Hybrid energy storage system using post-mining infrastructure (HESS)

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PROJECT INFORMATION

TITLE: "Hybrid energy storage system using post-mining infrastructure" (HESS)

PROJECT NO: 101112380 (RFCS-2022)

PROJECT BUDGET: 2 226 740,2 Euro

PROJECT DURATION: 36 months (01.07.23 – 30.06.26)

LINK TO THE WEBSITE: https://itpe.pl/en/hess/

HESS CONSORTIUM

The HESS project was implemented by an international consortium bringing together research institutes, universities, and industrial partners with complementary expertise in mining engineering, energy technologies, materials science, and energy storage systems. The consortium comprised the Institute of Fuel and Energy Technology (ITPE, Poland), KOMAG Institute of Mining Technology (Poland), Silesian University of Technology (SUT, Poland), VSB – Technical University of Ostrava (Czech Republic), and Premogovnik Velenje d.o.o. (PV, Slovenia).

The participation of both research organisations and industrial partners ensured that the project addressed not only scientific and technological challenges, but also practical aspects related to the future implementation of hybrid energy storage systems in post-mining infrastructure. This multidisciplinary cooperation enabled the integration of expertise in underground engineering, thermodynamics, materials development, numerical modelling, energy system integration, and techno-economic assessment, providing a solid foundation for the development and validation of the HESS concept.

HESS PROJECT GOAL

The goal of the HESS (Hybrid Energy Storage System) project is to develop and validate a hybrid energy storage concept based on the utilisation of post-mining infrastructure. The system integrates three technologies: the Pumped-Storage Hydropower (PSH) System, Compressed Gas Energy Storage (CGES) System, including CAES (air) and CCES (CO_2), and the Thermal Energy Storage (TES) System. A key component of the concept is an intelligent energy router, responsible for the optimal management of energy flows between the individual system components and the external power grid.

The energy router enables coordinated operation of all HESS subsystems by managing energy exchange with the national electricity grid, allowing the uptake of low-cost renewable energy during off-peak periods and its release during peak demand. The concept also considers the possibility of integrating multiple HESS installations operating within a distributed energy storage network.

The project combines technical, economic, and life cycle assessment (LCA) analyses as a basis for the design of a pilot installation and the future industrial deployment of the developed solutions.

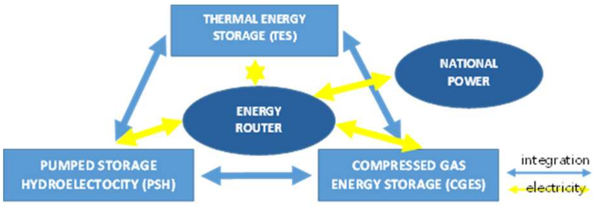

Fig. 1 Cooperation between individual HESS components

The project involves utilizing existing mine infrastructure as the basis for a multi-technology energy storage system. Integrating PSH, CGES, and TES enables the simultaneous storage of mechanical, compressed, and thermal energy, increasing the flexibility and efficiency of the entire system. The system operates on a daily basis, utilizing surplus energy from the grid during periods of low demand and returning it during peak periods. Additionally, the possibility of multiple HESS installations operating in a distributed system is assumed.

The assumed total energy storage capacity supposed to be min. 30 MWh.

Each HESS component should meet specific technical requirements:

• PSH: Ensure the tightness of tanks and water infrastructure for at least 10 years, guaranteeing long-term system stability.

• CAES: Achieve operating pressures of up to 80 bar (in case of the air) and up to 20 bar (for CO_2), while limiting pressure losses in the sealed shaft to a maximum of 5% of the initial pressure during a single system operation cycle.

• TES: Ensure thermal energy storage capacity up to 500°C and an energy recovery capacity of at least 1.5 MWt for a minimum of 2 hours.

EXPECTED RESULTS

The implementation of the above assumptions will enable the development of an integrated, multi-technology energy storage system with high efficiency and operational flexibility. HESS will enable efficient balancing of renewable energy, reduce transmission losses, and utilize existing post-mining infrastructure, significantly reducing investment costs. Additionally, the project will contribute to increased energy security, the development of energy storage technologies, and the transformation of post-mining regions in line with the principles of sustainable development and just transition.

PROJECT MILESTONES

1. Recognition of mine shafts and water reservoirs – M10
2. System analysis for compressed air storage system – M18
3. Selection of accumulation materials – M20
4. Parameters of the underground power generation unit and water pumping system – M24
5. Instructions for compressed gases storage in mine shafts – M24
6. Numerical model validation of TES system – M24
7. Technical and process dataset necessary to develop the assumptions for the router, and to carry out the techno-economic and LCA analysis – M26.

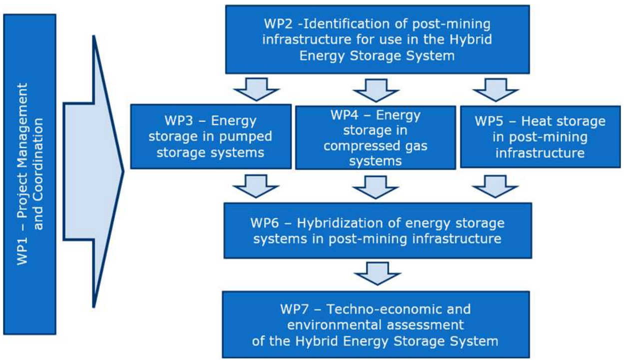

Fig. 2 Overall structure of the project

GANTT CHART OF HESS PROJECT

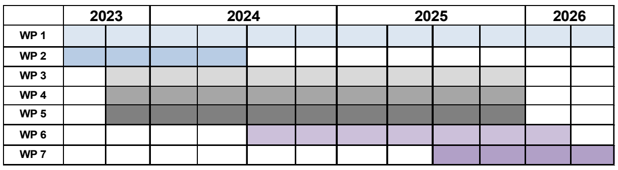

Fig. 3 Gantt chart of HESS project

PROJECT ACTIVITIES AND RESULTS

WP1 – Project Management and Coordination

Throughout the project, management, coordination, and progress monitoring activities were carried out to ensure effective implementation of the HESS work plan. Regular communication between consortium partners, continuous supervision of task execution, and preparation of the required technical and administrative documentation supported the timely delivery of project activities. Project meetings were organised at least every six months to review progress, coordinate upcoming work, and identify potential risks. These activities contributed to the efficient implementation of the project and the achievement of its planned objectives.

In parallel, dissemination and communication activities were carried out to promote the HESS project and share its results with relevant target groups, including academia, industry, public administration, and the general public.

