance of the project. Mine waste dumps from hard coal production were identified as sources of land degradation and potential hazards, including fire risk, gas emissions and contamination of surface and groundwater through leaching. In this context, H2GEO was presented as an approach aimed at reducing the amount of material deposited in mine waste dumps while maximising the use of stored waste.

The document also described the main technological directions of the project. These included processing mineral waste and fly ash, with the use of CO_2, for geopolymer composite production; developing hydrogen production from synthesis gas obtained by gasification of carbon-bearing fractions; and preparing high-quality material streams through beneficiation and a planned mobile mine waste separation system. The deliverable also indicated that the technology would be supported by environmental assessment, including LCA, and by identification of possible applications for the produced composites.

D1.3 summarised the role of consortium partners and the structure of the H2GEO work plan. The consortium combined research institutions, universities and industrial partners responsible for project coordination, mine waste dump inventory, material testing, gravity separation, mobile system development, thermochemical conversion, hydrogen production, geopolymer research, economic and environmental analyses, and development of the final technology concept. The work plan covered project management and dissemination, dump inventory and raw waste testing, jig beneficiation and separation product analysis, thermochemical hydrogen production, use of mineral fractions, and final economic, environmental, social, legal and LCA-related assessment.

Overall, D1.3 served as a public-facing document explaining the H2GEO project assumptions, consortium structure and work plan. It did not present detailed research results, but provided a clear overview of the project logic: identification and characterisation of mine waste dumps, separation of useful fractions, conversion of the energy fraction into hydrogen, use of mineral fractions in geopolymer and other material applications, and final assessment of the complete technological chain.

D.2.1. Rank of Dumps as Regards Their Use in Jig Beneficiation Process and Hazards to Environment and Man

Deliverable D2.1 presented the inventory and preliminary assessment of post-mining waste dumps in selected European countries. The document was prepared within Work Package 2 and constituted one of the first analytical steps in the H2GEO project. Its purpose was to identify mine waste dumps that could potentially serve as sources of material for further processing, especially for jig beneficiation, hydrogen production from carbon-bearing fractions and geopolymer composite production from mineral fractions.

The work was based on the assumption that post-mining waste dumps may represent both an environmental burden and a secondary raw material source. Therefore, the assessment combined two perspectives: the technological suitability of deposited material for separation and further use in the H2GEO technology chain, and the environmental or human-related hazards associated with waste dumps, including fire risk, geotechnical instability, leaching of pollutants and broader impacts on post-mining regions.

The inventory covered coal waste dumps in the Czech Republic, France, Germany, Spain, the United Kingdom, Belgium, Romania and Poland. The review was carried out by project partners according to geographical responsibility and used different data sources, including national databases, public GIS and geodata platforms, previous European projects, scientific literature, public registers and information from entities managing post-mining waste facilities. The quality and completeness of the data differed between countries, which was one of the main limitations of the inventory.

A set of selection criteria was defined to create a database of coal waste dumps potentially suitable for the H2GEO project. The criteria included the volume of deposited waste, with a minimum threshold of 100,000 m^3, access to the site and the possibility of obtaining owner consent for sampling, origin from underground hard coal mining, activity or reclamation status, and environmental risk. These criteria were important because further laboratory testing, beneficiation trials and technological evaluation required representative samples, sufficient material volume and realistic access conditions.

The database structure included, where available, the facility name, region or city, raw material, type of waste storage object, volume of mining waste, activity status, reclamation status, environmental risk assessment, GPS coordinates and additional notes. The spatial information was important for mapping, visualisation and future monitoring of the identified waste dumps.

The final inventory included 864 records. The largest number of records was collected for Belgium, with 277 records, followed by Romania with 159, Spain with 126, Germany with 90, the Czech Republic with 86, Poland with 84, France with 33 and the United Kingdom with 9 records. The low number of records for some countries did not necessarily reflect the actual number of coal waste dumps, but rather the availability and format of public data. In some cases, information was fragmented, incomplete or available only through map-based tools.

For Poland, the inventory was prepared using Marshal's Office databases, the GIG OPI TPP database and HALDEX materials based on interviews and visits to hard coal mines. The Polish inventory included 84 records, of which 8 were active mining waste landfills where waste was still being collected. The deliverable also indicated that 41 landfills were fully or partly reclaimed, while thermal and fire hazards were identified at 7 Polish post-mining landfills due to the presence of coal in the deposited material.

The results demonstrated that Europe still contains a substantial number of coal mining waste dumps that may be relevant for recovery, reclamation or risk mitigation activities. At the same time, the inventory confirmed that the practical use of such dumps requires site-specific assessment, access to representative samples, reliable and standardised data, and consideration of environmental, ownership and legal constraints.

Overall, D2.1 provided a structured overview of selected European post-mining waste dumps and defined the criteria for assessing their technological usefulness and environmental relevance. The deliverable created the resource base for subsequent H2GEO tasks, including raw waste testing, jig beneficiation, separation of carbon-bearing and mineral fractions, thermochemical conversion, geopolymer production and final assessment of the complete technology chain.

D.2.2. Analysis Results of Testing Raw Mine Wastes

Deliverable D2.2 presented the results of testing raw mine wastes selected for further research within the H2GEO project. The deliverable provided physicochemical, mechanical, mineralogical, thermal and biological characterisation of raw waste materials collected from selected post-mining dumps. These analyses formed the basis for assessing their suitability for jig beneficiation, hydrogen production from carbon-bearing fractions, geopolymer composite production from mineral fractions and reclamation-related applications.

The research covered six raw mine waste samples from three dumps. Haldex1 and Haldex2 came from the Panewnicka heap in Poland, while Karvina1 and Karvina2 came from the Jan Karel heap and Paskov1 and Paskov2 from the Paskov D heap in the Czech Republic. The samples were analysed using proximate and ultimate analyses, ash composition, ash fusion temperature measurements, trace element analysis, sieve and density analyses, thermal analysis, mechanical testing, SEM/EDS analysis, microscopic examination and biological activity testing.

The tested materials were relatively dry, with total moisture below 5%, but had high ash contents, confirming their dominant mineral character. Haldex and Karvina samples had dry ash contents generally in the range of 73–79%, while Paskov samples reached about 86%. The energy potential differed significantly between the materials. Haldex1 had the highest carbon content and calorific value, approximately 6110 kJ/kg in the as-received state. Haldex2, Karvina1 and Karvina2 showed lower but still relevant values, while Paskov1 and Paskov2 had the lowest calorific values, around 2420–2430 kJ/kg. Therefore, Paskov was less favourable for energy recovery.

Ash composition confirmed that the materials were rich in silica and alumina. SiO_2 content was approximately 57–61%, while Al_2O_3 content ranged from about 20% to 26%. These values indicated clear potential for using the mineral fraction as an aluminosilicate raw material in geopolymer production. The Si/Al molar ratio ranged from approximately 1.85 to 2.53, and calcium content was low in all samples. Characteristic ash fusion temperatures were high and exceeded the expected calcination range below 900°C, indicating that agglomeration during thermal treatment in a fluidised bed reactor was not expected under the assumed conditions.

Trace element analyses showed the presence of titanium, magnesium, lithium, strontium, nickel, scandium, cobalt and gallium. Differences between dumps were observed, but the deliverable emphasised that trace element content may vary strongly even within one heap. Therefore, any potential recovery of valuable elements would require source-specific assessment.

