JOURNAL OF ENERGY TECHNOLOGY
Vol. 19, No. 1, pp. 5–30, July 2026

Original Scientific Article

RESULTS OF THE HESS PROJECT – HYBRID ENERGY STORAGE SYSTEM IN POST-MINING INFRASTRUCTURE

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Submitted
9. 6. 2026

Accepted
26. 6. 2026

Published
15. 7. 2026

Abstract The project`s aim was to develop a Hybrid Energy Storage System (HESS) consisting of three different energy storage systems: Pumped Storage Hydroelectricity (PSH), Compressed Gas – Air/CO2 Energy Storage (CAES) and Thermal Energy Storage (TES) using a post-mining infrastructure. The possibility of using geothermal energy and the use and potential storage of CO2 were also included in the research. The assumed total energy storage capacity in the HESS project was in the range of 30 MWh. On the basis of the energy demand of each HESS component, a method of thermal and mechanical integration of the entire system was investigated and developed, together with an algorithm for the mutual interaction between the elements of the energy storage system. The optimal cooperation of the various elements of the HESS was decided to be supervised by an energy router. The router also manages energy exchanges with the national power grid for the intake of low-cost green energy and peak energy production. The single HESS energy router system should take into account the possibility of the cooperation of multiple HESS systems working in a distributed system.

Keywords
energy storage, post-mining infrastructure, pumped storage hydroelectricity, compressed gas – air/CO2 energy storage, thermal energy storage, RFCS Project HESS

https://doi.org/10.18690/jet.19.1.5-30.2026
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1 Introducton

European countries have declared a »coal exit« in the coming years, and, consequently, the remaining coal mines will have to shift from production to closure. Mine closure is a demanding process, which requires a great deal of financial resources, trained personnel and a well- prepared time line, which must be prepared in accordance with the environmental, ecological and geomechanical requirements. All three key aspects must be studied carefully in order to avoid or minimise impacts on the surface area and underground features below the allowed measures. Some of the mine closure practices showed different approaches towards the process. However, in some cases, alternatives have been introduced, tested and accessed for possible post-mining use as an integration into energy production or a storage solution.

Coal mining usually required a great amount of underground access and approach infrastructure for its effective operation. Construction was done under increased stability criteria, with an emphasis on a long-time life span of these objects. Support generally included the installation of elements and materials that represented a strong lining along shafts, drifts and main access to the mine network. In most cases, the support consisted of prefabricated concrete panels, strong closed steel arch systems, anchoring, reinforced poured concrete, cement (or other material) injection and a combination of the given options.

After the coal production stops the closure sequence follows, from the active mining areas of the coal mine towards the access objects, what leaves the structurally and geometrically favoured objects as a potential for alternative, post mining use.
Slovenia joined the EU-wide programme of coal exit after the Integrated National Energy and Climate Plan was signed in 2020. In accordance with similar plans across the EU, a completely new approach towards mining infrastructure occurred, and therefore the EU Commission's Research Fund for Coal and Steel added research of the potential post-mining infrastructure into the funding scheme.

In 2022, a consortium of partners (the Institute of Energy and Fuel Processing Technology (Poland), the Silesian University of Technology (Poland), the Institut Techniki Gorniczej (Poland), the Technical University of Ostrava (Czech Republic), and Premogovnik Velenje (Slovenia)) submitted a HESS (Hybrid Energy Storage

System in post-mining infrastructure) research project and succeeded in gaining the positive review together with fundings in 2023.

The project frame consisted of seven work packages, in which a coherent review of technologies, objects and other key factors were assessed for multiple locations. Over the project a decisive protocol was introduced and tested, in order to achieve the optimal, or near-to-optimal variants of the proposed solutions.

2 HESS Project objectives

The main aim of the project was the development of a Hybrid Energy Storage System (HESS) consisting of three different energy storage systems: a pumped storage hydroelectricity (PSH), compressed gas – air/CO_2 energy storage (CAES / CCES) and thermal energy storage (TES) using a post-mining infrastructure. The assumed total energy storage capacity was a min. of 30 MWh (10 MWh for each system).

The objective of the HESS project was to determine the feasibility of using post-mining shafts (and access the underground infrastructure), by identifying the structure of the shaft and rock layers (determining storage volume of the mine shaft and its permeability), in order to use all three considered types of energy storage systems.

To achieve this objective (Identification of a post-mining infrastructure for use in the Hybrid Energy Storage System), an analysis and assessment was carried out of the possibilities of using the underground and surface mine infrastructure for HESS development in Poland, the Czech Republic and Slovenia. An extensive database of coal mining shafts was created containing around 200 records. The hydrological and geological requirements were determined for the most optimal use for the underground pumped storage hydroelectricity, compressed gas energy storage and thermal energy storage. Minimum requirements have been defined for the implementation of HESS in the mining area. The locations for the implementation of HESS must match the detailed criteria, specified in the multi-criteria assessment, with a minimum storage capacity of 10 MWh and a cubic capacity of 10.000 m3.

The specific objective for the project is to ensure the tightness of the tanks in the pumped storage hydroelectricity system for a minimum of 10 years. The materials for the construction of water tanks in the PSH system were analysed and selected as part of this task. Corrosion and erosion, as well as water and brine permeability tests were carried out for each construction material. On the basis of the results, the minimum thickness of the tank walls was determined, ensuring their operation for at least 10 years. The results obtained, combined with the economic analysis, directed the selection of the tank construction material.

Another specific objective for the HESS project is achieving the working pressure ~ 80 bar for the air and ~ 20 bar for the CO_2 in the Compressed Gas Energy Storage System. The pressure losses in the sealed mining shaft should be less than 5% of the maximum pressure (during one cycle of CGES operation).