Information on project progress and results was published on the project website (https://itpe.pl/en/hess/), distributed through newsletters, deliverables, and presentations, and shared via the communication channels of the consortium partners and social media. Project outcomes were also presented at national and international scientific conferences, increasing the project's visibility and supporting knowledge transfer to potential end users and stakeholders. These included conferences: XVI CONFERENCE ON RESEARCH & DEVELOPMENT IN POWER ENGINEERING (2023, Warsaw, Poland), THE TREASURE WEEK IN THE CITY OF SCIENCE (2024, Katowice, Poland), meeting of the Coal Technical Groups (2024), Scientific and Technical Conference "Environmentally Friendly Industry", KOMEKO 2024, KOMEKO 2025 and KOMEKO 2026 (Szczyrk, Poland), International Conference on Energy Fuels Environment (EFE 2024) (Kraków, Poland), 7th Mineral Engineering Conference (MEC 2024) (Wisła, Poland), ENERGY WEEK: Energy Transformation Symposium (Gliwice, Poland), , EGU (The European Geosciences Union) General Assembly (2025, Vienna, Austria), Future of Post-mining Areas Conference (2025, Gliwice, Poland), Innovations and the Future of Mechanical Coal Processing: Modern Strategies and Challenges on the example of the JSW S.A. mines (2025, Brenna, Poland), International Energy and Environment Conference 2025 (Ostravice, Czech Republic), EGU General Assembly 2026 (Vienna, Austria), 7th International Conference on Energy and Responsibility – EnRe 2026 (Maribor, Slovenia), 52nd International Conference of SSCHE (Slovak Society of Chemical Engineering) (2026, Štrbské Pleso, Slovakia), and XXXI

Conferences: Heat Market, Energy Management and ICT, Gas Market 2026 (Nałęczów, Poland).

The results generated within the HESS project were disseminated through submissions to national and international peer-reviewed journals, including Energies, Rynek Energii, and Journal of Energy Technology.

The final outcomes of the HESS project were presented during the HESS Final Seminar, organised by ITPE in Zabrze on 22 June 2026. The event brought together representatives of the scientific community and industry to present and discuss the project's main scientific and technological achievements. The seminar provided an opportunity to disseminate the developed HESS concept, exchange knowledge, and discuss its future implementation potential.

Fig. 4 Overview of the HESS project website

WP1 deliverables achieved:

D1.1. The communication and dissemination plan (M1)
D1.2. Webpage created and initiated (M6)
D1.3. The comprehensive public overview of the project (M6)
D1.4. Publishable Report (M36)
D1.5. Final international seminar – project results presentation (M36).

WP2 – Identification of post-mining infrastructure for use in the Hybrid Energy Storage System

The activities carried out within WP2 focused on the adaptation of post-mining infrastructure for application in the Hybrid Energy Storage System (HESS). Particular emphasis was placed on the assessment of the technological and structural conditions governing the potential utilisation of mine shafts and underground workings for advanced energy storage applications.

As part of this work package, a comprehensive identification and evaluation of post-mining infrastructure were conducted to determine its suitability for two energy storage systems: Pumped-Storage Hydropower (PSH) system and Compressed Gas Energy Storage (CGES) system. An extensive database comprising approximately 200 mine shafts located in Poland, the Czech Republic, and Slovenia was developed. The assessment included detailed analyses of mine shafts and underground excavations located in these countries, with particular attention to their geometric, geotechnical, hydrogeological, and structural characteristics relevant to HESS implementation. A multi-criteria assessment methodology was subsequently developed to identify the mine shafts and underground excavations with the greatest potential for adaptation to PSH and CGES applications. The criteria for selecting shafts and their weight were determined. Locations for the implementation of HESS meeting the detailed criteria specified in the multicriteria assessment, with a minimum storage capacity of 10 MWh and a cubic capacity of 10,000 m^3/h were identified.

The methodology developed for selecting mine workings suitable for the implementation of a Pumped-Storage Hydropower (PSH) system considered a comprehensive set of technical, geological, hydrogeological, and infrastructural parameters. The key assessment criteria included shaft depth, which determines the available hydraulic head, shaft diameter, land availability for the construction of the upper reservoir, accessibility of electrical infrastructure, shaft configuration, the presence of existing hoisting equipment, shaft drainage conditions, and the methane content of the underground workings.

To ensure a consistent and objective evaluation of the analysed sites, a mathematical assessment framework was developed. The overall suitability score for each candidate location was calculated using predefined weighting factors reflecting the relative importance of the individual assessment criteria, together with the corresponding partial scores assigned to each parameter.

This approach enabled the comparative ranking of mine workings according to their suitability for PSH implementation.

In parallel, the potential of post-mining infrastructure for application in Compressed Gas Energy Storage (CGES) systems was investigated. The assessment focused on the technical and geological characteristics of mine shafts and underground workings that influence the safety, integrity, and operational performance of the storage system.

The evaluation considered shaft geometry, including depth and diameter, as well as shaft infrastructure, such as shaft function, the condition of the shaft lining, and the presence of shaft dams. In addition, hydrogeological factors - including groundwater chemistry, water inflow, and the occurrence of underground voids - were assessed due to their impact on the long-term safety and efficiency of CGES operation.

To support the selection process, a dedicated Multi-Criteria Decision Analysis (MCDA) system was developed for the evaluation of mine shafts and underground workings. The methodology was implemented as a software tool enabling automated data processing, quantitative assessment of evaluation criteria, and the ranking of candidate sites according to their suitability for integration into compressed gas energy storage systems.

The assessment results indicated that the deepest mine shafts located in Poland exhibit the highest potential for HESS implementation. In accordance with the design concept, which integrates Pumped-Storage Hydropower (PSH) and Compressed Gas Energy Storage (CGES) technologies within a single Hybrid Energy Storage System (HESS), pairs of shafts satisfying the technical requirements of both storage systems were identified.

Among the Polish sites, the highest overall suitability scores were achieved by the Budryk mine (Shaft II and Shaft III), LW Bogdanka (Shaft 2.1 and Shaft 2.2), and KWK Ruda (Grunwald III Shaft and Shaft V). In the Czech Republic, the Sever shafts of the ČSM mine demonstrated the greatest implementation potential. In contrast, the assessment of the Velenje mine in Slovenia indicated that, although the shafts are in good technical condition, their relatively limited depth does not provide sufficient storage capacity to meet the design requirements of the proposed HESS concept.

<u>Summary</u>

The work carried out within WP2 provided the basis for the development of the HESS concept by identifying and evaluating post-mining infrastructure suitable for PSH and CGES applications. A comprehensive database of mine shafts and a multi-criteria assessment methodology were developed, enabling the selection and ranking of the most suitable sites for HESS implementation. The results provided essential input for the subsequent design, modelling, and technical evaluation activities carried out in the following work packages.

<u>WP2 deliverables achieved:</u>

D2.1. Guidelines on the adaptation and use of inactive shafts possible to energy storage (M12)
D2.2. Guidelines on the conversion of underground mine working into water reservoir (M12).

WP3 - Energy storage in pumped storage systems

A significant part of the HESS project was dedicated to exploring the potential of deep mine shafts for energy storage applications based on pumped storage hydropower technology. The objective of the task was to assess the feasibility of adapting deep mine shafts to serve as underground energy storage facilities within pumped storage hydropower systems and to develop technical solutions enabling their practical implementation. This work built upon earlier activities aimed at assessing the potential of selected post-mining facilities and a transition from the site identification stage to the development of a specific technological concept.