Granulometric and density analyses confirmed that the raw material could be divided into two main streams: a carbon-bearing fraction and a mineral-rich fraction. The share of combustible fractions, defined as grains with density below 1.8 g/cm³, differed strongly between samples. The highest shares were found in the Panewnicka heap samples: 16.44% for Haldex1 and 11.60% for Haldex2 in the 30–3 mm grain class. Karvina samples contained lower shares, below 10%, while Paskov samples had the lowest values, 3.40% and 3.96%. In all samples, smaller grain classes contained a higher share of combustible material than coarser classes, confirming the importance of both grain size and density for separation design.

Thermal analyses were consistent with fuel-related properties. Haldex showed the highest mass loss and strongest exothermic effect, while Paskov showed the lowest values. Mechanical testing indicated that raw post-mining waste should be classified as low-strength aggregate. The Los Angeles coefficient ranged from 32.0 to 50.2, and the micro-Deval coefficient from 40 to 85. Absorbability and frost resistance results also confirmed that direct use in demanding construction applications would be limited without additional processing or refinement.

SEM/EDS analysis confirmed the dominant presence of silicon, aluminium and iron in the analysed grains. Occasional grains containing rare earth elements, including lanthanum, cerium, neodymium and europium, were also observed. Microscopic examination did not show visible features indicating oxidation, gasification or pyrolysis of organic matter. The AT4 respiratory activity test showed values below 4 mg O_2/g for all samples, indicating low biological activity and biological stability.

D2.2 also included guidelines for future reclamation activities, including the use of compost, manure, slurry or diluted bio-waste to improve poor heap substrates and support vegetation growth. Proposed seed mixtures included grass-only mixtures, grass mixtures with lucerne, white melilot and clover, and flower meadow mixtures, with a recommended sowing density of 2–3 g/m².

Overall, D2.2 confirmed that the analysed raw mine wastes could be used in the H2GEO technological concept, but only after appropriate separation and processing. The carbon-bearing fraction, especially from Haldex and partly Karvina samples, showed potential for further separation and gasification. The mineral-rich fraction, due to its high silica and alumina content and low calcium content, showed potential for geopolymer production and other material applications. At the same time, the analyses confirmed the high heterogeneity of mine waste and the need for detailed characterisation by source, grain size and density fraction.

D.3.1. Results of Laboratory Tests of Mine Wastes of Jig Beneficiation

Deliverable D3.1 presented the results of laboratory jig beneficiation tests of post-mining waste. The work verified whether raw mine waste could be separated into two main products: a lower-density combustible fraction and a higher-density mineral fraction. The results were also used to define input data for the development of a mobile mine waste processing system.

The tests were performed at the KOMAG laboratory jig stand using material prepared from the Haldex1 sample from the Panewnicka heap. The initial grain size was 30–0 mm, and three feed classes were tested: 30–10 mm, 10–3 mm and 30–3 mm. In total, 24 beneficiation trials were carried out. The variable parameters included grain size class, screen deck slot size, enrichment time and pulsation frequency. Two screen deck slots, 1.5 mm and 2.5 mm, enrichment times of 30 s and 60 s, and pulsation frequencies of 40, 60 and 80 min^{-1} were tested.

The results confirmed that jig beneficiation can effectively separate the tested mine waste into a combustible concentrate and a mineral-rich product. The most favourable results were generally obtained with the 2.5 mm screen deck slot, longer enrichment time and pulsation frequency of 60 min^{-1}. For the combined 30–3 mm class, the concentrate yield was about 27.6%, with ash content of 43.67% and calorific value of 16,118 kJ/kg. The mineral-rich product had ash content of 84.26% and calorific value of 1,430 kJ/kg.

The tests showed that enrichment time and screen deck slot size had a strong influence on separation quality. Longer enrichment time improved separation efficiency, while the 2.5 mm slot supported better water pulsation and more accurate density separation than the 1.5 mm slot. Based on the results, the unit load should probably not exceed 20–25 $t/h/m^2$ if acceptable separation efficiency is to be maintained.

D3.1 also provided design input for the future mobile separation system, the comprehensive technical documentation of which constituted the outcome of Milestone 3 in the present project. The deliverable indicated a disc pulsation valve as the preferred pulsator type, a rotary cell receiver as the preferred stone discharge system, and a 2000 mm × 2000 mm modular screen deck with flexible polyurethane screen surfaces. Separation products from Haldex1, Haldex2 and Karvina2 were also prepared for further analyses in Task 3.2.

Overall, D3.1 confirmed that jig beneficiation is a technically justified method for separating post-mining waste into fractions required by the H2GEO technology chain. The combustible fraction can be directed to thermochemical processing and hydrogen production, while the mineral-rich fraction can be used in geopolymer-related and other material applications.

D.3.2. Physicochemical Analyses and Mechanical Property Tests of the Separation Products

Deliverable D3.2 presented the physicochemical, mineralogical and mechanical characterisation of products obtained from jig beneficiation of selected post-mining waste samples. The analysed materials came from Task 3.1, where Haldex1, Haldex2 and Karvina2 were separated into two main streams: a carbon-bearing product enriched in coal particles and a mineral product dominated by high-density mineral grains. The objective was to verify whether these products were suitable for the next stages of the H2GEO technology chain, especially gasification and hydrogen production for the carbon-bearing fraction, and geopolymer-related applications for the mineral fraction.

The analyses confirmed that jig beneficiation significantly changed the quality of the raw material and produced two clearly different streams. The carbon-bearing products were enriched in combustible matter, while the mineral products had high ash content and low calorific value. For Haldex1 and Haldex2 carbon-bearing products, calorific values exceeded 24 MJ/kg, reaching approximately 24.5 MJ/kg and 25.2 MJ/kg in the 30–3 mm class, with ash contents of about 21.8% and 19.1%, respectively. Karvina2 showed a lower calorific value of about 19.0 MJ/kg and higher ash content of about 37.3–40.0%, indicating weaker separation efficiency for this material.

The mineral products showed opposite properties. Their ash contents exceeded 82%, and calorific values in the 30–3 mm class were low, amounting to approximately 1.9 MJ/kg for Haldex1, 2.3 MJ/kg for Haldex2 and 1.8 MJ/kg for Karvina2. Density analyses confirmed strong separation between coal-rich and mineral-rich particles. In the carbon-bearing product, the share of fractions below 1.8 g/cm³ reached about 85.2% for Haldex1, 91.4% for Haldex2 and 70.2% for Karvina2. In the mineral product, the high-density fraction above 1.8 g/cm³ accounted for approximately 96–98%.

The chemical and mineralogical analyses confirmed the suitability of the mineral products for further geopolymer-related testing. The mineral fractions were rich in silicon and aluminium, with SiO_2 content of approximately 57–59% in ash composition analyses and around 49–52% in XRF analyses, while Al_2O_3 content was generally about 22–25%. The SiO_2/Al_2O_3 ratio was within the range considered suitable for geopolymer production, and calcium content was low. XRD analyses identified mainly quartz, kaolinite, halloysite, illite, muscovite and, in some samples, dolomite. Trace elements, including lithium, nickel, scandium, cobalt and gallium, were generally more concentrated in the mineral fraction, although their recovery would require separate source-specific assessment.

The carbon-bearing products were also assessed in terms of parameters relevant to thermal processing. Sulphur content was higher in Haldex1 and Haldex2, at approximately 0.75% and 0.84%, respectively, while Karvina2 contained about 0.43% sulphur in the carbon-bearing product. This may affect emissions and syngas cleaning requirements during combustion or gasification. Heavy metals were more concentrated in finer grain fractions, which is important for later thermal processing, ash management and environmental assessment. Ash fusion temperatures of both product groups exceeded 1200°C, indicating limited risk of agglomeration during calcination in a fluidised bed reactor.

