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



Deliverable 1.5.

Final international seminar – project results presentation

30.06.2026

PROJECT	
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Project name	Hybrid energy storage system using post-mining infrastructure
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Call	RFCS-2022
Topic	RFCS-01-2022-RPJ
Type of action	RFCS-PJG
Service	REA/B/01

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1. Final Project HESS Seminar overview

On 22 June 2026, the final seminar of the project entitled “*Hybrid Energy Storage System Using Post-Mining Infrastructure*” (acronym HESS) was held at the headquarters of the Institute of Fuel and Energy Technology (ITPE), the coordinator of the HESS consortium. The event aimed to present the key project outcomes achieved by the Consortium Partners, discuss the scope of the completed research, design and analytical work, and demonstrate the potential for further development and implementation of the proposed solutions.

Representatives of all HESS Consortium Partners participated in the seminar, including the KOMAG Institute of Mining Technology (Poland), the Silesian University of Technology (Poland), VSB – Technical University of Ostrava (Czech Republic), Premogovnik Velenje d.o.o. (Slovenia), and the Institute of Fuel and Energy Technology (Poland). The participation of all consortium members enabled a comprehensive presentation of the results achieved within the individual work packages and highlighted their integration into the overall HESS system concept.

The seminar was open to the public and served as a platform for the exchange of knowledge, experience and opinions on the development of innovative energy storage technologies. Particular attention was devoted to the potential use of existing post-mining infrastructure for energy storage applications, especially in the context of mining region transition and increasing the flexibility and resilience of future energy systems.

During the event, consortium representatives presented the main achievements of the HESS project, covering the technical, environmental, and materials-related aspects of the developed hybrid energy storage concept, as well as its feasibility and implementation potential. The presentations summarized the results of the project, including the integration of pumped-storage hydropower, compressed gas energy storage, and thermal energy storage systems, together with the adaptation of post-mining infrastructure, technical requirements for key system components, materials assessment, and the evaluation of potential locations and operating conditions. The seminar also provided an opportunity for consortium partners to review and discuss the project outcomes and their relevance for the further development of sustainable energy storage technologies, particularly in the context of the growing share of renewable energy sources and the reuse of post-mining infrastructure.

A particularly interesting part of the programme was the visit to the ITPE Centre of Clean Technologies in Zabrze, during which participants had the opportunity to familiarize with ITPE's representative infrastructure, selected research facilities and technological solutions related to the project topic. This part of the seminar enabled a practical presentation of the Institute's research facilities and demonstrated its capabilities in conducting research in the fields of energy, environmental and process technologies. The study visit was very positively received by the participants and provided a valuable complement to the presentation part of the event.

The final HESS project seminar enabled the key project achievements to be summarised, the outcomes of cooperation within the international consortium to be presented, and potential directions for further activities related to the use of post-mining infrastructure for modern energy storage systems to be identified. The event confirmed the importance of an interdisciplinary approach to energy transition challenges, as well as the role of cooperation between research institutes, technical universities and industrial partners in developing innovative solutions for the energy sector.



Fig. 1 HESS seminar participants

2. Programme and summary of presentations

The seminar began with an official welcome address by the Scientific Secretary of the Institute of Fuel and Energy Technology, Professor Sławomir Stelmach, DSc, PhD, Eng., who opened the event and emphasised the importance of international cooperation in the implementation of the HESS project. Subsequently, the project leader, PhD Eng. Agata Czardybon, presented the seminar agenda and the main assumptions of the project, recalling its objectives, the scope of the work carried out and the key stages of its implementation. The presentation highlighted the concept of developing a hybrid energy storage system using existing post-mining infrastructure, as well as the interdisciplinary nature of the project, which combines issues related to mining, energy engineering, materials engineering and numerical modelling.

The seminar was structured into six thematic blocks, which logically reflected the successive stages of the HESS project implementation – from the identification and assessment of potential locations within post-mining infrastructure, through technological, materials-related and modelling studies of individual system components, to the integration of the developed solutions and the assessment of their potential implementation under industrial conditions.

The first thematic block of the seminar focused on assessing the potential use of post-mining infrastructure for the implementation of a hybrid energy storage system and on analysing selected energy storage technologies under post-mining conditions. This part presented the results of a multi-criteria assessment of mining excavations using the MCDA method, with particular emphasis on the adopted methodology, the significance of individual decision-making indicators, and the possibility of identifying facilities most suitable for further design analyses. An assessment of the suitability of post-mining infrastructure for the implementation of a pumped-storage power plant as an element of a hybrid energy storage system was also presented.

The second thematic session focused on research and technical analyses related to the design of an underground water reservoir and the key components of a mine shaft-based pumped-storage hydropower system. The presented work covered the technical parameters of the reservoir model, the potential use of mine shafts and underground excavations within the PSH system, and the characteristics of the system's main equipment. The session also included studies on structural materials and protective coatings for the reservoir, addressing their resistance to corrosion and erosion, water and mine brine penetration, and leaching undermine brine and chemically aggressive environmental conditions.

The third thematic session was devoted to research and analyses of compressed gas energy storage technologies and the adaptation of mine shaft infrastructure for HESS applications. Presentations covered thermodynamic analyses of CAES and CCES systems, including the modelling of various compression system configurations. The session also included the results of gas permeability tests for sealing materials, experimental studies on CO₂ compression and purification processes, and the key technical requirements for adapting mine shafts to the proposed applications.

The fourth thematic session focused on research into thermal energy storage using sensible heat storage materials and phase change materials (PCMs). The presented work included the characteristics and technological parameters of TES tanks, CFD modelling of thermal energy storage processes, laboratory investigations of basalt and PCM materials, and numerical modelling of latent heat storage systems.

The next thematic block focused on the integration of energy storage subsystems in the HESS, implemented as part of WP6. The operating assumptions of the energy router were presented as a key element responsible for coordinating the cooperation between PSH, CGES and TES. The principles of managing energy flows between the individual technologies were discussed, ensuring optimisation of the operation of the entire system and efficient use of available energy resources.

The following part of this block presented issues related to the integration of all HESS system components and the methodology for conducting technical and economic analyses for various configurations of energy generation and storage equipment. The approach enabling the assessment of cooperation between individual system components was discussed, as well as the analysis of the impact of variable technological configurations on operating parameters and the overall efficiency of the hybrid energy storage system.

The final thematic block of the seminar was devoted to the assessment of the HESS technology and its potential future implementation under industrial conditions. This session presented the results of the techno-economic analysis of the hybrid energy storage system using post-mining infrastructure, with particular emphasis on profitability, system efficiency, and the potential limitations of the proposed solutions. This part was complemented by implementation analyses prepared by the foreign partners, including the potential use of the project results in the Czech Republic and the feasibility of implementing the HESS concept at the Velenje mine in Slovenia.

The life cycle assessment (LCA) of the HESS system was also discussed, providing insight into the environmental impact of the technology over its operational lifetime.

The session also included a SWOT analysis presentation of the HESS technology, identifying the main strengths and weaknesses of the developed concept, as well as opportunities and threats related to its future implementation. Together, these presentations provided a comprehensive overview of the technological, environmental, economic, and regulatory aspects of the HESS system.

Following the presentation sessions, a concluding discussion was held, providing participants with an opportunity to exchange experiences gained during the implementation of the project, discuss the key outcomes achieved by the consortium, and share perspectives on the future development and practical application of the HESS concept.

HESS Project Meeting Agenda (22.06.2026, Zabrze)

8.30	Open meeting and welcome by ITPE
8.30-8.40	Hybrid Energy Storage System (HESS) Project: objectives, scope and key assumptions – <i>Agata Czardybon PhD, Eng. (ITPE)</i>
8.40-8.50	Evaluation of post-mining infrastructure for the implementation of a Hybrid Energy Storage System considering Compressed Gas Energy Storage requirement – <i>Professor Marcin Lutyński, DSc, PhD, Eng. (SUT)</i>
8.50-9.00	Assessment of the suitability of polish post-mining infrastructure for the implementation of HESS in terms of the requirements of a Pumped-Storage Hydropower System – <i>Dominik Bałaga, PhD, Eng. (KOMAG)</i>
9.00-9.15	Thermodynamic analysis of CAES and CCES systems: operating parameters and equipment characteristics – <i>Michał Jurczyk, PhD, Eng. (SUT)</i>
9.15-9.30	Research on thermal energy storage in single-phase materials. TES tank characterization taking into account technological parameters and device characteristics – <i>Krzysztof Rusin, PhD, Eng. (SUT)</i>
9.30-9.45	Studies on thermal energy storage in single-phase materials and phase change materials – <i>Tomasz Spietz, MSc, Eng. (ITPE)</i>
9.45-9.55	Numerical modelling of latent heat storage systems – <i>Kinga Kulik, MSc, Eng. (ITPE)</i>
9.55-10.05	Coffee break
10.05-10.20	Technical parameters of the example underground water reservoir model – <i>Konrad Kołodziej, MSc, Eng. (SUT)</i>
10.20-10.35	Pumped-Storage Hydropower system in mine shafts: technological parameters and equipment characteristics – <i>Piotr Matusiak, PhD, Eng. (KOMAG)</i>
10.35-10.50	Selection of lining materials for sealing mine shafts in HESS applications and assessment of their gas permeability properties – <i>Konrad Kołodziej, MSc, Eng. (SUT)</i>
10.50-11.05	Durability and transport properties of concrete and protective coatings for HESS – <i>Krzysztof Supernok, MSc, Eng. (ITPE)</i>
11.05-11.20	Analysis of the CO ₂ compression and purification for the CCES system – <i>Tomasz Spietz, MSc, Eng. (ITPE)</i>
11.20-11.30	Coffee break
11.30-11.45	Mine shaft adaptation for HESS: baseline requirements and key technical challenges – <i>Konrad Kołodziej, MSc, Eng. (SUT)</i>
11.45-11.55	Energy router software – <i>Wiktoria Markusik, MSc, Eng. (KOMAG)</i>
11.55-12.05	Integration of particular components of the HESS – <i>Associate Professor Janusz Lasek, DSc, PhD, Eng., (ITPE)</i>
12.05-12.20	Techno-economic assessment of hybrid energy storage technology in post-mining infrastructure – <i>Tomasz Billig, MSc, Eng. (ITPE)</i>
12.20-13.15	Lunch break
13.15-13.30	Life cycle assessment of the HESS – <i>Katarzyna Rychlewska, PhD, Eng. (ITPE)</i>
13.30-13.40	Feasibility of HESS technology implementation in the Czech Republic – <i>Zbyszek Szeliga, PhD, Eng. (VSB)</i>
13.40-13.50	Assessment of the feasibility of HESS implementation in Velenje, Slovenia – <i>Sergej Jamnikar, PhD, Eng. (PV)</i>
13.50-14.00	SWOT analysis – <i>Sergej Jamnikar, PhD, Eng. (PV)</i>
14.00-15.00	Technical tour
15.00-16.00	Current Issues and Actions Related to Project Completion

3. Seminar Presentations



since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

HESS project: objectives, scope and key assumptions

Agata Czardybon

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

HESS Project Meeting Agenda	
8.35-8.40	Hybrid Energy Storage System (HESS) Project: objectives, scope and key assumptions – ITPE
8.40-8.50	Evaluation of post-mining infrastructure for the implementation of a Hybrid Energy Storage System considering Compressed Gas Energy Storage requirement – SUT
8.50-9.00	Assessment of the suitability of post-mining infrastructure for the implementation of HESS in terms of the requirements of a Pumped-Storage Hydropower System – KOMAG
9.00-9.15	Thermodynamic analysis of CAES and CCES systems: operating parameters and equipment characteristics – SUT
9.15-9.30	Research on thermal energy storage in single-phase materials. TES tank characterization taking into account technological parameters and device characteristics – SUT
9.30-9.45	Experimental studies on sensible and latent thermal energy storage materials – ITPE
9.45-9.55	Numerical modelling of latent heat storage systems – ITPE
9.55-10.05	<i>Coffee break</i>
10.05-10.20	Technical parameters of the example underground water reservoir model – SUT
10.20-10.35	Pumped-Storage Hydropower system in mine shafts: technological parameters and equipment characteristics – KOMAG
10.35-10.50	Selection of lining materials for sealing mine shafts in HESS applications and assessment of their gas permeability properties – SUT
10.50-11.05	Durability and transport properties of concrete and protective coatings for HESS – ITPE
11.05-11.20	Analysis of the CO ₂ compression and purification for the CCES system – ITPE
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12.05-12.20	Techno-economic assessment of hybrid energy storage technology in post-mining infrastructure – ITPE
12.20-13.15	<i>Lunch break</i>
13.15-13.30	Life cycle assessment of the HESS – ITPE
13.30-13.40	Feasibility of HESS technology implementation in the Czech Republic – VSB
13.40-13.50	Assessment of the feasibility of HESS implementation in Velenje, Slovenia – PV
13.50-14.00	SWOT analysis – PV
14.00-15.00	<i>Technical tour (research facilities relevant to the project topic)</i>
15.00-16.00	Current issues and actions related to project completion

„Hybrid Energy Storage System Using Post-mining Infrastructure” (HESS)

RFCS-2022 Research Fund for Coal and Steel

Project no.: 101112380

Start date: 01/07/2023

End date: 30/06/2026

Budget: 2 226 740,2 Euro



**Institute of Energy
and Fuel Processing
Technology (ITPE) - POLAND**



**Institute of Mining
Technology (KOMAG) -
POLAND**



**Silesian University
of Technology (SUT) -
POLAND**



**VSB - Technical University
of Ostrava (VSB) –
CZECH REPUBLIC**



**Premogovnik Velenje D.O.O
(PV) - SLOVENIA**

Polish Partners: Co-financed by the Minister of Science and Higher Education



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**„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)**

HESS Project Consortium



Institute of Energy and Fuel Processing Technology (ITPE) POLAND, Czardybon, Dobras, Ignasiak, Supernok, Spietz, Kulik, Lasek, Głód, Dobras, Fryza, Więclaw- Solny (*Department of Energy Transition*), Rychlewska (*Department of Environmental Engineering*), and Billig (*Department of Circular Economy*)



Institute of Mining Technology (KOMAG) POLAND, Kowol, Matusiak (*Division of Preparation Systems*), Jendrysik (*Division of Mechatronics Systems*), Kaczmarczyk, Kalita (*Division of Machines and Equipment*), Michalak (*Laboratory of Modelling Methods and Ergonomics*)



Silesian University of Technology (SUT) POLAND, Lutyński, Kołodziej (*Faculty of Mining, Safety Engineering and Industrial Automation*), Bartela, Ochmann, Jurczyk, Rusin (*Faculty of Energy and Environmental Engineering*)



VSB - Technical University of Ostrava (VSB) CZECH REPUBLIC, Honus, Szeliga (*Department of Energy Engineering*)



Premogovnik Velenje, d.o.o. (PV) SLOVENIA, Jamnikar.



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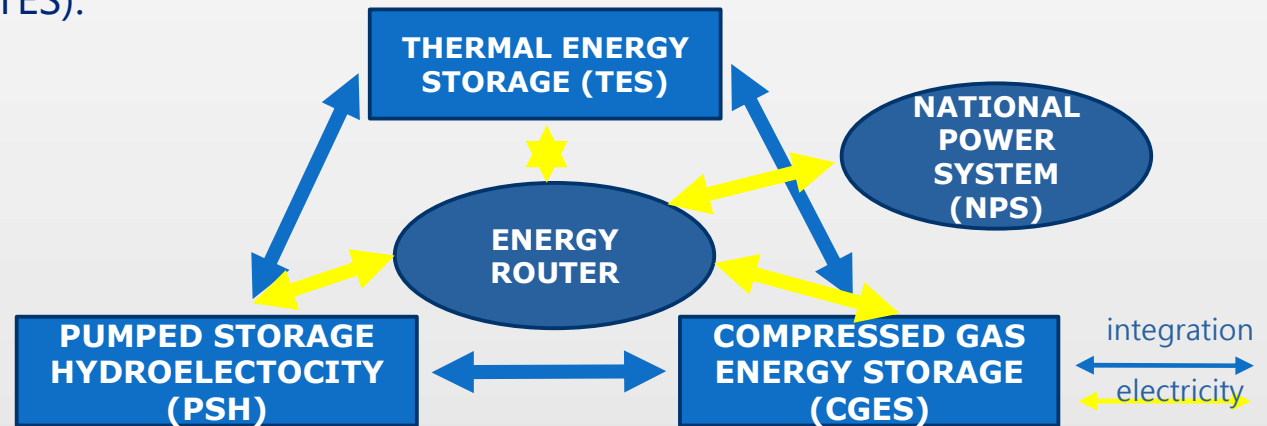
**„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)**

Assumptions and goals of the HESS project



to develop a Hybrid Energy Storage System (HESS) using post-mining infrastructure consisting of three different systems:

- Pumped Storage Hydroelectricity System (PSH)
- Compressed Gas Energy Storage System (CGES) – Air (CAES) & CO₂ (CCAES)
- Thermal Energy Storage System (TES).

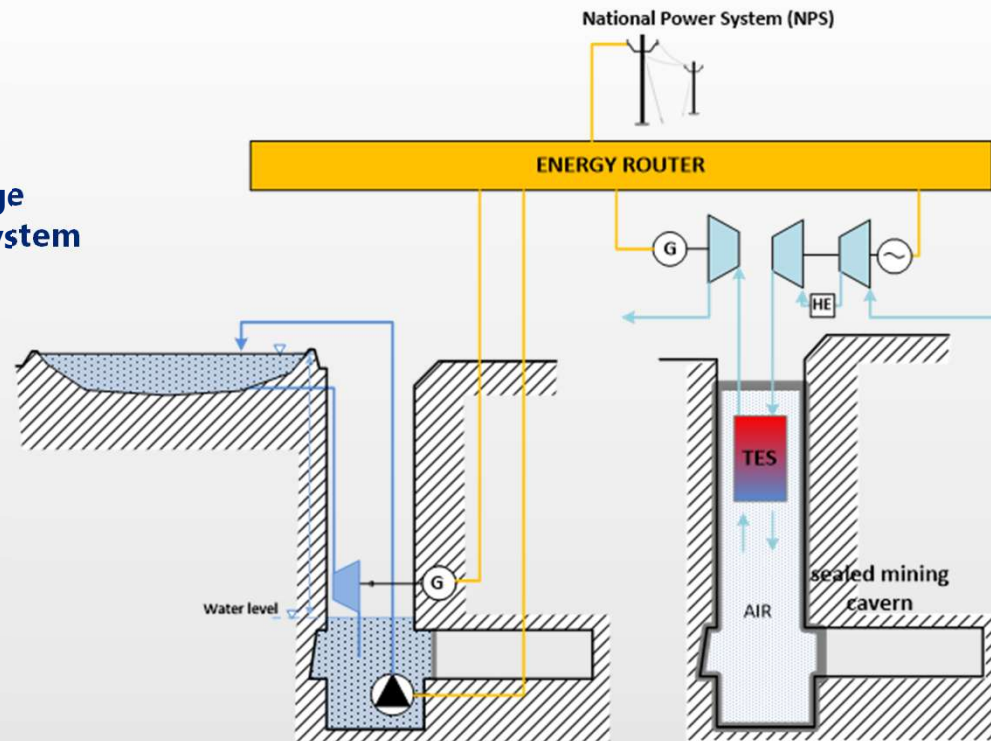


HESS integrates three energy storage systems (PSH, CGES and TES) using an intelligent energy router. The exchange of mechanical and thermal energy **improves energy efficiency, flexibility and storage capacity**. The energy router also manages energy exchange with the power grid and heat consumers.

Diagram of HESS based on PSH and CAES/TES



Pumped Storage
Hydroelectricity System



Compressed Air Energy Storage System /
Thermal Energy Storage System

One mine shaft will serve as the lower water reservoir in the PSH system. The second shaft will function as the compressed air storage tank in CAES system. TES tank will be placed in the mine shaft space, reducing **costs through the use of a thin-walled reservoir. The shaft diameter will determine the TES tank geometry.** Heat generated during gas compression will be stored in TES and reused during system discharge.



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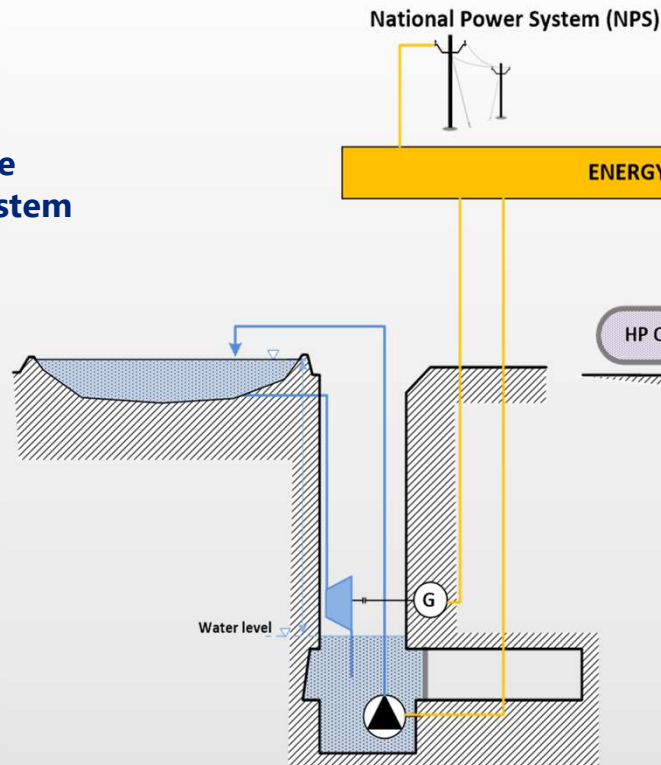


„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 10112380 (RFCS-2022)

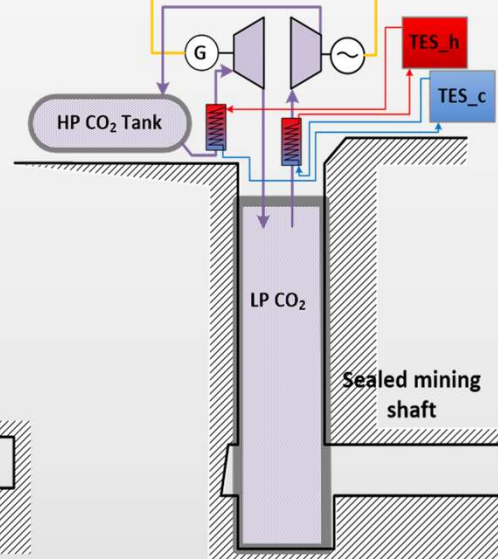
Diagram of HESS based on PSH and CCES/TES



Pumped Storage Hydroelectricity System



Compressed CO₂ Energy Storage System / Thermal Energy Storage System



The TES consists of two tanks: a hot tank and a cold tank, using Therminol VP-1 as the heat transfer fluid and a basalt packed bed as the thermal storage medium. The TES system is located outside the mine. The shaft will serve as the low pressure CO₂ storage tank. The high-pressure tank is also located outside the mine.



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
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Objective of the HESS project



- determine **technical feasibility of using post-mining shafts** in Poland, Czech and Slovenia by identifying the structure of the mine shaft and rock layers for use in PSH and CGES;
- achieve **minimum** energy storage capacity of **10 MWh** for each system;
- ensure the tightness of tanks in Pumped Storage Hydroelectricity System for a minimum of **10 years**;
- in Compressed Gas Energy Storage System - **achieve the working pressure: ~ 80 bar for the air (CAES) and ~ 20 bar for the carbon dioxide (CCES)**;
- for the Thermal Energy Storage (TES) **to ensure the energy storage temperature up to 500°C**;
- create the **energy router concept** for measuring pressures, temperatures, flows, data collection, energy storage management, optimisation of HESS especially in terms of operating costs;
- carried out the **techno-economic** and **environmental assessment** (LCA) of the HESS, which will be the basis for the validity of industrial implementation of this technology.



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
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❖ Innovation of HESS project

- **Integration of three energy storage systems:** PSH, CGES, TES by an intelligent energy router
- **Use of post-mining infrastructure** for Hybrid Energy Storage System.

❖ Expected impacts of HESS project

- **Support the reuse of post-mining infrastructure**, offering a cost-effective and sustainable alternative to mine decommissioning
- **Using abandoned mines for energy storage** reduces investment costs and places systems closer to energy consumers, lowering transmission losses
- **Support decarbonization and the circular economy** by extending the use of existing industrial sites
- HESS will **help stabilize the national power grid** by optimizing energy flows

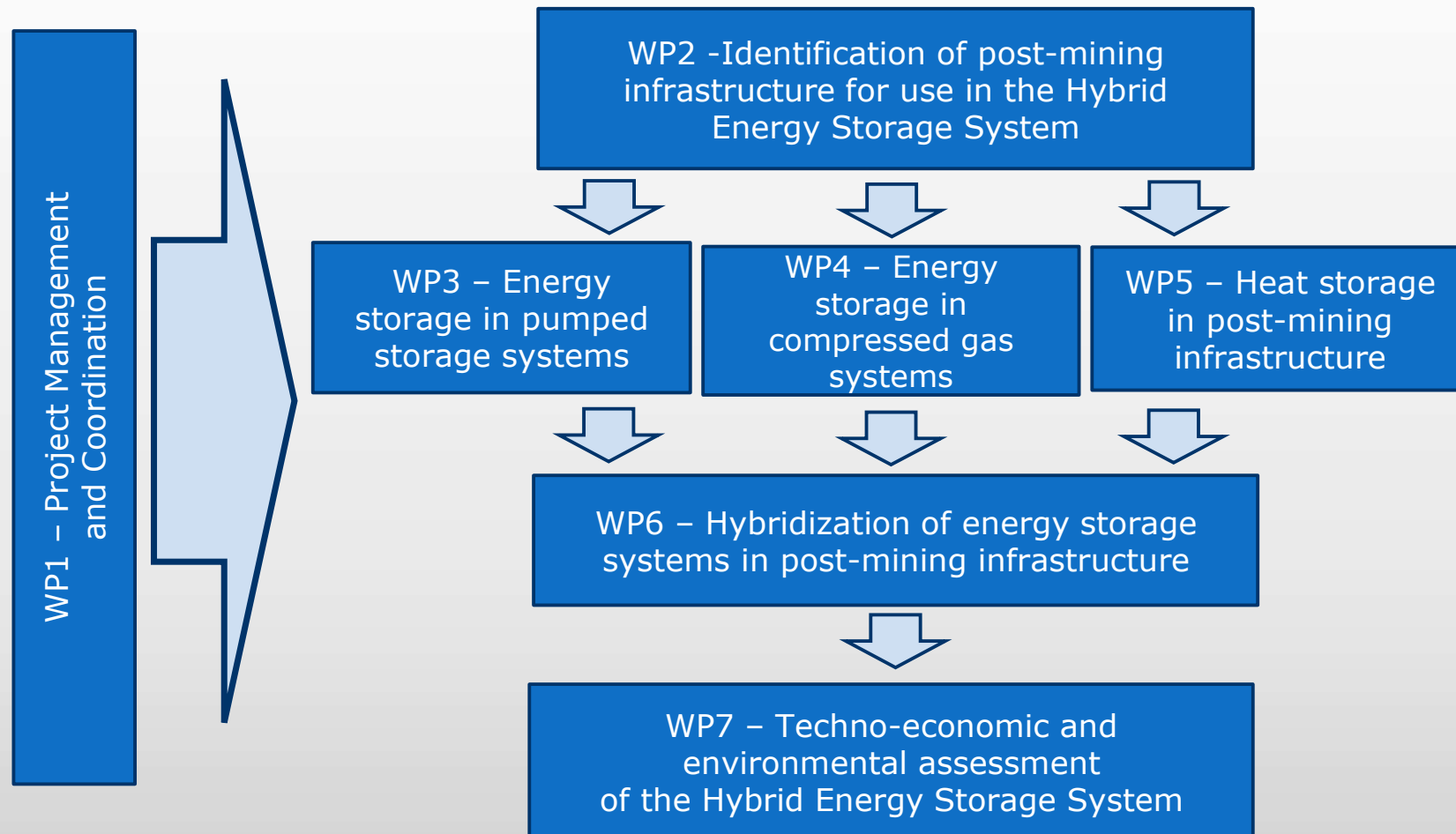


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„Hybrid energy storage system using post-mining infrastructure” (HESS)
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HESS project structure



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

GANTT CHART OF HESS PROJECT



		2023		2024				2025				2026	
WP1	Project Management and Coordination												
WP2	Identification of post-mining infrastructure for use in the Hybrid Energy Storage System												
WP3	Energy storage in pumped storage systems												
WP4	Energy storage in compressed gas systems												
WP5	Heat storage in post-mining infrastructure												
WP6	Hybridization of energy storage systems in postmining infrastructure												
WP7	Techno-economic and environmental assessment of the Hybrid Energy Storage System												

MS1. MS3. MS5. MS2. MS7.
MS4.
MS6.