The starting point for the analyses was the assumption that existing mining infrastructure could be utilized as a component of an energy storage system. In the proposed concept, Shaft II of the Budryk Mine, with a depth exceeding 1,100 m, serves as the lower water reservoir, while the upper reservoir is located on the surface. Electrical energy is stored in the form of the potential energy of water transferred between the reservoirs. During periods of surplus electricity generation, water is pumped to the upper reservoir, whereas during periods of increased demand it flows through a hydropower system, enabling the generation of electricity.

One of the most important outcomes of the work was the development of a technical concept for a Pumped Storage Hydropower (PSH) module utilizing a mine shaft as an integral part of the energy storage system. The analyses made it possible to define the key parameters of the proposed system, including storage capacity, hydraulic parameters, the configuration of the technological installation, and the selection of the main energy conversion equipment. As a result, a coherent concept covering the energy, hydraulic, and shaft infrastructure components of the system was developed.

The calculations performed showed that, for the assumed shaft and reservoir parameters, an energy storage capacity of approximately 23 MWh can be achieved. This value exceeds the initially assumed storage target and confirms the significant potential of deep mine shafts for energy storage applications. The study also demonstrated the possibility of operating the system on a daily cycle, enabling cooperation with renewable energy sources and supporting the stabilization of the power grid.

An important aspect of the work was the selection of hydropower equipment adapted to the conditions encountered in a deep mine shaft. Due to the very high hydraulic head and relatively low flow rate, a Pelton turbine coupled with a synchronous generator was identified as the most suitable solution. The analyses also covered water transport systems, the design of the pressure pipeline, and the use of the existing mine dewatering infrastructure for pumping water to the upper reservoir. Consideration of these elements made it possible to define the operating principles of the system in both power generation and pumping modes.

The task also included an analysis of the main infrastructure components required for system operation, including water reservoirs, the pipeline network, the pumping system, hydropower equipment, and service infrastructure. Particular attention was paid to issues related to operation under high hydrostatic pressures and the possibility of utilizing existing underground workings and mining equipment. The analyses enabled the definition of technical requirements and the identification of solutions supporting the safe operation of the proposed system under shaft conditions.

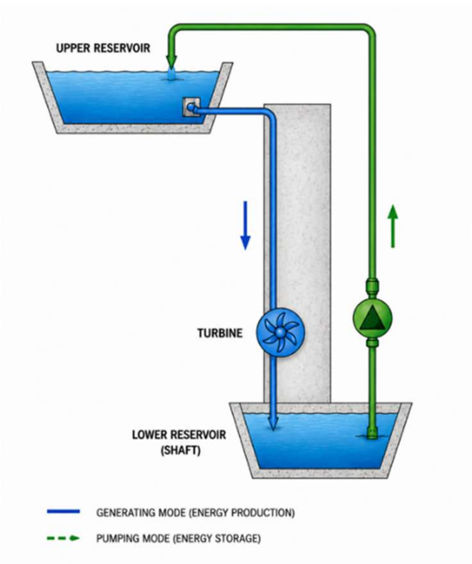

Fig. 5 Schematic diagram of PSH module operation.

In parallel, the feasibility of using underground mine workings, particularly shafts, as water reservoir components for an energy storage system was analysed. The study focused on evaluating whether the existing shaft lining and surrounding rock mass could safely withstand cyclic variations in water pressure and elevated temperatures.

The analyses considered a representative shaft with a diameter of approximately 9.5 m and a reinforced concrete lining of about 45 cm thickness, located in conditions typical of deep mines in the Upper Silesian Coal Basin. Operating fluid pressures ranged from 2-8 MPa, with water or air temperatures of 30-40°C, and a rock mass temperature gradient of approximately 0.03°C/m. The model also accounted for in-situ stress conditions at depths of around 1000 m, including vertical stresses of 25 MPa and variable horizontal stresses.

The results of analytical and numerical simulations indicate that cyclic pressure variations in the shaft did not induce cracking of the lining or loss of stability of the surrounding rock mass. Maximum lining displacements reached approximately 10 mm, while relative cross-sectional deformation did not exceed 0.2%. This suggests that a properly maintained or reinforced shaft lining may safely operate under cyclic loading conditions typical of underground energy storage systems.

Temperature effects were also considered. A medium temperature range of 30–40°C does not significantly affect the mechanical properties of concrete or rock; however, it may induce thermal stresses that should be considered in design and operation. In shallower shaft sections, thermal effects may reduce cracking risk, whereas at greater depths continuous monitoring is recommended.

Additionally, the PRESS-SHAFT computational tool was developed to assess the risk of shaft lining damage due to combined pressure and temperature effects. The tool enables estimation of safe operating ranges for various geomechanical parameters, supporting the assessment of potential post-mining sites for energy storage applications.

As part of the implementation of an underground pumped-storage (PSH) power plant within HESS, a comprehensive assessment of construction materials for underground water reservoirs in mine shafts was conducted. Based on a literature review and analysis of available technologies, two concrete classes (C20/25 and C35/45) and two protective coating systems, Sikagard® M790 and Sikagard® WallCoat T, were selected for investigation.

The selected concrete types represent different stages of shaft construction technology development. C20/25 concrete reflects older structures characterised by higher porosity and reduced watertightness, whereas C35/45 concrete represents modern solutions designed for enhanced resistance to water and gas ingress and improved long-term durability.

The Sikagard® WallCoat T protective system is a thin-layer epoxy coating designed for stable concrete substrates. Sikagard® M790 is a flexible Xolutec®-based membrane capable of bridging microcracks and accommodating substrate deformations. This selection enabled assessment under a broad range of conditions representative of underground mine shaft environments.

Concrete specimens were prepared in accordance with relevant European standards and subjected to laboratory testing under conditions simulating deep underground mining environments.

The tests covered the assessment of chemical resistance of the materials to chloride, sulfate, magnesium, and acidic environments, as well as mine brine simulating operating conditions. The analyses included changes in compressive strength, mass variation, microstructural alterations, pH changes, mineral leaching, and resistance to pressurised liquid penetration. Additional erosion tests and long-term stability assessments in contact with liquid media were also performed.

The results showed that both concretes exhibited relatively good resistance in chloride, sulfate, magnesium, and saline environments, with only minor changes that did not significantly affect performance. No significant structural degradation or loss of mechanical properties was observed under these conditions. The most severe degradation occurred in 5% HCl solution, causing accelerated deterioration such as strength reduction and increased porosity; however, these conditions represent accelerated testing and are not typical of PSH operating environments.

The application of Sikagard® systems significantly improved durability. Sikagard® M790 effectively reduced ion migration and liquid ingress, stabilising material properties, while Sikagard® WallCoat T provided protection dependent on exposure conditions. C35/45 concrete consistently showed better performance than C20/25 due to its lower permeability and denser microstructure.

Overall, the results confirm the suitability of C35/45 concrete combined with Sikagard® M790 or Sikagard® WallCoat T for ensuring long-term durability and safety of underground reservoir structures in PSH systems.