Mechanical testing showed that direct use of the mineral products as aggregate in demanding construction applications would be limited. The Los Angeles coefficient ranged from 29.7% to 45.2%, while micro-Deval coefficients were high, about 60–78%, indicating poor abrasion resistance. Water absorption and frost resistance results also showed that construction use would require careful selection of grain classes and additional verification. Overall, D3.2 confirmed that jig beneficiation produced differentiated streams suitable for different H2GEO pathways: carbon-bearing products, especially from the Panewnicka heap, for gasification and hydrogen production, and mineral products for geopolymer and other material applications, but not for direct high-grade aggregate use without further processing.

D.3.3. Analysis of Possibilities of Using Selected Fractions from Mine Wastes for Recovery of Rare Trace Elements and Power Production

Deliverable D3.3 analysed possible directions for using selected fractions obtained from post-mining waste after beneficiation. The assessment focused on three main areas: recovery of rare trace elements and metals, use of the mineral fraction in material applications, and use of the coal-bearing fraction for power production and gasification. The analysis was based mainly on laboratory results from Task 3.2, including trace element content, heavy metals, fuel properties, ash composition, ash fusion temperatures and microscopic observations.

The results showed that the tested separation products contained selected trace elements, mainly lithium, nickel, scandium, cobalt and gallium. Lithium reached the highest concentrations, up to 78.1 mg/kg in the Karvina2 coal-bearing fraction and up to 125 mg/kg in the Karvina2 mineral fraction. Rare earth elements such as europium, samarium, yttrium and ytterbium were also identified, but generally at lower levels. The mineral fraction usually contained higher concentrations of trace elements than the coal-bearing fraction, which makes it more relevant for any potential recovery pathway. However, the total concentration of trace and rare earth elements was about 270 ppm, meaning that practical recovery would require further technological and economic assessment.

The deliverable discussed possible recovery methods, including physical separation, leaching, precipitation, solvent extraction, ion exchange and adsorption. Adsorption was indicated as a promising option because of its relative simplicity and availability, but the document emphasised that recovery of rare trace elements from post-mining heaps could not be considered practically viable without additional source-specific and economic verification. Heavy metal analyses also showed the presence of arsenic, cadmium, chromium, copper, lead, zinc and mercury in the coal-bearing fraction, which is important for environmental control during any thermal processing.

The mineral fraction was assessed as a potential raw material for construction and geopolymer-related applications. Its composition was dominated by SiO_2 and Al_2O_3, with SiO_2 content of approximately 56.97–58.69% and Al_2O_3 content of about 22.12–25.20%. The SiO_2/Al_2O_3 molar ratio of 3.84–4.50 was considered suitable for geopolymer production. Possible applications included geopolymer materials, cement and concrete additives, ceramics, lightweight aggregates, road construction materials, soil stabilisation materials and sorbents. Ash fusion temperatures above 1200°C supported the possibility of further thermal activation, although direct use as aggregate in demanding applications would still require caution due to limited mechanical properties.

The coal-bearing fraction was analysed as a potential fuel for direct combustion and gasification. The Haldex1 and Haldex2 fractions from the Panewnicka heap showed the most favourable fuel properties, with calorific values of approximately 24.75–24.83 MJ/kg, low moisture content of about 1.4–1.6%, ash content of about 21.7–22.5% and total carbon content of approximately 62.9–63.5%. Karvina2 had a lower calorific value, about 18.19 MJ/kg, and higher ash content. Direct combustion was considered possible for selected technologies, but sulphur content, ash content, dust emissions, storage safety and ash management would need to be controlled.

Gasification was identified as a more flexible route for using the coal-bearing fraction, because it could convert the carbon-rich material into synthesis gas for energy production, hydrogen or chemical products. In the H2GEO context, Haldex1 and Haldex2 were considered the most suitable fractions for gasification. However, sulphur content of approximately 0.72–0.77% and chlorine content up to 0.081% indicate the need for effective syngas cleaning systems. Overall, D3.3 confirmed that the mineral fraction is most promising for geopolymer and material applications, while the coal-bearing fraction, especially from the Panewnicka heap, can be considered for energy production and gasification. Recovery of rare trace elements remains a possible future direction, but only after further technological and economic validation.

D.4.1. Evaluation of Data from Operational Tests of the Plasma Gasifier

Deliverable D4.1 presented the results of operational tests of plasma gasification of a separated carbon-bearing fraction obtained from post-mining waste. The work was carried out at the CEETe facility of VSB – Technical University of Ostrava and focused on verifying whether the material could be converted into synthesis gas suitable for further hydrogen-oriented processing. The influence of selected operating parameters, particularly the steam-to-fuel ratio and feed rate, on syngas composition and process performance was also assessed.

The tests were conducted in a laboratory-scale plasma gasification unit equipped with DC plasma torches. Nitrogen was used as the plasma-forming gas and steam as the gasification medium. The feedstock was a sorted HALDEX carbon-bearing fraction characterised by favourable fuel properties, including relatively low moisture and ash contents, a high carbon content and a sufficiently high calorific value. Its ash properties allowed operation at elevated temperature with liquid slag discharge.

A series of gasification tests was carried out under different feed rates and steam-to-fuel ratios. The reactor was operated at a temperature above the ash flow temperature, and the syngas composition was monitored continuously. The analysed components included the main combustible and non-combustible gas constituents, while nitrogen content was determined from the overall gas balance.

The process remained stable during the main operating periods. The produced gas contained substantial amounts of carbon monoxide and hydrogen, confirming effective thermochemical conversion of the carbon-bearing material. The nitrogen content was influenced by the use of nitrogen in the plasma torches and therefore diluted the combustible components of the raw syngas.

The results demonstrated a clear relationship between the steam-to-fuel ratio and syngas composition. Lower steam addition favoured carbon monoxide formation, while increasing the steam input raised the hydrogen share and reduced the carbon monoxide content. This trend was attributed mainly to the water–gas shift reaction and confirmed that the hydrogen content of the gas can be influenced through process parameter adjustment.

The mass balance indicated a high conversion of feedstock into syngas and a comparatively limited production of solid residue. Increasing steam addition improved the syngas yield and reduced the share of slag within the tested range. Tests conducted at a lower feed rate showed stronger nitrogen dilution because the plasma-forming gas flow represented a greater proportion of the total gas stream. The most favourable results were therefore obtained at a higher feed rate, elevated operating temperature and increased steam-to-fuel ratio.

D4.1 also included an assessment of the electrical characteristics of the plasma torches at different nitrogen flow rates. The results confirmed that the plasma-forming gas flow influenced torch voltage and should therefore be considered in process control and optimisation.

The deliverable identified several practical limitations, including the limited quantity of available feedstock, relatively short test duration, the time required to stabilise the gas composition and the lack of direct measurement of some components after gas cooling and cleaning. These factors should be addressed in future, longer-duration tests.

Overall, D4.1 confirmed that the separated carbon-bearing fraction from post-mining waste can be converted into hydrogen- and carbon-monoxide-rich syngas using plasma gasification. The results support the H2GEO concept of using the carbon-bearing fraction as feedstock for hydrogen-oriented thermochemical conversion. Further work should focus on optimisation of the steam-to-fuel ratio, feed rate, nitrogen consumption, gas-cleaning system and long-term process stability.