The further research was related to the development of the Compressed Air and CO_2 Energy Storage system. As part of the implementation, extensive thermodynamic modelling was carried out using in-house computational codes. The subject of the study were adiabatic energy storage systems in compressed air (CAES) and in compressed carbon dioxide (CCES). The work resulted in a multi-variant analysis, based on which the variants of the studied systems were recommended for further work. The focus was that the identified variants should be characterised by acceptable operating parameters, energy indicators and the possibility of integration with an energy router.

The specific objective for the project is to ensure an energy storage temperature up to 500°C, and to achieve an energy recovery capacity of at least 1,5 MWt for at least 2 hours.

As part of the research, an extensive analysis of the available solid, liquid and phase change materials dedicated to heat storage was performed, in accordance with the project's objectives. Materials for storage were selected that can be used at three temperature levels: 100°C, 300°C, 500°C. In addition, experimental tests were performed using solid ceramic materials. These materials have demonstrated favourable thermophysical performance with regard to heat storage; however, their elevated cost does not currently allow them to be used on an industrial scale. Experimental studies are also being conducted with the thermal energy storage tank, with the objective of investigating the potential for heat storage in natural rock materials and providing experimental data for the validation of numerical models.

Another objective of the HESS project is the creation of the energy router concept for measurements, data acquisition and performance integration of all the HESS modules, energy storage management and cooperation with the National Power System.

At the present time, work is being carried out on the integration concept and the calculation model of the HESS configuration. The exchange, collection and analysis of data from previous research tasks is ongoing. The initial installation works have been completed, the control cabinet has been adapted, a server for network communication and a controller with an operator panel have been installed, and the system components have been integrated into a cohesive infrastructure. After the installation, the basic system functions were tested, enabling the launch of its key elements. Work has also begun on a computer application for managing the energy router, which will coordinate the system, process data and present the parameters in a graphical format. Additionally, work is ongoing on visualisation tools to monitor the system in real time.

An important final aim of the project is to conduct a technical, economic and environmental assessment of the Hybrid Energy Storage System. These assessments are based on the information obtained at earlier stages of the project. The techno-economic assessment of HESS in the post-mining infrastructure is in the stage of preparation in the form of a Pre-feasibility Study confirming the technological and economic feasibility. The technical, economic and environmental analyses carried out will be the basis for determining the possibilities of industrial implementation of the HESS technology.

3 Methodology

3.1 Site selection

The site selection and related analysis were focused on issues related to the adaptation of post-mining infrastructure for the purposes of energy storage purposes in the Hybrid Energy Storage System (HESS). Particular attention was paid to the analysis of the technological and structural conditions that determine the potential use of mine workings and shafts in the context of modern energy storage systems. A key aspect was identifying the existing engineering solutions and their potential integration with hydroelectric and compressed air systems, enabling efficient management of the energy surpluses in the context of the energy transition.

During the research, the identification, classification and technical assessment were carried out of objects that could be adapted for the new function. A detailed analysis was conducted on the physical parameters such as depth, diameter and the condition of the structural lining, as well as the functionality and further usability of the given infrastructure. Interdisciplinary aspects were considered, including the rock mass mechanics, mining engineering, hydrogeology and energy system modelling, which allowed for the development of criteria for evaluating and selecting the most suitable locations.

The research also attempted to determine the potential benefits of transforming the post-mining infrastructure into energy storage systems. The impact was analysed of the geotechnical and hydrogeological conditions on the long-term stability and efficiency of the planned solutions. Issues related to the durability of the structural lining, the potential for rock mass deformation, and the risk of mine water migration were considered, allowing for the identification of key factors affecting the safety and functionality of the system.

3.2 Identification of Shaft Infrastructure as a Potential Base for Energy Storage

As part of the conducted research, a key issue was the identification of the shaft infrastructure as a potential base for implementing energy storage systems. The undertaken actions included a comprehensive inventory of the shafts, with particular emphasis on their current operational status, geometric parameters, and previous function within the mine structure in Poland, the Czech Republic and Slovenia. Both shafts in operation and those designated for decommissioning were considered, allowing for the creation of an up-to-date database of objects that could be adapted for energy storage systems.

A detailed classification of the infrastructure was carried out, dividing the shafts based on their affiliation with mining enterprises and their geographical distribution. The acquired data were verified through an analysis of the technical documentation and consultations with the mining institutions, enabling precise characterisation of each object. Information regarding the depth, diameter, and the current technical condition of the shaft lining was considered, as well as the operational functions such as material transport, ventilation and the mine drainage.

The analysis covered not only the basic parameters of the shafts, but also the hydrogeological and structural aspects that could impact their future use within energy storage systems significantly. Special attention was paid to the conditions arising from the geological factors and the potential integration of the shafts with the existing power infrastructure. The conducted research allowed for an assessment of the potential limitations resulting from the decommissioning processes, which, in some cases, may prevent the adaptation of shafts for new functions.

The acquired data enabled the assessment of potential locations in terms of their suitability for implementing energy storage systems. Particular attention was paid to structures with an appropriate depth and diameter that could serve as underground water reservoirs or chambers for storing compressed gases. In the next stages of analysis, the selected shafts will undergo a more detailed evaluation regarding their structural stability and their potential integration with the existing power infrastructure.

The use of geoinformatics methods and mathematical modelling tools allowed for preliminary simulations related to the potential operation of energy storage systems within the analysed shafts.

3.3 Characteristics of mine shafts and suitability assessment

The development of an infrastructure suitability assessment system enabled the prioritisation of the analysed objects in terms of their potential application. The introduction of a multi-criteria assessment methodology allowed for an objective classification and identification of locations that meet the technical requirements and can be subjected to further, more detailed research. This approach provided a comprehensive foundation for future design work, facilitating the selection of the most optimal solutions.

The conducted analyses provided valuable insights into the possibilities of repurposing post-mining infrastructure in the context of the energy transition. It was demonstrated that these facilities could serve as valuable assets in the development of energy storage systems, opening up prospects for their further adaptation to the needs of a sustainable power system. The research laid the groundwork for the subsequent project stages, which will include in-depth technical analyses and feasibility assessments of the selected concepts under real operational conditions.