Summary

As part of WP3, a pumped-storage power plant concept was developed using Shaft II of the Budryk Mine as the lower reservoir. System parameters, including a capacity of approximately 23 MWh, were determined, and the technological system was designed, including the selection of a Pelton turbine as optimal for high-head and low-flow conditions.

Geomechanical and thermal analyses were conducted, confirming the safe operation of the shaft lining under cyclic loading conditions, and a PRESS-SHAFT tool was developed to assess the risk of damage. Concurrently, the durability of construction materials was assessed, identifying C35/45 concrete and Sikagard® systems as the most suitable.

The results confirmed the feasibility and safety of using mine shafts in PSH systems and provide a basis for further design and implementation work.

WP3 deliverables achieved:

D3.1. The pumped storage systems in mine shafts (M30)
D3.2. Technical parameters of the example underground water reservoir model (M18).

WP4 – Energy storage in compressed gas systems

WP4 conducted research on compressed gas energy storage systems, including CAES (Compressed Air Energy Storage) and CCES (Compressed Carbon Dioxide Energy Storage). The feasibility of using deep mine shafts as underground high-pressure reservoirs was analyzed, defining the technical, structural, and operational requirements necessary for their safe adaptation. The Budryk III shaft, 1,090 m deep and 9 m in diameter, was selected as the reference facility, for which advanced geomechanical analyses were performed using the PRESS-SHAFT tool. These analyses included assessing the behavior of the shaft lining and the surrounding rock mass under the influence of cyclical changes in compressed gas pressure, confirming the feasibility of using appropriately prepared post-mining infrastructure for energy storage.

The calculations assumed a maximum operating pressure of 8 MPa, corresponding to the most demanding operating conditions of the considered energy storage system. The results showed that the shaft lining remained stable at most depths and had an adequate level of structural safety. Only in the near-surface zone, up to a depth of approximately 80 m, was a potential risk of tensile stresses, which could lead to a loss of tightness, identified. To eliminate this risk, a concept was developed involving the use of a reinforced concrete sealing plug approximately 100 meters long, isolating the zone most exposed to high pressure. Analyses confirmed that after implementing this solution, the active part of the storage facility is located exclusively in an area where natural rock mass stresses effectively balance the pressure of the compressed medium, ensuring stable and safe operation of the system.

Another important element of the research was the assessment of the impact of faults and major geological discontinuities on the safe operation of the energy storage facility. It was demonstrated that the location, orientation, and mechanical properties of such structures can significantly affect the stress state around the shaft.

As part of the work, thermodynamic and energy models were developed for various energy storage system variants. For CAES technology, three system configurations were analyzed, differing in the number of compression stages and heat recovery method.

The basic variant utilized single-stage air compression and cooling prior to storage in the well. More advanced variants utilized two- and three-stage compression systems equipped with intercoolers, enabling more efficient thermal energy recovery and integration with the TES storage system. During discharge, the stored heat is used to heat the compressed air before it expands in an expander, which drives the electricity generator. Analyses showed that configurations utilizing multi-stage compression and heat recovery achieve energy efficiency of approximately 65%.

The proposed CAES concept utilises a post-mining shaft as a high-pressure compressed air reservoir integrated with a basalt-filled Thermal Energy Storage (TES) unit (Fig. 6). The system stores both compressed air and compression heat, operating in a daily charge-discharge cycle. Reuse of existing mining infrastructure significantly reduces investment costs, while the surrounding rock mass provides favourable mechanical and thermal conditions for operation.

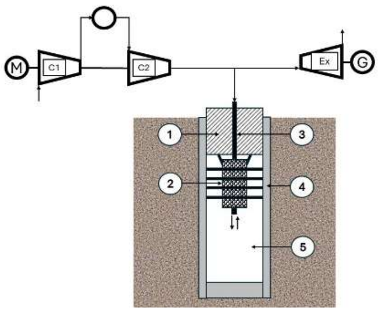

Fig. 6 Mine shaft utilization diagram: 1 – shaft sealing, 2 – TES tank, 3 – compressed air inlet/outlet pipe; 4 - shaft casing, 5 – compressed air reservoir.

In parallel, a concept for a CCES was developed. In this solution, CO_2 operates in a closed circuit, where it is compressed, cooled, stored in a mine shaft, and then reused to produce energy during the expansion process. TES plays a key role here as well, enabling the recovery and reuse of thermal energy. The proposed CCES concept utilises a post-mining shaft as an underground low-pressure CO_2 reservoir, integrated with a surface high-pressure CO_2 vessel and a two-tank Thermal Energy Storage (TES) system using basalt as the storage medium and thermal oil as the heat transfer fluid. The use of supercritical CO_2 significantly increases energy storage density compared with compressed air, while the integrated heat exchanger also enables coupling with district heating or other energy systems. Analyses have shown the possibility of achieving energy efficiency ranging from approximately 50% to 67%, while maintaining high system operational flexibility.

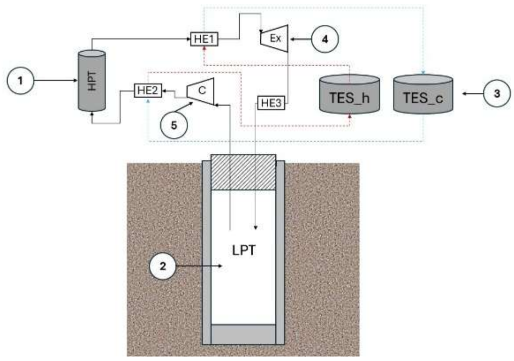

Fig. 7 The CCES scheme: 1 - high-pressure vessel; 2 - low-pressure vessel; 3 – TES tanks; 4 – carbon dioxide expander; 5 – carbon dioxide compressor.

One of the objectives of the work carried out within WP4 was to determine the mechanical, operational, and durability properties of construction and sealing materials intended for the adaptation of mine shafts for compressed gas storage in CAES and CCES systems.

The experimental programme included two concrete grades C20/25 and C35/45 together with the selected protective coating systems Sikagard® WallCoat T and Sikagard® M790 intended for the sealing of pressure-retaining linings in underground CCES gas storage facilities. The materials were tested under aggressive environments comprising chloride, sulphate, magnesium solutions, mine brine and water in the presence of CO_2, simulating conditions relevant to underground gas storage systems. The investigations focused on changes in the mechanical and physicochemical properties of the materials, including compressive strength, mass variation, structural degradation, and carbonation processes.

The results demonstrated that the presence of CO_2 significantly accelerates concrete carbonation and degradation, particularly under water and brine exposure. Although C35/45 concrete exhibited higher durability than C20/25, it did not provide sufficient long-term gas tightness under pressurised CO_2 conditions. The application of Sikagard® protective coatings substantially reduced material degradation and limited CO_2 penetration into the concrete. Among the investigated solutions, the Sikagard® M790 system exhibited the highest barrier performance.