PROJECT MILESTONES:

- **Recognition of mine shafts and water reservoirs** (KOMAG)
- **System analysis for compressed gas storage system** (SUT)
- **Selection of energy accumulation materials** (SUT)
- **Parameters of the underground power generation unit and water pumping system** (KOMAG)
- **Guidelines instructions for compressed gases storage in mine shafts** (SUT)
- **Numerical model validation of TES system** (SUT)
- **Technical and process dataset necessary to develop the assumptions for the router, and to carry out the techno-economic and LCA analysis** (ITPE)



„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

HESS PROJECT MILESTONES (7)

MS1	Recognition of mine shafts and water reservoirs	<i>Indication of specific postmining site suitable for the HESS implementation, at least 1 from each country with minimum storage capacity of 10 MWh meeting specific criteria set out in the multicriteria assessment cubic capacity of 10 000 m³/h</i>	KOMAG	M10
MS2	Parameters of the underground power generation unit and water pumping system	<i>Storage capacity of PSH equal 10 MWh (according to the project assumptions)</i>	KOMAG	M24
MS3	System analysis for compressed air storage system	<i>Selection of two optimal configurations of energy storage system</i>	SUT	M18
MS4	Guidelines instructions for compressed gases storage in mine shafts	<i>Definition of instruction for a system with a system storage capacity of at least 10 MWh for at least two cases.</i>	SUT	M24
MS5	Selection of accumulation materials	<i>Ranking of the selected materials in terms of their suitability for TES according to their heat capacity, mechanical strength, and market availability and cost</i>	SUT	M20
MS6	Numerical model validation of TES system	<i>A numerical model whose the discrepancy between experimental results will be not more than 20%.</i>	ITPE	M24
MS7	Technical and process dataset necessary to develop the assumptions for the router, and to carry out the techno-economic and LCA analysis.	<i>Reports and datasets containing heat and mass balances of the particular components of the HESS - PSH, CAES, TES (based on WP3-WP5)</i>	ITPE	M26



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„Hybrid energy storage system using post-mining infrastructure“ (HESS)
No. 101112380 (RFCS-2022)

HESS PROJECT DELIVERABLES (18)

WP1	D1.1. The communication and dissemination plan D1.2. Webpage created and initiated D1.3. The comprehensive public overview of the project D1.4. Publishable Report D1.5. Final international seminar – project results presentation	ITPE ITPE ITPE ITPE ITPE	M1 M6 M6 M36 M36
WP2	D2.1. Guidelines on the adaptation and use of inactive shafts possible to Energy storage D2.2. Guidelines on the conversion of underground mine working into water reservoir	KOMAG SUT	M12 M12
WP3	D3.1. The pumped storage systems in mine shafts D3.2. Technical parameters of the example underground water reservoir model	KOMAG SUT	M30 M18
WP4	D4.1. Thermodynamic analysis of the proposed systems D4.2. Guidelines for the baseline condition of the reference shafts D4.3. Lining materials selection and Properties	SUT SUT SUT	M18 M30 M27
WP5	D5.1. Thermal energy storage material studies D5.2. TES performance report	SUT SUT	M12 M30
WP6	D6.1. Integration of particular components of the HESS D6.2. Energy router software	ITPE KOMAG	M33 M33
WP7	D7.1. Techno-economic assessment of hybrid energy storage technology in postmining infrastructure D7.2. Life cycle assessment (LCA) of the HESS	ITPE ITPE	M36 M36



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



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**„Hybrid energy storage system using post-mining infrastructure“ (HESS)
No. 101112380 (RFCS-2022)**

Current issues and actions related to HESS project completion

Final Project Activities

30.06.2026

D 1.4. Publishable report

D 1.5. Final international seminar – project results presentation

D 7.1. Techno-economic assessment of hybrid energy storage technology in postmining infrastructure

D 7.2. Life cycle assessment (LCA) of the HESS

31.07.2026

- Completion of financial data by each partner in the system
- Preparation of final technical report – the same format as mild-term report

September-November

Evaluation meeting with a RFCS representative (online) - participation of the entire HESS consortium



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

Current issues and actions related to project completion

Final Project Activities

- **Shaft Adaptation - complete the chapter (Konrad) – 25.06.26 godz. 10.00**
- **PATENT the concept of hybrid energy storage – CCES ??? - July**
- **Geothermal Energy - Sergej, Jakub, Piotr, Marcin, Zbyszek - July**
 - *Assessment of Geothermal Energy Resources and Availability*
 - *Evaluation of Geothermal Heat Integration in the Pumped Storage Hydropower (PSH) System*
 - *Evaluation of Geothermal Heat Utilization in the CO₂ Compressed Energy Storage (CCES) System*
 - *Investigation of Dry Ice Formation during CO₂*
- **Provisions from the Application Regarding the TESS System – Jakub - July**

„for the Thermal Energy Storage (TES) to ensure the energy storage temperature up to 500°C and to achieve an energy recovery capacity of at least 1.5 MWt at least 2 hours”



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
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Thank you for your attention

Project co-financed by the European Commission within the framework of the Research Fund for Coal and Steel – RFCS program under the contact no. 101112380 (RFCS-2022) titled „Hybrid Energy Storage System using post-mining infrastructure” (HESS) and by the State Subsidy within the framework of the program „Co-financed International Projects” (PMW) established by the Minister of Science and Higher Education.



HESS PROJECT WEBSITE - <http://www.itpe.pl/en/hess/>



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**„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)**



since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

EVALUATION OF POST-MINING INFRASTRUCTURE IN POLAND FOR THE IMPLEMENTATION OF A HYBRID ENERGY STORAGE SYSTEM CONSIDERING COMPRESSED GAS ENERGY STORAGE REQUIREMENT

Authors: Marcin Lutyński, Konrad Kołodziej, Grzegorz Smolnik and Jakub Ochmann

Silesian University of Technology

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26



**„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)**

Presentation Outline

Section I: MCDA Screening

- Methodology & Strategic Importance
- Multi-Criteria Weighted Analysis
- Metric-by-Metric Deep Dive

Section II: Geomechanical Model step II Screening

- PRESS-SHAFT Application Logic
- Budryk III Stability Assessment
- Summary & Final Selection

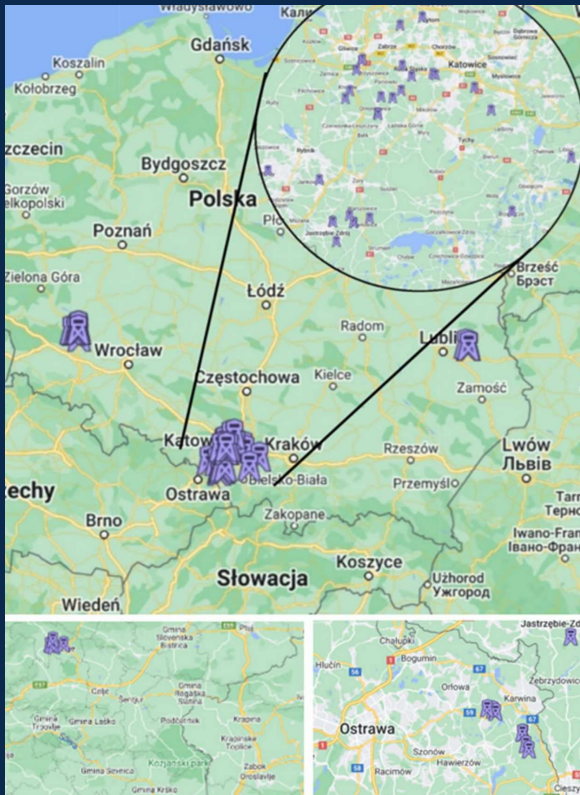


Politechnika
Śląska



Introduction

Repurposing Mine Shafts for Energy Storage



Locations of mine shafts in Poland, Slovenia, Czech Republic

Context:

Green energy transition drives the economic reuse of decommissioned post-mining infrastructure.

Target Applications:

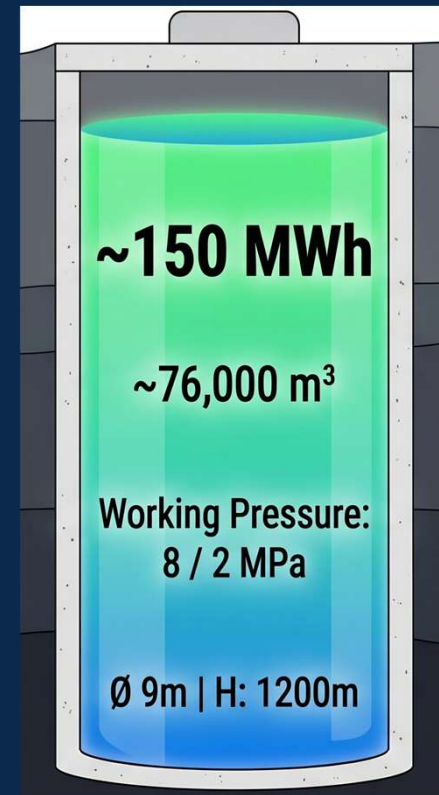
- Compressed Air Energy Storage (CAES).
- Pumped-storage hydroelectric plants.

The Concept:

Utilizing deep shafts and adjacent underground workings as high-capacity, pressurized fluid reservoirs.

Structural Advantage:

Existing concrete shaft linings are already designed to be relatively airtight against natural aquifers.



Estimation of Energy storage value in reference shaft



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STEP I: MCDA STRATEGIC SCREENING

The Initial Validation Barrier

Advanced numerical modeling for every shaft is economically unfeasible. MCDA provides a robust, standardized filter for 200+ shafts.

- **Rapid Prioritization:** Identifies potential in minutes.
- **Consistency:** Uniform criteria across EU partners.
- **Risk Mitigation:** Early detection of fatal flaws.

DECISION LOGIC

Cost-Effective
Selection



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MCDA WEIGHTED ARCHITECTURE



Geometry (50%)

Primary drivers of energy capacity and economic ROI (Depth & Diameter).



Construction (30%)

Lining integrity and the feasibility of sealing technological inlets.



Hydrogeology (20%)

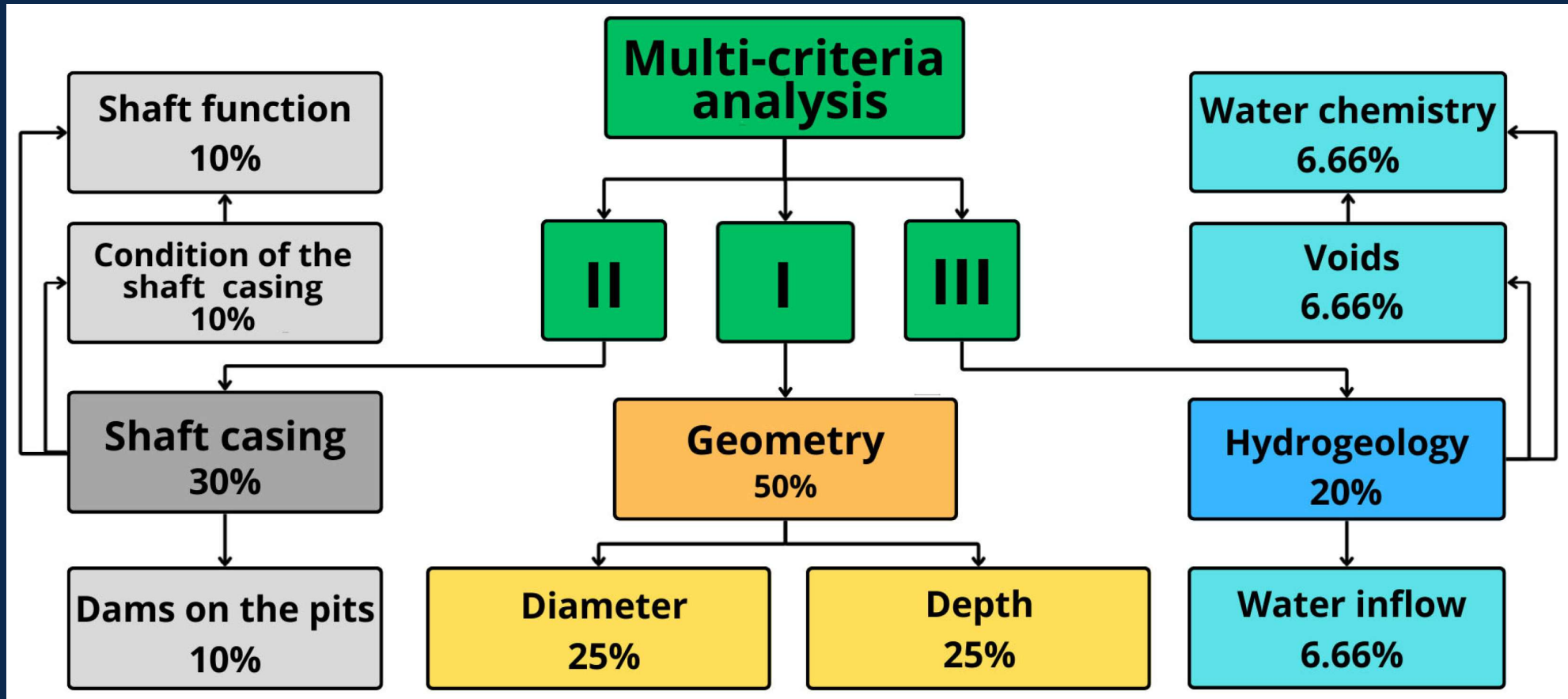
Hydrogeological stability, inflow rate, and water aggressiveness.



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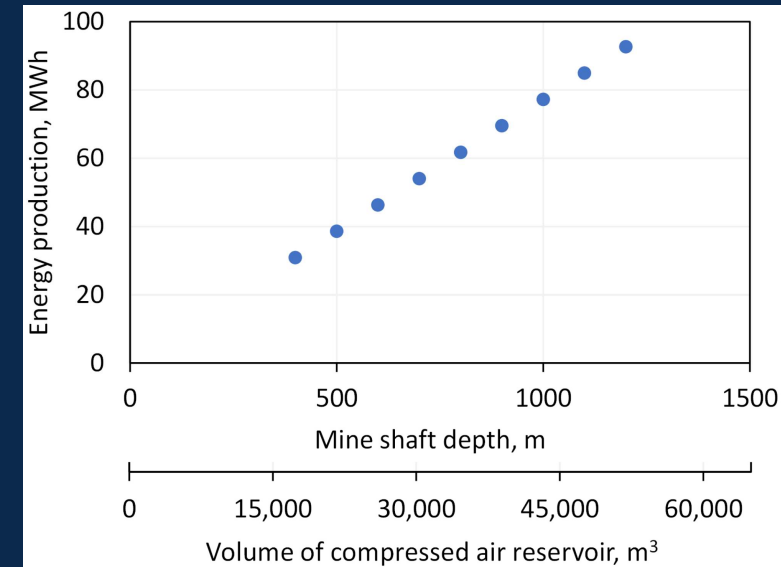
MCDA STRATEGIC SCREENING



METRIC: SHAFT DEPTH

Depth Significance

Energy potential is directly proportional to the effective pressure head provided by depth.



Electricity production from the adiabatic CAES system depending on the shaft height and compressed air reservoir volume.

Scoring Thresholds

Shaft depth (H)			
<800 m	0		Excluded from analysis
800–1000 m	5		Basic viability
1001–1150 m	7		Increased capacity
>1150 m	10		Optimal capacity



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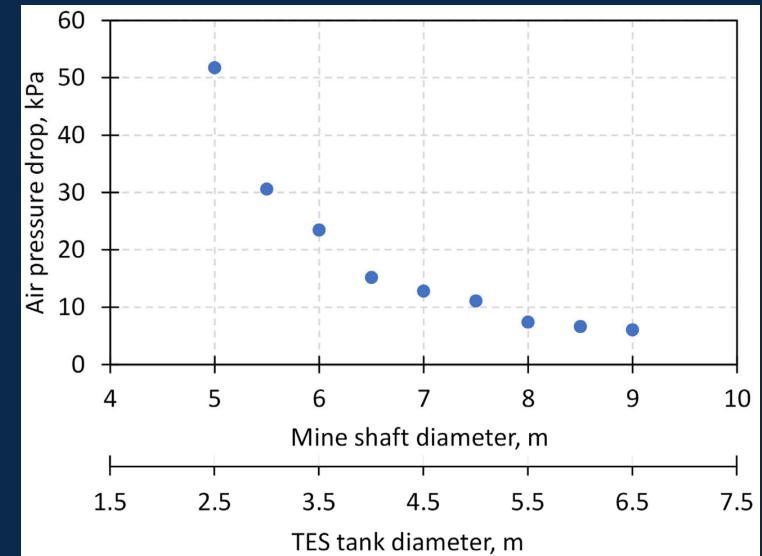
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METRIC: SHAFT DIAMETER

TES Compatibility

Minimum width is required to accommodate the **Thermal Energy Storage (TES)** tank and maintenance corridors.

*Smaller diameters lead to critical pressure drops during discharge cycles.



Value of the pressure drop of the air flowing through the TES tank depending on the diameter of the shaft.

Scoring Thresholds

Shaft diameter (D)	<7.5 m	0	Excluded from analysis
	7.50–7.99 m	5	Basic geometry
	8.00–8.49 m	8	Standard geometry
	>8.50 m	10	Optimal geometry for TES



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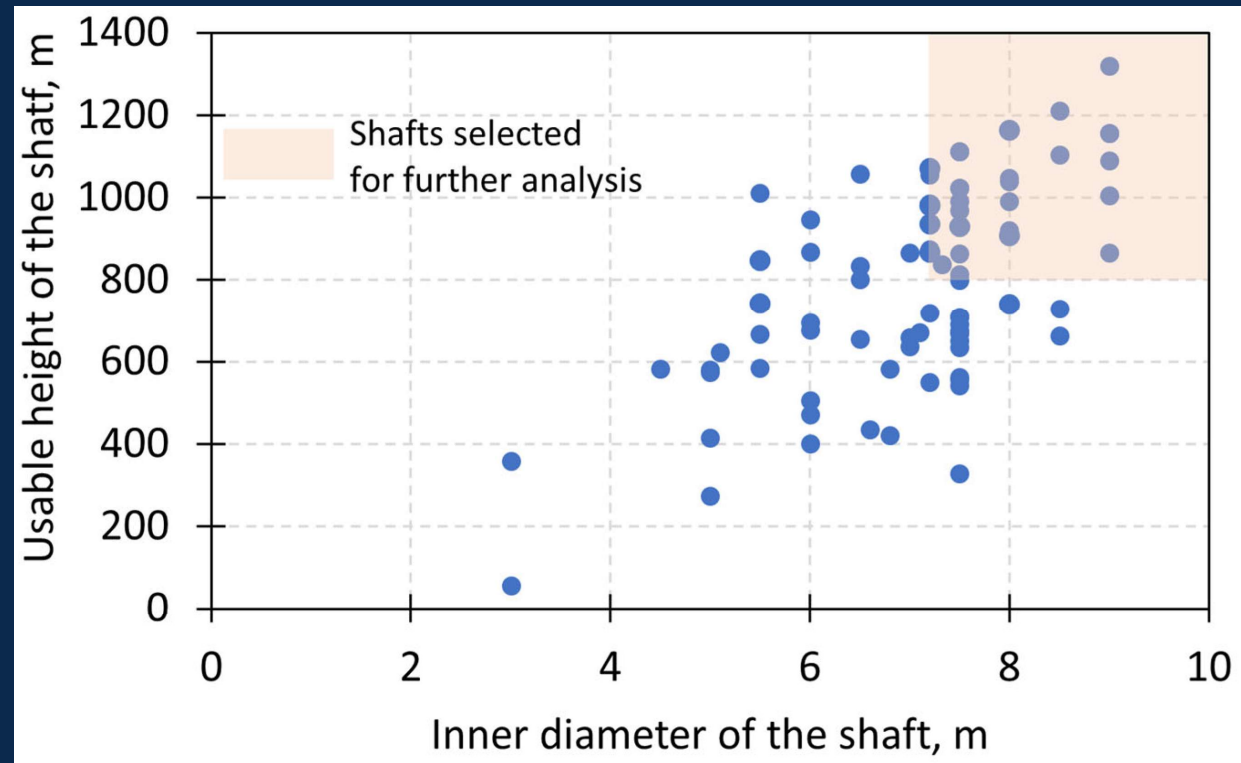


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METRIC: EVALUATION CRITERIA AND STORAGE POTENTIAL

Depth Significance

The resulting potential indicates that for the minimum boundary parameters (approx. 35,000 m³), the estimated energy capacity of the system is 178 MWh (for a 3 h discharge cycle). This represents approximately 12% of the reference capacity of the Huntorf power plant



Scatter plot showing mining shafts in Poland meeting the minimum characteristic dimension criteria.



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METRIC: EVALUATION CRITERIA AND STORAGE POTENTIAL

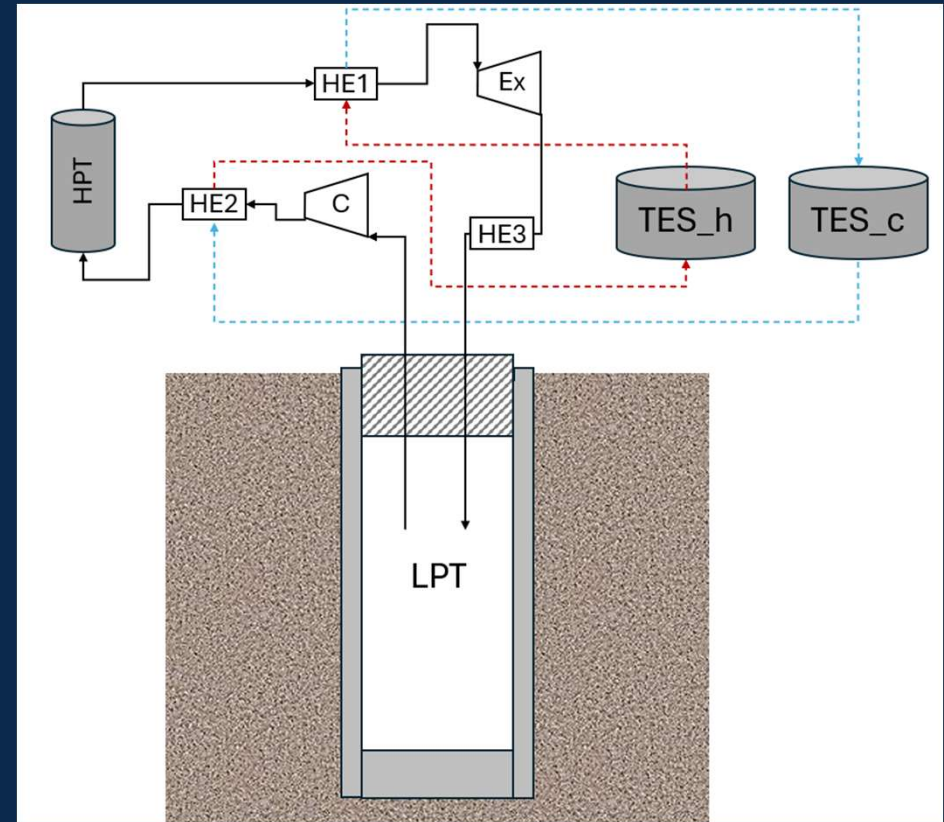
CCES concept

In the case of a compressed carbon dioxide energy storage system, the volume of the shaft affects the amount of carbon dioxide in the system and, consequently, the potential for energy storage. Thermal energy storage units are located on the surface; therefore, their design does not affect the assessment of the mining infrastructure.

Storage pressure (LPT): 0.64 MPa

Storage temperature (LPT): 30 °C

Storage potential: ~32 MWh



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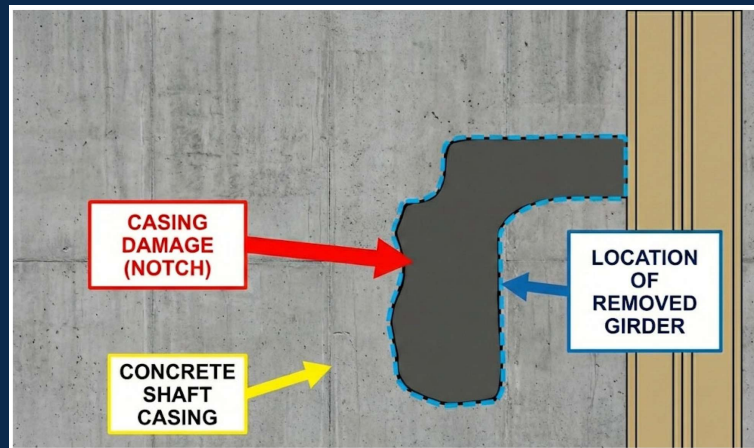


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METRIC: SHAFT PURPOSE

Ventilation Shafts (10 pts)

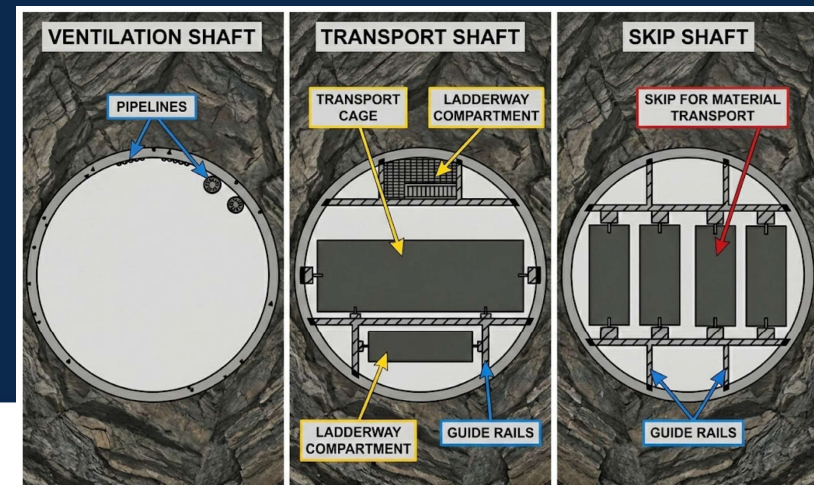
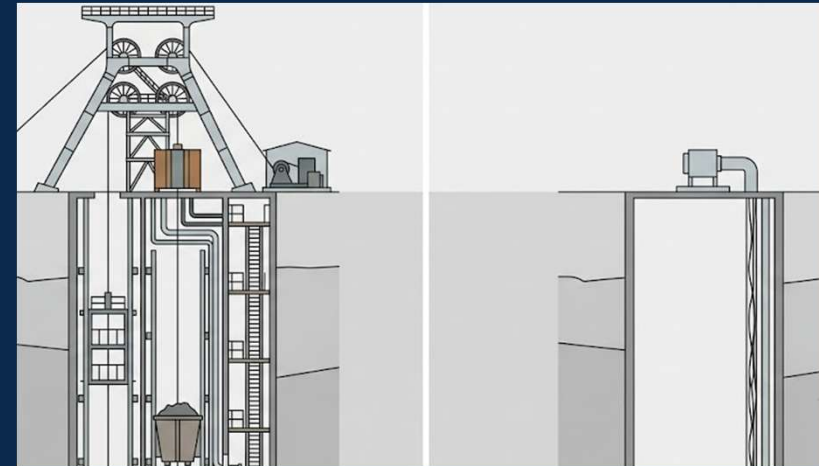
Highest adaptive value. Minimal internal equipment reduces decommissioning time and avoids structural "notches" in the lining.



A notch in the shaft casing left after removal of the girder.

Transport / Skip Shafts (1 pt)

Heavy equipment (guides/girders) integrated into the lining requires significant mechanical repair after disassembly.



Differences in the equipment of individual types of mining shafts. Black marks indicate places where equipment elements are inserted into the casing.