3.4 A Multi-Criteria system for the assessment of mine shafts and underground workings

As part of the conducted research, a multi-criteria assessment system was developed for evaluating the mining shafts and underground workings to determine their potential suitability for implementing energy storage systems. The developed methodology considered a wide range of technical, geological and economic parameters, which were analysed to create a comprehensive evaluation tool.

The assessment system was based on several key parameters analysed in the context of their potential adaptation. Shaft depth was considered a crucial technical parameter determining storage capacity and the ability to utilise elevation differences for energy generation in pumped storage systems. Deeper shafts were preferred, due to their higher energy accumulation efficiency. The shaft diameter influenced the feasibility of installing the technological infrastructure, including pipes for transporting water or other storage media. Wider shafts allowed for more flexible engineering solutions.

The availability of surface infrastructure was also analysed, including the existing energy installations, access roads and the possibility of integration with the power grid. Shafts located near power transmission infrastructure were more favourable for energy storage implementation. The hydrogeological conditions considered the presence and characteristics of the mine water, potential risks to shaft stability, and the possibility of using underground water as a storage medium. High water infiltration could require additional sealing systems.

The shaft lining stability was assessed in terms of its technical condition, applied materials, and the degree of degradation. Shafts with well-preserved linings had greater implementation potential, whereas those with weakened structures might require costly modernisation. The risk associated with coal seam exploitation included the threat of land deformation, seismic activity and potential rock mass movements. The stability of the shaft's surroundings was crucial for its long-term use as an energy storage facility.

The presence and characteristics of mine water were also significant, as water could be both beneficial, enabling its use as a storage medium, and problematic, requiring sealing and potentially impacting the shaft structure. A detailed chemical and physical analysis of the water was essential to assess the corrosion risks and contamination levels.

The developed assessment model employed multi-criteria analysis methods, including hierarchical analysis and scoring methods, enabling an objective classification of the shafts and underground workings. The evaluation results identified the most promising sites for implementation and outlined the necessary modernisation measures for efficient adaptation.

The findings demonstrated that the application of a multi-criteria assessment system identifies locations with the best adaptation parameters effectively, making it a crucial element in planning energy storage strategies in post-mining infrastructure.

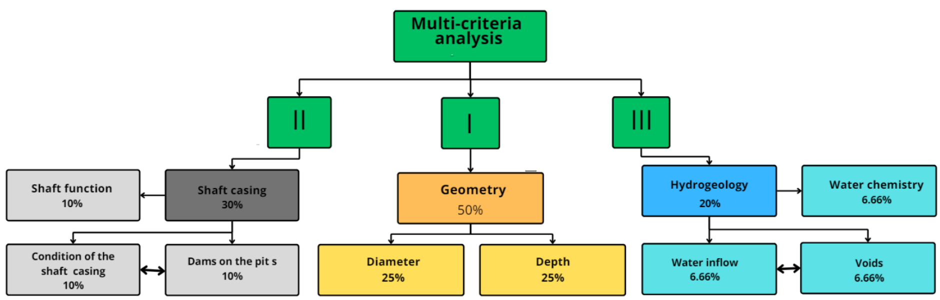

Figure 1: Distribution of weights in multi-criteria analysis

Source: HESS Technical Report

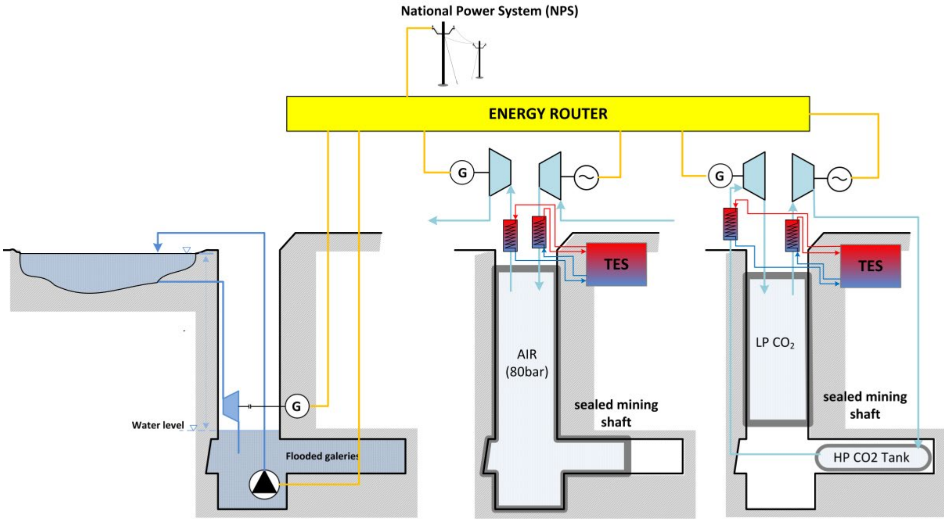

Figure 2: Three different types of energy storage in the HESS system
Source: HESS Technical Report

3.5 Description of the optimal shaft configuration for compressed air/CO_2 energy storage - Energy storage in compressed gas systems

The study also included an attempt to determine the suitability of compressed air technology for the geological conditions of post-mining shafts. It was indicated that CAES systems could be an effective solution to address energy supply instability from renewable sources such as wind and solar power. The fundamental principles of the technology were discussed, including the geological structure requirements and the necessary modifications to the existing shafts, such as lining sealing, water outflow management, and adapting the infrastructure to withstand high air pressure.

A classification and evaluation of mining shafts in the three countries were conducted, to determine their suitability for CAES adaptation. The assessment considered the geometric parameters, depth, diameter, structural integrity of the shaft lining, and availability of the energy infrastructure. It was found that the shafts in Poland, particularly in the Upper Silesian region, have the greatest implementation potential, due to their number, depth and well-developed supporting infrastructure. In contrast, the available infrastructure in the Czech Republic and Slovenia is more limited, and the shafts tend to be smaller in size, posing challenges for implementing this technology.