Gas permeability tests were also carried out on C20/25 and C35/45 concrete, as well as on Sikagard® M790 and Sikagard® WallCoat T protective coating systems. Tests were performed using the steady-state flow method with helium as the reference gas over a pressure range from atmospheric pressure to 60 bar. The results showed that C35/45 concrete exhibited approximately three times lower gas permeability than C20/25 concrete; however, improving the concrete grade alone was insufficient to achieve the required level of gas tightness. The application of Sikagard coatings reduced gas permeability by approximately three orders of magnitude for M790 and four orders of magnitude for WallCoat T compared with the reference C20/25 concrete. These findings confirm that protective coating systems are an essential component of mine shaft adaptation for compressed gas storage applications. Among the tested solutions, Sikagard® WallCoat T demonstrated the highest gas barrier performance, while Sikagard® M790 proved particularly suitable for areas requiring crack-bridging capability and accommodation of local deformations.

Based on the test results, operating medium losses were estimated for a model tank with an 8-meter diameter, 1000-meter height, and 1-meter wall thickness operating at a pressure of 60 bar. As a result, the projected pressure drop after 12 hours decreased from approximately 0.086 bar to approximately 0.00015 bar. This indicates negligible CO2 losses under operating conditions when using Sikagard coating systems.

Despite the theoretically high integrity of the proposed CCES system, WP4 analyzed the potential risk of carbon dioxide contamination and migration during cycling. Any changes in CO_2 composition or migration into the surrounding rock mass are expected to be highly localized and primarily associated with structural defects, cracks, or local leakage pathways, rather than bulk transport through intact materials. Any trace amounts of CO_2 entering the geological formation would be mitigated by natural trapping mechanisms, including capillary trapping, dissolution in formation water, adsorption, and long-term mineral sequestration. However, these processes are considered negligible in terms of system mass balance and overall efficiency.

To minimise the adverse effects of impurities such as water vapour, oxygen, methane, nitrogen, and particulate matter on corrosion, heat transfer, and equipment durability, a dedicated CO_2 purification system was proposed for the CCES concept. Cryogenic purification was identified as the preferred technology due to its high CO_2 recovery, minimal working fluid losses, and the ability to achieve CO_2 purity exceeding 99.99%. A conceptual purification unit with a capacity of approximately 1000 kg/h was developed, comprising pre-filtration, cooling, compression, condensate separation, deep dehydration, impurity removal, liquefaction, and cryogenic distillation. The purified liquid CO_2 is stored in a cryogenic tank with a capacity of approximately 100 tonnes, providing system buffering and ensuring stable operation during maintenance and transient conditions.

A complementary literature review on the interaction of supercritical CO_2 with structural materials confirmed that dry CO_2 has negligible corrosive effects, whereas moisture is the primary factor responsible for material degradation through carbonic acid formation. Additional impurities, including O_2, SO_2, H_2S, and NO_x, may further accelerate corrosion. These findings highlight the importance of effective CO_2 purification and dehydration, continuous gas composition monitoring, and the application of protective barrier coatings to ensure the long-term integrity and reliable operation of CCES systems.

In order to analyse separation phenomena in CO_2-containing mixtures under supercritical conditions, a dedicated experimental setup was designed and constructed. The facility enables experiments at pressures up to 100 bar and temperatures above the critical point of CO_2. It consists of a 3 dm^3 high-pressure reactor equipped with pressure monitoring and gas sampling ports, a temperature control system, an auxiliary gas dosing module, and a high-pressure CO_2 supply system with a pneumatic booster.

Experiments were conducted using CO_2-air and CO_2-methane mixtures under conditions representative of CCES systems, i.e., at 100 bar and 40°C. Gas samples were collected from both the upper and lower sections of the reactor to evaluate potential compositional stratification along its height. In mixtures with higher air content, a slight tendency was observed for lighter gases (nitrogen and oxygen) to accumulate in the upper part of the reactor, while higher CO_2 concentrations were measured in the lower part. However, the magnitude of this effect was limited. At lower air concentrations, the gas composition remained essentially homogeneous, whereas CO_2-CH_4 mixtures exhibited only very weak component separation.

The results indicate that significant gas stratification may occur mainly at elevated concentrations of non-condensable gases, typical of transient conditions such as start-up or leakage. However, under normal CCES operating conditions, with high system tightness, low impurity levels, and effective CO_2 purification, no meaningful component separation is expected. The observed concentration gradients are too small to affect compression, storage, or expansion processes and therefore do not impact system stability or efficiency.

As part of the work, a literature review was conducted on CO_2 storage in supercritical conditions (above 31.1°C and 7.38 MPa). This condition is advantageous for CCES applications due to the combination of high density and low viscosity of CO_2, which reduces compression work and allows for a more compact device design.

CO_2 storage in cryogenic tanks and high-pressure cylinders is a mature technology, while dedicated solutions for supercritical conditions are still in the development phase and are based mainly on pressure vessels designed in accordance with the requirements of the PED directive and ASME standards. Key safety aspects include the risk of leaks, oxygen displacement, CO_2

accumulation in depressions and dry ice formation during rapid decompression.

Therefore, CCES systems require the use of pressure protection, continuous monitoring, CO_2 detection systems and adequate ventilation.

Summary

WP4 focused on the development and assessment of compressed gas energy storage technologies based on compressed air (CAES) and compressed carbon dioxide (CCES), including the adaptation of deep post-mining shafts as underground pressure reservoirs. Geomechanical analyses confirmed the technical feasibility of using the Budryk III mine shaft for high-pressure gas storage, while thermodynamic modelling demonstrated that the integration of CAES/CCES with Thermal Energy Storage (TES) can achieve round-trip efficiencies of approximately 50–67%, depending on the system configuration. The work also included the evaluation of construction and sealing materials for underground reservoirs, showing that Sikagard® protective coating systems significantly improve gas tightness and durability under aggressive CO_2 environments, reducing gas permeability by up to four orders of magnitude. In parallel, concepts for CO_2 purification, storage, and monitoring were developed to ensure long-term operational safety and reliability of CCES installations. Overall, WP4 provided the technical basis for the safe implementation of compressed gas energy storage systems utilizing post-mining infrastructure and demonstrated their potential for large-scale energy storage applications.

WP4 deliverables achieved:

D4.1. Thermodynamic analysis of the proposed systems (M18)
D4.2. Guidelines for the baseline condition of the reference shafts (M30)
D4.3. Lining materials selection and properties (M27).

WP5 – Heat storage in post-mining infrastructure

Another key element of WP5 is the Thermal Energy Storage (TES) system, which stores heat generated during the compression of the gaseous working medium and reuses it during the discharge phase. Its main purpose is to increase overall system efficiency by reducing energy losses associated with compression and expansion processes. This solution enables the recovery of part of the thermal energy that would otherwise be lost in conventional systems, thereby improving the overall energy efficiency of the HESS concept.

The initial phase of WP5 involved the selection of heat-storing materials for the TES system. A comprehensive analysis of available materials was conducted, including solids, working fluids, and phase change materials (PCMs). Their thermal, physical, and chemical properties were assessed, along with economic aspects and market availability. Analyses were performed for three representative operating temperature levels: 100°C, 300°C, and 500°C, corresponding to different HESS system operating scenarios.