D.4.2. Set of Parameters for H_2 Separation by PSA Method

Deliverable D4.2 defined the operating basis for hydrogen separation from gasification-derived gases using Pressure Swing Adsorption. The work was carried out by ITPE using a laboratory PSA unit and linked the gasification stage with hydrogen purification within the H2GEO technology chain.

The investigations covered two representative gas compositions: raw syngas and syngas after the water–gas shift reaction. The shifted gas contained a higher hydrogen share and a lower carbon monoxide content, making it more favourable for subsequent purification. Synthetic mixtures prepared from pure gases were used to ensure repeatable test conditions and stable control of the process.

The PSA tests were conducted under controlled temperature, pressure and gas-flow conditions. The laboratory installation was designed for operation with several adsorption columns and enabled different cycle configurations to be tested. Each column contained a layered adsorbent bed composed of activated carbon and zeolite. Activated carbon was used mainly for the removal of carbon dioxide, methane and part of the carbon monoxide, while zeolite supported the removal of residual carbon monoxide and nitrogen.

Different proportions of the adsorbent materials were evaluated to determine their influence on separation performance. Breakthrough tests were carried out to establish suitable adsorption times and identify the order in which individual gas components appeared at the column outlet. Hydrogen was detected first because of its weak adsorption, while carbon monoxide was identified as the principal impurity limiting the duration of the adsorption step and the achievable hydrogen purity. Carbon dioxide was retained for a considerably longer period, confirming its strong adsorption on the layered bed.

Two PSA cycle concepts were considered. The first was a simpler system based on two columns, while the second used a more advanced multi-column configuration. The multi-column arrangement was assessed as more favourable because it enabled better utilisation of the adsorbent beds, smoother pressure equalisation and improved hydrogen purification and recovery.

The proposed adsorption and regeneration times were treated as initial operating parameters requiring further experimental optimisation. The results indicated that the gas after the water–gas shift reaction was generally more suitable for hydrogen separation than raw syngas. The advanced cycle configuration was expected to provide higher hydrogen purity and recovery than the simpler arrangement.

The low-pressure off-gas contained mainly separated carbon dioxide together with residual combustible components. Its further use or treatment was identified as an important factor affecting the energy efficiency and environmental performance of the complete hydrogen production process.

Overall, D4.2 confirmed that a layered activated-carbon and zeolite bed can be used for hydrogen purification from both raw and shifted syngas. Carbon monoxide breakthrough was identified as the main factor determining the adsorption-step duration and product quality. The selected adsorbent structure, pressure-swing concept and cycle configurations provide a technical basis for further optimisation and scale-up of the hydrogen separation system within the H2GEO technology.

D.4.3. Development, Evaluation and Validation of the Computational Model against the Operational Data Obtained during the CBF Gasification Tests

Deliverable D4.3 presented the development and validation of computational models for the gasification of a carbon-bearing fraction obtained from post-mining waste. Two technological variants were analysed in CHEMCAD: plasma gasification and fluidised bed gasification. The models were validated using experimental data generated within the project and subsequently used to develop an integrated model of a hydrogen production plant.

The plasma gasification model was based on operational test data obtained under selected feed, temperature and steam conditions. During model validation, the elemental balance was adjusted to account for uncertain or unmeasured streams, including carbon accumulation and the formation of minor sulphur- and chlorine-containing compounds. The model reproduced the principal process streams and syngas composition with good accuracy, confirming that it adequately represented the experimental process.

A separate model was prepared for fluidised bed gasification using data from tests of the carbon-bearing fraction. The balance included the principal feed and gasification-medium streams, as well as the formation of gaseous products, solid residue and tar. After validation, the model also showed good agreement with the experimental results. The relatively high nitrogen content of the experimental syngas was associated with the use of air and additional nitrogen during the tests.

Based on the comparison of the two technologies, fluidised bed gasification was selected as the preferred basis for the full-scale hydrogen production concept. The main reasons were its lower electricity demand, better heat-recovery potential, higher technological maturity and greater suitability for large-capacity industrial applications. Plasma gasification remained a technically viable alternative but was considered less favourable for the reference implementation scale.

The complete process model included fuel preparation and gasification, syngas cooling and cleaning, dust and acid-gas removal, water–gas shift conversion, mercury and ammonia removal, sulphur recovery, syngas compression, hydrogen purification by PSA and a steam cycle for electricity generation. Oxygen was used instead of air in the industrial concept to limit nitrogen dilution and improve the quality of the gas directed to hydrogen separation.

The PSA section was designed to produce high-purity hydrogen with a high recovery rate. Residual off-gas from the separation process was directed to energy recovery, supporting steam and electricity generation and improving the overall efficiency of the installation.

The model confirmed that the proposed plant could produce hydrogen continuously from the carbon-bearing fraction while also generating slag, recovered sulphur and useful energy. The integrated energy balance indicated that internal electricity demand could be covered and that surplus electricity could potentially be generated, depending on the final operating configuration and process assumptions.

Water and condensate management were identified as important elements of the process. Condensate streams generated during syngas cooling, washing, treatment and compression could be treated and recycled, significantly reducing freshwater demand and wastewater generation.

Overall, D4.3 confirmed that both computational models were consistent with the experimental data and suitable for further process integration. Fluidised bed gasification was selected as the preferred technology for the complete hydrogen production concept because of its lower energy demand and better industrial-scale applicability. The developed model provided the qualitative and quantitative basis for the subsequent economic, environmental and technical assessment of the H2GEO technology.

D.5.1. Determination of Mineral Part Properties in Terms of Thermal Processing Parameters

Deliverable D5.1 presented the results of thermal treatment tests of the mineral fraction obtained from post-mining waste processing. The work focused on identifying calcination conditions suitable for preparing this material for further use in geopolymer composite production. It therefore linked the beneficiation stage with subsequent research on geopolymer synthesis and material properties.

The main objective was to determine whether the mineral fraction could be effectively processed in a bubbling fluidised bed reactor. Before calcination, the material was crushed and classified to obtain a grain-size distribution suitable for stable fluidisation. Preliminary observations confirmed that the prepared mineral fraction could be processed under the assumed reactor conditions.

Several calcination variants were investigated. The tests covered different temperatures, residence times, process atmospheres and pressure conditions. Air and mixtures containing oxygen and carbon dioxide were used as process gases. The composition of the exhaust gas was monitored to evaluate the course of thermal conversion and the release of gaseous components.

Calcination substantially reduced the amount of residual combustible matter in the mineral fraction. This confirmed that thermal processing can effectively remove organic residues that could adversely affect the quality, stability and repeatability of geopolymer binders and fillers.

The calcined products retained their aluminosilicate character and remained rich in silicon- and aluminium-containing phases. Microscopic and chemical analyses confirmed the heterogeneous composition of the material, including local areas enriched in iron, calcium and alkali compounds. Although process atmosphere and pressure affected selected product properties, they did not eliminate the general suitability of the mineral fraction for geopolymer-related research.

No single calcination variant was found to be superior in all respects. Tests performed under elevated pressure resulted in less favourable removal of residual combustible matter. Based on the combined thermal-treatment results and preliminary geopolymer studies, a selected intermediate-temperature variant using a mixed process atmosphere was chosen for the preparation of a larger batch of calcined material for further testing.