The collected data identified key challenges related to adapting shafts for energy storage functions. The fundamental issues included ensuring high structural tightness, controlling the impact of mine water, and geomechanical risks arising from potential rock mass instability. Additionally, the regulatory constraints were discussed, emphasising the need for detailed feasibility studies for specific locations.

The conducted analysis provided comprehensive insights into the potential for transforming the post-mining infrastructure for energy storage applications and serves as a foundation for further in-depth research and future investment planning in CAES technology in Poland, the Czech Republic and Slovenia.

Generally, the objects must require conditions comparable to Pumped Storage Power Plant shaft installations, however, the most important factor is the structural integrity of the casing in order to prevent leakage of the compressed media.

In the research, comprehensive thermodynamic models of two energy storage systems were performed: in compressed air and in compressed carbon dioxide. The energy storage systems considered are based on the storage of energy in the potential of compressed gas, which, at the discharge stage of the system (electricity generation) is directed to an expander that drives a generator. A key element of these systems are compressed gas reservoirs, which can be tanks, salt caverns, or underground spaces such as a post-mining infrastructure. The models were based on the characteristic parameters of the reference post-mining infrastructure, which have been determined by requirements in other systems. In the planning stage of the analytical boundary conditions, the previous operating experience of CAES systems was identified, which are used in the United States and Germany successfully. The thermodynamic models were enhanced with detailed maps of the operational parameters of the machines – compressors and expanders. This feature enhances the precision of the calculations by considering the impact of parameters such as the pressure in the compressed gas reservoir, or the degree of charge of the heat tank on the efficiency of the machines. The models created are distinguished by their capacity to assess multiple variants of each analysed system while preserving the stability of the calculations.

A commonality among all the systems analysed was the utilisation of a post-mining shaft as a compressed gas reservoir. During the charging phase, air is pumped into the shaft space, while carbon dioxide is pumped into tanks located in the mine shaft. Additionally, it was planned that a heat reservoir would be constructed in the mine shaft, which would engender a number of advantages, such as the possibility of building a thin-walled TES tank, consequently leading to a reduction in financial expenditure.

The work analysed the following configurations of the systems under study:

- Adiabatic CAES with a single-stage air compressor and a single-stage expander - at the stage of evaluation of the energy indicators, this system achieved the highest energy efficiency of the energy storage cycle at around 70%. This system also allows the storage of heat with the highest temperature potential (around 1000 K), as the air compressor was not sectioned, resulting in the absence of a cooler. However, due to the design assumptions of the energy router, this configuration was excluded from further research work, as thermal integration into the router is impossible due to the lack of a cooler (heat exchanger). In addition, the achieved compressed air temperatures far exceeded the boundary conditions for the defined heat accumulator.
- Adiabatic CAES with a two-stage air compressor and single-stage expander, and adiabatic CAES with a three-stage air compressor and single-stage expander have been demonstrated to exhibit energy cycle efficiencies of approximately 65%, due to the lower temperature potential of the stored heat. The employment of multi-stage air compressors facilitates the selection of compression ratios for each stage, enabling the achievement of the desired heat storage temperature within the TES tank. Moreover, the utilisation of multi-stage compressors allows for the incorporation of intercoolers (heat exchangers), thereby integrating the heat of the CAES system into the planned energy router. The utilisation of heat with a lower temperature potential (up to 570 K) not only facilitates the implementation of additional processes within the energy router, but also supports the district heating system, thereby offering a distinct advantage of the proposed energy storage systems.
- The adiabatic CCES with a single-stage compressor and carbon dioxide expander is a closed-loop system in which carbon dioxide circulates, depending

on the system cycle stage, between a low-pressure and a high-pressure CO2 reservoir. The multivariate analysis was based on varying the pressure of CO2 storage in the low-pressure reservoir, which allowed the configuration to be selected as designed, i.e., with a capacity of approximately 80 MWh. The energy efficiency of the energy storage system cycle was, depending on the variant studied, between about 50% and about 67%. Systems characterised by an LPT tank pressure variation parameter of 0 and 1 were recommended for further work within the energy router.

3.6 Underground object's casing material tests

The aim of the underground object's casing material tests was the assessment of the functional and physicochemical properties of the construction materials of the underground water reservoirs in terms of chemical and mechanical resistance. The selection of construction materials for the pumped storage tanks will be performed based on the test results obtained, in order to ensure the tightness of the tanks in the PSH.

The scope of the work included carrying out tests of the selected construction materials for underground water reservoirs in PSH in order to determine:

- corrosivity: chloride corrosion, sulphate corrosion, magnesium corrosion, acid corrosion
- erosivity
- permeability
- leaching.

For the preliminary tests with design partners, two basic building materials were selected, which were concrete class C20/25 and concrete class C35/45, prepared in accordance with the PN-EN12390-2:2019-7 Standard. These are some of the most commonly used concrete classes, which are used to build various types of foundations, building structures or construction materials. Concrete class C35/45 has a higher mechanical strength.

3.7 Heat storage in post-mining infrastructure

As part of the Heat storage in post-mining infrastructure research, a key assessment of the potential heat storage techniques was carried out from the perspective of implementing the planned energy router. This assessment involved the extensive identification of storage techniques and materials, which will enable the planning of how the planned energy storage systems can be interconnected and optimised to achieve satisfactory energy capacity, self-consumption and power system balancing at a subsequent stage of the work. The work proceeded by defining the advantages and disadvantages of the various heat transfer and storage techniques, as well as the main obstacles to the implementation of each technique. This was achieved by drawing upon the experience of the authors and other research groups that have published data on heat storage operation widely. The expected values were also defined of the parameters to be met by potential storage materials. The work was divided into two parts: experimental research and extensive literature analysis.