Based on the evaluation, materials were selected for further testing. For temperatures around 300°C and 500°C, basalt proved to be a particularly advantageous material, characterized by high heat capacity, resistance to thermal cycling, wide availability, and low cost. Among the phase change materials, Solar Salt, Hitec XL, and LiNaK were identified, which enable energy storage in the form of both sensible and latent heat. Additionally, the properties of working fluids used for heat transfer and transfer, including Solar Salt and Therminol 66, were analyzed.

The literature analyzes were complemented by experimental tests of the Alferrock ceramic material, produced from by-products of the aluminum industry. They showed high stability in heating and cooling cycles to temperatures above 1000°C and small changes in sample mass, confirming its potential in high-temperature heat storage. However, due to manufacturing costs, this material was not recommended as the basic solution for large-scale TES systems within the project.

The obtained results allowed us to identify the most promising materials for the TES tank and formed the basis for experimental studies conducted in the next phase of the project, including real-world heat materials. Their goal was to evaluate the performance of heat storage systems and identify key parameters relevant to the design of a thermal energy storage unit integrated with an adiabatic compressed air energy storage system.

Experimental studies of the TES unit were conducted under controlled heated airflow conditions, analysing two storage material variants: a basalt bed for sensible heat storage and a bed with PCM capsules filled with Solar Salt. Solar Salt was selected for testing based on preliminary melting, solidification, and encapsulation tests.

Heat storage experiments in the basalt bed were carried out at the SUT test stand, equipped with a TES tank of approximately 0.1 m^3. The installation included an air heating system, valves enabling flow reversal during charging and discharging, and a measurement system for recording temperature distribution and pressure drop in the bed. To enable high-temperature testing, ITPE designed and built a 30 dm^3 laboratory test stand for investigating PCM materials at temperatures of up to 500°C.

The experimental studies demonstrated that the basalt bed is an effective material for sensible heat storage, providing high cycle energy efficiency of 84–95% and stable operation within the analyzed temperature range. Analysis of the charging and discharging processes confirmed the correct propagation of the thermal front in the bed and high efficiency of thermal energy recovery. Increasing the airflow increased the thermal power during discharge but simultaneously shortened the effective heat transfer time. Basalt was characterized by high thermal power in the initial discharge phase, which then gradually decreased as the temperature difference between the bed and the flowing air decreased. It was also shown that, within the analyzed range, basalt grain size had little impact on storage efficiency, but could affect flow resistance.

Tests of the PCM (Solar Salt) confirmed its technical suitability for use in a high-temperature storage system. A melting point of 226–228°C, a solidification point of approximately 220°C, and a phase change heat of 118–120 J/g were determined, and the material's thermal stability was confirmed up to 500°C. During the storage operation, a characteristic temperature plateau associated with the phase transition was observed, allowing for more uniform heat transfer than with a basalt bed. The PCM storage achieved a cycle energy efficiency of 84–95%, comparable to the basalt storage, but was characterized by lower instantaneous power and a more complex design resulting from the need for material encapsulation. Despite its beneficial properties in stabilizing the working fluid temperature, the PCM-based solution is less economically advantageous than the basalt bed, particularly for large-scale heat storage in post-mining infrastructure.

The obtained results allowed us to determine the operating characteristics of both TES variants, identify their potential applications, and provide data necessary for the validation of numerical models and the design of a full-scale heat storage system for the HESS system.

The final stage of the work focused on the development and validation of numerical models for both sensible and latent heat storage systems using the experimental data. Good agreement between simulation results and measurements confirmed the validity of the developed models. Numerical analyses showed that increasing the air flow rate improved the thermal efficiency of the storage unit (67–90%) while reducing its exergy efficiency (12–50%) due to increased pressure losses. The validated model was subsequently used to simulate a full-scale TES system for the CAES application, achieving a thermal efficiency of approximately 96% and confirming the suitability of the proposed design. In addition, a numerical model of the PCM storage unit was developed, enabling detailed analysis of the melting and solidification processes of Solar Salt and supporting further optimisation of latent heat thermal energy storage systems.

<u>Summary</u>

WP5 focused on the development of the Thermal Energy Storage subsystem, which is a key component of the HESS concept, enabling the recovery and reuse of heat generated during gas compression. The work included the selection and experimental evaluation of heat storage materials, leading to the identification of basalt as the preferred sensible heat storage medium and Solar Salt as the most promising PCM. Experimental and numerical studies confirmed high energy efficiencies of 84–95% for both storage concepts and demonstrated the suitability of basalt for large-scale TES applications due to its high performance, low cost, and simple design. The validated numerical models and experimental results provide the basis for the design and optimization of a full-scale TES system integrated with the HESS technology.

<u>WP5 deliverables achieved:</u>

D5.1. Thermal energy storage material studies (M12)
D5.2.TES performance report (M30).

WP6 – Hybridization of energy storage systems in post-mining infrastructure

WP6 of the HESS project involved developing a concept for the optimal integration of a hybrid energy storage system (HESS). The analyzed system combines three energy storage technologies: a pumped-storage hydropower plant (PSH), a compressed gas energy storage system (A-CAES or CCES), and a thermal energy storage system (TES). A minimum energy capacity of 10 MWh was assumed for each subsystem. The work included mass and energy balances, an analysis of operational parameters, and a preliminary technical and economic assessment of the proposed configurations.

The analysis takes into account the current conditions of the electricity market, in particular the growing share of renewable energy sources and the increasing volatility of energy prices on the Day-Ahead Market (DAM). It was demonstrated that the increase in the number of hours with very low and negative energy prices increases the economic potential of large-scale energy storage facilities, enabling the purchase of energy during periods of surplus production and its sale during periods of high demand. At the same time, the important role of energy storage systems in providing system services, such as frequency regulation, grid stabilization, and ensuring the ability to rebuild the system after a failure (black start), was emphasized.

Data on the operation of the Żarnowiec and Porąbka-Żar pumped-storage power plants and the results of earlier stages of the HESS project were used to develop the system operation model. Based on this, mass and energy balance models were developed for all analyzed energy storage technologies, and the possibilities of their mutual thermal and mechanical integration were determined.

For pumped-storage storage, the relationships between tank capacity, device power, and charging and discharging times were determined. The analysis showed that, for comparable energy capacities, all three technologies can effectively operate within a single HESS system, but they differ in their storage infrastructure requirements. The highest energy storage density relative to tank volume was achieved for the A-CAES system, while the lowest was achieved for the CCES system, which requires large, low-pressure tanks. For the economic evaluation, an algorithm was developed to determine the optimal storage charging and discharging periods based on actual electricity prices from the day-ahead market. Instead of using fixed price thresholds, an analysis of average prices over periods corresponding to the storage operating cycle lengths was used, allowing for a better representation of energy market volatility. Simulations showed that the greatest economic benefits are achieved for a cycle spanning approximately 5 hours of charging and 3 hours of energy generation.