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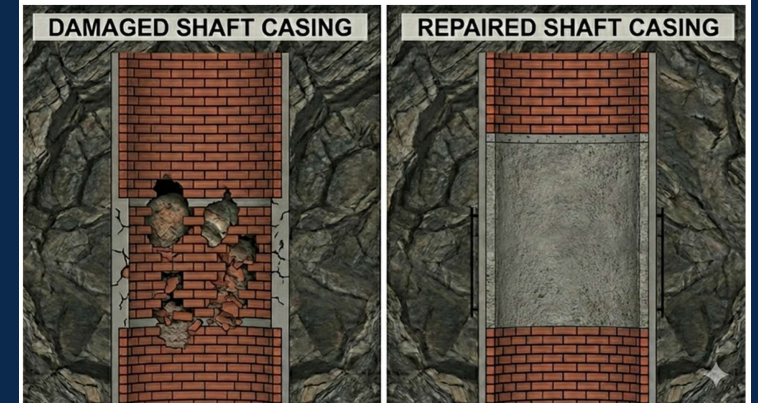
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METRIC: CASING QUALITY

Scoring is based on the projected volume of shotcrete needed to restore the "Baseline Condition."

Condition	Shotcrete Volume	Score
Good	< 450 m ³	10 pts
Average	450 - 1000 m ³	5 pts
Poor	> 1000 m ³	1 pt

Volume calculated based on cylinder V_f (radius) vs V_{nf} (radius - reinforcement layer).*



Graphical representation of a corroded section of the casing reinforced shotcrete.



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*D.2.2

METRIC: INLET SEALING

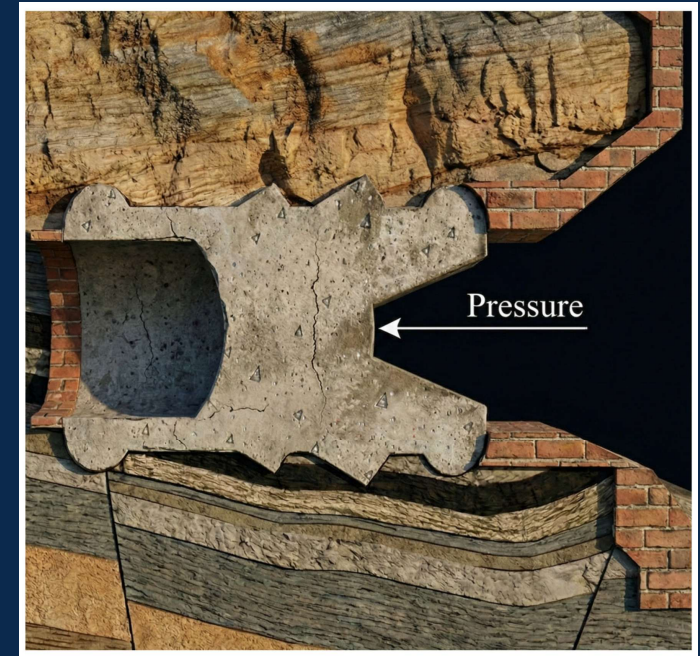
Pyramid Dam Integrity

Every horizontal connection must be sealed with high-pressure plugs.

The thickness of a concrete pyramid dam should be calculated in centimeters according to:

$$d_t \geq \frac{p_x \cdot r}{2k_c - p_x} + \frac{a^2}{8r}$$

Plug Volume	Estimated Concrete Consumption	Score
Small	<450 m ³	10
Average	450-1000 m ³	5
Large	>1000 m ³	1



Pyramid dam built for the construction of a CAES installation in the shaft.



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*D.2.2

METRIC: WATER INFLOW

To estimate the impact of hydrogeological conditions on the feasibility of establishing a compressed air energy storage facility in a decommissioned mine shaft, the water inflow rate must be analyzed. This parameter depends on the tightness and integrity of the shaft lining as well as the hydrogeological conditions of the surrounding rock mass.



Water Supply	Range	Score
Small	0	10
Average	$Q \leq 10 \text{ dm}^3/\text{min}$	6
Large	$Q > 10 \text{ dm}^3/\text{min}$	1



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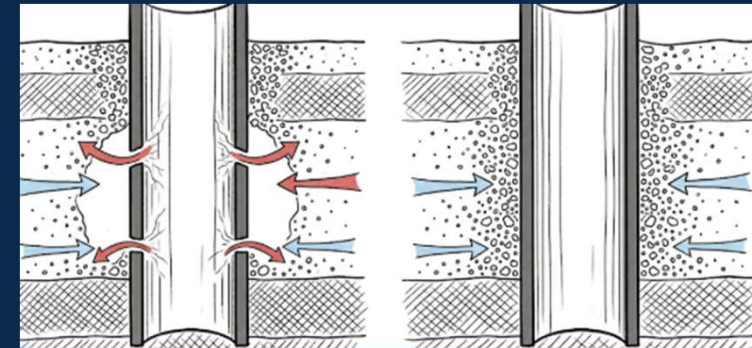


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METRIC: SUFFOSION PHENOMENON AND ROCK-LINING CONTACT QUALITY

The presence of voids behind the shaft lining constitutes a critical structural risk, potentially leading to shaft deformation and the formation of sinkholes on the surface that threaten the stability of the surrounding infrastructure.

Voids	Score
No voids	10
Few small voids, no threat	6
Numerous voids behind the casing, the threat of large empty volume	1



METRIC: WATER CHEMISTRY

Water infiltration into the shaft space constitutes one of the most severe threats to the long-term structural integrity of the lining. Unlike typical civil engineering environments, groundwater in mining areas is often characterized by extreme mineralization and acidity, resulting from the oxidation of sulphide minerals (e.g., pyrite) in the rock mass. This leads to the formation of Acid Mine Drainage (AMD), which acts aggressively on the cement binder matrix.



Type of Aggressiveness	Aggressiveness Index	Unit Measure	Degree of Water Aggressiveness			
			la ₁	la ₂	m _a	h _a
Leaching	T _w	°n	6 > T _w ≥ 3	T _w < 3	-	-
Acid	H ⁺	pH	7 > pH ≥ 6.5	6.5 > pH ≥ 5	5 > pH ≥ 4.5	pH < 4.5
Carbonate	aCO ₂	mg/L	5 < aCO ₂ ≤ 10	10 < aCO ₂ ≤ 40	aCO ₂ > 40	-
Magnesium	Mg ²⁺	mg/L	150 < Mg ²⁺ ≤ 1000	1000 < Mg ²⁺ ≤ 2000	Mg ²⁺ > 2000	-
Ammonium	NH ₄ ⁺	mg/L	10 < NH ₄ ⁺ ≤ 100	100 < NH ₄ ⁺ ≤ 500	NH ₄ ⁺ > 500	-
Sulfate	SO ₄ ²⁻	mg/L	250 < SO ₄ ²⁻ ≤ 350	350 < SO ₄ ²⁻ ≤ 500	500 < SO ₄ ²⁻ ≤ 1000	SO ₄ ²⁻ > 1000

Degrees of water aggressiveness according to PN-80/B-01800

Parameter	Unit	XA1	XA2	XA3
		Chemical Environment Not Very Aggressive	Medium-Aggressive Chemical Environment	Highly Aggressive Chemical Environment
pH	mg/dm ³	≤6.5 ≥ 5.5	<5.5 ≥ 4.5	<4.5 ≥ 4.0
Mg ²⁺	mg/dm ³	≥300 ≤ 1000	>1000 ≤ 3000	>3000 to saturation
NH ₄ ⁺	mg/dm ³	≥15 ≤ 30	>30 ≤ 60	>60 ≤ 100
SO ₄ ²⁻	mg/dm ³	≥200 ≤ 600	>600 ≤ 3000	>3000 ≤ 6000
CO ₂ agr.	mg/dm ³	≥15 ≤ 40	>40 ≤ 100	>100 to saturation

Limit values of exposure classes according to PN-EN 206 regarding chemical corrosive aggressiveness of groundwater

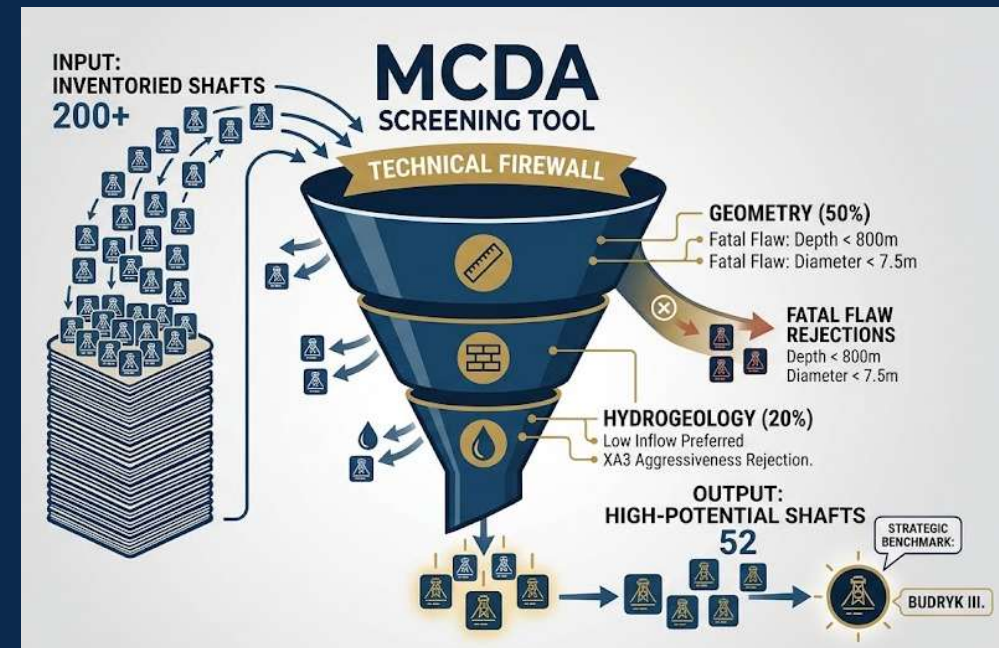


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SECTION I SUMMARY: MCDA OUTCOMES

- **Technical Firewall:**
The MCDA tool effectively filtered over 200 inventoried shafts down to 52 high-potential candidates, identifying fatal flaws early.
- **Regional Dominance:** Poland holds the vast majority of adaptable infrastructure (~3100 MWh potential), while Czech and Slovenian assets face severe depth constraints.
- **Strategic Benchmark:** Budryk III emerged as the 'Gold Standard' due to relatively high volume, perfect localization and good casing condition reducing reapering costs.

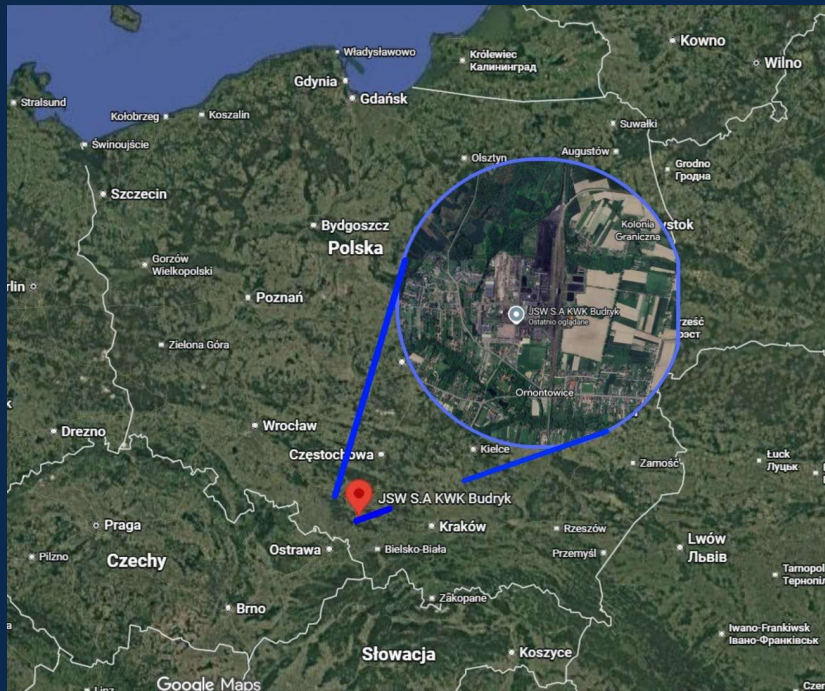


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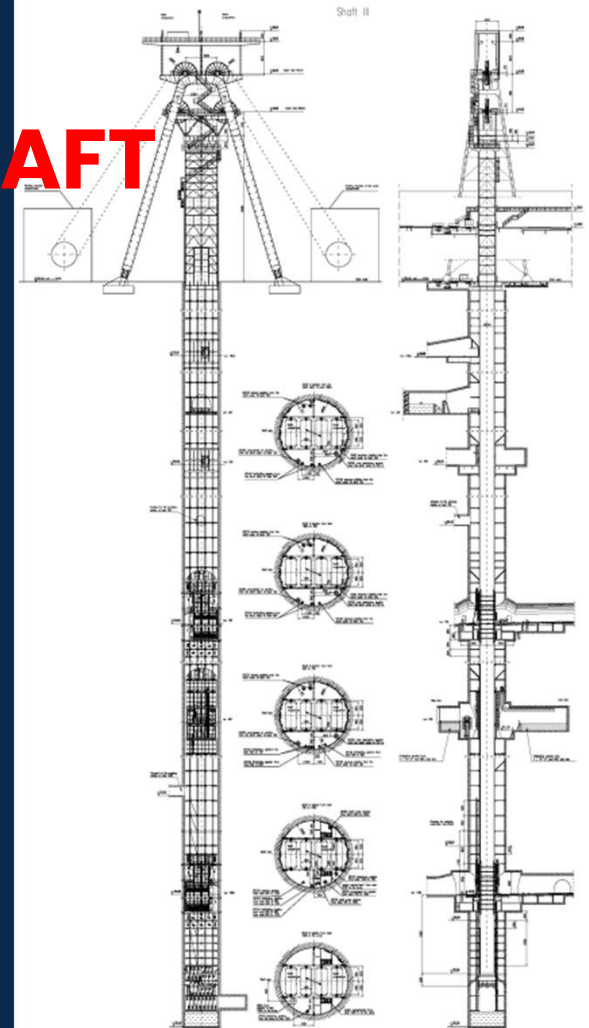


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SECTION I SUMMARY: MCDA OUTCOMES – REFERENCE SHAFT



Localization of selected shaft.



Schematic view of Shaft III Budryk Mine



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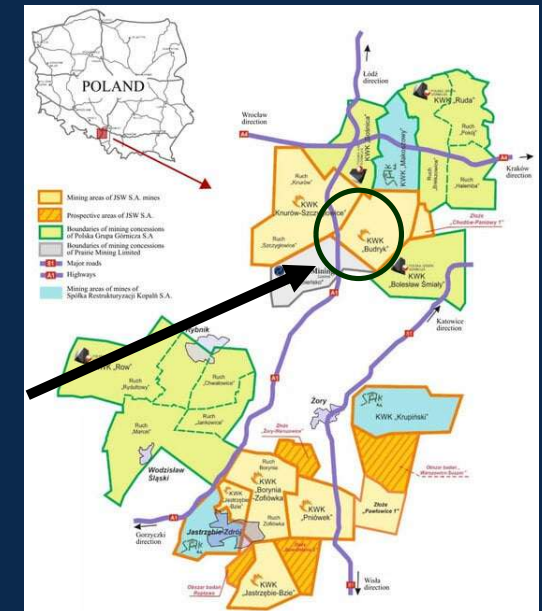


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GEOGRAPHIC AND REGIONAL LOGISTICS CONTEXT

INFRASTRUCTURE & LOGISTICS

- **Asset Age:** Youngest deep coal mine in Poland (mining started in 1994), ensuring low structural degradation.
- **Transport Connectivity:** Fully active industrial railway siding integrated with the JSW network for heavy component delivery. Perfect connection to A1 and A4 highway



REGIONAL MARKET POTENTIAL

- **Katowice:** ~280,000 residents
- **Gliwice:** ~170,000 residents
- **Zabrze:** ~150,000 residents
- **Ruda Śląska:** ~130,000 residents

The mine is located in the center of the Silesian Metropolitan area, ensuring high demand and grid stability requirements.



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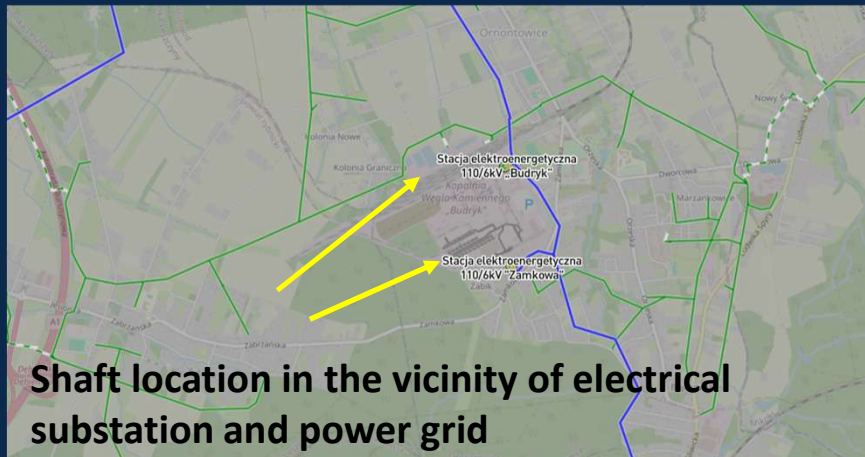


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MINE INFRASTRUCTURE AND SHAFT INVENTORY

SITE CHARACTERISTICS & GRID CONNECTION

- Structural Quality:** Youngest deep coal mine in Poland (commissioned in 1994). Minimal long-term structural or fatigue-induced degradation.
- Grid Interconnection:** Direct high-voltage interface via neighboring "Budryk" and "Zamkowa" substations (110 kV).



Inventory of Mining Shaft Infrastructure

Shaft ID	Depth [m]	Diameter [m]
Shaft I	1157.20	9.00
Shaft II	1157.45	9.00
<u>Shaft III</u>	<u>1089.89</u>	<u>9.00</u>
Shaft V	1005.00	9.00
Shaft VI	1320.00	9.00

Shaft III Operational Function:
Material-Personnel-Transport, Downcast (Intake).



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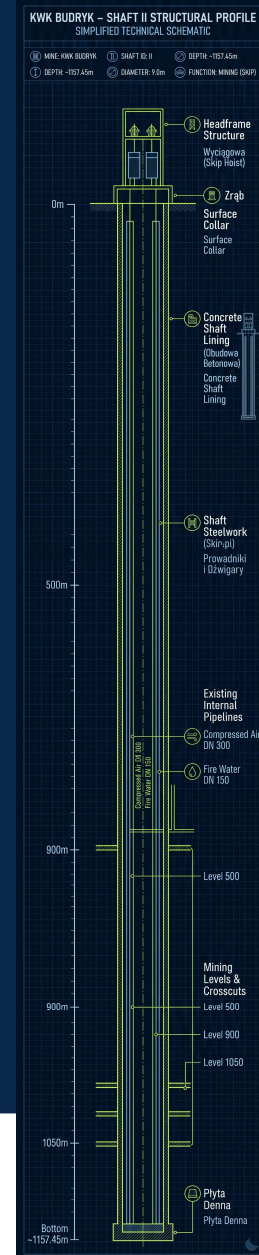


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SHAFT III STRUCTURAL PROPERTIES FOR CAES RESERVOIR

RESERVOIR PARAMETERS & LINING DETAILS

- ✓ **DESIGN PROFILE:** MATERIAL-PERSONNEL-TRANSPORT FUNCTION, DOWNCAST (INTAKE) SYSTEM.
- ✓ **VOLUMETRIC CAPACITY:** PROVIDES SUFFICIENT INTERNAL VOLUME FOR A LARGE-SCALE COMPRESSED AIR RESERVOIR (~76,000 M³ THEORETICAL VOLUME BASED ON GEOMETRY).
- ✓ **CONCRETE LINING:** STANDARD THICKNESS RANGES FROM 0.4 M TO 0.5 M, SYSTEMATICALLY INCREASED TO 0.75 M IN COAL SEAM HORIZONS.
- ✓ **HIGH-PRESSURE REINFORCEMENT:** OUTFITTED WITH DOUBLE BRICK-AND-CONCRETE LINING (0.88 M COMBINED THICKNESS) IN SPECIALIZED STRESS SECTIONS.
- ✓ **BASE FOUNDATION:** ANCHORED BY A MONOLITHIC 1.5 M THICK CONCRETE BOTTOM PLUG.
- ✓ **INLET SEALING INTEGRITY:** FEATURES 3 DISTINCT BLIND STATIONS (AT DEPTHS OF 349.2 M, 904.6 M, AND 1085.1 M) WITH NO ACTIVE MINE NETWORK CONNECTIONS.



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STEP II: GEOMECHANICAL VALIDATION AND STRUCTURAL ANALYSIS OF THE SELECTED SHAFTS

Advanced Structural Analysis

Verification of shaft-rock mass interaction under cyclic operational parameters using numerical stress-strain mapping.

- **Cyclic Pressure Testing:** Simulating lining and rock mass response to dynamic gas pressure.
- **Stress-Strain Mapping:** Detecting critical areas where expansion forces risk reservoir integrity.
- **Risk Zone Identification:** Differentiating natural rock barriers from vulnerable surface strata.

SAFETY LOGIC

Structural Integrity
Verification



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SECTION I SUMMARY: MCDA OUTCOMES – REFERENCE SHAFT

Traditional State (Past):

- Lining designed to resist external loads
- Structure operates safely under compression

State (Future):

- High internal cyclic pressure (up to 8 MPa) applied by the storage medium
- Net outward forces induce tensile and shear stresses

The Engineering Challenge:

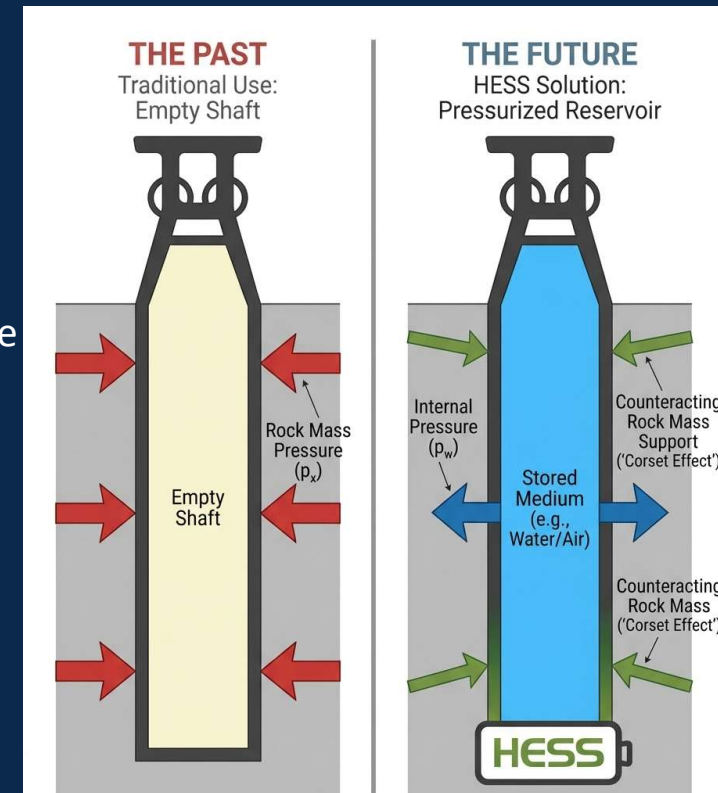
- Concrete and rock masses are inherently weak in tension

Key Risks:

- Lining fracture, debonding at the rock-concrete interface, and hydraulic fracturing of the rock mass

The "Coreset Effect"

Safety is achieved only when the Counteracting Rock Mass Support (p_r) balances the internal air pressure. The model must verify if this balance holds along the entire vertical profile.



GEOMECHANICAL PARADIGM SHIFT:
Mine Shaft under Load vs. Mine Shaft in Balance

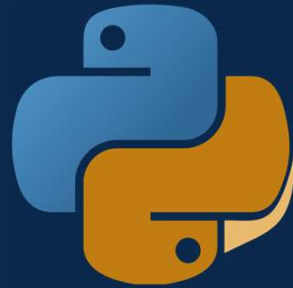


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PRESS-SHAFT: Modeling Logic



THM Framework

Custom-built environment automating complex **Thermo-Hydro-Mechanical** interactions. It integrates heat exchange, fluid mechanics, and structural stress mapping.

Discrete Resolution

The model does not treat the shaft as a single uniform unit. It resolves the stability status at strict 10-meter vertical intervals.

- Variable lithology input.
- Depth-dependent geostatic pressure.
- Real-time thermal expansion calculations.



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Analytical Criteria for Validation

PRESS-SHAFT model

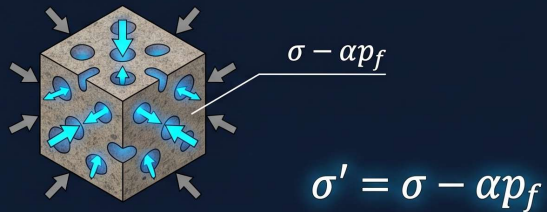
Effective Stress: Internal pore pressure (p_f) directly weakens the natural rock mass confinement

Thermal Expansion: Stored medium temperature (T) induces additional thermal load on the structure

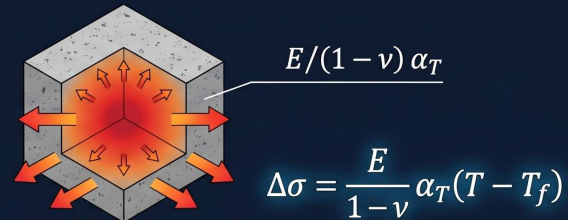
Tensile Failure: High internal pressure (p_w) creates a critical risk of hydraulic fracturing in the lining

Shear Failure: Extreme stress limits define the Mohr-Coulomb failure envelope for the surrounding rock

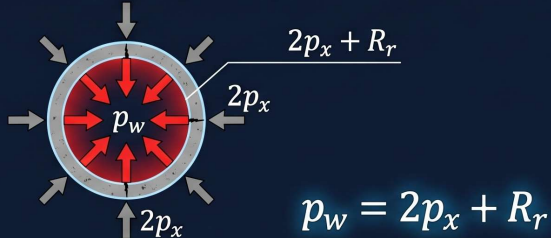
1. EFFECTIVE STRESS



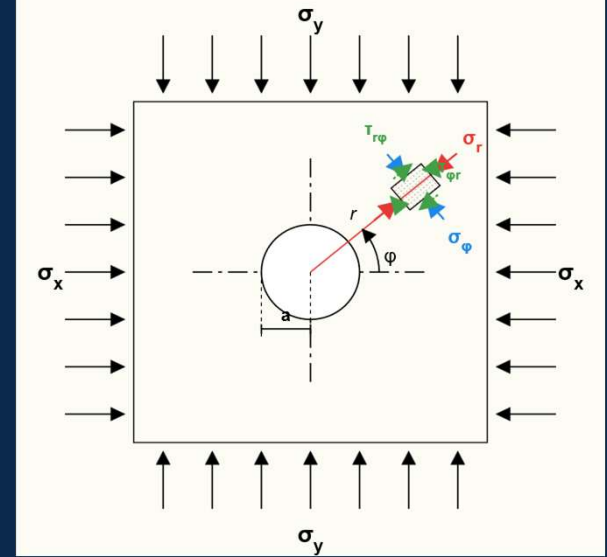
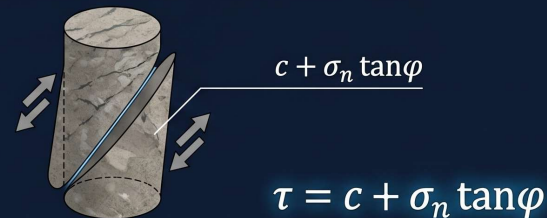
2. THERMAL EXPANSION



3. TENSILE FAILURE

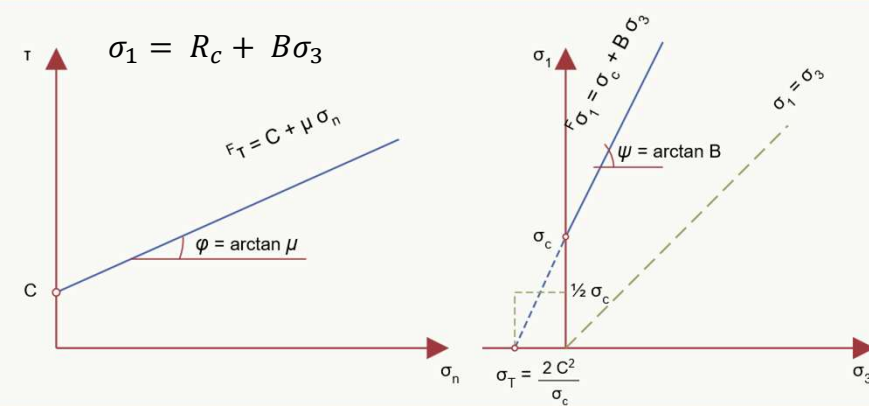


4. SHEAR FAILURE



Stress distribution on the excavation boundary under internal fluid pressure and isotropic horizontal stress.

$$\sigma_\theta = 2p_x - p_w, \sigma_z = p_z, \sigma_r = p_w$$



The Coulomb failure criterion expressed in terms of shear/normal stresses and principal stresses.