Experimental studies: the present section investigated the fundamental thermophysical parameters (i.e., thermal conductivity coefficient, specific heat capacity) of a ceramic storage material in the form of spherical elements with a diameter of approximately 16 mm, which are utilised for heat storage in a packed bed. The rationale for conducting this research was the innovativeness of the proposed material, given that ceramic materials are only just gaining popularity for heat storage.

A comparative analysis of two types of heat storage material was conducted, distinguished by their colour, which indicated their structural composition. The research demonstrated that the material exhibited consistency in its performance as a heat storage material. This is evidenced primarily by the low value of the thermal conductivity coefficient, which preserves the temperature potential of the stored energy and limits its natural dissipation. Furthermore, the material exhibited no evidence of internal structural degradation during cyclic heating and cooling from 40°C to 1030°C. A notable drawback of the material under investigation is its cost; however, the increasing popularity of ceramic materials as heat accumulators may lead to a reduction in their cost, and, consequently, mitigate the negative economic implications associated with these solutions.

4 Results

4.1 Site selection and infrastructure decision criteria

A selection of mining shafts with the highest potential for adaptation to energy storage systems was carried out as part of the conducted research. The selection process was based on the results of a multi-criteria analysis, in which the key technical, geological, and infrastructural parameters were assessed. The analysis included the shafts with the highest structural stability, appropriate depth, and favourable hydrogeological conditions.

Most of the shafts that match the given criteria were in Poland, followed by the Czech Republic, whereas Slovenia's shafts were excluded due to their shallower depths.

According to the given criteria, the II KWK Budryk shaft (Poland) represents the best choice from reviewed shafts. Its current function is a ventilation shaft, which means no additional equipment was installed in the shaft. The shaft reached a depth of 1157,45 metres with a diameter of 9,0 metres. The upper part of the shaft is situated at an elevation of 292,60 metres above sea level and does not have a headframe. Currently, the fan station is equipped with two main fans. The given situation represents a limited amount of additional modification operations and allows use transformation without significant additional investments.

4.2 Construction and Equipment of the Shaft Casing

The shaft was sunk in a single concrete casing with a thickness ranging from 0,55 m to 0,6 m, thickened to 0,75 m or 0,8 m in areas with coal seams and their immediate vicinity. Partially, the shaft was sunk in a masonry casing with a thickness from 0,51 m to 1,03 m, along with a foundation thickness ranging from 2,0 m to 0,52 m, a concrete casing of 0,8 m thickness, and a double casing – masonry and concrete with a concrete liner, with a total thickness of 0,99 m, as well as a double concrete casing with waterproofing, with a total thickness ranging from 1,0 m to 1,2 m. A concrete plug of 0,5 m thickness was installed at the bottom of the shaft, beneath the concrete casing.

Generally, the shaft configurations with depths above 1000 m, diameters of 7,5 m or larger, solid, water-proof casing and overall good conditions, should match the given conditions. The number of optimal shafts is reduced according to the given criteria.

4.3 Pumped storage power plant

The given parameters allow the use of the shaft for a pumped storage power plant. According to the other assumptions and performance based chosen equipment (Pelton turbine), the energy produced would be 23 MWh, which is twice the initially assumed 10 MWh. In such a case, filling half of the lower reservoir would ensure the expected 10 MWh.

Additional data analysis and calculations proved that the system could be applied to shallower shafts, with a smaller diameter, as in the case of Velenje Coal Mine, where the depths reach 416,42 m (NOP Shaft) and 390,70 m (NOP II Shaft). In limited depths, the existing underground reservoir capacity (>12.000 m^3) is of great importance in the existing roadway network. These facilities must all have water-proof casing and good stability conditions.

Normally, during a pumping operation, the pumped storage power plant will pump water from the lower reservoir in the shaft to the upper reservoir located on the mine site. Based on the analysis of the situational plan of the infrastructure elements on the mine site, possible locations (variants) were determined for such a reservoir.

In the optimal variant, the reservoir is located directly next to the shaft. Its surroundings include the dense surface infrastructure of the mine, which would need to be demolished to achieve the desired reservoir volume. The advantage of this location is the minimisation of losses resulting from water transport on horizontal sections on the surface and the costs of such an installation. The danger associated with this reservoir location (close to the shaft) is related to the load on the terrain that such a reservoir entails and its impact on the stability of the shaft structure. Due to the cyclic filling and emptying of the reservoir, such a load will vary over time.

The described criteria serve as a foundation for further detailed studies and feasibility assessments, which will determine the final list of locations designated for adaptation. The next phase of analysis will consider environmental aspects, investment costs and integration with the national power grid.

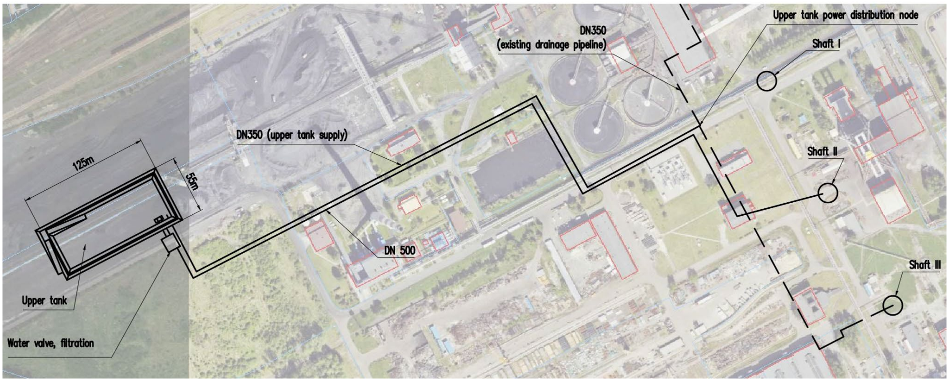

Figure 3: Presentation of Budryk coal mine area with marked facilities for a pumped storage power plant