As part of the analyses, each of the energy storage systems under consideration was calculated for selected technological equipment parameters, particularly the power of the compressors, expansion devices, pumps, and turbines, as well as the duration of the charging and discharging cycles. This was particularly important in the case of the PSH system, which considered the possibility of utilizing the existing mine drainage system. This solution reduces the capital expenditure associated with the construction of new technical infrastructure but is associated with lower energy efficiency compared to a system designed from scratch as a classic pumped-storage power plant. Consequently, the reduction in CAPEX may be partially offset by higher operating costs resulting from increased energy consumption in the pumping cycle and lower energy recovery efficiency during generation.

The preliminary economic analysis included only revenues resulting from price arbitrage. The results indicate that while the efficiency of individual technologies remains virtually independent of operating cycle duration, the length of charging and discharging has a significant impact on revenues. Among the analyzed technologies, the highest unit profits from price arbitrage were achieved for the A-CAES system. However, in practice, the cost of infrastructure construction, operating costs, and the ability to provide system services will also determine the investment's profitability.

One of the key outcomes of the HESS project was the development of the Energy Router system, responsible for coordinating the operation of all components of the hybrid energy storage system. The objective of the work was to create a solution enabling efficient management of energy flows between energy storage systems, the power grid, and energy consumers, while taking into account market conditions and the technical characteristics of individual installations.

As part of the task, an Energy Router demonstrator was developed in the form of a complete laboratory setup equipped with a PLC controller, HMI operator panel, supervisory server, and industrial communication system. The demonstrator was designed to reflect the target system architecture and enable testing of control algorithms, verification of data exchange between devices, and assessment of component integration. The test stand also provided a platform for the safe development and validation of software before its application in a real energy storage system.

One of the key achievements of the work was the development of a simulation environment capable of reproducing the operation of the different energy storage technologies considered within the project. Simulation models were developed for the Pumped Storage Hydropower (PSH) system and for the Compressed Gas Energy Storage system integrated with Thermal Energy Storage (CGES-TES). These models make it possible to analyse the behaviour of energy storage systems under different operating conditions, monitor energy flows, and assess the impact of control strategies on the performance of the overall system. The data obtained from these simulations formed the basis for the development of energy management algorithms.

Particular attention was devoted to the development of algorithms responsible for planning the charging and discharging processes of energy storage systems. For the CGES system, an algorithm was developed that analyses forecasted electricity prices and selects the most economically advantageous operating scenarios for the following day. The algorithm takes the storage system efficiency into account and evaluates different charging and discharging schedules to maximize economic benefits from energy trading. A separate algorithm was developed for the PSH system, tailored to the specific operating characteristics of pumped storage hydropower plants and enabling the identification of the most favourable periods for energy storage and generation based on variations in electricity prices.

An important aspect of the developed solution was also the acquisition and processing of market data used by the decision-making algorithms. The possibilities of using day-ahead market data were analysed, and a method for integrating these data into the energy management system was developed. This enabled electricity price fluctuations to be considered in the planning of storage system operation and in decisions regarding the direction of energy flows within the system.

The project also included the development of visualization tools enabling monitoring of system operation. Two complementary visualization environments were created. The first was a local HMI interface integrated with the demonstrator, allowing operators to observe system operating parameters, energy storage status, energy flows, and the effects of control algorithms. The second was a web-based application providing remote access to data and enabling system monitoring through a standard web browser. These tools support the analysis of energy flows between storage systems, the power grid, and energy consumers, as well as the evaluation of the economic performance of the Energy Router.

The work carried out confirmed the feasibility of integrating different energy storage technologies within a single energy management framework. The developed simulation models, control algorithms, and visualization environments established a foundation for the further development of an intelligent energy management system for hybrid energy storage solutions based on post-mining infrastructure. The achieved results enable the analysis of interactions between different energy storage technologies and support the assessment of their potential to increase power system flexibility and facilitate the integration of renewable energy sources.

Future work should focus on the further development of decision-making algorithms, the expansion of the range of data used for storage operation planning, and the integration of the developed system with real energy storage installations. An important direction for future development will also be the inclusion of additional factors affecting the economic performance of energy storage systems, enabling further improvements in the efficiency and effectiveness of energy management.

Summary

The objective of WP6 was to develop and evaluate an integrated Hybrid Energy Storage System combining PSH, CAES or CCES, and TES with use an intelligent Energy Router. Thermodynamic models and mass-energy balances were developed for all storage technologies, together with a preliminary technical-economic assessment based on electricity market conditions and price arbitrage strategies. The analyses confirmed the technical feasibility of integrating the different storage technologies and demonstrated the potential of post-mining infrastructure to reduce investment costs while supporting large-scale energy storage. A laboratory demonstrator of the Energy Router was developed, together with simulation models, control algorithms, and visualization tools for monitoring and optimizing energy flows. The developed solutions provide a foundation for intelligent energy management and support the future deployment of hybrid energy storage systems based on post-mining infrastructure.

WP6 deliverables achieved:

D6.1. Integration of particular components of the HESS (M33)
D6.2. Energy router software (M33).

WP7 – Techno-economic and environmental assessment of the Hybrid Energy Storage System

The activities carried out within WP7 focused on the comprehensive technical and economic assessment of the proposed Hybrid Energy Storage System (HESS). A complete technical concept of the integrated system was developed, including two alternative HESS configurations combining Pumped-Storage Hydropower (PSH) with either Compressed Air Energy Storage (CAES) or Compressed Carbon Dioxide Energy Storage (CCES), both supported by a Thermal Energy Storage (TES) subsystem.

The work included the development of process flow diagrams, detailed technical descriptions of all HESS subsystems, and the definition of the basic technological parameters, operating conditions, and integration principles of the proposed solutions. Furthermore, the basic facilities and equipment required for system implementation were identified, together with the characteristics of the main process streams, products, and resource requirements. Engineering solutions for adapting post-mining shafts to HESS implementation were also developed, including shaft sealing systems, plug construction, protective concrete coatings, and ventilation.

A comprehensive mass and energy balance of the integrated HESS concept was performed to evaluate system performance and energy flows.

The technical assessment was complemented by an economic evaluation, including the estimation of capital expenditures (CAPEX), operating expenditures (OPEX), and key economic performance indicators (NPV, IRR, SPBT, LCOE). The results provide the basis for assessing the technical feasibility, economic viability, and future industrial implementation of the proposed hybrid energy storage technology. The analysis showed that the main component of LCOE is the capital costs, therefore acquisition of external funding sources such as grants is crucial for the industrial implementation to reduce LCOE and thus improve financial feasibility of the system. Additional case analysis of non-repayable grant acquisition showed significant reduction of LCOE for Case 1 and further reduction for Case 2.

As part of WP7, a SWOT analysis was carried out to assess key internal and external factors affecting the development and implementation of HESS technology. It distinguishes between strengths and weaknesses inherent to the solution and opportunities and threats arising from the external environment, including market, technological, regulatory, and socio-economic conditions. This approach provides a concise assessment of the technology's current position and its future implementation potential.