Overall, D5.1 confirmed that thermal treatment is an important preparatory stage for the use of the mineral fraction in geopolymer production. Calcination reduced residual organic matter, preserved the required aluminosilicate composition and provided a more suitable and reproducible feedstock for subsequent material investigations. Final selection of industrial operating conditions should also take into account energy consumption, process-gas demand and overall treatment costs.

D.5.2. Determination of Geopolymer Properties

Deliverable D5.2 presented the results of research on the preparation, optimisation and characterisation of fly ash-based geopolymer materials. Particular attention was given to the influence of chemical admixtures and water content on workability, pore structure and compressive strength. The study addressed the practical difficulty of obtaining geopolymer mixtures that combine satisfactory workability with high mechanical performance.

The geopolymer system was based on low-calcium fly ash with a high content of silicon- and aluminium-bearing phases and a substantial amorphous fraction. An alkaline solution containing sodium hydroxide and sodium silicate was used as the activator. The prepared samples were initially cured under elevated-temperature and high-humidity conditions and subsequently stored under controlled conditions until testing.

Three types of chemical admixtures were investigated: a polycarboxylate-based superplasticiser, an anti-sedimentation agent and a defoaming agent. Different water contents and admixture dosages were evaluated. The principal assessment criteria were mixture fluidity and compressive strength at selected curing ages.

The superplasticiser was the most effective admixture for improving workability. However, increasing the water content or superplasticiser dosage generally reduced compressive strength. Lower-water mixtures provided more favourable strength development, while compositions containing excessive amounts of liquid or admixture were excluded from further optimisation.

The anti-sedimentation agent produced only limited improvements in workability and early strength and did not improve long-term mechanical performance. The defoaming agent also slightly increased fluidity but caused an unexpected reduction in compressive strength. The combined use of several admixtures therefore did not provide a beneficial balance between workability and strength.

Representative compositions were selected for more detailed testing. The highest mechanical performance was obtained for the reference mixture without admixtures and for a composition containing a low superplasticiser dosage. Increasing the superplasticiser content or introducing additional admixtures progressively reduced strength. The results confirmed that improvements in mixture fluidity were generally achieved at the expense of mechanical performance.

Thermal, spectroscopic, mineralogical, microscopic and porosity analyses confirmed the formation of an amorphous geopolymer structure and sodium aluminosilicate hydrate gel. Continued curing refined the pore structure, although reduced porosity did not always result in higher strength. Mechanical performance was also influenced by the quality and density of the geopolymer matrix and by interfacial bonding within the material.

Overall, D5.2 confirmed that high-strength geopolymer materials can be produced using the investigated fly ash-based system. The best results were obtained for the reference composition and for mixtures containing only a limited amount of superplasticiser. Chemical admixtures require careful selection and optimisation because products developed for conventional cement systems may behave differently under the highly alkaline conditions of geopolymer production.

D.5.3. Development of Methods of Using Mineral Fractions in New Building Materials and in Agriculture

Deliverable D5.3 presented methods for using mineral fractions obtained from jig beneficiation of post-mining waste in construction materials, geopolymer granulates, agriculture and land reclamation. The work followed a zero-waste approach, in which individual grain-size fractions were directed to applications matched to their properties instead of being treated as one uniform waste stream.

Two principal material pathways were investigated. Fine mineral fractions were used for the production of geopolymer granulates, while coarser fractions were incorporated as aggregate into structural geopolymer composites. An intensive counter-current mixer was used to homogenise dense mixtures, form granules and coat aggregate particles with geopolymer paste. This processing method was selected because of the heterogeneous nature of post-mining waste and the limitations of conventional mixing equipment.

Geopolymer granulates were produced from fine mineral material combined with fly ash, alkaline activators and water. The obtained granules had a compact and generally regular form and did not require high-temperature sintering. Their mechanical properties indicated potential use as synthetic lightweight aggregates. However, leaching tests identified the need for further environmental assessment and optimisation before practical application.

Structural geopolymer composites were prepared using mixtures of fine and coarse mineral fractions. The fine material acted as a filler, reducing voids between larger grains and improving continuity of the geopolymer matrix. Selected compositions achieved mechanical properties indicating potential use in structural construction applications. The results also showed that a high proportion of solid waste could be incorporated while limiting the consumption of alkaline activators.

The deliverable also assessed the potential use of the mineral fraction in agriculture and biological reclamation. Pot and field experiments confirmed that the material should not be used as an independent growth substrate. More favourable vegetation development was obtained when the mineral fraction was combined with fertile soil, fertiliser or organic amendments. Appropriate mixtures supported grass establishment, reduced seed washout and limited visible plant stress.

A concept for a wet remediation system using biowaste was also developed. The proposed mobile unit would loosen the compacted surface of a waste dump, apply a suspension containing water, compost and seeds, and compact the upper layer in one operation. Wet application was selected because it reduces dust, supplies moisture and organic matter, improves contact between seeds and the substrate and supports vegetation on difficult post-mining surfaces.

Overall, D5.3 confirmed that mineral fractions from post-mining waste can be used in several complementary pathways. Fine fractions can be converted into geopolymer granulates, coarser fractions can be incorporated into structural geopolymer composites, and selected materials can support land reclamation when combined with suitable soil and organic components. These results support the H2GEO zero-waste concept, in which separated mineral streams are directed to useful products or reclamation applications rather than returned to disposal sites.

D.5.4. Development of the Method for Recovery of Minerals and Chemicals with Initial Evaluation of Its Profitability

Deliverable D5.4 assessed the potential recovery of rare earth elements and other valuable components from post-mining waste generated during coal beneficiation. The work included chemical and mineralogical characterisation, leaching and precipitation tests, preliminary economic assessment, and electrostatic and magnetic separation trials.

The analysed materials were dominated by silica- and alumina-bearing phases and contained relatively low concentrations of rare earth elements. This confirmed the presence of potentially valuable components but also indicated that the feedstock was relatively poor from the perspective of stand-alone industrial recovery.

Mineralogical analyses showed that the rare earth elements were largely associated with resistant aluminosilicate and clay minerals. This limited their mobility and made extraction using mild treatment methods ineffective. Water-based and salt-assisted leaching resulted in only limited element release, while thermal activation followed by acid leaching improved the mobilisation of selected elements but did not provide sufficiently high overall recovery.

The highest recovery was achieved using strong mixed-acid digestion, which more effectively decomposed the mineral matrix. Rare earth elements were subsequently separated from the leachate through precipitation and converted into a concentrated product. Although this approach demonstrated technical feasibility, it required substantial quantities of aggressive chemical reagents.

The preliminary economic assessment showed that the reagent and processing costs were considerably higher than the potential market value of the recovered elements. The main reasons were the low rare earth element content in the feedstock, their association with resistant mineral phases and the high consumption of costly acids. Additional expenditure related to energy, labour, waste treatment, transport, utilities and equipment would further reduce the economic viability of the process.

Electrostatic and magnetic separation were also evaluated as potential pre-concentration methods. In most cases, these processes did not provide significant enrichment of rare earth elements, although selected materials showed some improvement after magnetic separation. The effectiveness of physical pre-concentration was therefore strongly dependent on the properties and origin of the waste.

Overall, D5.4 confirmed that post-mining waste contains rare earth elements and other potentially valuable components, but the analysed materials are not currently an economically justified stand-alone source for their recovery. Intensive chemical treatment can technically release a substantial proportion of the elements, but the associated costs and environmental burden remain high. Rare earth element recovery should therefore be considered only as a complementary option integrated with broader waste valorisation, particularly material applications based on the silica- and alumina-rich fractions.