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Building the Numerical Scenario

Structural Baseline Definition

Before running the simulation, the model requires a precise material profile:

- **Casing Specs:** UCS, Tensile Strength, and Young's Modulus.
- **Operational Envelope:** Max Working Pressure (e.g., 8 MPa).
- **Thermal Thresholds:** Medium temp vs. Rock mass gradient.

Safety Verification

Determining the exact depth transition from unstable (Tensile) to stable (Shear).

PRESS_SHAFT	
Properties of the shaft's lining	
Unconfined Compressive Strength [MPa]	
Tensile Strength [MPa]	
Young's modulus [GPa]	
Poisson's ratio [-]	
Increase rate of strength with confining stress [-]	
Internal pressure in the energy storage	
Pressure of the medium inside the shaft [MPa]	
Thermal properties	
Temp. of rock mass and shaft lining at -10 m bgl [°C]	
Temp. of medium inside the shaft [°C]	
Thermal expansion coeff. of the shaft's lining [C ⁻¹]	
Temp. gradient of the rock mass [°C/m]	



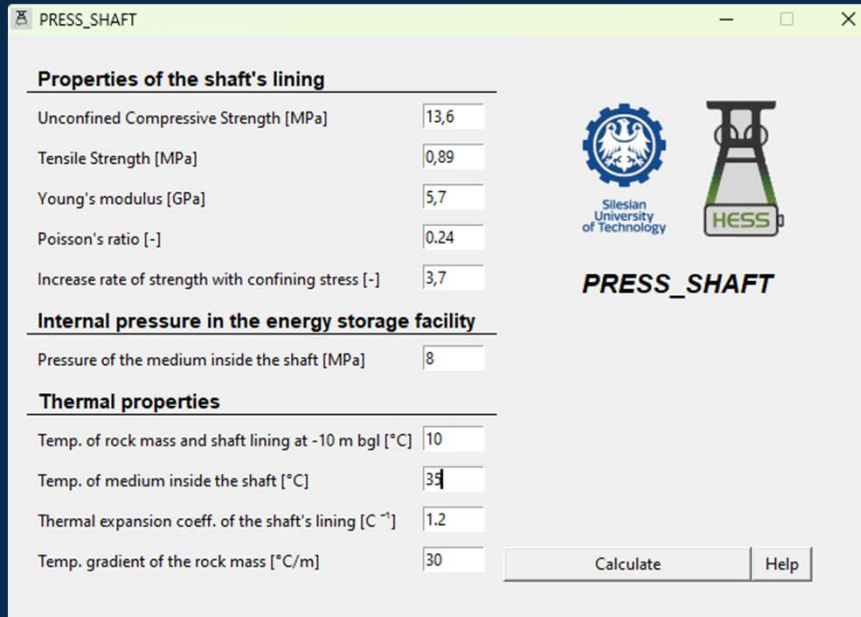
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The Computational Tool & Real-Case Scenario

Real-Case Scenario parameters

Parameter	Condition
Depth & Diameter	1000 m 9.5 m
Concrete Lining	45 cm (Rc: 24 MPa)
Max Working Pressure	8 MPa
Medium Temperature	35°C



Properties of the shaft's lining

Unconfined Compressive Strength [MPa]: 13,6

Tensile Strength [MPa]: 0,89

Young's modulus [GPa]: 5,7

Poisson's ratio [-]: 0,24

Increase rate of strength with confining stress [-]: 3,7

Internal pressure in the energy storage facility

Pressure of the medium inside the shaft [MPa]: 8

Thermal properties

Temp. of rock mass and shaft lining at -10 m bgl [°C]: 10

Temp. of medium inside the shaft [°C]: 35

Thermal expansion coeff. of the shaft's lining [C⁻¹]: 1,2

Temp. gradient of the rock mass [°C/m]: 30

Calculate Help



h [m]	Shear failure	Tensile failure	Zero tensile strength
10.0	stable	hydraulic fracture	hydraulic aperture
20.0	stable	hydraulic fracture	hydraulic aperture
30.0	stable	hydraulic fracture	hydraulic aperture
40.0	stable	hydraulic fracture	hydraulic aperture
50.0	stable	hydraulic fracture	hydraulic aperture
60.0	stable	hydraulic fracture	hydraulic aperture
70.0	stable	hydraulic fracture	hydraulic aperture
80.0	stable	hydraulic fracture	hydraulic aperture
90.0	stable	hydraulic fracture	hydraulic aperture
100.0	stable	hydraulic fracture	hydraulic aperture
110.0	stable	stable	hydraulic aperture
120.0	stable	stable	hydraulic aperture
130.0	stable	stable	stable
140.0	stable	stable	stable
150.0	stable	stable	stable
160.0	stable	stable	stable

INPUT: Multi-parameter Definition

- Custom-built Python application automating complex Thermo-Hydro-Mechanical (THM) calculations.
- Translates the theoretical Mohr-Coulomb and Kirsch frameworks into instant stability assessments.
- Automatically calculates shear failure, tensile failure (hydraulic fracturing), and exact safe operational depths.

OUTPUT: Depth-by-Depth Stability Profile

- Results indicate a critical transition at 110 m depth.
- Depths 0–100 m: High risk of hydraulic fracturing under 8 MPa pressure (requires reinforcement).
- Depths >110 m: The existing shaft infrastructure remains completely stable.



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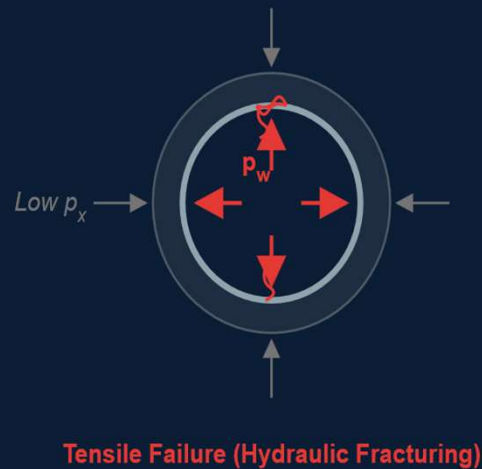
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The Shallow Zone Paradox & Deep Section Risks

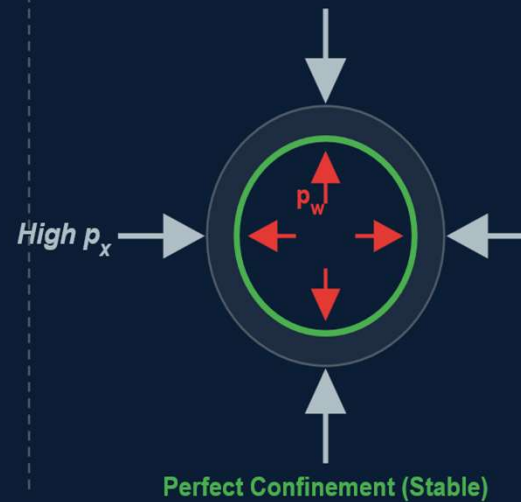
Shallow Zone

- Natural horizontal stress (p_x) is insufficient.
- Working pressure (p_w) induces tensile hoop stress.
- High risk of hydraulic fracturing (requires reinforcement).

SHALLOW ZONE (< 110 m)



DEEP SECTION (> 110 m)



Deep Section

- Extreme geological compression confines the shaft.
- Effectively counteracts internal pressure (p_w).
- The concrete lining remains completely stable.



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Conclusions & Engineering Feasibility

Scientific Conclusions

- **THM interactions are critical:**

The PRESS-SHAFT model effectively automates Thermo-Hydro-Mechanical stability assessments.

- **The Depth Paradox confirmed:**

Shallow sections are the weakest link, facing severe risks of hydraulic fracturing.

Engineering Feasibility

- **Natural confinement:**

Deep shaft sections effortlessly withstand 8 MPa without upgrades.

- **Economic viability:** Repurposing deep coal mine shafts drastically reduces CAPEX for large-scale energy storage.



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Project co-financed by the European Commission within the framework of the Research Fund for Coal and Steel – RFCS program under the contact no. 101112380 (RFCS-2022) titled „Hybrid Energy Storage System using post-mining infrastructure” (HESS) and by the State Subsidy within the framework of the program „Co-financed International Projects” (PMW) established by the Minister of Science and Higher Education, agreement No. 5462/FBWiS/2023/2



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**„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)**



FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

Assessment of the suitability of post-mining infrastructure for the implementation of a Hybrid Energy Storage System in terms of the requirements of a Pumped-Storage Hydropower System



Ph.D. Eng. Dominik Bałaga

Ph.D. Eng. Krzysztof Kaczmarczyk

www.komag.eu



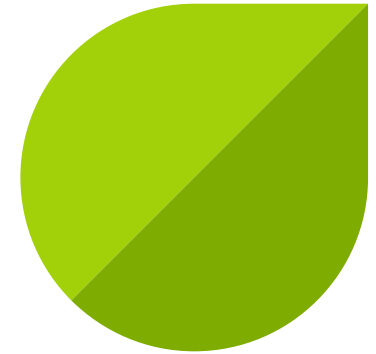
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Recognition of mine shafts and water reservoirs

Assessment of post-mining infrastructure suitability for HESS deployment in Poland, Czech and Slovenia.

Description of the final selected location based on detailed criteria defined in the multi-criteria assessment and further research within WP3 and WP4 - BUDRYK, shift II and III



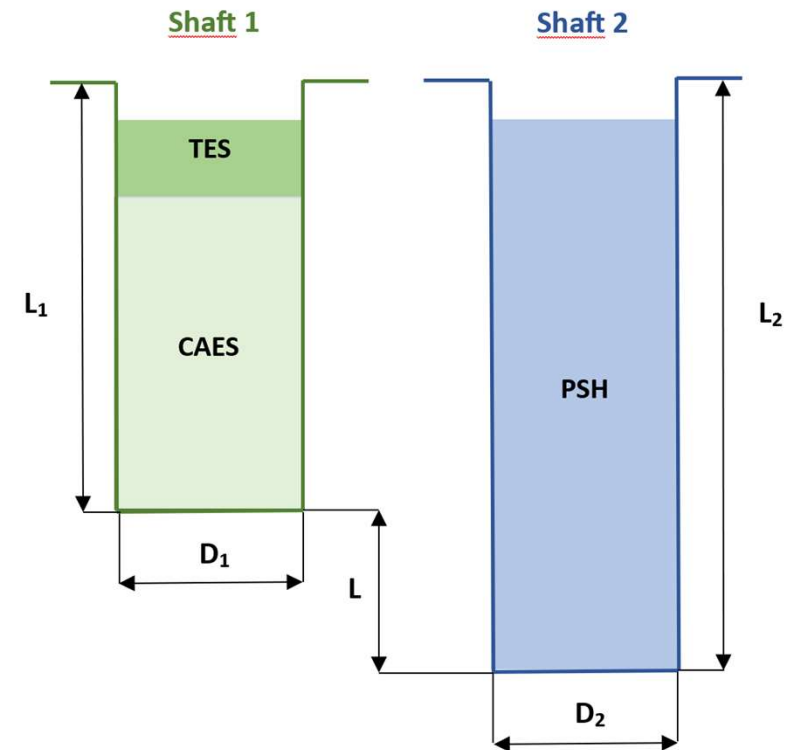
Criteria

Main objectives:

1. Minimum storage capacity of 10 MWh
2. Reservoir volume of 10000 m³

Multi-criteria system for assessing shafts and underground workings:

1. Shaft depth
2. Shaft diameter
3. Area for the upper tank
4. Shaft configuration (distance between shafts)



Preliminary calculations based on criteria

Input data

1	Volume of the upper tank	V	m ³	7 000,0
2	Height difference	h	m	800,0
3	Water shedding time	t	h	1,0
4	Density	ρ	kg/dm ³	1,0
5	Turbine set efficiency	η		0,70

Calculation of turbine power and storage capacity

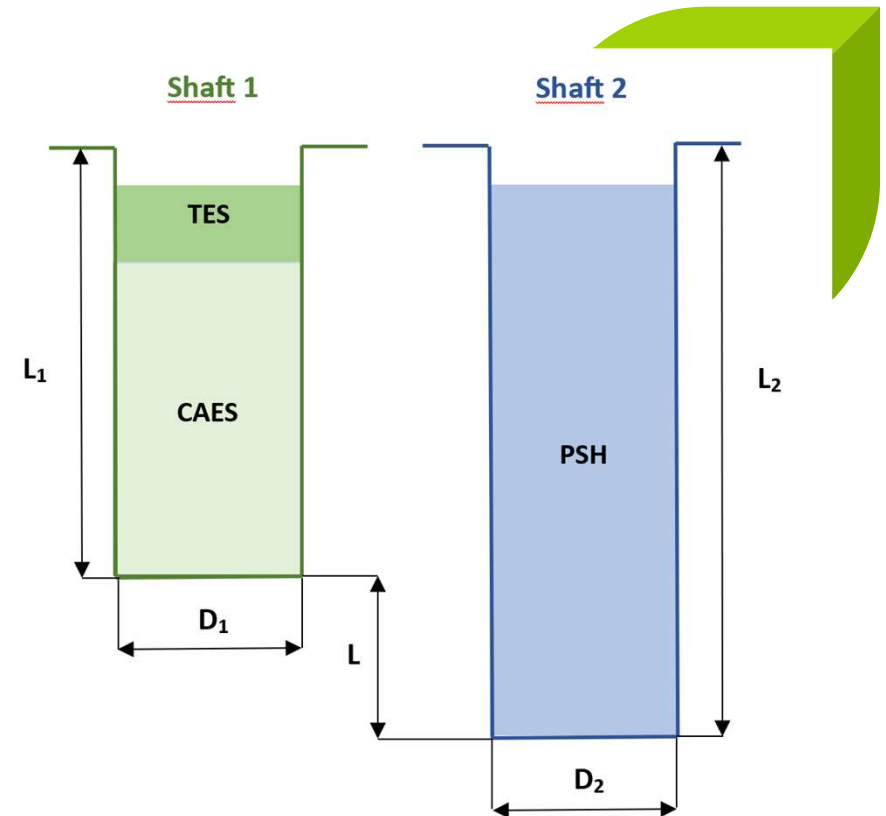
1	Time	t1	s	3 600
2	Acceleration due to gravity	a	m/s ²	9,81
3	Mass	m	kg	7 000 000
4	Force	F	N	68 670 000,00
5	Work	W	Nm	54 936 000 000,00
6	Computing power	P	Nm/s = W	15 260 000,00
7	Real power	P1	kW	10 682,00
8	Water discharge speed	Prz	m ³ /s	1,94
9	Storage capacity	C	MWh	10,68

Shaft depths and diameters

1	TES - depth	L1	m	800,0
2	TES - diameter	D1	m	7,5
3	PSH - depth	L2	m	1 000,0
4	PSH- diameter	D2	m	9,0
5	Estimated volume of the lower tank	V	m ³	12 723,1

Main goals:

1. 10 MWh storage
2. Capacity 10,000 m³, have been fulfilled.



Criteria

Shaft depth and diameter

Table 1 Calculated effective falls of the turbine HU depending on the shaft height HS and diameter Dzd

Effective fall of the turbine H_U [m]												
$D_{zd} \backslash H_s$ [m]	1100	1050	1000	950	900	850	800	750	700	650	600	550
9	1013	958	903	848	792	735	677	618	545	480	412	309
8,5	1003	948	892	836	779	713	653	591	527	460	364	237
8	991	935	879	822	756	696	634	571	505	413	297	
7,5	976	920	855	797	737	675	612	529	457	348		
7	951	894	835	775	713	635	568	497	392	255		
6,5	929	869	809	734	669	602	508	429				
6	889	827	763	698	610	536	424					
5,5	850	769	701	630	527	403						
5	781	689	613	500								



Table 2 Scoring for effective falls of a turbine HU depending on shaft depth HS and diameter Dzd

$D_{zd} \backslash H_s$	Depth [m]											
Diameter [m]	1100	1050	1000	950	900	850	800	750	700	650	600	550
9	10	9	7	6	4	3	1	0	-2	-4	-5	-8
8,5	10	8	7	5	4	2	1	-1	-3	-4	-7	-10
8	9	8	7	5	3	2	0	-1	-3	-5	-8	-100
7,5	9	8	7	4	3	1	0	-2	-4	-7	-100	-100
7	8	7	6	4	2	0	-1	-3	-6	-10	-100	-100
6,5	8	6	5	3	1	-1	-3	-5	-100	-100	-100	-100
6	7	5	4	2	0	-2	-5	-100	-100	-100	-100	-100
5,5	6	4	2	0	-3	-6	-100	-100	-100	-100	-100	-100
5	4	2	0	-3	-100	-100	-100	-100	-100	-100	-100	-100

Criteria

Tank volumes V_z depending on the turbine effective fall H_U

Table 3 presents the calculated volumes of the reservoir (V_z) required to store 10 MWh of energy. These values depend on the turbine's effective fall (H_U) and the number of points assigned to each case for the bottom water reservoir located in the mine's side workings. A value of 0 was assigned to the average reservoir volume (V_z). The remaining values were given proportionally, ranging from +10 points for the largest volumes to -10 points for the smallest volumes.

Table 3 Tank volumes V_z depending on the turbine effective fall H_U and the points assigned to them

Reservoir volume [m^3]															
$H_u[m]$	1000	950	900	850	800	750	700	650	600	550	500	450	400	350	300
$V_z[m^3]$	5246	5523	5829	6172	6558	6995	7495	8071	8744	9539	10493	11659	13116	14990	17488
score	10	10	9	8	8	7	6	5	4	3	1	0	-3	-6	-10



Criteria

Surface area for upper water reservoir

The scoring of shafts based on the availability of space for the construction of the top water reservoir is presented in Table 4.

Locations where there is sufficient space to build the top water reservoir were assigned 2 points. If there is not enough space to construct the reservoir, the shaft was assigned –2 points.

Table 4 Scoring regarding the space availability for constructing the top water reservoir

Scoring depending on area availability for constructing the top water reservoir	
enough available area	2
unavailable area	-2



Criteria

Shaft configuration (distance between shafts)

The operating conditions of equipment in an underground pumped-storage power plant can be compared to those of a stationary pumping station. In both cases, proper ventilation is required, and this usually needs two shafts.

According to the assumptions of the Hybrid Energy Storage System (HESS), each energy storage facility should be located within the same post-mining area. It is also preferred that the locations are close to the shaft used for storing compressed fluids and to the thermal energy storage facility. Such a configuration was assigned 5 points.

A score of 2 points was given when there is a connection between the considered shaft and a nearby shaft. If the connected shaft is located far away, the score is 0 points. A single shaft received -5 points due to difficulties with ventilation.



Table 5 Scoring regarding the space availability for constructing the top water reservoir

	Points
Two adjacent shafts - including one CAES and the other PSH	5
Two neighboring shafts	2
Two distant connected shaft	0
Single shaft	-5



Criteria

Hoisting devices

The analysis also included operational factors that may affect future investment and operating costs.

- The first criterion was the availability of hoisting equipment. Shafts equipped with active systems for transporting personnel and materials received the highest score.
- The second criterion was methane hazard. Non-methane mines were considered the most favourable because they do not require explosion-proof equipment or advanced ventilation systems. The score decreased as the methane hazard category increased.
- The final criterion was mine dewatering. Locations with low or no water inflow received the highest scores, as they require less energy and lower costs for water management. High groundwater inflow resulted in lower scores due to the additional energy needed for dewatering.

Scoring for availability of hoisting devices

Scoring of the availability of hoisting devices	
shaft tower with material and people transportation hoist in at least 1 shaft	2
adaptation to the installation of an auxiliary emergency and inspection hoist in one of the shafts	0
no hoisting devices in the connected shafts	-2



Scoring depending on the category of methane hazard

Scoring depending on methane content of mine workings	
non-methane	5
methane hazard category I	-1
methane hazard category II	-2
methane hazard category III	-3
methane hazard category IV	-4

Summary of multicriterial system for shafts assessment

After defining the scores for each parameter and assigning weights to the evaluation criteria, it became possible to identify the mine shafts that best meet the required conditions.

Logical functions were developed to automatically assign scores for each criterion based on data collected for each shaft, such as shaft depth and diameter, availability of space for a top water reservoir, shaft configuration, methane hazard category, and drainage conditions.

Mathematical formulas were then applied, using the defined weights and partial scores, to calculate the total score for each analysed case.

The developed multi-criteria shaft evaluation system makes it possible to sort the records in the “Mine Shafts in Poland, Czech Republic and Slovenia” database according to the total score and to identify the shafts that best meet the specified criteria.

As a result of the analysis and the application of this evaluation system, total scores were assigned to all shafts. After sorting the database by total score for the underground water reservoir option in the shaft, the shafts with the highest scores were selected.

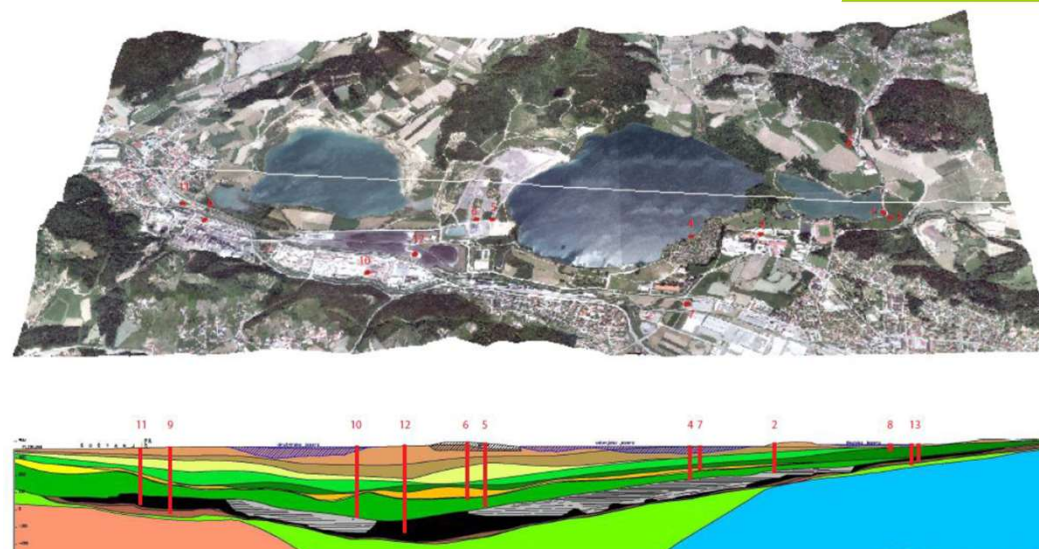


Slovenian shaft

Review of shafts located in Slovenia:

No.	Name	Diameter [m]	Depth [m]
1	Kronprinz Rudolf Schacht*		118,2
2	Škale Shaft (A)	3,90	168
3	Kronprinz Rudolf Wetterschacht*		93,5
4	Glinšek Shaft*		178+17,4
5	Preloge transport shaft*		373
6	Ventilation shaft Preloge*		336
7	Ventilation shaft Pesje (A)	4,00	141,76
8	Ventilation shaft Hrastovec**		42,8
9	Ventilation shaft Šoštanj I (A)	5,90	234,72
10	Transport shaft Nove Preloge (A)	7,20	416,42
11	Intake shaft Šoštanj II(A)	5,00	332,57
12	Ventilation shaft Nove Preloge (A)	6,15	390,7

*Decommissioned, **Sealed short mine-surface ventilation connection, (A) Active



Slovenian shaft

Selected Slovenian shafts, with the largest volume and diameter.

No.	Name	Diameter [m]	Depth [m]
10	Transport shaft Nove Preloge (A)	7,20	416,42
12	Ventilation shaft Nove Preloge (A)	6,15	390,7

(A) Active

Transport shaft Nove Preloge – NOP (1984/1987)

In the beginning of 1980, construction of the new main mine shaft begun and with its 416 m depth, the shafts' importance remained until the present day.

Shaft construction took four years, additional connecting objects and facilities were finalized by 1987. The shaft operates on daily basis by transporting staff, materials, consumables and equipment to and out of the mine. The two-sided two-level cage system allow transport of up to 70 employees in single run or material/equipment transport in dimensions of approximately 4,5 x 2 m.

The NOP shaft will remain also for mine closure activities as it represents the most effective mine supply facility.

Transport shaft Nove Preloge - NOP (Prevažalni jašek Nove Preloge - NOP)	
Shaft construction year	1984
Shaft original function	Staff transport, material and equipment transport
Shaft depth	416,42 m
Shaft shape and dimensions (diameter)	Circular, 7,20 m
Shaft support and lining	Steel arch, bolting, mesh, concrete lining (0,30 m)
Existing head gear	Hauling device, two sided transport cage

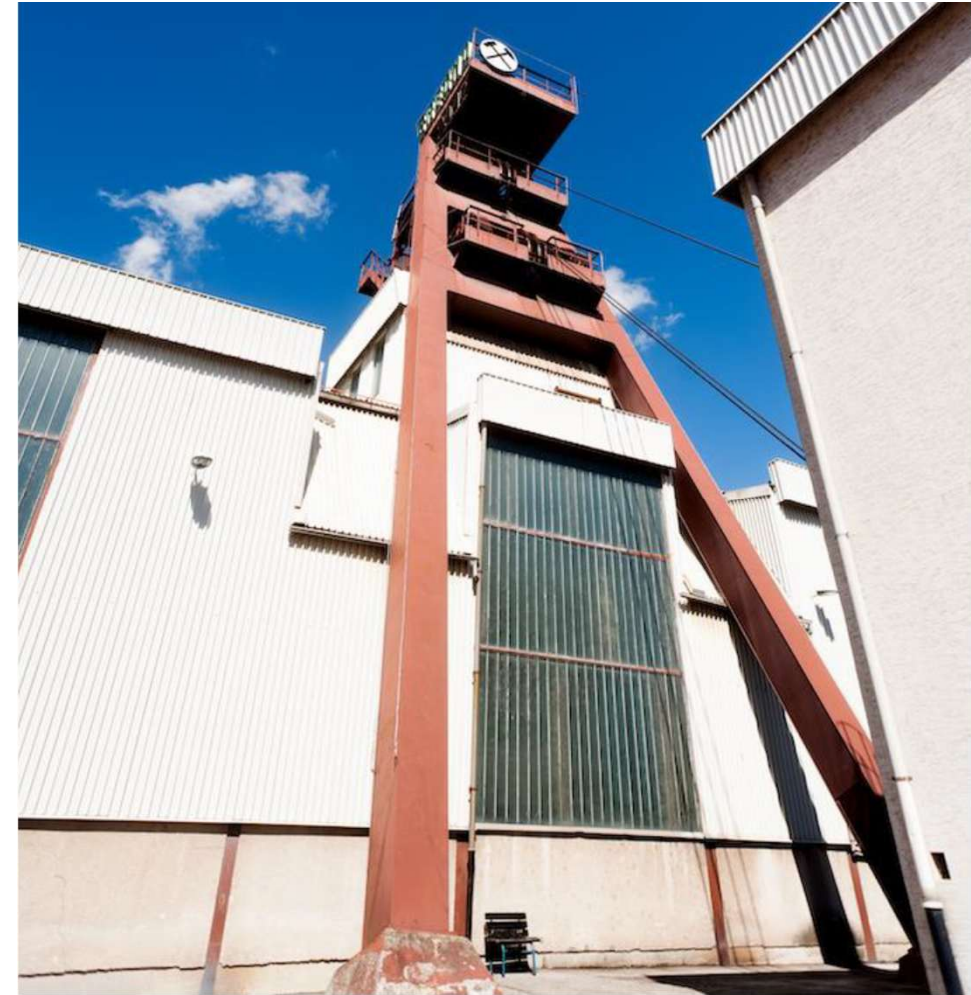


Fig 2: Transport Shaft Nove Preloge - NOP

Slovenian shaft

Selected Slovenian shafts, with the largest volume and diameter.