STRENGTHS. HESS enables avoidance of significant investment costs by reusing existing post-mining infrastructure, offering a cost-effective and sustainable alternative to mine closure. The technology allows integration with geothermal energy resources and can contribute to stabilisation of national power grids through flexible energy storage and management. Additionally, it provides socio-economic benefits for post-mining regions by supporting their transformation and development.

WEAKNESSES. Key limitations include restricted access to underground assets, lack of trained personnel, and insufficiently defined cost estimates. A significant barrier is also the absence of dedicated legislation, regulatory frameworks, and clearly defined safety requirements, which may hinder implementation and approval processes.

OPPORTUNITIES. HESS aligns with environmental objectives and EU decarbonisation and circular economy policies, increasing its strategic relevance. The concept of an "energy router" and scalable storage capacity enhances its market potential. Further opportunities include adaptation of the technology to metal mines, modification for shallower shafts and existing underground networks, and re-evaluation of already closed or closing mines.

THREATS. Potential risks include uncertainty regarding the structural integrity of underground workings, possible community resistance, and inconsistencies between mine closure plans and HESS implementation requirements. Additional challenges involve surface stability issues and complex ownership and responsibility structures.

As part of the HESS project, a re-analysis of selected Slovenian and Czech mines was carried out to assess their potential for future implementation of hybrid energy storage technologies. Although the analysed mine shafts did not fully meet the initial project criteria regarding shaft depth, geometry, and storage capacity, the broader underground infrastructure was found to offer promising opportunities for energy storage applications.

In Slovenia, the Velenje mine was assessed as a potential site for both PSH and CAES/CCES systems. The mine has well-preserved shafts and underground galleries with reinforced lining, providing favourable conditions for long-term structural stability after mine closure. Existing surface reservoirs, including Lake Velenje and former process tanks, could serve as upper reservoirs, while the NOP and NOP II shafts, pumping infrastructure, and underground galleries could be used as part of the underground storage system. Although the shaft dimensions limit the achievable storage capacity, the available underground volume, particularly within the gallery network, indicates the potential to approach 10 MWh. The Velenje site may therefore represent an adaptive implementation scenario, in which a modified technical configuration or lower storage capacity is balanced by reduced investment costs through the use of existing infrastructure.

In the Czech Republic, the feasibility assessment identified the ČSM Mine as the most promising location for HESS implementation. Based on the multi-criteria analysis, the Sever shafts were selected as the preferred option for PSH, while one shaft was considered suitable for CAES. However, the rapid mine closure process initiated in 2026, including shaft backfilling and decommissioning, prevented the practical implementation of the HESS concept at this site. The mine operator had already committed to alternative post-mining strategies, mainly focused on methane extraction, due to technical, safety, and economic considerations.

Despite these limitations, the assessment confirmed that post-mining infrastructure in the Czech Republic remains a valuable resource for future energy storage applications. In particular, the Jeremenko Mine was identified as an attractive alternative, despite not meeting all initial HESS selection criteria. Its existing pumping infrastructure, significant shaft depth, and continuous mine water management create favourable conditions for further analysis. Previous studies confirmed the technical feasibility of an underground PSH system with a capacity of approximately 10 MWh, while also highlighting challenges related to mine water quality. These findings support the HESS concept of a closed-loop system using clean water, which could reduce corrosion and gas emission risks. Additionally, the geothermal potential of pumped mine water creates opportunities for integration with district heating systems, further increasing the energy utilisation potential of post-mining infrastructure.

As a part of WP7 Life cycle assessment (LCA) of both hybrid energy storage variants was conducted. The LCA accounts the impacts from all the stages of plant's life cycle, namely the extraction of raw materials, manufacturing of plant components, plant construction and operation. LCA enables identification of the most significant impacts and the stages to be observed for improvement, avoiding the damage to be spread from one stage to another, an environmental problem to another or from one region to another within a systematic and holistic approach.

This research used the LCA methodology to compare two HESS systems based on various forms of pressure energy storage, i.e. adiabatic compressed air or compressed carbon dioxide storage systems, as well as to identify environmental impacts and hot-spots of two hybrid energy storage systems developed within the HESS project.

The functional (FU) unit chosen was "1 kWh of annual electricity fed to the grid". 1 kWh of electrical energy is a common FU in life cycle studies regarding storage technologies and electrical power generation.

The scope of this study encompassed a "cradle-to-gate" perimeter, which covers the construction stage of both designed HESS plants using hard coal post-mining shafts located in Poland, Upper Silesia, and its operation for period of one year. "Cradle-to-gate" is the common approach during hydropower plants life cycle assessment studies. System maintenance and repairs were also excluded due to a lack of reliable data to estimate the required material and energy input for proposed HESS variants maintenance.

For this study, we used the openLCA 2.6.0 software to develop and link unit processes. The ReCiPe 2016 v1.03 method was applied, characterized by expressing the results of the environmental impact from a midpoint H perspective. Ecoinvent 3.12 database was used as the background data source.

Conducted LCA results indicates that in the case of both HESS variants contribution resulting from HESS infrastructure construction are largely dominated by the impacts associated with electricity generation, which is by far the main contributor to the impacts of systems under consideration. The environmental performance of 1 kWh electricity fed annually to the grid by both developed HESS systems is rather burdened by the electricity's required to operate both systems sourced from polish national grid than by the equipment and construction stage. When connected to the same high voltage polish grid, the PSH-CAES and PSH-CCES systems have very similar impacts for all 18 midpoint categories. When focusing on the climate change impact only, measured through GHG emissions, the production of 1 kWh of electricity by PSH-ACAES and PSH-CCES systems is associated with the emission of 1.52 kg CO_2-eq/kWh and 1.55 kg CO_2-eq/kWh, respectively. On the other hand, the construction phase of both system have an significantly lower contribution to climate change – 0.00044 kg CO_2-eq/kWh and 0.00117 kg CO_2-eq/kWh for PSH-ACAES and PSH-CCES, respectively.

WP7 deliverables achieved:

D7.1. Techno-economic assessment of hybrid energy storage technology in post-mining infrastructure (M36)
D7.2. Life cycle assessment (LCA) of the HESS (M36).

Summary

WP7 provided a comprehensive technical, economic, and environmental assessment of the HESS concept, integrating the results obtained throughout the project into a unified implementation framework. Two hybrid energy storage configurations combining PSH with either CAES or CCES, supported by TES, were evaluated in terms of technical feasibility, energy performance, investment and operating costs, and economic indicators (NPV, IRR, SPBT, and LCOE). The analyses demonstrated that capital investment represents the dominant component of the levelised cost of energy, highlighting the importance of external funding mechanisms to improve the financial viability of future HESS installations. The work was complemented by a SWOT analysis and a life cycle assessment, confirming the technical feasibility, environmental sustainability, and significant implementation potential of HESS based on post-mining infrastructure. Overall, WP7 established a solid foundation for the future demonstration and industrial deployment of hybrid energy storage systems supporting the energy transition and the reuse of post-mining assets.