Source: HESS Technical Report

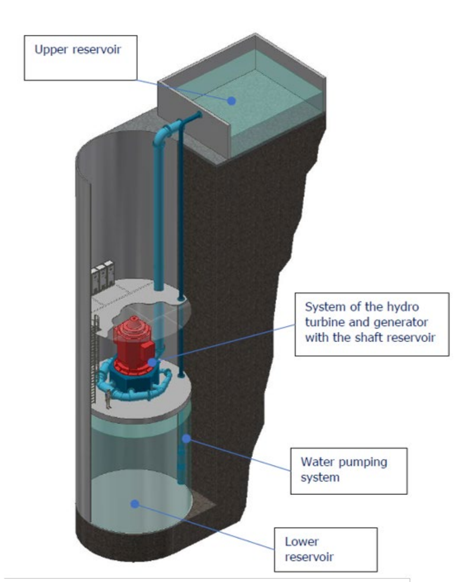

Figure 4: System of the hydro turbine and generator with the shaft reservoir

Source: HESS Technical Report

4.4 Compressed Air/CO2 storage in an underground structure

An extensive, multivariate thermodynamic analysis was conducted, which yielded recommendations for compressed gas energy storage systems utilising post-mining infrastructure. The primary focus of the analysis was the impact of the TES tank diameter on the pressure drop of the compressed air. It was demonstrated that the minimum diameter of a mine shaft should permit the construction of a tank with an internal diameter of at least 5 metres, as, below this value, the pressure loss causes a drastic reduction in the capacity of the energy storage system. The calculations indicated that, for a mine shaft with a diameter of 9 metres, a mine shaft with a minimum length of 750 metres is necessary to achieve an energy storage system with a capacity of 80 MWh.

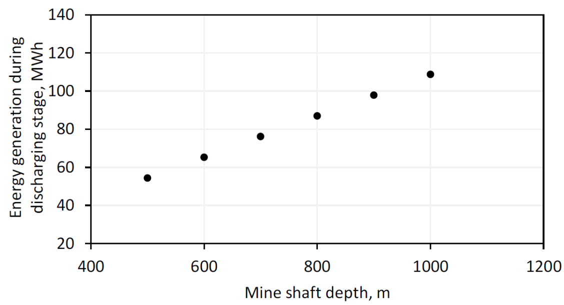

Figure 5: Dependence of the energy capacity of the CAES system on the depth of the mine shaft, assuming an internal diameter of 9 metres
Source: HESS Technical Report

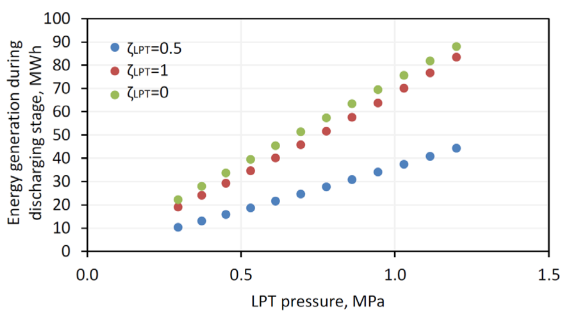

Figure 6: Dependence of the energy capacity of the CCES system on the carbon dioxide pressure in the low-pressure tank
Source: HESS Technical Report

4.5 Heat storage in post-mining infrastructure

Experimental studies were also conducted using an existing laboratory-scale heat tank. The stand includes a heat tank filled with basalt and the heat transfer fluid is air heated by an electric air heater. The design of the heat storage tank is comparable to that of a large-scale TES in a mine shaft; however, the laboratory tank is considerably slenderer than the systems documented in the existing literature. The multivariate experimental investigations are based primarily on changes in the mass flow values of the air and maximum inlet air temperatures. In addition, the design of the laboratory bench allows for bi-directional airflow through the TES, which also corresponds to the operational characteristics of the potential large-scale system.

Figure 7: Thermal energy storage tank in a variant without thermal insulation
Source: HESS Technical Report

In accordance with the objectives of the project, a range of storage materials was selected for three types of heat storage: solid materials, liquid materials and phase change materials. It was hypothesised that, within the energy router, heat storage and transfer could occur at three temperature levels: 100°C, 300°C and 500°C. These temperature ranges were utilised as the input, with 500°C representing the limiting temperature for an adiabatic CAES. As illustrated in the Figures below, the collected data are presented on the range of applicability of the different solid, liquid and different phase-change materials used for heat storage.

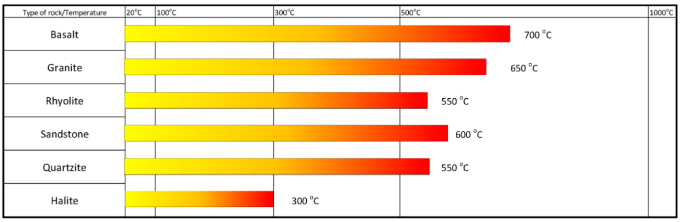

Figure 8: Range of temperature applicability of solid materials for heat storage
Source: HESS Technical Report

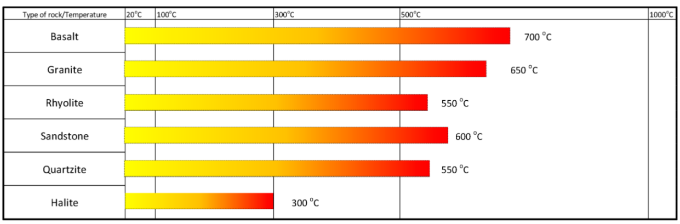

Figure 9: Range of temperature applicability of liquid materials for heat storage
Source: HESS Technical Report

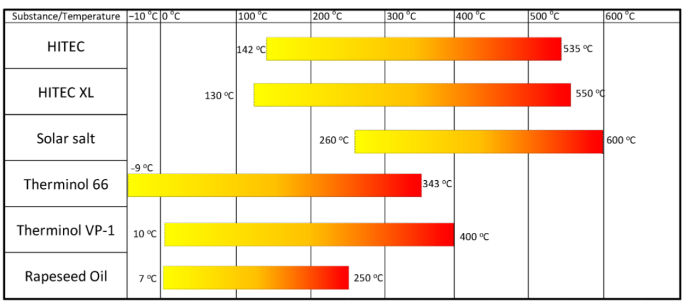

Figure 10: Range of temperature applicability of phase-change materials for heat storage
Source: HESS Technical Report

5 Conclusions - HESS system adaptations for the Velenje Coal Mine

According to the given research work and with consideration of the limitations, an assessment was prepared of the HESS system for the case of the Velenje Coal Mine. It is assumed that, after the mining, only stable objects (mine shafts, access roadway network, pumping station) will remain. All these objects match the HESS project criteria, except for the shaft dimensions, where, as a compensation factor, a wide range of underground roadways is used as a supplement.