No.	Name	Diameter [m]	Depht [m]
10	Transport shaft Nove Preloge (A)	7,20	416,42
12	Ventilation shaft Nove Preloge (A)	6,15	390,7

(A) Active

Ventilation shaft Nove Preloge II – NOP II (2017)

As the active mining area started to decrease and with a focus on reducing mined coal transport distances, the decision for new shaft in closest vicinity of surface stockpile was made. The primary idea included skip equipped transport system for mined coal with underground staging bunkers. Construction begun in 2011, but after the conditions and circumstances varied from planned, the idea was modified to reduce the planned depth and purpose of the shaft to Ventilation shaft Nove preloge II – NOP II. The shaft was connected to the mine in 2017, other construction works continued and in 2023 the double fan ventilation unit was finalized.

Ventilation shaft Nove Preloge II – NOP II (Zračilni Jašek Nove Preloge II – NOP II)	
Shaft construction year	2017/2023
Shaft original function	Ventilation (Return)
Shaft depth	390,70
Shaft shape and dimensions (diameter)	Circular, 6,15 m
Shaft support and lining	Steel arch, bolting, mesh, concrete lining (0,60+ m)
Existing head gear	Ventilation unit (two mine fans)



Fig 3: Ventilation Shaft Nove Preloge II – NOP II

Slovenian shaft

Underground water reservoirs selection.

Ventilation shaft Nove Preloge II – NOP II (2017)

Main pumping station (MPS) and Support pumping stations (SPS1, SPS2), where water collectors are built with additional support elements and reinforced with concrete lining.

The total volume of water collectors in pumping stations are 5.250m³ (MPS), 1.500 m³ (SPS1) and 1.200 m³ (SPS 2).

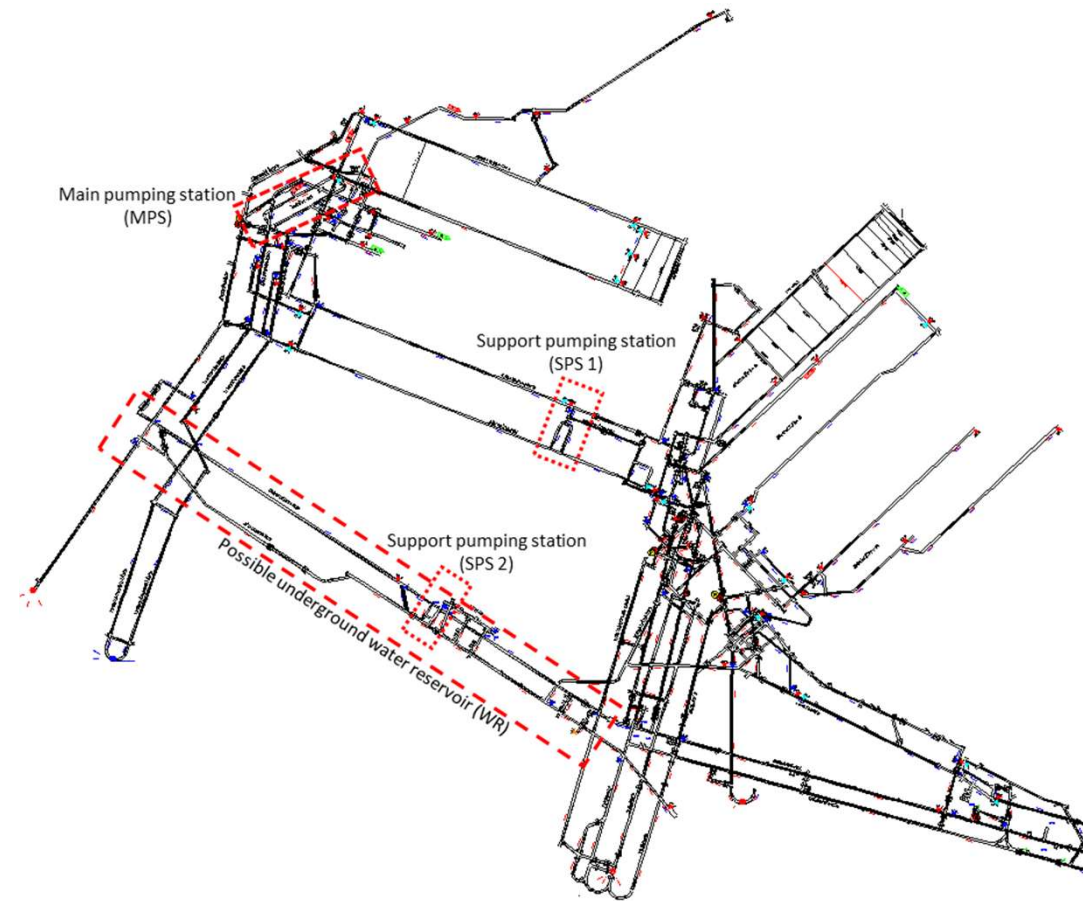
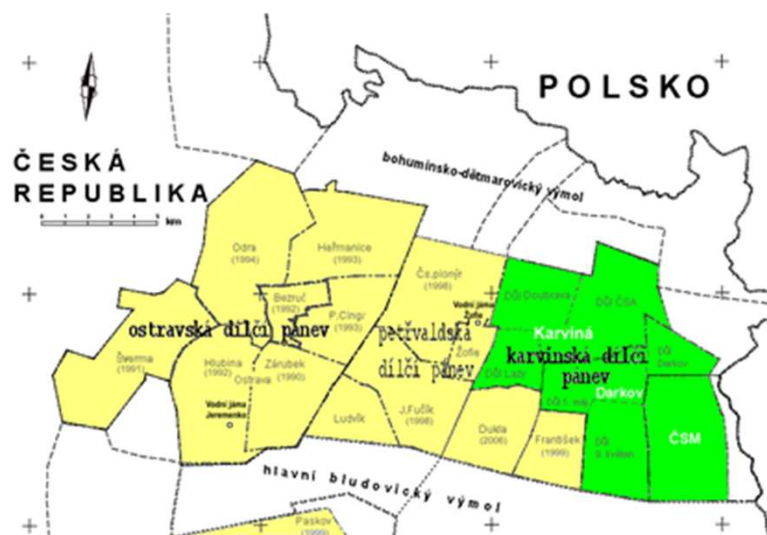


Fig 4: Active part of Coal Mine Velenje with marked possible water reservoir objects (roadways) and mine pumping stations

Czech shafts

Review of shafts located in the Czech Republic:

No.	Name	Mine	Diameter [m]	Depht [m]
1	Jan	ČSA	7,50	962,2
2	ČSA 2		7,50	1049,3
3	ČSA 3		7,50	994,8
4	Da-1	Darkov	7,50	878,3
5	Mír 5		7,50	887,2
6	Mír 4		7,50	1011,5
7	Sever (ventilation exhaust shaft)	ČSM	7,50	1005
8	Sever (ventilation inlet shaft)		7,50	1104,4
9	Jih (ventilation exhaust shaft)		7,50	972,1
10	Jih (ventilation inlet shaft)	Jeremenko	7,50	1103,9
11	Jeremenko 1		5,00	819,0
12	Jeremenko 2		7,50	1062,0



Czech shafts

Selected Czech shafts, with the largest volume, diameter, and distance:

No.	Name	Mine	Diameter [m]	Depht [m]
1	Jan	ČSA	7,50	962,2
2	ČSA 2		7,50	1049,3
3	ČSA 3		7,50	994,8
7	Sever (ventilation exhaust shaft)	ČSM	7,50	1005
8	Sever (ventilation inlet shaft)		7,50	1104,4
9	Jih (ventilation exhaust shaft)		7,50	972,1
10	Jih (ventilation inlet shaft)		7,50	1103,9

ČSA Mine (former name - Důl Československá armády) is a former mining complex of the OKD company, in the Moravian-Silesian in the Czech Republic, consisting of two mining plants:

- Jan Karel,
- Doubrava.

The area of the mining area was 26 km² and was located in Karvina, Orlová and Doubrava.

Mining ended in February 2021.

Because CSA MINE is in liquidation and the shafts are being filled in, we do not take them into account

K. Ú. STONAVA

No.	Name	Mine	Diameter [m]	Depht [m]
7	Sever (ventilation exhaust shaft)	ČSM	7,50	1005
8	Sever (ventilation inlet shaft)		7,50	1104,4
9	Jih (ventilation exhaust shaft)		7,50	972,1
10	Jih (ventilation inlet shaft)		7,50	1103,9



The area of the mining area is 26 km² and is located in Stonawa, Karwina, Olbrachcice and Kocobędz.

Polish shafts

Review of shafts located in Poland.

An Excel spreadsheet was created containing 200 Polish shafts from various mining companies: JSW, PGG, PKW, LW Bogdanka, SRK, KGHM, Silesia, Siltech, Węglokoks, Kłodawa. Shaft evaluation criteria have been established. Based on this multi-criteria assessment, 3 pairs of shafts were selected (only hard coal mines).



Polish shafts

Selected Polish three pair of shafts, with the multi-criteria system

Lp.	Przedsiębiorca	Zakład górniczy	Szyb	Głębokość [m]	Średnica [m]	Punktacja spadku użytecznego turbiny H_u	Punktacja objętości zbiornika V_z	Punktacja obszaru pod zbiornik	Punktacja konfiguracji	Punktacja urządzeń wyciągowych	Punktacja metanowości	Punktacja odwadniania	Waga sumaryczna
No.	Entrepreneur	Mining plant	Shaft	Depth [m]	Diameter [m]	Turbine useful drop scoring H_u	Tank volume scoring V_z	Scoring of the tank area	Configuration scoring	Scoring of hoisting equipment	Methane scoring	Dewatering scoring	Total weight
	1	2	4	6	7	14	15	16	17	18	19	20	21
168	Bogdanka	LW "Bogdanka"	2.2	1018,25	7,50	6	10	2	2	5	5	-3	4,65
169	Bogdanka	LW "Bogdanka"	2.1	1097,74	7,50	8	10	2	2	0	5	-3	4,55
13	JSW	KWK Budryk	II	1157,45	9,00	10	10	2	2	5	-4	-3	4,1
14	JSW	KWK Budryk	III	1089,89	9,00	9	10	2	2	5	-4	-3	3,9
63	PGG	KWK Ruda Halemba	Grunwald III	1112,50	7,50	9	10	2	2	0	-2	-3	3,7
58	PGG	KWK Ruda Bielszowice	V	1111,60	7,50	9	10	2	2	0	-4	-3	3,4

Conclusions:

However, due to the planned use of two adjacent or closely located shafts for energy storage in a pumped storage power plant in a form of compressed gases, the most favourable locations were the following three pairs of shafts already mentioned in Milestone 1:

Shafts II and III located on the area of the Budryk coal mine,

- **Shafts II and III located on the area of the Budryk coal mine,**
- Shafts 2.1 and 2.2 located on the area of the Bogdanka Coal Mine,
- Grunwald III and V shafts belonging to the "Halemba" and "Bielszowice" plants, respectively, which are parts of the "Ruda" coal mine.

A particularly interesting pair are the shafts located in the area of Budryk coal mine, because one of them, as a result of a separate analysis based on different criteria, was selected as a compressed gas storage facility.

The analysis of mining shafts in the Czech Republic included shafts from the ČSM, ČSA, Darkov and Jeremenko hard coal mines. With the exception of the ČSM mine, shafts in the remaining mines are either in the process of being filled or have already been designated for filling. Therefore, only the shafts from the ČSM mine were subjected to multi-criteria analysis. Based on the collected data, shafts located in the Sever field were selected for the construction of a pumped-storage power plant (PSH).

Analysis of mining shafts in Slovenia showed that it was not possible to build an energy storage with the assumed capacity of 10 MWh, due to the shafts being too small in depth and diameter.

Nove Preloge Transport Shaft (H = 416.42 m, D = 7.2 m)

Nove Preloge Ventilation Shaft (H = 390.7 m, D = 6.15 m)





Thank you for your attention

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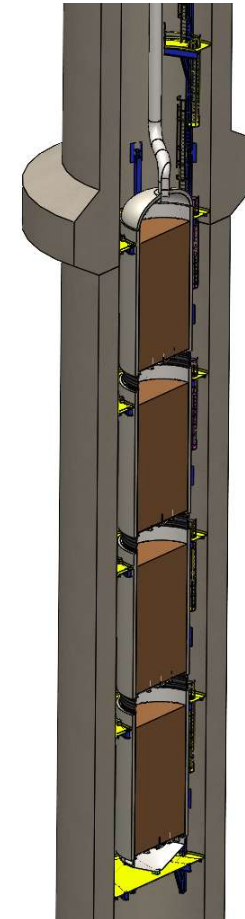
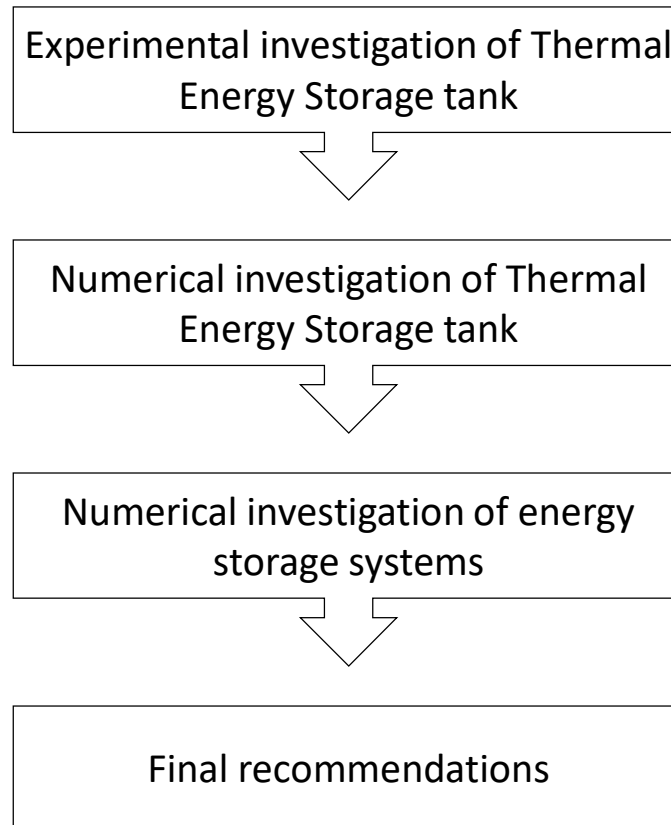
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Thermodynamic analysis of two CAES and CCES systems: technology overview, performance parameters, equipment characteristics, and cost assessment

Michał Jurczyk
Silesian University of Technology

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

Work plan



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Hybrid Energy Storage System using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

Solid materials – TES Review

Average values in temperature of 20°C

Type of rock/ Parameter	Density, kg/m ³	Specific Heat, J/kgK	Thermal capacity, kJ/m ³ K	Thermal conductivity, W/mK
Basalt	2786.3	852.1	2374.3	2.1
Granite	2642.8	859.7	2554.9	3.0
Rholite (25°C)	2677.7	865.3	2378.1	
Gneis (25°C)	2777.5	876.0	2380.5	3.0
Sandstone	2481.5	774.5	1917.0	2.3
Limestone	2600.0	810.0	2288.0	2.2
Quartzite	2576.0	814.3	2339.0	5.2
Halite	2170.0		1915.0	6.1
Magnetite (300°C)	4700.0	652.9		6.1
Cofalit	3120.0	1034.0	3220.0	2.1
Castable ceramics	3500.0	866.0	3030.0	1.4
HT Concrete	2750.0	916.0	2520.0	1.0



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Hybrid Energy Storage System using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

Solid materials – TES Review

During the experimental phase, basalt stones with a density of 2680 kg/m³ and a thermal conductivity of approximately 2.3 W/(m·K) were used.

The specific heat capacity was adopted based on a previous literature review conducted within the HESS project, and its value is calculated using the following correlation:

$$cp_b = 91.523 \cdot \ln(T_b) + 498.25$$



energies



Review

Review of Thermal Energy Storage Materials for Application in Large-Scale Integrated Energy Systems—Methodology for Matching Heat Storage Solutions for Given Applications

Michał Jurczyk ¹, Tomasz Spietz ², Agata Czardybon ², Szymon Dobras ², Karina Ignasiak ², Łukasz Bartela ¹, Wojciech Uchman ^{1,*} and Jakub Ochmann ^{1,*}



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Hybrid Energy Storage System using post-mining infrastructure” (HESS)
No. 101112380 (RFCs-2022)

Laboratory station – TES



- The container is 3 meters high and has a diameter of 219 mm
- Basalt packed beds with a diameter of approximately 14 mm and 19 mm
- Porosity of the rock packed bed about 38%
- Maximum allowable air capacity approximately 240 kg/h
- Maximum allowable air temperature 110 °C



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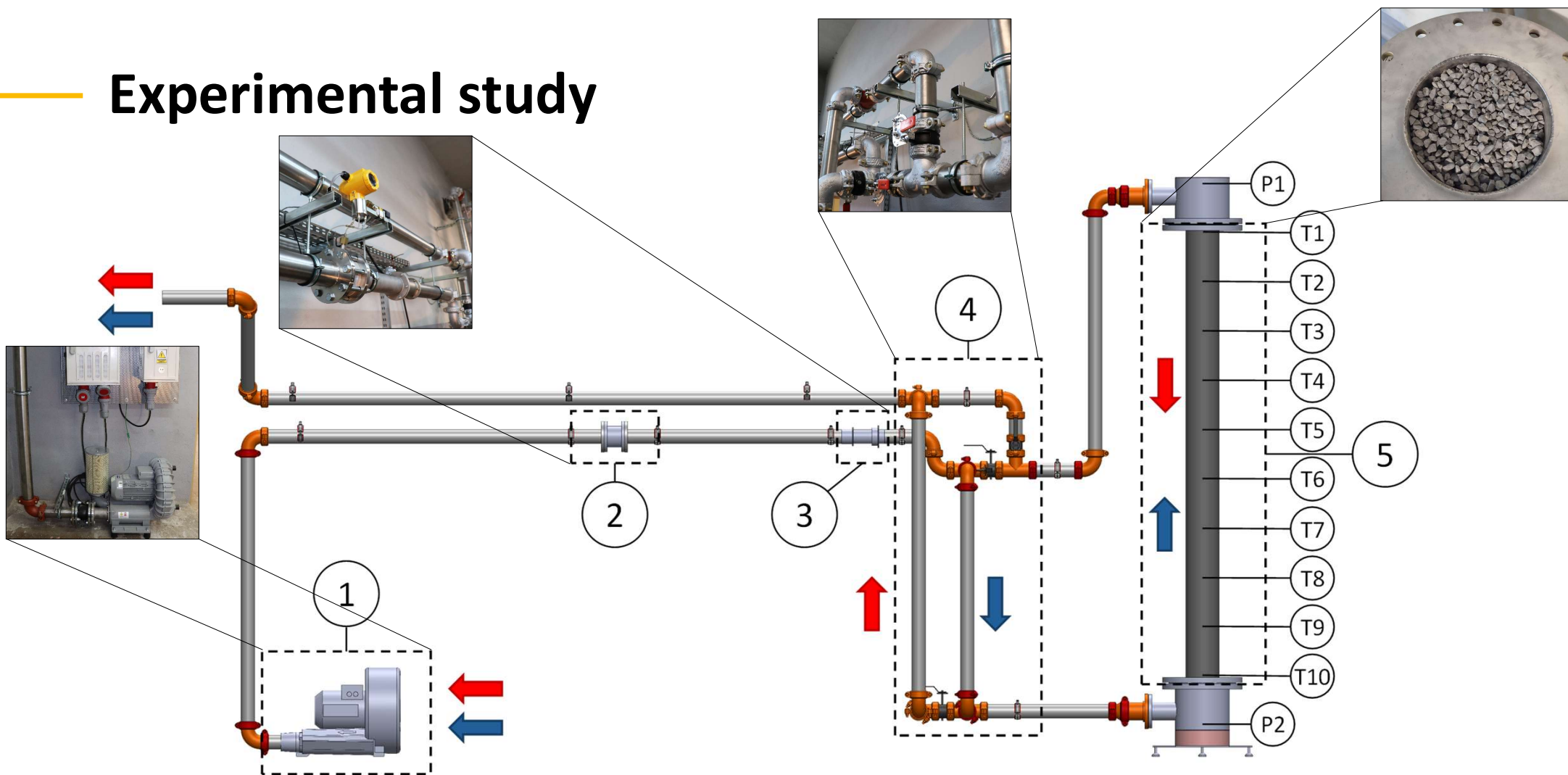


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Experimental study



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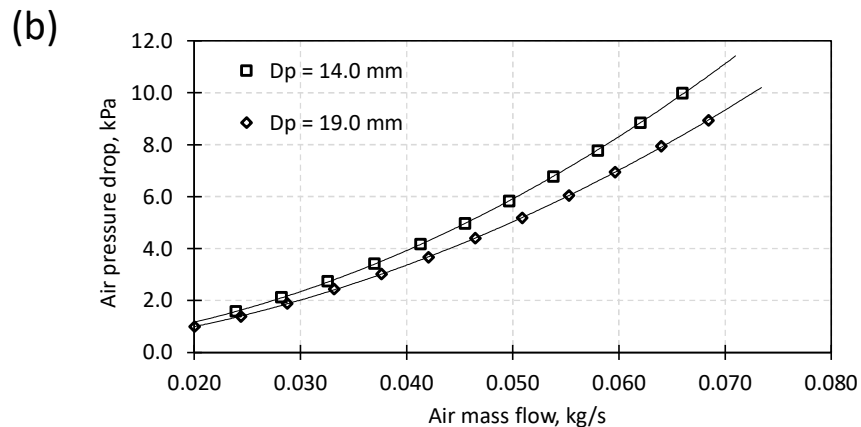
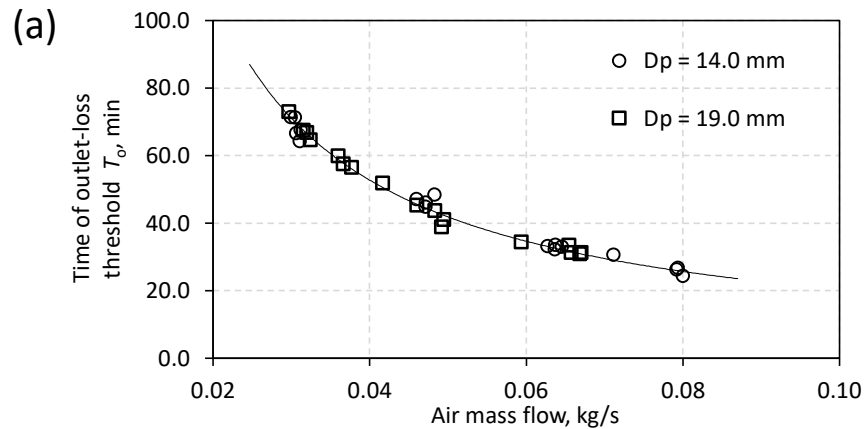


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Hybrid Energy Storage System using post-mining infrastructure" (HESS)
No. 101112380 (RFCS-2022)

Experimental results – TES tank



- Lower air mass flow rate increases the time to reach outlet heat losses during charging.
- Particle size had no significant effect on the outlet loss time in the tested conditions.
- Higher air mass flow rate causes a higher pressure drop in the storage bed.
- Pressure losses also depend on the particle size of the rock bed and affect system efficiency.



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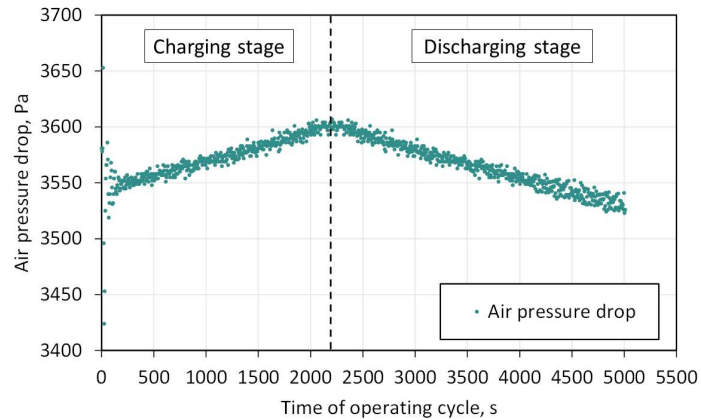
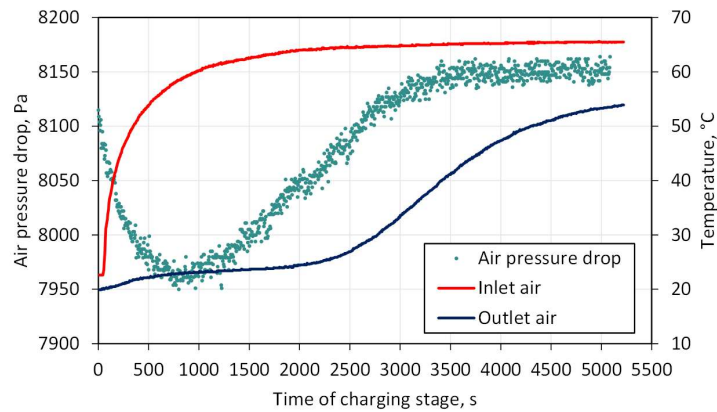
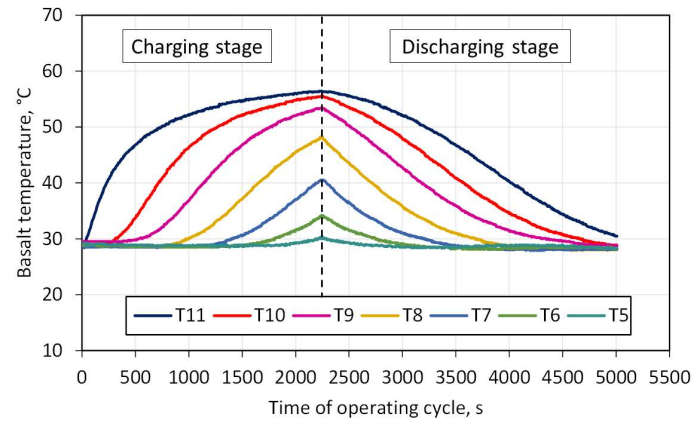
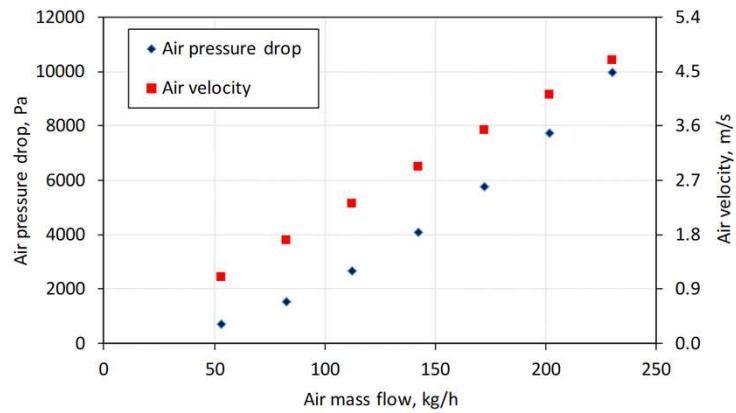


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No. 101112380 (RFCS-2022)

Experimental results – TES tank



8



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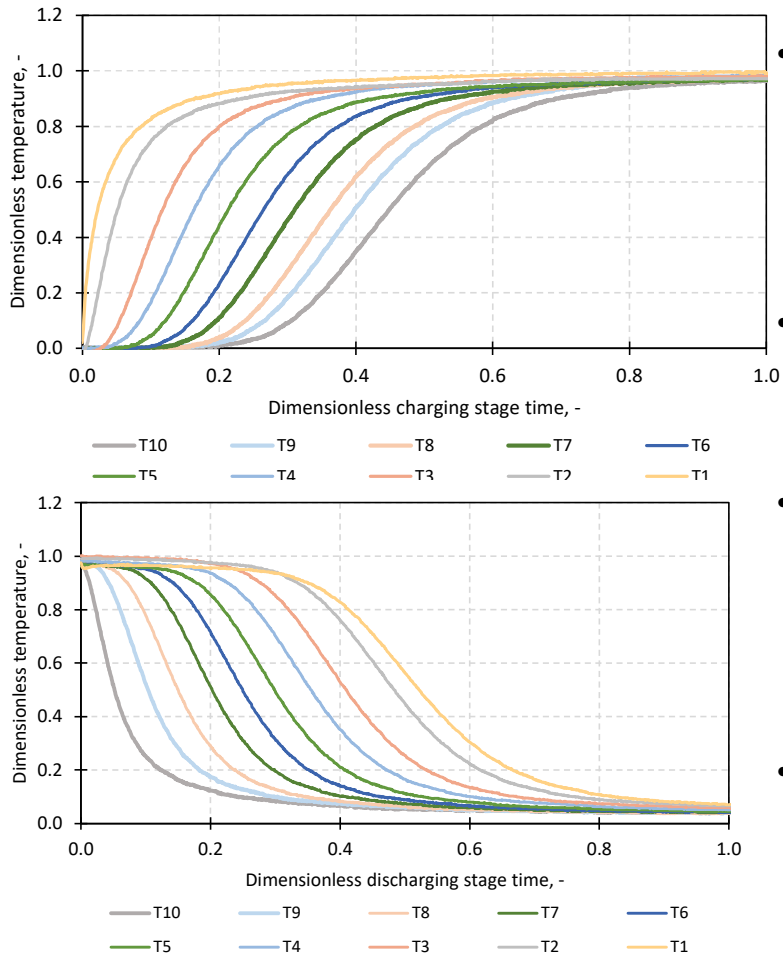


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Experimental results – TES tank



- The maximum recorded temperature of the storage material does not reach the maximum setpoint of the inlet air temperature to the storage unit, even under steady-state thermodynamic conditions. This is due to imperfect heat transfer between the air and the storage material, and the maximum basalt temperature will asymptotically approach the maximum air temperature within a given experimental series.
- Heat exchange between the air and the rock material during airflow through the storage unit results in a non-uniform temperature distribution of the storage material, with a decrease toward the outlet.
- During the charging stage, an increase in the outlet air temperature (T10) is observed after a relatively short time. An increase in outlet losses from the storage unit is undesirable from the perspective of full-scale energy storage system operation; therefore, it should be minimized, for example, by increasing the volume of the storage material relative to the amount of heat supplied.
- During the discharging stage, it is not possible to maintain a constant outlet air temperature from the TES unit, which will have a direct impact on the decrease in air expander power in the considered A-CAES system.