D.6.1. Final Concept of H2GEO Technology

Deliverable D6.1 presented the final concept of the integrated H2GEO technology for the management of post-mining waste heaps. The document integrated the results of the previous work packages into a coherent technological chain covering waste recovery, separation, energy conversion, hydrogen production and mineral material valorisation. It therefore served as the main integration deliverable of the project and provided the basis for further economic, environmental, social and legal analyses.

The H2GEO concept was based on treating coal-related post-mining waste as a heterogeneous secondary resource rather than a uniform waste stream. The material contains both a carbon-bearing fraction and a mineral fraction, which require different technological pathways. The carbon-bearing fraction was directed to gasification and hydrogen production, while the mineral fraction was directed to natural aggregates, synthetic granulated aggregates, geopolymer concrete and geopolymer materials.

The reference scale of the technology was determined by the energy pathway. The nominal hydrogen production plant was based on a fuel input of 250 MW and required approximately 300 thousand Mg/year of carbon-bearing fraction. Assuming an average carbon-bearing fraction content of 10% in post-mining waste, the separation and classification system would have to process about 3.0 million Mg/year of raw material. This would generate approximately 2.7 million Mg/year of mineral fraction requiring further material use. The hourly feed rate to the separation system was estimated at approximately 682 Mg/h, including 68.2 Mg/h of carbon-bearing fraction and 613.8 Mg/h of mineral fraction.

The separation system was designed as the first key node of the H2GEO chain. It included preliminary classification, magnetic removal of metal contaminants, jig separation of the 31.5–3 mm fraction, TBS separation of the 3–0.5 mm fraction, product dewatering and closed process water circulation. The main equipment included four S-100 pulsating jig separators and three teetered bed separators. The total installed power of the separation system was estimated at approximately 1.34 MW. The quality and quantity of both downstream streams depend directly on this node.

Two gasification technologies were analysed for the energy pathway: plasma gasification and fluidised bed gasification. Plasma gasification was considered as a complementary option, but it was not selected as the reference technology because a 250 MW plant would require approximately ten parallel plasma reactors, increasing electricity demand, operational complexity and scale-up risk. Fluidised bed gasification was selected as the reference pathway due to lower electricity demand, better heat recovery potential, broader industrial references and greater suitability for scale-up. The assumed main parameters were a gasification temperature of 850°C, an O_2/CBF ratio of 0.69 kg/kg, a steam/CBF ratio of 0.75 kg/kg and carbon conversion of 95%.

The hydrogen production plant included CBF receiving and storage, fuel preparation and feeding, fluidised bed gasification, air separation, syngas treatment, water–gas shift, acid gas removal, sulphur recovery, PSA hydrogen separation, slag handling, steam cycle, cooling systems and process water treatment. The PSA unit was defined as the final hydrogen purification stage, producing hydrogen with a purity of approximately 99.9 vol.% and recovery of about 85%. The hydrogen product is compressed to approximately 6.5 MPa, while residual PSA off-gas is combusted in a boiler to support steam and electricity generation.

The mass and energy balance of the hydrogen production system was based on D4.3 modelling results. The model assumed a carbon-bearing fraction feed rate of approximately 36.6 Mg/h. Hydrogen production was 3.09 Mg/h, corresponding to 3,090.37 kg/h. Assuming 8,000 operating hours per year, the plant would consume approximately 292.5 thousand Mg/year of carbon-bearing fraction and produce about 24.7 thousand Mg/year of hydrogen. Additional outputs would include approximately 77.1 thousand Mg/year of slag and 1.38 thousand Mg/year of sulphur. Gross electricity production from the gasification and hydrogen production system was estimated at about 263.6 thousand MWh/year, while electricity consumption was approximately 245.2 thousand MWh/year.

The mineral pathway was divided into four product streams. From the 2.7 million Mg/year of mineral fraction, 85% was assigned to natural aggregate production, while three 5% streams were assigned to geopolymers from calcined mineral fraction, geopolymer concrete and synthetic granulated aggregates. This corresponded to approximately 2.295 million Mg/year of natural aggregates and 135 thousand Mg/year for each of the other three pathways. The calcined mineral fraction pathway was identified as less favourable because of high electricity demand and the low share of calcined mineral fraction in the final geopolymer product. Geopolymer concrete and synthetic aggregate production were considered more promising large-scale material routes.

The geopolymer concrete pathway was linked directly with the ST16 mixture from D5.3, which achieved compressive strength of approximately 30.4 MPa and flexural strength of 8.1

MPa, corresponding to the C25/30 concrete class range. The synthetic aggregate pathway was based on dynamic granulation in an intensive counter-current mixer and laboratory results showing crushing strengths of approximately 6–10 MPa. A key advantage of these mineral pathways was the possibility of using a common raw material base and shared process equipment, allowing production to be adapted to market demand and material availability.

The integrated energy balance showed that the complete H2GEO system has significant internal electricity demand. The total electrical consumption of the main technological nodes was estimated at approximately 46.02 MW, corresponding to about 323.8 thousand MWh/year. The gasification and hydrogen production system can generate approximately 32.94 MW of electricity. If the produced hydrogen is additionally converted to electricity in fuel cells at 60% efficiency, an extra 60 MW could be obtained, and total annual electricity production could reach approximately 743.5 thousand MWh/year.

Overall, D6.1 confirmed the technical feasibility of combining waste separation, gasification, hydrogen production, mineral classification, geopolymer concrete production and synthetic aggregate production in one integrated energy-material system. The concept showed that post-mining waste can be separated into fractions and directed to different value chains, reducing waste stored in heaps and replacing natural raw materials with secondary resources. At the same time, commercial implementation depends on the availability, quantity and quality of the waste stream, as well as on optimisation of the most energy-intensive stages, especially the pathway based on calcined mineral fraction.

D.6.2. Results of Economic Analyses

Deliverable D6.2 presented the results of economic analyses carried out within the H2GEO project, with particular attention to the raw material potential of post-mining waste and the change in land value after reclamation. The analysis focused on the Central Mining Waste Dump in Knurów as a reference case for assessing the economic effects of waste recovery, material valorisation and land redevelopment.

The analysed dump is located at Szybowa Street in the Silesian Voivodeship and belongs to Jastrzębska Spółka Węglowa S.A. The site covers approximately 16.5 ha and has been operated since the 1960s. According to the data used in the deliverable, approximately 28.83 million Mg of mining waste had been deposited there by the end of 2018. The stored material consists mainly of waste rock and coal-processing waste, with claystones as the dominant lithological component and smaller shares of mudstones, sandstones and coal-processing fines.

The economic assessment treated the dump as a heterogeneous material source containing a carbon-bearing fraction and a dominant mineral fraction. The average organic carbon content was assumed at approximately 6.7%, while the average calorific value was 22,662 kJ/kg. On this basis, the recoverable carbon-bearing fraction was estimated at approximately 1.93 million Mg. The remaining mineral fraction accounted for about 26.90 million Mg, including mainly aluminosilicate and carbonate materials, with smaller shares of iron-sulphide phases and trace elements. The aluminosilicate fraction was the dominant component, estimated at about 21.05 million Mg.

Two utilisation pathways were considered for the carbon-bearing fraction. The first assumed direct use as a solid fuel. With a recoverable carbon-bearing fraction of approximately 1.93 million Mg and an effective calorific value of 22,662 kJ/kg, the total chemical energy potential was estimated at about 43,750 TJ. Assuming 35% electricity generation efficiency, this could correspond to approximately 4.25 TWh of electricity. Using a reference coal price of 1000 PLN/Mg, the potential value of this fraction was estimated at approximately 1.93 billion PLN.