5.1 Surface features and surface water reservoirs

According to the HESS project, the potential use of post-mining infrastructure included the research and assessment of the existing Velenje mine shafts and access infrastructure for energy generation and storage purposes.

In the case of the Velenje Coal Mine shafts, the mine infrastrucure does not match the HESS project criteria in secions of the shaft's dimensions (depth, diameter). After a secondary review, the overall setting (Figure 11) could represent the potential of energy generation.

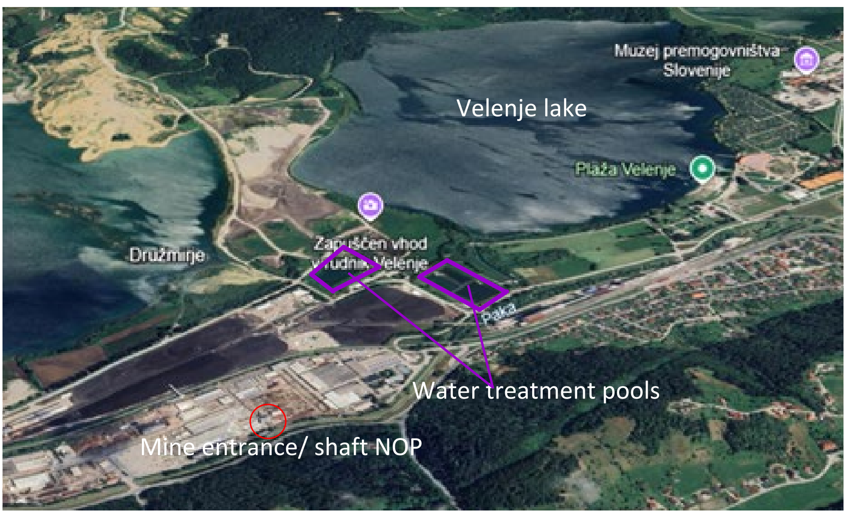

Figure 11: Surface area above Velenje Coal Mine showing subsidence lakes and water treatment pools

Source: Google Maps

Due to vicinity of lakes and/or existing surface water reservoirs, which were used in the past for waste water treathent and are no longer in use, the potential is accessed with additional input data.

As shown in Figure 11, the Velenje lake or water treatment pools could be used as surface reservoirs. Velenje lake represents an infinite water source, whereas the water treatment pools designs provide approximately 70.000 m^3 of potential water storage reservoir. In both cases, the access to the water is free, and the height difference in both cases allows gravitational flow towards the mine shaft (the average height difference is about 10 m).

5.2 Mine infrastructure for HESS system adaptation

The main Velenje Coal Mine shaft shows less favourable dimensions, with a total depth of 416,42 m and diameter of 7,20 m. The two-sided two-level cage system is in use for staff, material and equipment transport. The NOP shaft will also remain for the mine closure activities, as it represents the most effective mine supply facility.

The underground reservoirs and mine pumping station are located in the section of the mine which will remain until the end of the closure works and, optionally, after the closure works will be completed.

The location of the pumping station, -41,5, is in relative vicinity of the shaft NOP (distance 770 m), and since the pumping station is active, all the equipment is already installed, therefore any additional costs are reduced by the given value.

The combination shaft NOP – roadway "Severna talninska zveza" and mine pumping station represent a potential for water driven energy generation with the possibility of pumping water to the surface.

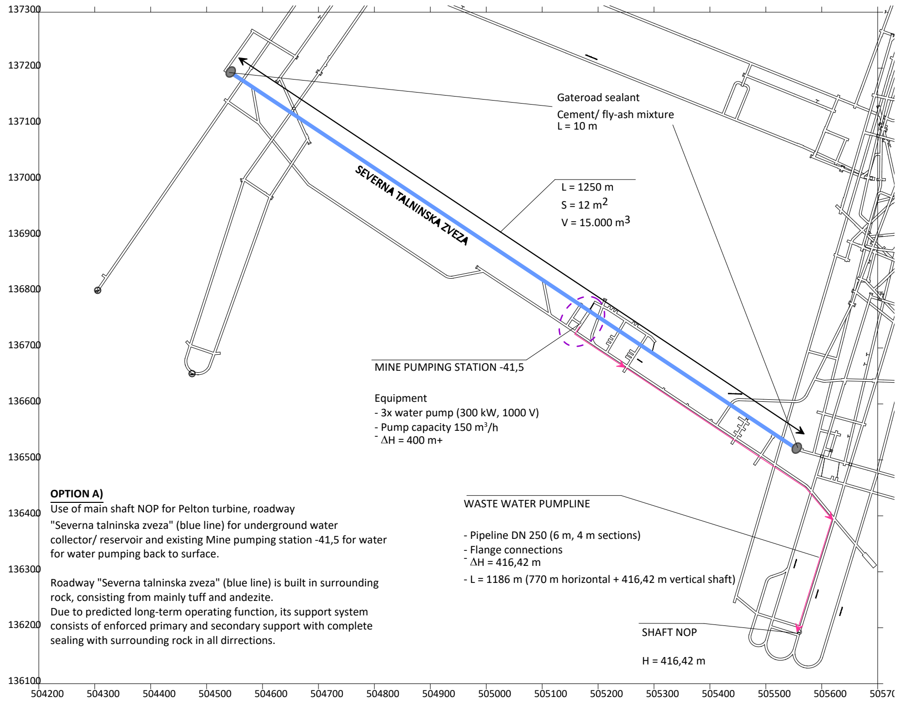

Figure 12: Locations of mine objects "Severna talninska zveza" roadway, mine pumping station -41,5, shaft NOP with the main parameters. The roadway "Severna talninska zveza" is characterised as an underground water reservoir with a storage capacity of 15.000 m3
Source: own