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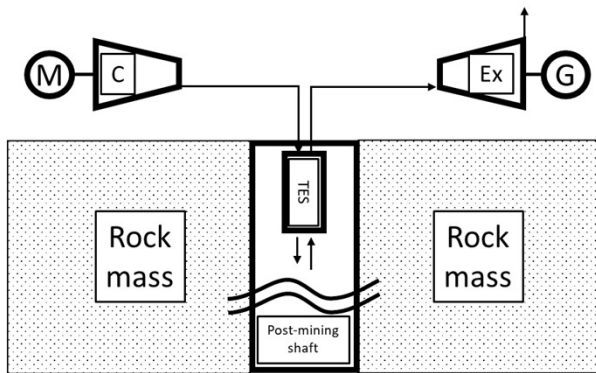
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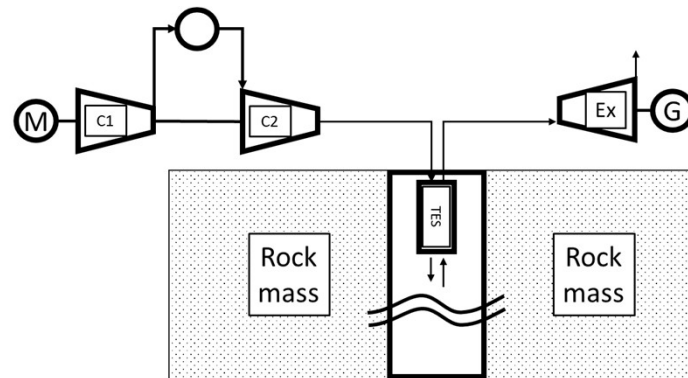
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Numerical investigation of energy storage systems – A-CAES

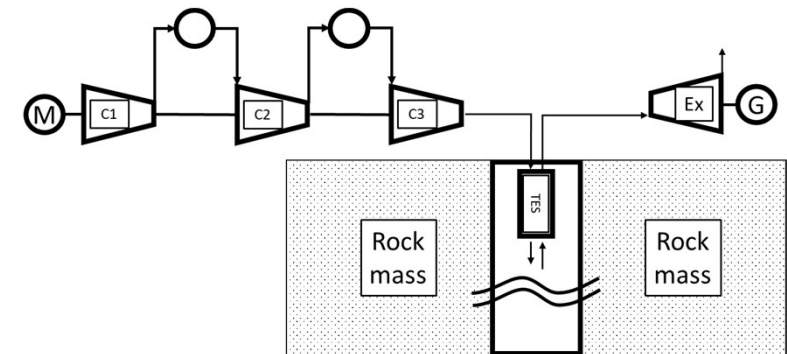
Case I



Case II



Case III



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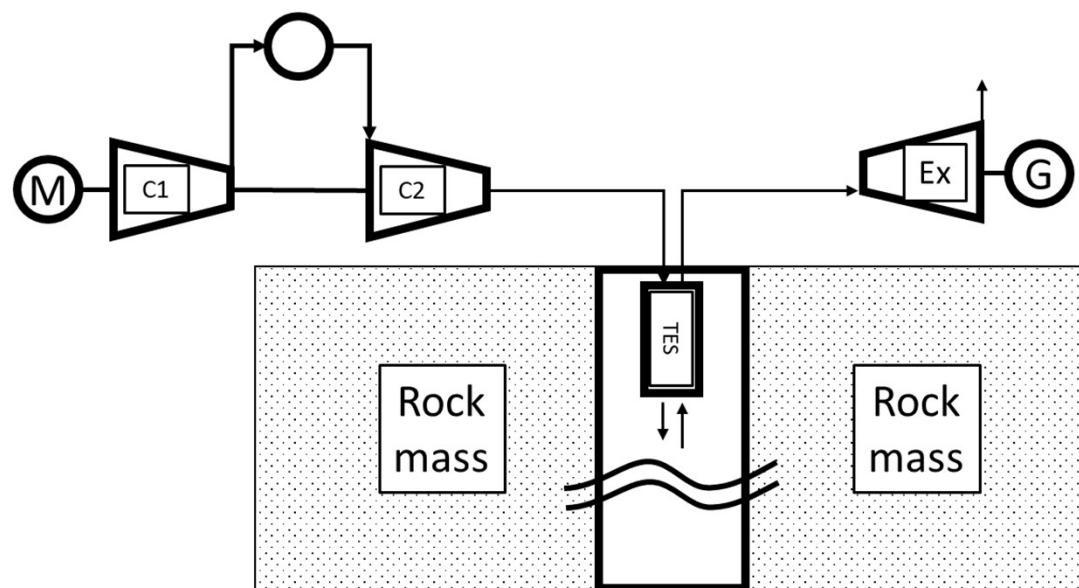


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Investigation results of energy storage systems – A-CAES



Air storage temperature	30	°C
Air compression temperature	500	°C
Charging time	5	h
Discharging time	3	h
Isentropic efficiency – compressor	0.80	-
Isentropic efficiency – expander	0.80	-
Electromechanical efficiency	0.98	-
Total electric power - compressor	33.28	MW
Electric energy consumed per cycle	166,4	MWh
Air mass flow rate - charging	56,61	kg/s
Ambient pressure	101.325	kPa
C1 section outlet pressure	0.4	MPa
Air storage presure	5.0	MPa
C1 section outlet temperature	155	°C
C2 section outlet temperature	up to 500	°C
Total electric power - expander	36.00	MW
Electric energy produced per cycle	108	MWh
Air mass flow rate - discharging	94,34	kg/s
Round-trip efficiency	0,65	-



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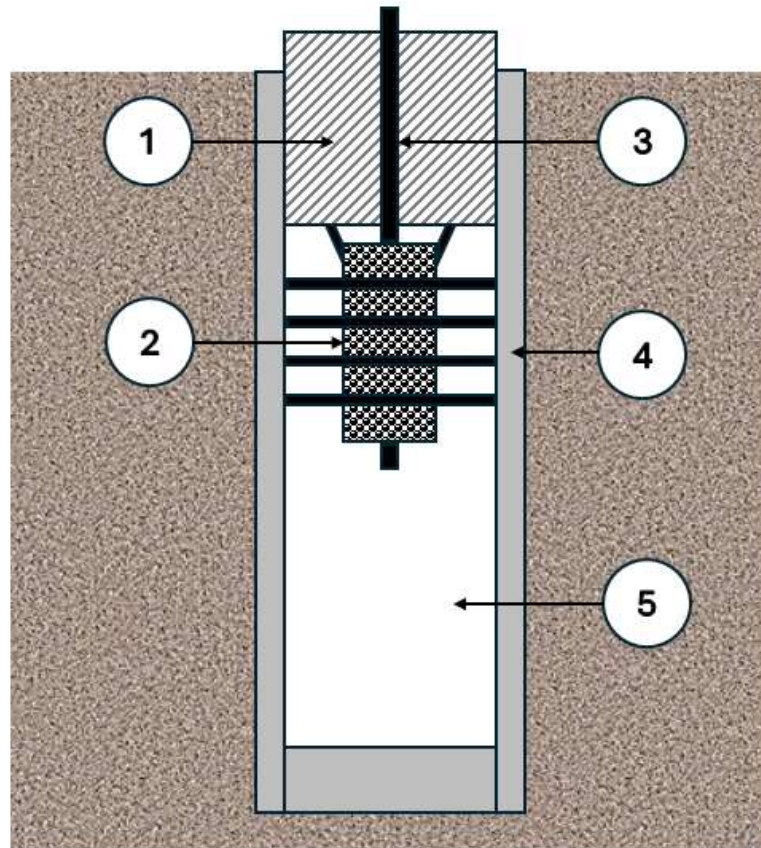


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Investigation results of energy storage systems – A-CAES



Plug diameter	9.0	m
Plug height (analysed variant)	100	m
Design pressure (lower face)	5.1	MPa
Max. pressure for full-height calculation	8.0	MPa

- 1 – shaft plug
- 2 – TES tank
- 3 – compressed air inlet/outlet pipe
- 4 – shaft casing
- 5 – compressed air reservoir



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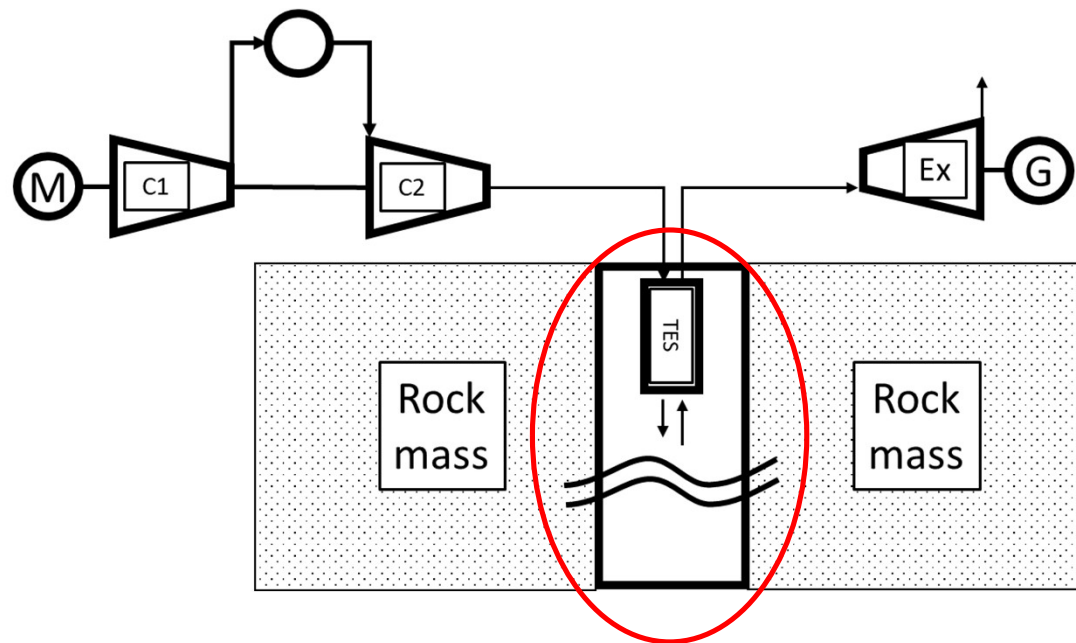
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Numerical investigation of energy storage systems – A-CAES



TES internal diameter	5.0	m
TES segment height	10.0	m
Total length of segments (recommended)	40.0	m
Particles diameter (packed bed)	16	mm
Bed material density (basalt)	2 768	kg/m ³
Bed material specific heat (basalt)	970	J/(kg·K)
Bed porosity	0.38	—
Total basalt mass	1 347	t
Material thermal resistance (basalt)	> 800	°C
Maximum bed temperature	500	°C
Minimum bed temperature	30	°C



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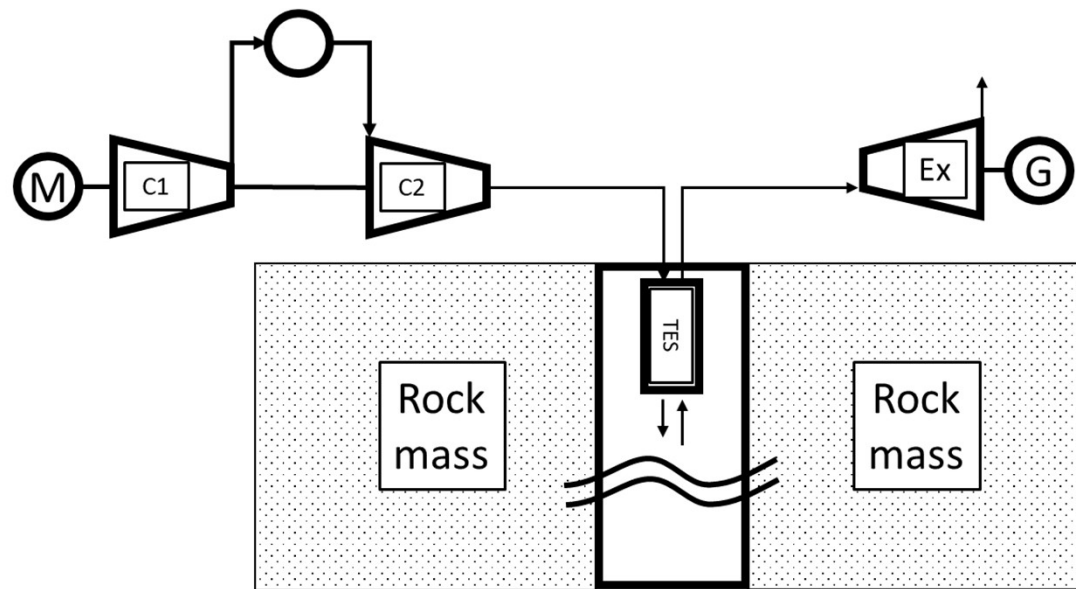


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Numerical investigation of energy storage systems – A-CAES



Compressors
Expander
Thermal Energy Storage — TES
Civil and shaft-related works
Auxiliary equipment (pipelines, valves, intercooler)
A-CAES CAPEX – summary for analyzed scenario

Costs, PLN
40 934 400
86 760 000
12 000 000
22 410 000
14 750 000
176 854 400



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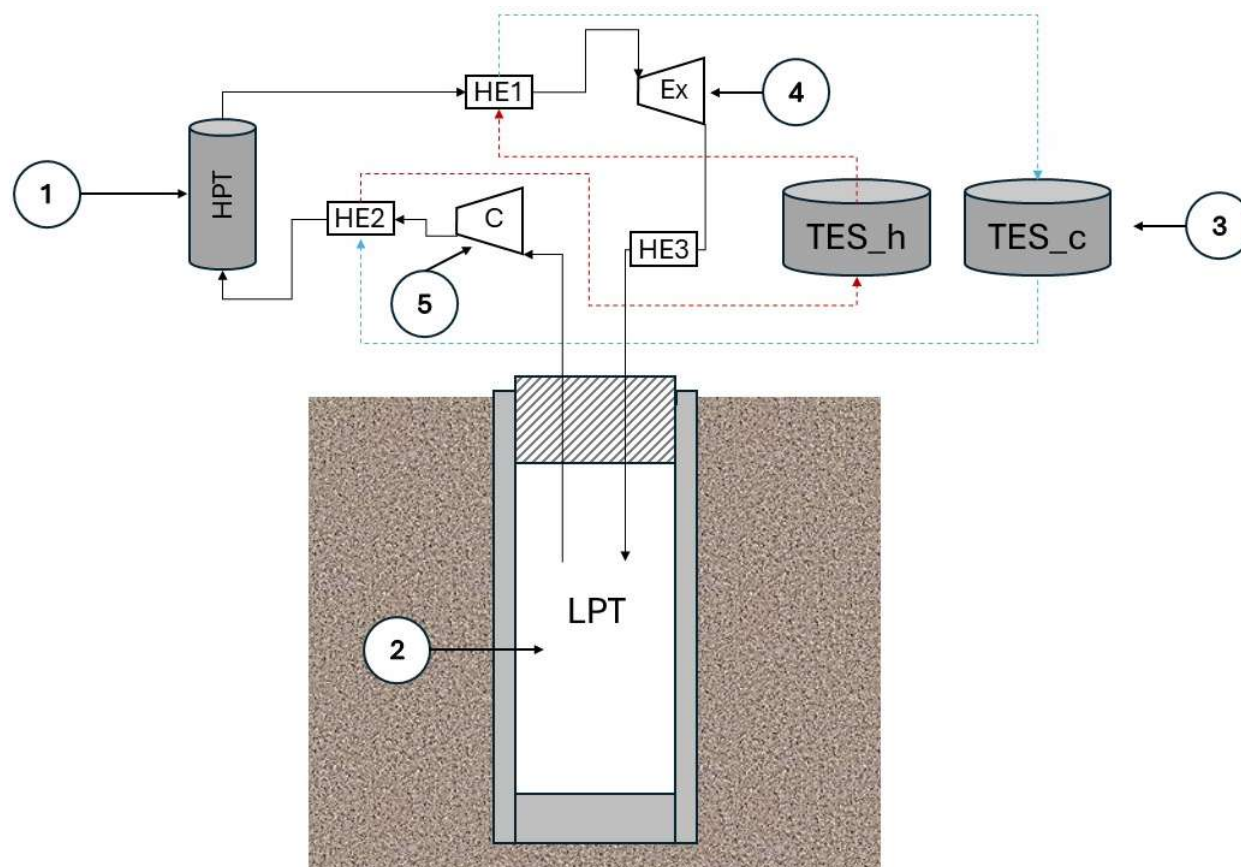


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Hybrid Energy Storage System using post-mining infrastructure” (HESS)
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Energy storage systems – CCES



- 1 – high-pressure vessel
- 2 – low-pressure vessel
- 3 – TES tanks
- 4 – carbon dioxide expander
- 5 – carbon dioxide compressor



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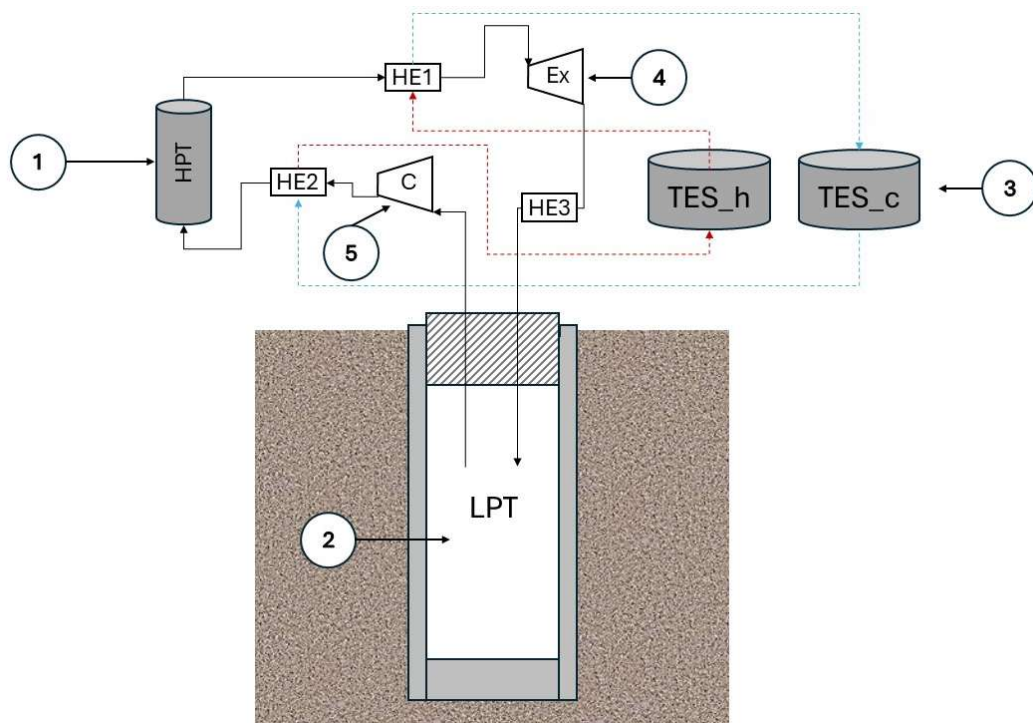


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Hybrid Energy Storage System using post-mining infrastructure” (HESS)
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Numerical investigation of energy storage systems – CCES



CO2 storage temperature (LPT and HPT)	30	°C
CO2 compression temperature	300	°C
Charging time	5	h
Discharging time	3	h
Isentropic efficiency – compressor	0.80	-
Isentropic efficiency – expander	0.80	-
Electromechanical efficiency	0.98	-
TES energy efficiency	0.95	-
Total electric power - compressor	10.06	MW
CO2 mass flow rate - charging	39.88	kg/s
Inlet pressure (from LPT)	0.64	MPa
Outlet pressure (to HPT)	8.00	MPa
Electric energy consumed per cycle	50.32	MWh
Total electric power - expander	10.84	MW
CO2 mass flow rate - discharging	66.46	kg/s
Outlet pressure (to LPT)	0.64	MPa
Electric energy produced per cycle	32.52	MWh
Round-trip efficiency	0.65	-
Required net storage volume (LPT)	63 300	m3
Required net storage volume (HPT)	1 023	m3



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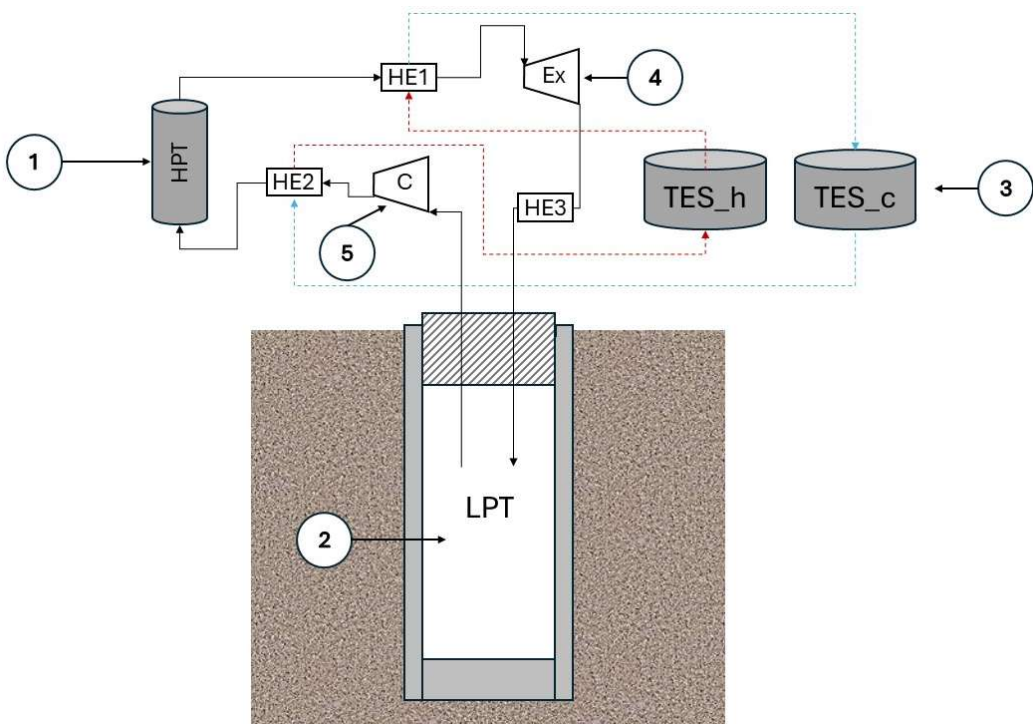


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Numerical investigation of energy storage systems – CCES



Heat transfer fluid	Therminol VP-1 synthetic thermal oil	-
Volume per TES tank	707	m3
Basalt mass per tank	1 213	t
Total basalt mass (both tanks)	2 426	t
Total Therminol VP-1 mass	490	t
Particles diameter (packed bed)	16	mm
Bed material density (basalt)	2 768	kg/m ³
Bed material specific heat (basalt)	970	J/(kg·K)
Bed porosity	0.38	—
Material thermal resistance (basalt)	> 800	°C
Maximum bed temperature	300	°C
Minimum bed temperature	30	°C



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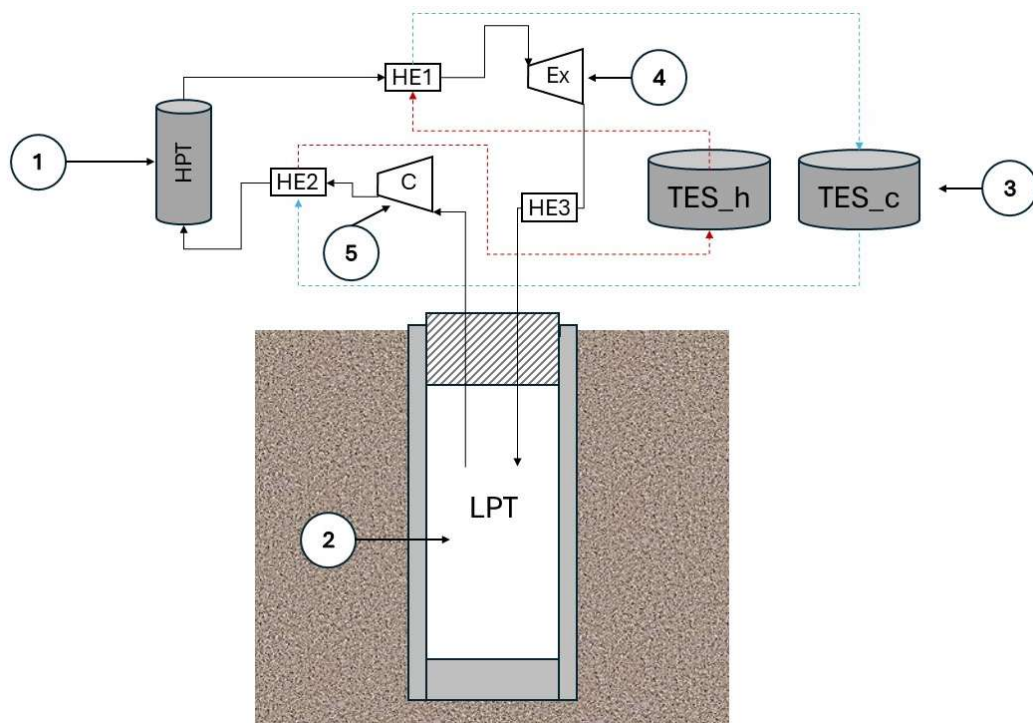


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Numerical investigation of energy storage systems – CCES



Compressor
 Expander
 Carbon dioxide low-pressure storage
 Carbon dioxide high-pressure storage
 Thermal Energy Storage — TES
 Heat exchangers
 Auxiliary equipment (pipelines, valves, intercooler)
CCES CAPEX – summary for analyzed scenario

Costs, PLN
 12 370 000
 26 120 000
 14 200 000
 44 200 000
 18 720 000
 9 100 000
 14 750 000
~130 000 000



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Thank you for your attention