The second pathway assumed conversion of the carbon-bearing fraction into hydrogen through gasification. Under the adopted assumptions, including a hydrogen production yield of 13.2% relative to the carbon-bearing input, the analysed dump could theoretically provide approximately 254.97 thousand Mg of hydrogen. This corresponds to an energy equivalent of approximately 8.49 TWh. With an assumed hydrogen price of 6.61 PLN/kg, the potential market value was estimated at approximately 1.69 billion PLN. Direct fuel use therefore gave a higher simple market value, while hydrogen production represented a more advanced and strategically relevant pathway consistent with decarbonisation and hydrogen economy development.

The mineral fraction was assessed mainly in terms of possible use as aggregate, geopolymer feedstock or reclamation material. With an estimated mass of approximately 26.90 million Mg and a conservative reference price of 18 PLN/Mg for low- and medium-quality mineral materials, its total indicative value was estimated at approximately 484.2 million PLN. The deliverable also noted that geopolymer applications may increase product value, but they are associated with higher processing costs, especially due to alkaline activators and controlled production conditions.

A separate part of D6.2 assessed the change in land value after reclamation. The current value of degraded land under the dump was assumed at 10 PLN/m², corresponding to approximately 1.65 million PLN for 16.5 ha. Five post-reclamation land-use scenarios were analysed: forest-agricultural use, green and recreational use, photovoltaic renewable energy use, industrial use with limitations, and full industrial potential. Depending on the scenario, the target land value ranged from 35 to 200 PLN/m², corresponding to total land values from approximately 5.78 million PLN to 33.00 million PLN. The potential increase in land value therefore ranged from about 4.1 million PLN to about 31.4 million PLN.

Overall, D6.2 showed that the economic potential of the analysed heap results from three connected effects: recovery of the carbon-bearing fraction, utilisation of the mineral fraction and increase in land value after reclamation. For the Knurów case, the largest estimated value was associated with the carbon-bearing fraction, followed by the mineral fraction and then land value increase. The results should be treated as indicative estimates based on assumed material quantities, reference prices and selected land-use scenarios. Further assessment should include detailed cost modelling, market analysis, permitting constraints, logistics, reclamation costs and sensitivity analysis for fuel, hydrogen, aggregate and land prices.

D.6.3. Results of Market, Social, Legal Aspects and LCA Analysis

Deliverable D6.3 assessed the market, social, legal and environmental conditions for implementing the H2GEO technology, which integrates the recovery of post-mining waste with hydrogen production and the manufacture of aggregates and geopolymer materials. The analysis confirmed that the concept is consistent with circular-economy principles because the carbon-bearing fraction is used for hydrogen production, while mineral fractions, ashes and slags are converted into construction products. This industrial-symbiosis approach may reduce dependence on primary raw materials, limit the amount of waste remaining in mining dumps and support the redevelopment of post-mining regions.

The market analysis showed a clear difference between the current dominance of fossil-based hydrogen and the European Union's long-term objectives for low-emission hydrogen. The use of locally available post-mining waste was identified as an important competitive advantage, as it may reduce feedstock and transport costs and limit dependence on global raw-material markets. The European hydrogen market was projected to reach approximately USD 69.17 billion by 2033, while the geopolymer market may increase to about USD 2.10 billion, driven mainly by demand for durable and lower-emission construction materials. The development of regional H2GEO facilities could support the creation of circular-economy hubs, new industrial activities and employment in former mining areas.

The analysis also indicated that the economic competitiveness of H2GEO may improve as a result of climate-policy instruments, particularly the EU Emissions Trading System and the Carbon Border Adjustment Mechanism. These instruments increase the cost of carbon-intensive products and may strengthen the market position of low-emission hydrogen and geopolymer materials. Three long-term development scenarios—baseline, optimistic and pessimistic—were considered up to 2050. The main market risks include changing energy prices, limited availability of some conventional geopolymer precursors, including fly ash, and dependence on imported critical materials. H2GEO reduces part of this exposure by using local mining waste and by integrating energy and material recovery within one value chain.

The social analysis covered two post-mining areas: Kostuchna and Murcki in Katowice, and Makoszowy/Sośnica on the border of Gliwice and Zabrze. A total of 100 resident questionnaires and eight institutional questionnaires were analysed. Approximately 68% of residents considered mining dumps to be an environmental or social problem. The most frequently identified nuisances were landscape degradation, dust and air pollution, restricted access and safety concerns. At the same time, 89% positively assessed the possibility of transforming these areas for recreational, environmental, social or economic purposes.

Residents most strongly preferred renaturalisation, green areas, viewpoints, cycle paths, parks and other recreational functions. The results showed that future implementation should not focus solely on technological waste processing but should also preserve or develop landscape, environmental and recreational functions. Awareness of H2GEO was relatively low, with only 21% of respondents declaring prior knowledge of the technology. Nevertheless, 58% believed that its implementation could improve regional environmental conditions.

The project's economic potential was also recognised: 92% of respondents expected the creation of new jobs and 87% saw opportunities for local economic development. However, public acceptance was conditional. Approximately 77% supported implementation provided that high environmental standards were ensured. The main concerns related to increased heavy-vehicle traffic, dust, noise, emissions, general nuisance and insufficient trust in the technology. Public acceptance therefore requires transparent communication, environmental monitoring, clear information on transport and emission controls, and the presentation of the final land-reclamation concept. Local institutions may play an important intermediary role by supporting consultation, education and communication with residents.

The legal analysis confirmed that implementation of H2GEO would require a complex sequence of administrative procedures under EU and Polish waste, environmental, construction and energy law. Post-mining material remains waste unless it is legally classified otherwise, and its treatment must comply with the waste hierarchy, the proximity principle and the requirements concerning recovery, transport, storage, record-keeping and environmental protection. Waste-treatment activities generally require appropriate permits, registration in the BDO database and ongoing quantitative and qualitative records.

The investment process was divided into planning and environmental, construction and operational stages. The first stage requires compliance with the local spatial development plan or obtaining a development-conditions decision, as well as an environmental decision supported by an environmental impact assessment and public consultation. The construction stage includes a building permit and, where necessary, a water permit. Before operation, the relevant installations may require an integrated permit, an occupancy permit and additional sector-specific decisions.

Because the H2GEO chain includes several technologically distinct operations, the legal analysis assumed four independent installations requiring separate sets of administrative decisions. The waste-recovery section may require permission to extract material from the heap, an amended extractive-waste management plan, waste-collection and waste-treatment permits, financial security for possible environmental claims and a decision confirming end-of-waste status for products placed on the market. The gasification and hydrogen-production installation may additionally require an integrated permit, technical approvals from the Office of Technical Inspection, EU ETS registration, energy concessions, major-accident documentation and, where carbon capture and storage is applied, a concession for underground CO_2 storage. Certification may also be required to market hydrogen as a low-emission product. The geopolymer concrete and artificial aggregate installation was not considered to require an integrated permit, although product, construction and environmental requirements would still apply.

The environmental assessment was carried out using Life Cycle Assessment in accordance with ISO 14040 and ISO 14044. Modelling was performed in openLCA 2.5.0 using the ecoinvent 3.10 database and the Environmental Footprint 3.1 method. The model covered recovery of material from the dump, mechanical separation into carbon-bearing and mineral fractions, gasification and syngas purification, and the production of hydrogen, natural aggregates, synthetic aggregates and geopolymer products.