Among the existing shafts, the mine closure plans predict that the ventilation shafts will remain operational until mine closure. As the shafts and access roadway network designs included a reinforced support system despite the favourable geologic and geomechanical conditions, the lifespan of the given objects is estimated to be long after mine closure.

According to the HESS project tasks, the assessment of post-mining object for energy storage by CO_2 or air compression matches the object properties.

Given the data of the shaft`s properties, the shaft`s lining and roadway support, the further analysis is justified of the objects` suitability for energy storage.

If a reservoir volume of approximately 13.500–14.000 m³ or more could be achieved, a possible energy storage of 10 MWh is predicted.

The most effective approach towards the given option is determination of a reservoir volume of 12.000 m³, to develop a roadway-based storage system as an alternative to the shaft-based solution, with a capacity of approximately 9.1 MWh.

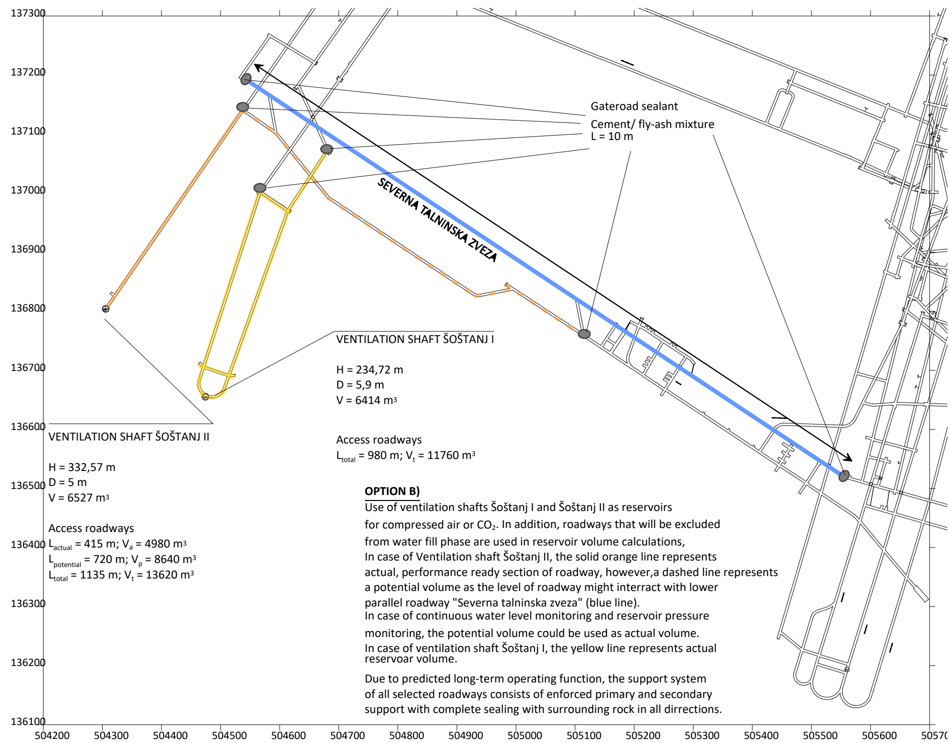

Figure 13: Section of the mine outline with marked objects for possible compressed air or CO2 underground storage reservoirs (energy storage). The measured objects dimensions and calculated values show theoretical volumes of the optionally chosen object combinations: Shaft Šoštanj I with auxiliary objects 18.174 m3, shaft Šoštanj II with auxiliary objects from 11.507 m3 to 20.147m3

Source: own

“The work presented in this paper was carried out within the framework of the HESS project (Hybrid Energy Storage System Using Post-Mining Infrastructure), Grant No. 101112380, supported by the EU Research Fund for Coal and Steel

(RFCS). The project is co-financed by the Polish Ministry of Education and Science under the 'International Projects Co-financed' programme."

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Povzetek v slovenskem jeziku

Rezultati projekta HESS – Hibridni sistem shranjevanja energije v post-rudarski infrastukturi. Cilj projekta je bil razviti hibridni sistem za shranjevanje energije (HESS), ki ga sestavljajo trije različni sistemi za shranjevanje energije: črpalna hidroelektrarna (PSH), shranjevanje energije s stisnjenim plinom – zrakom/CO2 (CAES) in shranjevanje toplotne energije (TES) z uporabo infrastrukture po rudarjenju. V raziskavo je bila vključena tudi možnost uporabe geotermalne energije ter uporaba in potencialno shranjevanje CO2. Predpostavljena skupna zmogljivost shranjevanja energije v projektu HESS je bila v območju 30 MWh.

Na podlagi potreb po energiji vsake komponente HESS je bila raziskana in razvita metoda toplotne in mehanske integracije celotnega sistema, skupaj z algoritmom za medsebojno interakcijo med elementi sistema za shranjevanje energije. Za optimalno povezovanje različnih elementov HESS je bil izbran kontrolnik - usmerjevalnik energije. Usmerjevalnik upravlja tudi izmenjave energije z nacionalnim elektroenergetskim omrežjem za prevzem nizkocenovne zelene energije in konic energije. Enotni sistem usmerjevalnika energije HESS mora upoštevati možnost sodelovanja več sistemov HESS, ki delujejo v povezanem sistemu.