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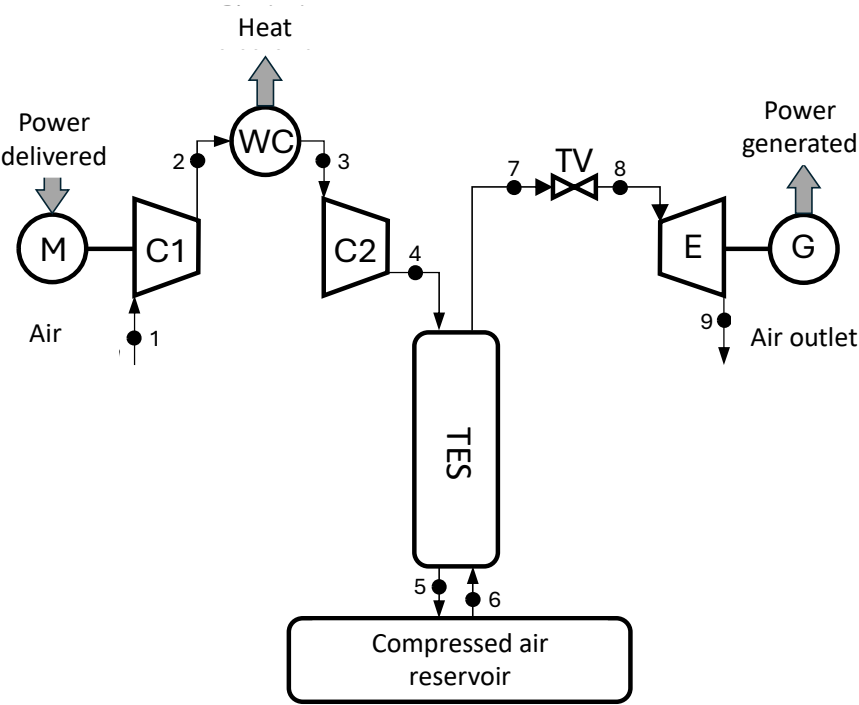
UCZELNIA
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INICJATYWA DOSKONAŁOŚCI

Research on thermal energy storage in single-phase materials. TES tank characterization taking into account technological parameters, device characteristics and costs

Krzysztof Rusin
Silesian University of Technology

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

Modelling of the A-CAES system



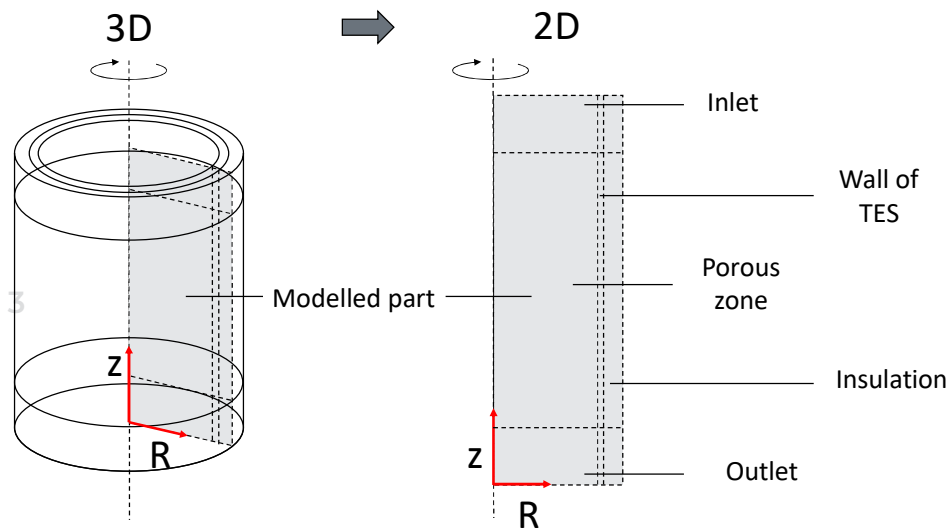
Scheme of the A-CAES system

Comparison of models

	Model I	Model II
Heat transfer	Full thermodynamic and flow analysis	Changes of parameters based on correlations
Cyclic operation	Yes	No
Time of simulations	About 86 h	<1 min
Aim	Verification of the TES tank operation working in A-CAES system	Estimation of post-mining shafts potential
Software	ANSYS Fluent	Excel + VBA



CFD modeling of one segment



The computational domain

Momentum equation:

$$\begin{aligned} \frac{\partial(\epsilon \rho_f \vec{v})}{\partial t} + \nabla \cdot (\epsilon \rho_f \vec{v}) \\ = -\epsilon \nabla p + \nabla \cdot (\mu_{eff} \cdot (\nabla \vec{v} + (\nabla \vec{v})^T)) - \left(\frac{\mu_f}{\alpha} + \frac{C_2 \rho_f}{2} |\vec{v}| \right) \vec{v} \end{aligned}$$

Energy equation:

$$\begin{aligned} \frac{\partial(\epsilon \rho_f E_f)}{\partial t} + \nabla \cdot (\vec{v} (\rho_f E_f + p)) \\ = \nabla \cdot (\epsilon k_f \nabla T + (\vec{\tau} \cdot \vec{v})) + h_{fs} A_{fs} (T_s - T_f) \end{aligned}$$

$$\frac{\partial((1 - \epsilon) \rho_s E_s)}{\partial t} = \nabla \cdot ((1 - \epsilon) k_s \nabla T_s) + h_{fs} A_{fs} (T_f - T_s)$$

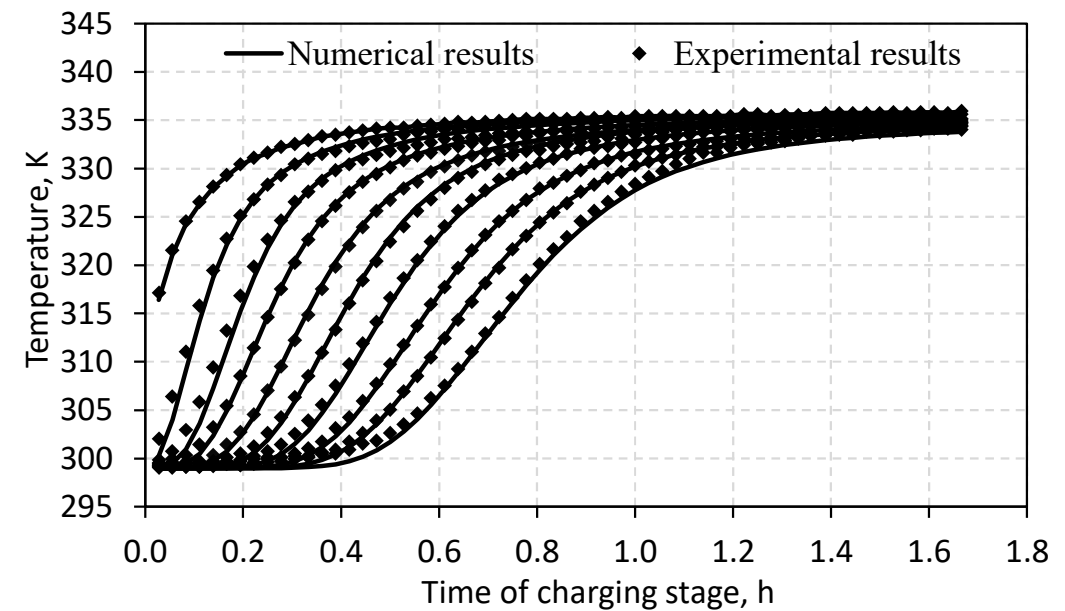
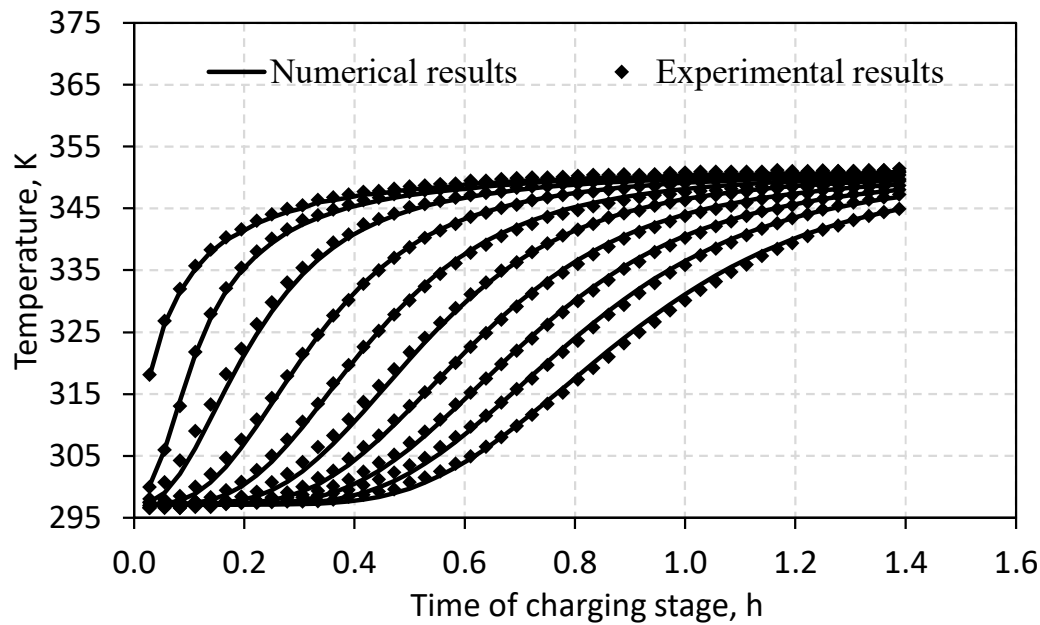
Continuity equation

$$\frac{\partial(\epsilon \rho_f)}{\partial t} + \nabla \cdot (\epsilon \rho_f \vec{v}) = 0$$

Turbulence model

$k - \omega$ SST

Numerical model validation



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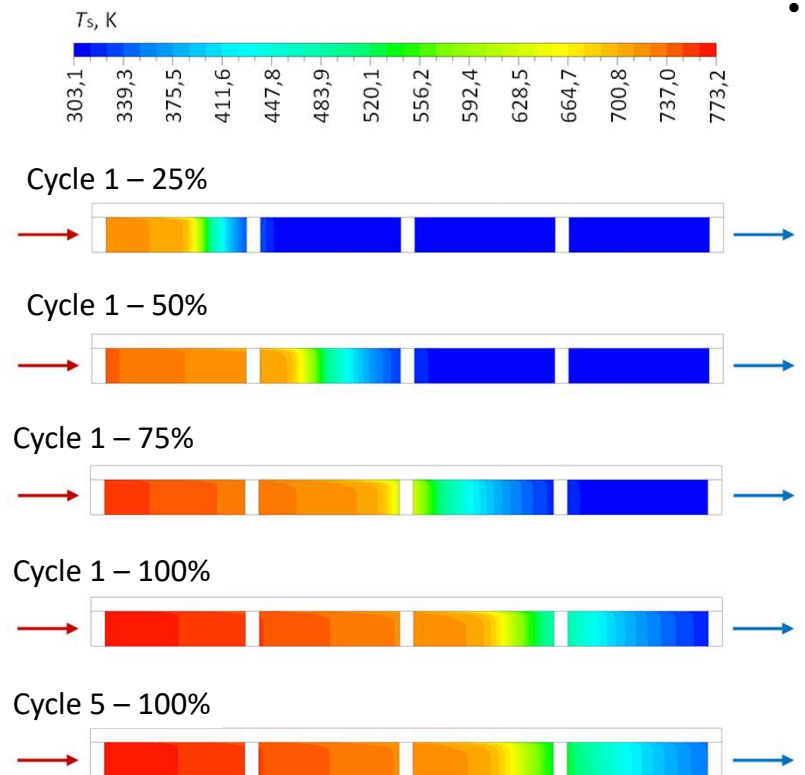


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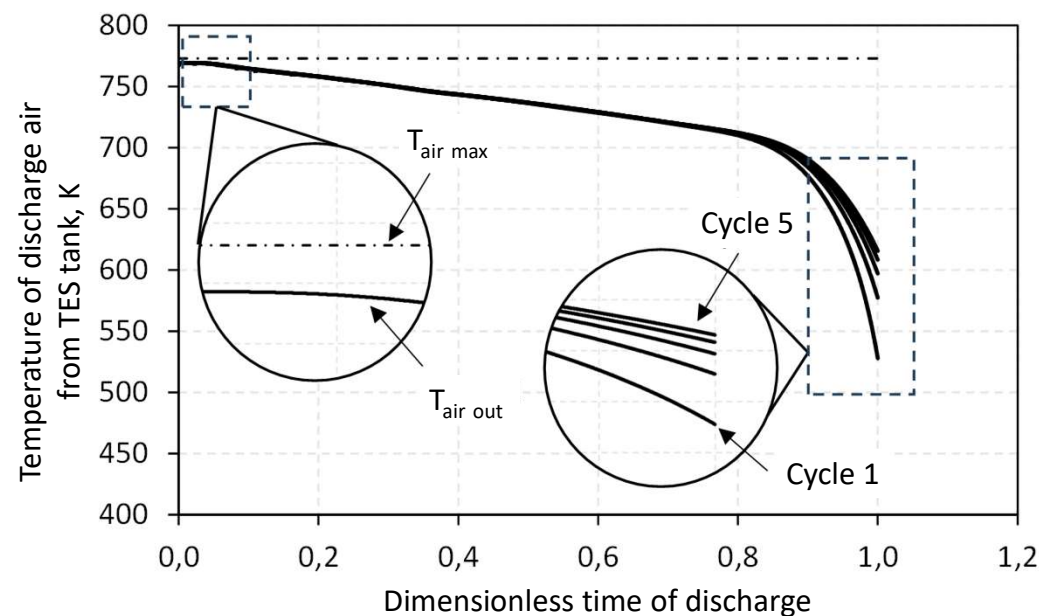
Hybrid Energy Storage System using post-mining infrastructure" (HESS)
No. 101112380 (RFCS-2022)

A-CAES simulations – Model I



Temperature distribution for different cycles of operation

- The reference A-CAES system used a 1000 m deep air reservoir with a diameter of 9 m



Air temperature at the outlet from the TES during the discharge stage for consecutive cycles of operation



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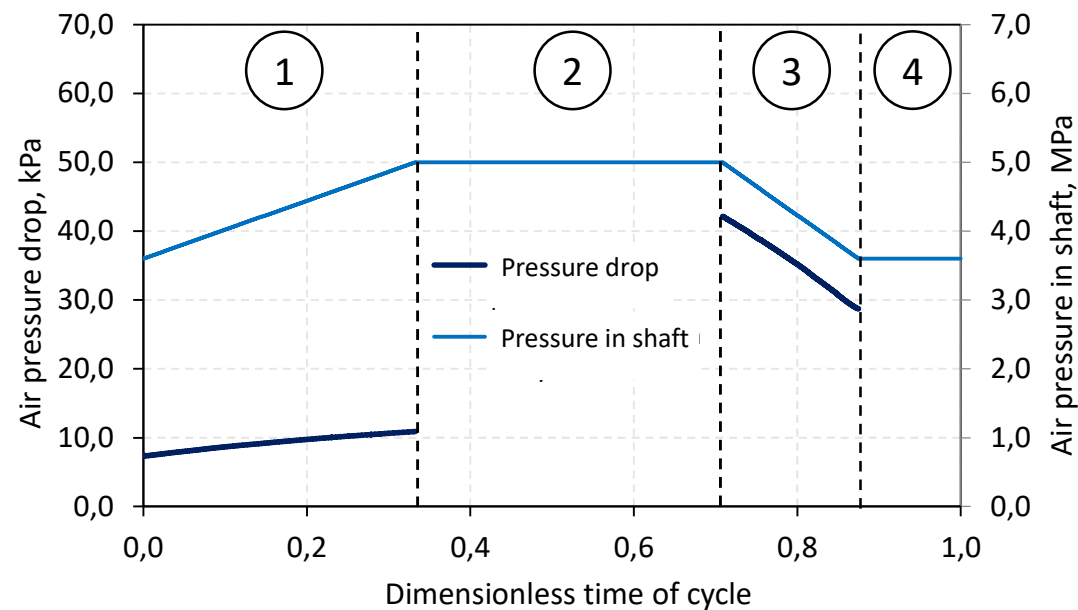


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A-CAES simulations – Model I



Air pressure drop in TES (left axis) and air pressure in the shaft (right axis) during the operation of the A-CAES system:

(1) charging stage, (2) storage stage, (3) discharging stage, (4) idle stage

$$\eta_{en} = \frac{\sum_{i \in D} \delta Q_{htf,i}}{\sum_{i \in C} \delta Q_{C htf,i} + \sum_{i \in (C \cup D)} \delta E_{w,i}} \cdot 100\%$$

$$H_{en} = \frac{\sum_{i \in D} \delta Q_{htf,i}}{\sum_{i \in C} \delta Q_{C htf,i}} \cdot 100\%$$

- Roundtrip energy efficiency of the A-CAES system is **67,71%**,
- Energy efficiency of the TES tank is **97,12%**.



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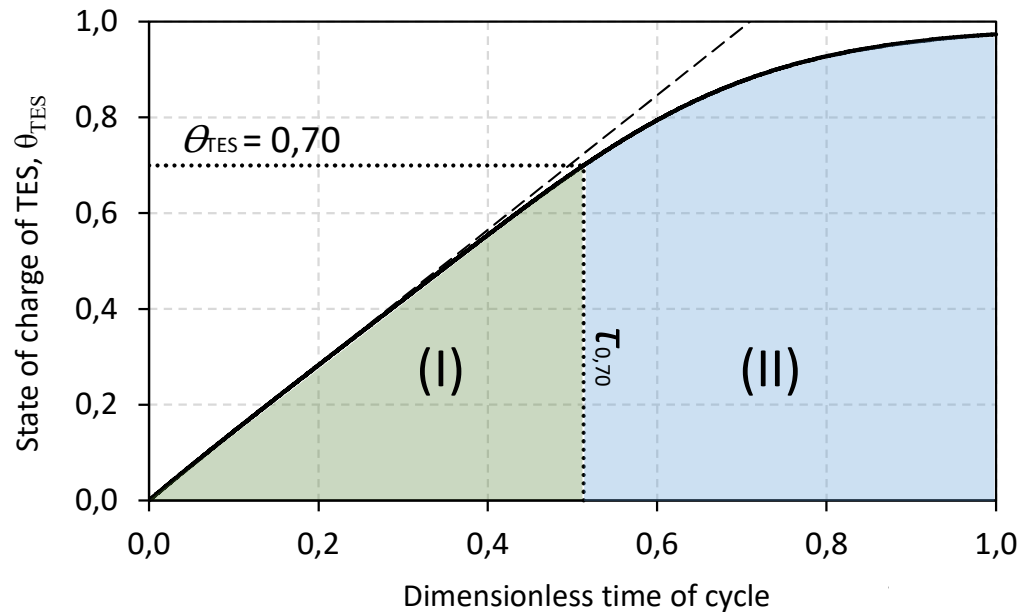


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Time constant



State of charge increment during the charging stage: (I) accumulation, (II) topping-up

$$\theta_{TES} = \frac{T_{avg} - T_{min}}{T_{air max} - T_{min}}$$

$$\frac{\tau_{0,70}}{V_{TES}} = f(\rho_{pb}, cp_b, cp_f, \dot{m}_f)$$

$$\frac{\tau_{0,70}}{V_{TES}} = C_\tau \cdot \frac{\rho_{pb}}{\dot{m}_f} \cdot \frac{cp_b}{cp_f}$$

$$\theta_{TES}(t) = \alpha_\tau \cdot \frac{e^{\beta_\tau \cdot t^{\gamma_\tau}} - e^{-\beta_\tau \cdot t^{\gamma_\tau}}}{e^{\beta_\tau \cdot t^{\gamma_\tau}} + e^{-\beta_\tau \cdot t^{\gamma_\tau}}} = \alpha_\tau \cdot \tan h(\beta_\tau \cdot t^{\gamma_\tau})$$

$$\frac{\alpha_\tau}{\tau_{0,70}} = 0,9688 \cdot \tau_{0,70}^{-0,9989}$$

$$\frac{\beta_\tau}{\tau_{0,70}} = 34,075 \cdot \tau_{0,70}^{-2,6545}$$

$$\frac{\gamma_\tau}{\tau_{0,70}} = 0,7659 \cdot \tau_{0,70}^{-0,9443}$$



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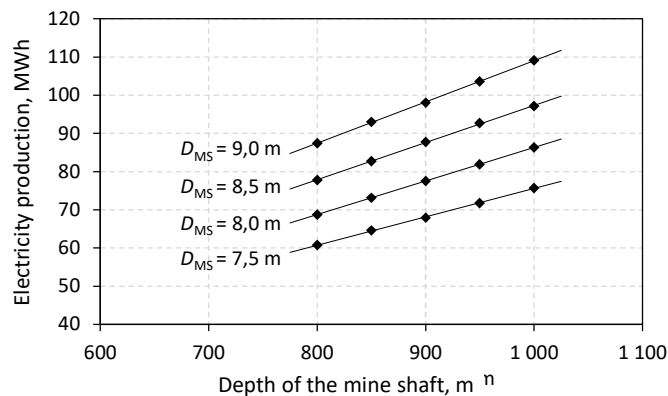
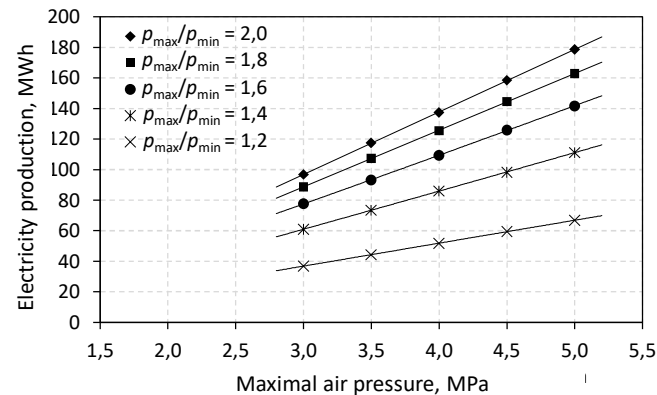


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A-CAES simulations – Model II



Electricity production as a function of (a) maximal air pressure, (b) depth of the mine shaft

Operation range of the TES tank
 $0,08 - 0,75 \theta_{TES}$

Pressure drop
 $\Delta p(\theta_{TES})$

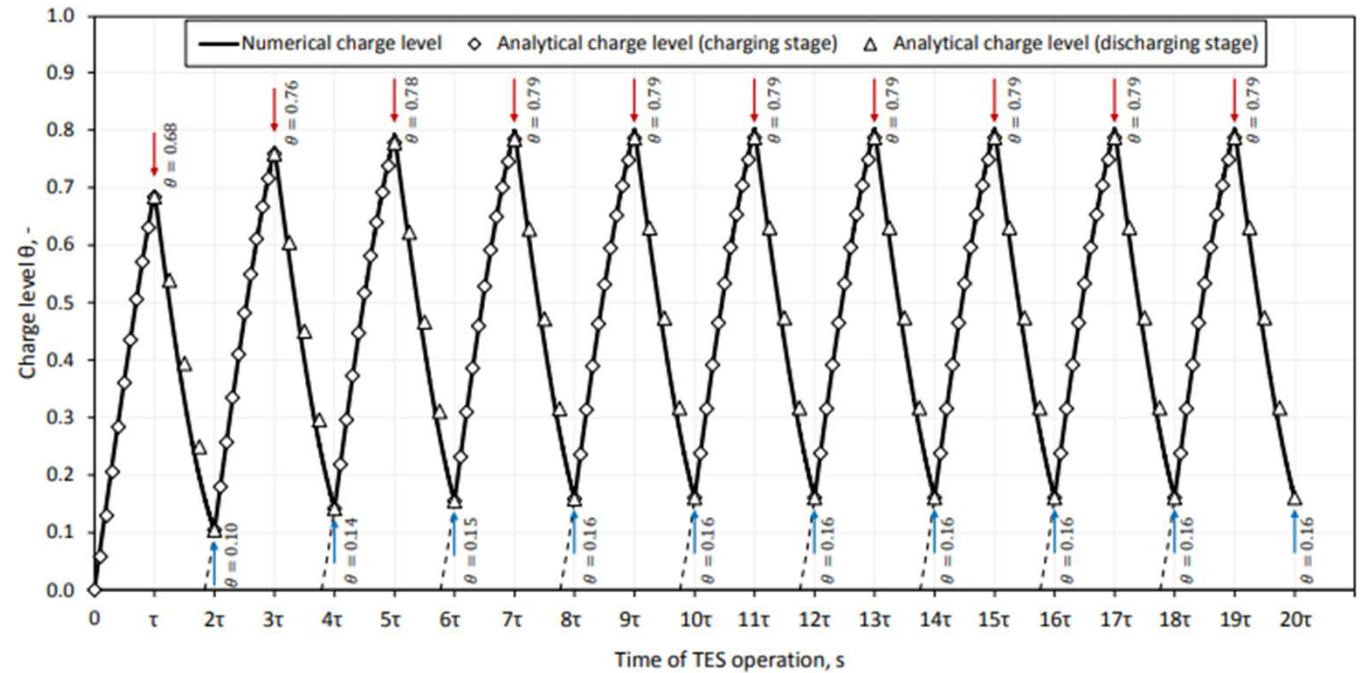
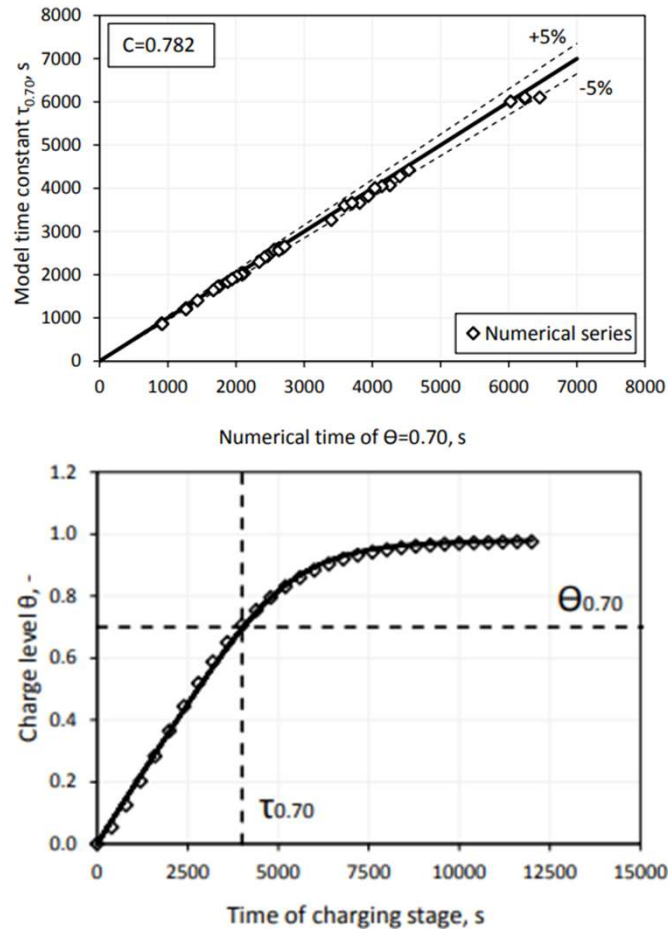
Temperature of the air during the discharge stage
 $T_{out,d}(\theta_{TES}) = (a \cdot e^{b \cdot \theta_{TES}} + c \cdot e^{d \cdot \theta_{TES}}) \cdot T_v$