The carbon footprint of H2GEO hydrogen was estimated at 1.90 kg CO_2 eq/kg H_2, approximately 84% lower than the 11.83 kg CO_2 eq/kg H_2 obtained for conventional steam methane reforming. Geopolymer binders also performed favourably, with climate-change impacts of approximately 144.4–189.4 kg CO_2 eq/Mg, compared with typical values of about 700–900 kg CO_2 eq/Mg for Portland cement. For finished concrete, however, the H2GEO geopolymer concrete reached 346 kg CO_2 eq/m³, compared with 238 kg CO_2 eq/m³ for the reference OPC concrete. The higher result was primarily caused by sodium silicate production, which accounted for approximately 65–70% of the geopolymerisation impact.

Overall, D6.3 showed that H2GEO has favourable environmental and market potential, particularly for low-emission hydrogen and geopolymer binders, while also offering opportunities for regional development and the reclamation of mining-waste areas. Its implementation nevertheless depends on reducing the environmental burden of alkaline activators, ensuring compliance with a complex administrative framework, controlling local nuisances and conducting transparent consultation with residents and institutions. The project should therefore be presented as an integrated process combining waste recovery, industrial development, environmental improvement and the creation of new functions for post-mining land.

MS1 Creation of the database system

Milestone MS1 resulted in the creation of the H2GEO database system for collecting, verifying, standardising and archiving the main data generated during the project. The system provides a consistent basis for comparing results, conducting further analyses and assessing the implementation potential of the H2GEO technology.

The database contains information from the inventory of post-mining waste dumps, laboratory analyses of raw waste and separation products, jig beneficiation tests, thermochemical conversion and hydrogen production, and research on geopolymer materials and other applications of the mineral fraction. Process parameters and the results of mechanical, chemical, mineralogical and energy-related analyses are organised according to common categories and data structures.

The collected information was reviewed to identify missing values, inconsistent terminology, differences in measurement methods and potential errors. The data were classified into four main groups: mining waste, jig beneficiation, thermochemical conversion and geopolymer production. The data are stored in structured tabular form, enabling their long-term accessibility and further processing.

A major part of the work concerned the harmonisation of information on post-mining waste deposits collected from nine European countries. As the source datasets differed in scope, terminology, detail and coordinate systems, a common classification methodology was developed for parameters such as raw material type, waste-dump type, activity status, reclamation status and environmental risk. The standardised data were integrated into a common GIS database, enabling consistent comparison and spatial analysis.

Two interactive web applications were created using ESRI software. The H2GEO Mine Waste Database provides access to standardised information on post-mining waste deposits and enables exploration of their locations and principal characteristics. The H2GEO Production Potential application presents the results of spatial analyses identifying deposits with the highest potential for supplying material for hydrogen production and geopolymer composites. Both applications are available online and support preliminary site selection and future implementation planning.

Selected project datasets were also published in the ZENODO repository. They include information on mine-waste deposits, material properties, jig separation processes and possible uses of the obtained carbon-bearing and mineral fractions. This ensures permanent storage, public accessibility and the possibility of reusing the data in accordance with open-science principles.

Overall, MS1 delivered an integrated and standardised database combining material, technological and spatial information generated within the H2GEO project. The database, GIS methodology, interactive applications and publicly available datasets provide a reliable platform for further research and for assessing the potential utilisation of post-mining waste resources.

MS3 Technical documentation of the prototype of mobile system for separation of mine wastes

Milestone MS3 documented the development of the technical design of the S-100 mobile system for separating post-mining waste directly at waste-dump sites. The system was developed within the H2GEO project to separate heterogeneous mine waste into a carbon-bearing fraction for further energy conversion and a mineral fraction for material applications. The separation process is based on density differences and is carried out in a pulsating water medium.

The main component of the system is a newly designed pulsating jig with one working compartment measuring 2 m × 2 m and a total working area of 4 m². The compartment is divided into two independent pulsation zones, each supplied separately with working air and lower water. The working trough is equipped with modular slot screens with a slot size of 2.5 mm, selected on the basis of previous laboratory beneficiation tests. A modified clamping system simplifies screen installation and replacement and reduces maintenance downtime.

The feed material, with a grain size of approximately 30–2 mm, is distributed across the working through and subjected to cyclic water pulsation. During transport along the screen deck, the material is stratified into three products: a heavy mineral fraction, a light carbon-bearing fraction and a fine-grained fraction passing through the screen openings. The mineral product is continuously discharged by a rotary scraper receiver, while the carbon-bearing product leaves the device through an overflow outlet. Fine material is removed together with process water through the lower boxes.

The mineral-product receiver uses a rotary scraper equipped with six arms and replaceable steel or polyurethane blades. Its rotational speed can be adjusted to the properties and quantity of the treated material. Additional sealing and flushing solutions were introduced to reduce the accumulation of fine particles, limit wear and improve the operational durability of the receiver.

Water pulsation is generated by a pneumatic system consisting of a blower, an air tank, a ZP-4 disc pulsation valve, air collectors and two pulsation chambers. The two-section valve independently controls air inlet and outlet, enabling adjustment of pulsation frequency and cycle shape. The amount of lower water, which influences material transport, bed loosening and separation efficiency, is controlled through a dedicated installation with adjustable dampers and a flow meter.

An electronic SES control system was developed as an integral part of the prototype. It controls the pulsation valve, working-air blower and mineral-product receiver and enables the main operating parameters to be adjusted to the feed characteristics and process load. The control system consists of a sealed control cabinet, a mobile programmable controller, a graphical operator panel, measuring equipment and actuators.

The measurement system includes pressure sensors in the pulsation chambers, a lower-water flow meter, limit switches and an encoder connected to a float sensor. The float measures the position of the separation layer in the working bed and provides the principal signal for automatic control of the scraper speed. The controller continuously compares the actual and required float positions and adjusts the discharge rate within predefined limits. Communication between the controller, operator panel and frequency converters is implemented through Ethernet, while the float encoder communicates through a CAN network.

The system also includes a working-air blower driven by a 30 kW motor, a 7.5 kW control-air compressor and a 4 kW scraper drive. Frequency converters allow continuous adjustment of blower output and scraper speed. The service platform, stairs, ladder and guardrails provide access for operation and maintenance under industrial conditions.

Overall, MS3 delivered the technical basis for a mobile mine-waste separation prototype capable of producing stable carbon-bearing and mineral streams for the subsequent stages of the H2GEO process. The design combines a compact pulsating jig, adjustable product discharge, automated process control and equipment adapted to operation under demanding waste-dump conditions. The documentation was developed by ITG KOMAG and verified in cooperation with Haldex, drawing on the industrial partner’s experience in mining-waste processing.

Summary

The H2GEO project confirmed the technical potential of converting post-mining waste into hydrogen, aggregates and geopolymer materials within an integrated circular-economy system. Laboratory and modelling studies demonstrated effective separation of carbon-bearing and mineral fractions, the suitability of the carbon fraction for gasification and hydrogen production, and the potential use of mineral fractions in geopolymer composites, synthetic aggregates and reclamation. The final technology concept showed that the complete process chain is technically feasible, while economic, market, environmental, social and legal analyses identified both implementation opportunities and key constraints. The most important challenges concern process scale, energy demand, alkaline activator impacts, permitting requirements, local nuisance control and market conditions. Overall, H2GEO provides a coherent basis for further pilot-scale development and for the valorisation of post-mining waste as a secondary raw-material source.