Comparison of the models

	Model I	Model II
$\eta_{en,A-CA}$	67,71%	64,83%



TES tank operation



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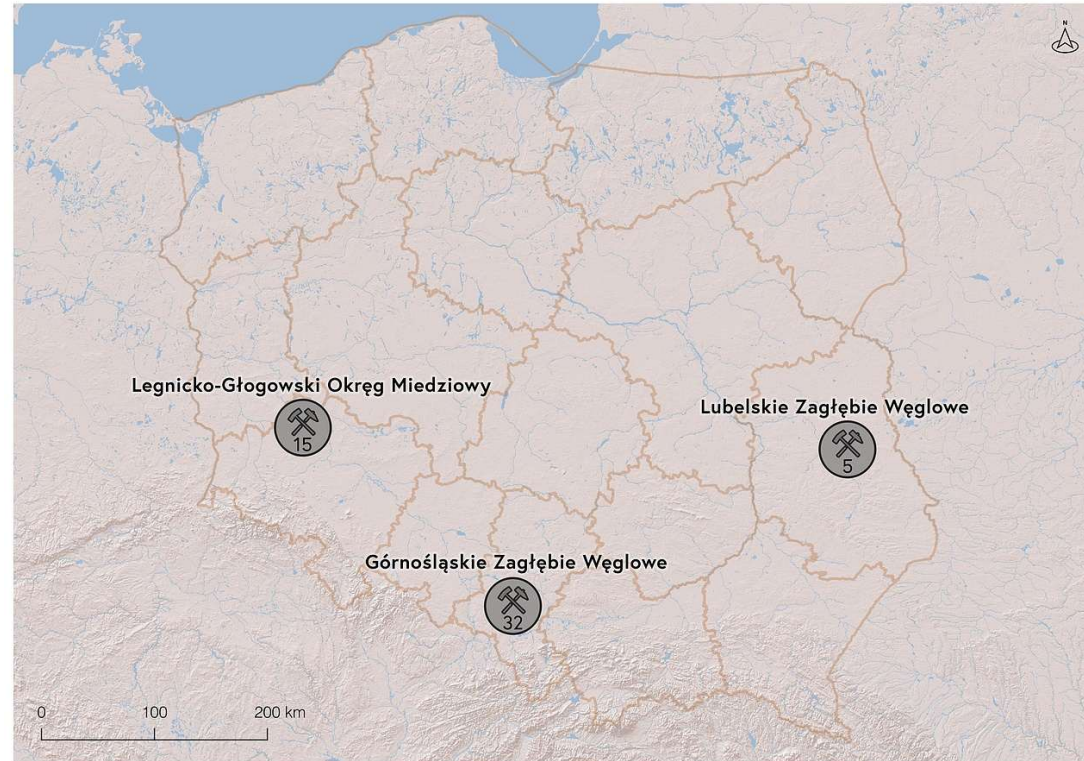
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Conclusions

- A simplified A-CAES model was applied to evaluate 52 mine shafts with depths ranging from 801 to 1320 m and diameters between 7.5 and 9.0 m, enabling an assessment of their energy storage potential.
- The Budryk mine shafts were selected for detailed analysis



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**Hybrid Energy Storage System using post-mining infrastructure” (HESS)
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since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

Experimental Studies on Sensible and Latent Thermal Energy Storage Materials

Tomasz Spietz, Kinga Kulik, Szymon Dobras,
Agata Czardybon

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

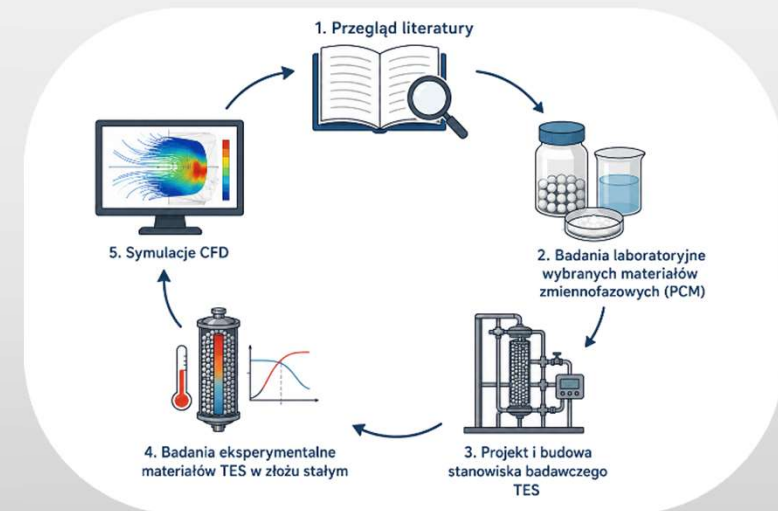
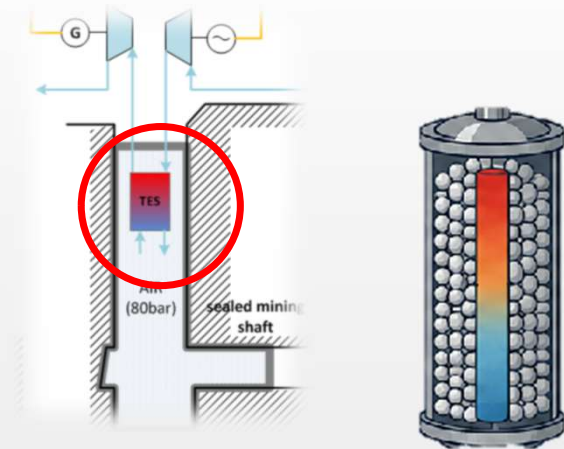
W5 HEAT STORAGE IN POST-MINING INFRASTRUCTURE

Main goal

- Experimental studies of TES materials in order to select appropriate materials and evaluate their potential in a packed-bed

Scope of research

- Literature review
- Lab-scale research on selected phase-change materials (PCMs)
- Design and construction of TES test rig
- Experimental studies TES materials in packed-bed
- CFD simulations



TES – thermal energy storage



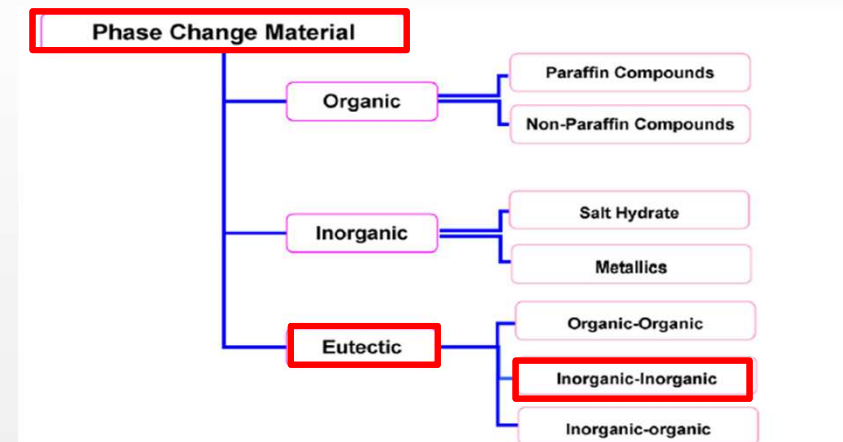
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„Hybrid energy storage system using post-mining infrastructure” (HESS)
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WP5 - Literature review

- About 70 papers about molten salts have been reviewed.
- A summary of PCMs for the operating temperature range (up to 500°C) has been created.
- Results have been presented in Energies Journal



Selected PCMs:

- Hitec XL 48%Ca(NO₃)₂ 45%KNO₃ 7%NaNO₃,
- LiNaK 32% Li₂CO₃ - 35% K₂CO₃ - 33% Na₂CO₃
- Solar Salt 40% KNO₃ 60% NaNO₃



Review

Review of Thermal Energy Storage Materials for Application in Large-Scale Integrated Energy Systems—Methodology for Matching Heat Storage Solutions for Given Applications

Michał Jurczyk¹, Tomasz Spietz², Agata Czardybon², Szymon Dobras², Karina Ignasiak², Lukasz Bartela¹, Wojciech Uchman^{1,*} and Jakub Ochmann^{1,*}



IMPACT
FACTOR
3.2

CITESCORE
7.3

<https://doi.org/10.3390/en17143544>



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Composition of PCM, % wt.	Density, kg/m ³ (at 25°C)	Heat capacity, Cp, J/(g·K)	Thermal conductivity, λ, W/mK (liquid)	Melting temperature, °C	Heat of fusion, J/g	Toxic hazard	Hygroscopicity	Maximum operating temperature, °C	Volume change, %	Price, \$/kg	Reference
38 KNO ₃ - 15 NaNO ₃ - 47 LiNO ₃	NA	1.6	0.5	100	NA	H, Ir	2	500		19.25	[16]
54 KNO ₃ - 20 NaNO ₃ - 26 LiNO ₃		1.09		118	NA	H, Ir	2	435		11.03	[12]
52 KNO ₃ - 18 NaNO ₃ - 30 LiNO ₃	1.975 (140°C), 1.78	1.64	NA	123	155	H, Ir	2	435, 540		12.60	[8], [14], [17]
48 Ca(NO ₃) ₂ - 45 KNO ₃ - 7 NaNO ₃ (Hitec XL)	1.992 (300°C)	1.45 (at 300°C), 1.272	0.52 at 300°C	120, 130	55.4	H, Ir	2	550-554		0.61	[1-2], [10], [17]
60 KNO ₃ - 30 LiNO ₃ - 10 Ca(NO ₃) ₂		1.395		132	na	H, Ir	2	567		12.60	[10]
67 KNO ₃ - 33 LiNO ₃	1.93 (140°C)			133	170	Ir	2		13.50%	13.84	[8]
66.6 KNO ₃ - 10 LiNO ₃ - 23 Ca(NO ₃) ₂ (HPHTF-B)	NA	1.5 (300°C)	0.5696	136	NA	H, Ir	2	600		4.70	[16]
67 KNO ₃ -14 LiNO ₃ - 19 Ca(NO ₃) ₂ (HPHTF-A)	NA	2.08 (300°C)	0.506	137	NA	H, Ir	2	600		6.29	[16]
55 KNO ₃ - 10 LiNO ₃ - 25 Ca(NO ₃) ₂ (HPHTF-C)	NA	1.4 (300°C)	0.5791	138	NA	H, Ir	2	600		4.69	[16]
53 KNO ₃ - 40 NaNO ₂ - 7 NaNO ₃ (HITEC)	1.98	1.56 (at 300°C), 1.439	0.2 at 300°C	142	80, 59	T, Ir	1	530-535, 630, 450		0.95	[1-2], [9], [10-12], [17]
68.6 ZnCl ₂ - 7.5 NaCl - 23.9 KCl	2 (600°C)	0.81	NA	204	NA	H, C	3	850		0.65	[16]

„Hybrid energy storage system using post-mining infrastructure” (HESS)
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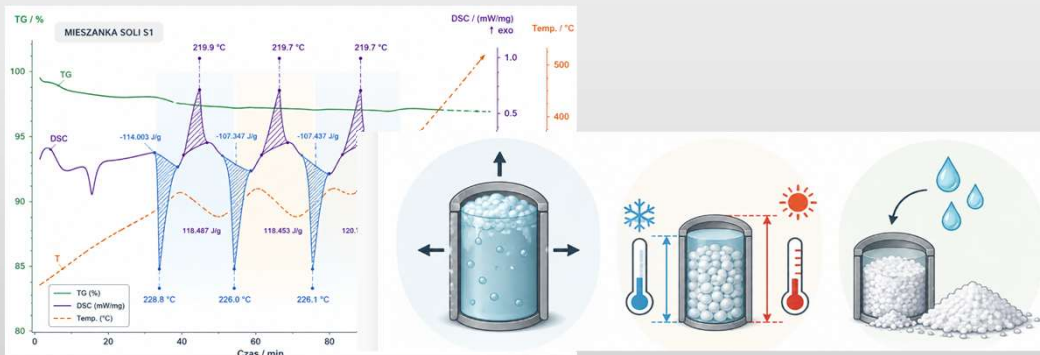
WP5 – Laboratory-scale research

- **Hitec XL**, $T_m = 120^\circ\text{C}$, $H_f = 55 \text{ kJ/kg}$, operating temperature $120\text{--}450^\circ\text{C}$, very hygroscopic.
- **Solar Salt** - $T_m = 220^\circ\text{C}$, $H_f = 117 \text{ kJ/kg}$ cheap, non-toxic, practically non hygroscopic, easy to handle, operating temperature $220\text{--}500^\circ\text{C}$.
- **LiNaK**, $T_m = 400^\circ\text{C}$, $H_f = 270 \text{ kJ/kg}$, very good stability ($800\text{--}850^\circ\text{C}$), low toxicity, expensive.



Practical issues:

- Incomplete dehydration of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ (**CN**) leading to foaming and pressure increase in PCM capsule
- Different thermal expansion of tested PCM
- Hygroscopic nature of anhydrous CN



H_f – heat of fusion



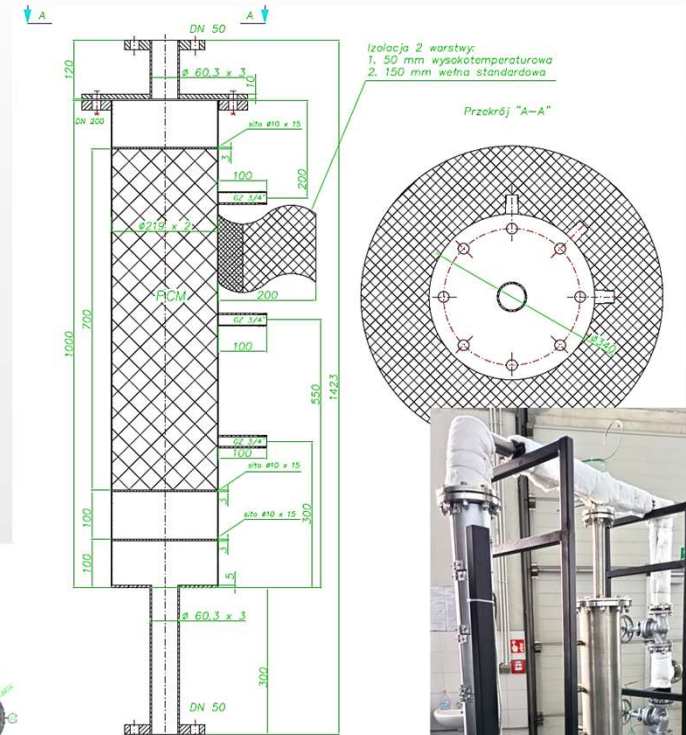
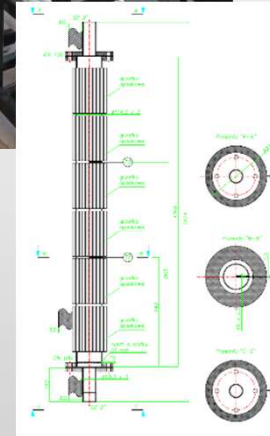
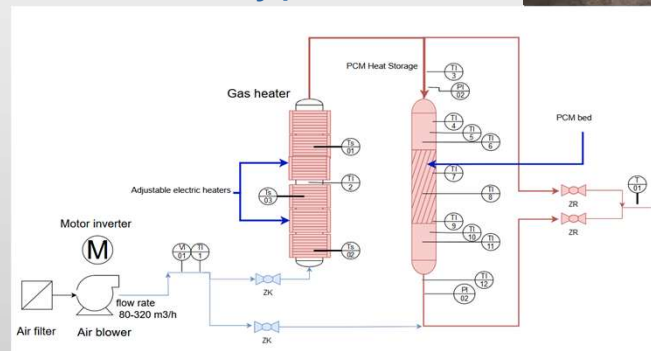
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WP5 - design and construction of TES test rig

- ITPE designed and constructed test rig for test TES materials at elevated temperatures
- Air-based fixed bed system
- Capacity – 25L of TES material
- Operating temperature up to 500°C
- Temperature measurements across the column
- 200 mm of insulation (two types)



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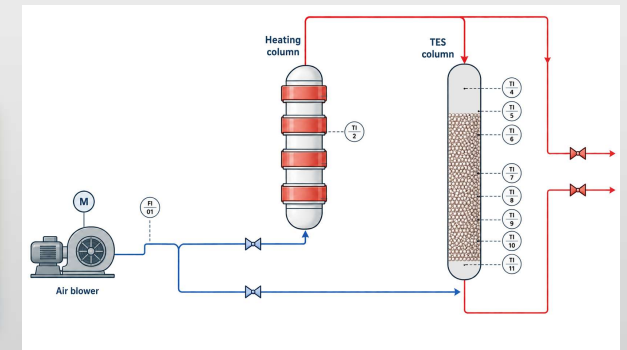
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WP5 – TES studies

- Variables: air flow rate (50-100 m³/h) and packed-bed temperature (150-400°C)
- Materials studied: basalt (sensible heat storage) and PCM (latent heat storage)
- The thermal response of TES was investigated (i.e., temperature profiles, energy input/output, power, charging/discharging efficiency, pressure drops, overall storage efficiency)



Results will be presented in Energies (currently under review)



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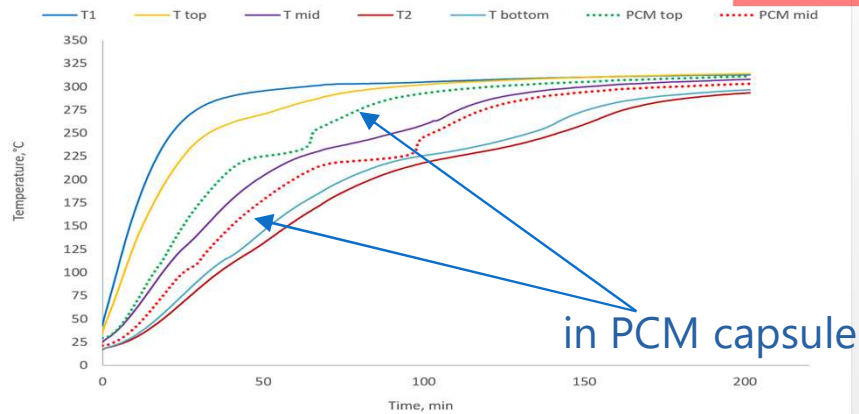


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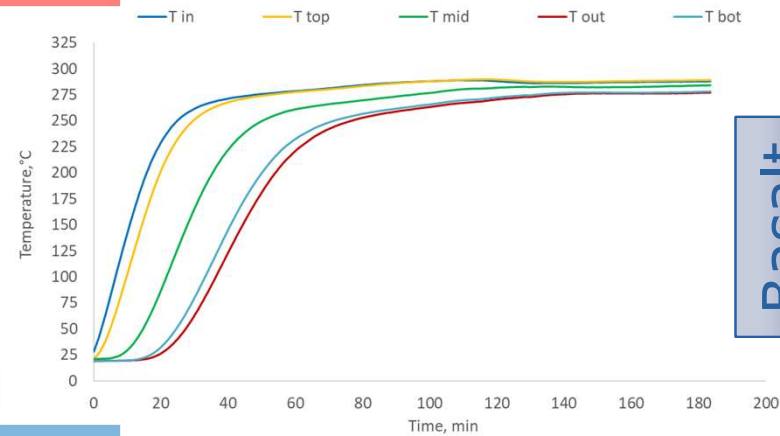
WP5 – Results of TES studies

Charging

PCM

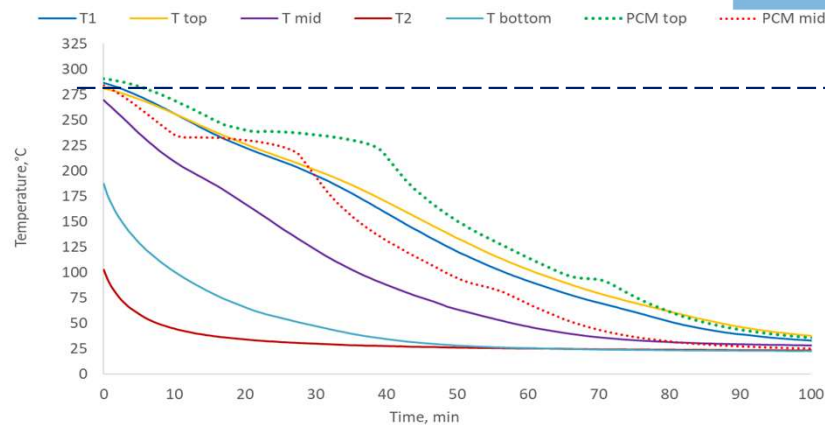


Basalt

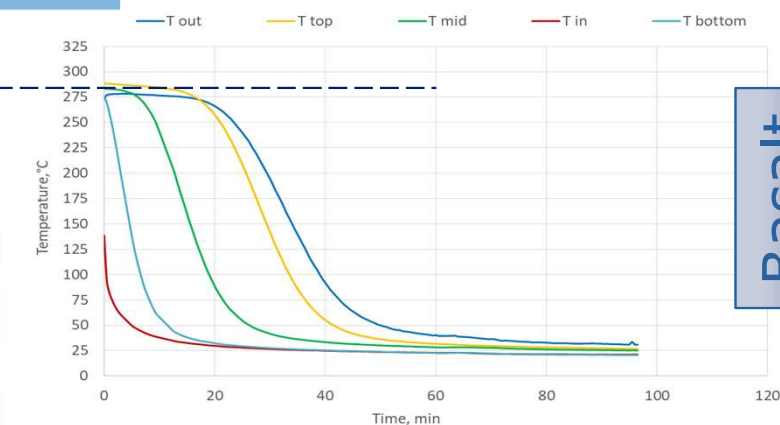


Discharging

PCM



Basalt

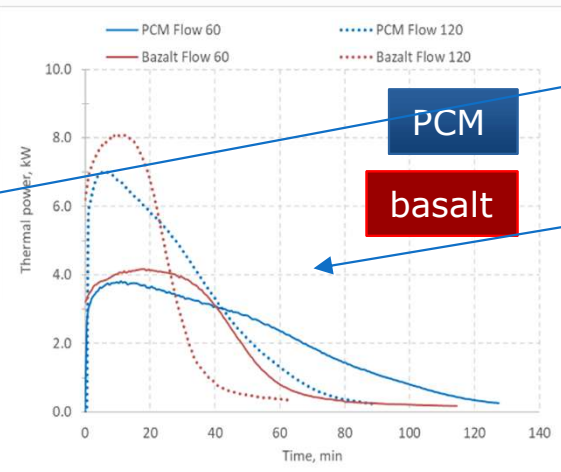
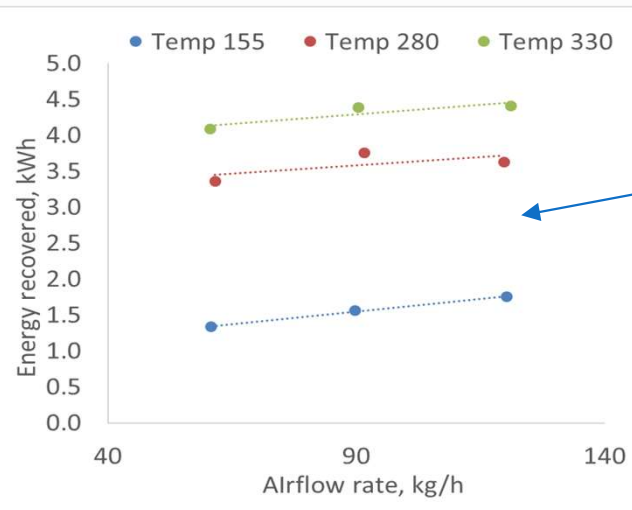


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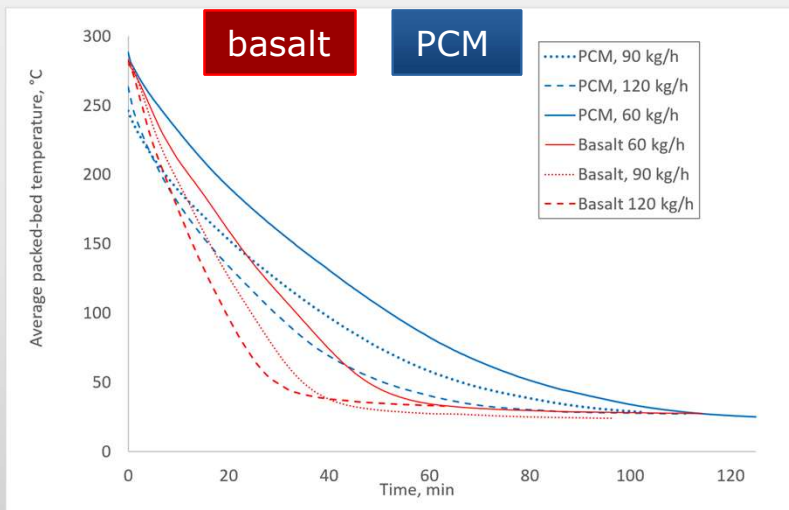


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WP5 – Results of TES studies



- Stored energy depends mainly on packed-bed temperature
- Higher air flow rate increases thermal power
- TES efficiency average: **87%**



At similar average packed-bed temperature:

- Energy density,
basalt: 470 – 520 MJ/m³, PCM: 610-690 MJ/m³ ↑
- Energy recovered,
basalt: 3.4 – 3.8 kWh, PCM: 4.3 – 4.9 kWh ↑
- Average Power,
basalt: 1.8 – 3.4 kW, PCM: 2.5 – 3.1 kWh ↑
- Maximum Power, **Basalt 8 kW** ↑ **PCM 7 kW**



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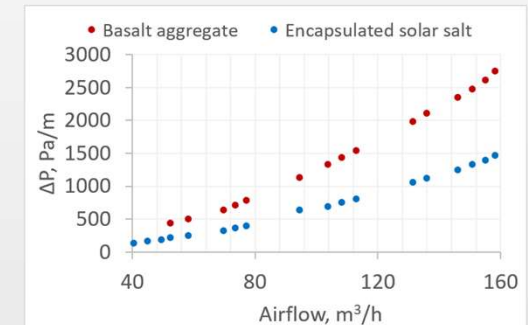


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Mass of PCM 25 kg, basalt 42 kg, volume of the bed: 25 dm³

Summary

- The storage efficiency of the TES is high (about 90%)
- Basalt – allows slightly higher maximum power than PCM but provides lower stored energy and lower average power
- Solar Salt as PCM offers better thermal performance than basalt
- PCM capsules have lower pressure drop than basalt bed
- PCM preparation is more complex, more time-consuming, and more expensive than the use of sensible heat storage material
- Solar salt is practically stable and easy to operate up to 500°C. Basalt can operate even at higher temperatures.



Deliverables provided:

- D5.1 – Thermal energy storage material studies
- D5.2 – TES performance report



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since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

Numerical modelling of latent heat storage systems

Authors: Kinga Kulik, Tomasz Spietz, Szymon Dobras, Agata Czardybon,

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

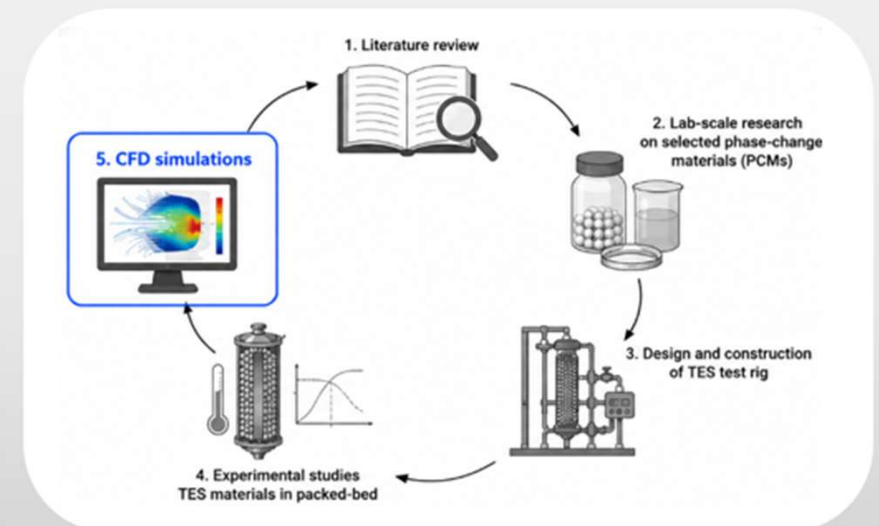
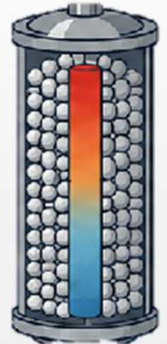
W5 HEAT STORAGE IN POST-MINING INFRASTRUCTURE

Scope of research

- Literature review
- Lab-scale research on selected phase-change materials (PCMs)
- Design and construction of TES test rig
- Experimental studies TES materials in packed bed
- **CFD simulations**

The CFD part represents the numerical continuation of the experimental work carried out within WP5

TES – thermal energy storage



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Numerical modelling of latent heat storage systems

Objective of the simulation: CFD (ANSYS Fluent) simulation of a packed-bed (TES) system with bottles filled with Solar Salt PCM

Scope of analysis: Thermal and phase-change phenomena occurring in the system

- Variant 1 – simplified model:
 - Constant temperature applied to the model surface
 - All PCM bottles melt in the same way
 - Analysis of: PCM temperature profile, PCM melting front (liquid fraction).
- Variant 2 – extended model:
 - Realistic column geometry with a packed bed of bottles
 - Forced upward flow of hot air through the column
 - Analysis of: Air and PCM temperature profile, PCM melting front (liquid fraction).



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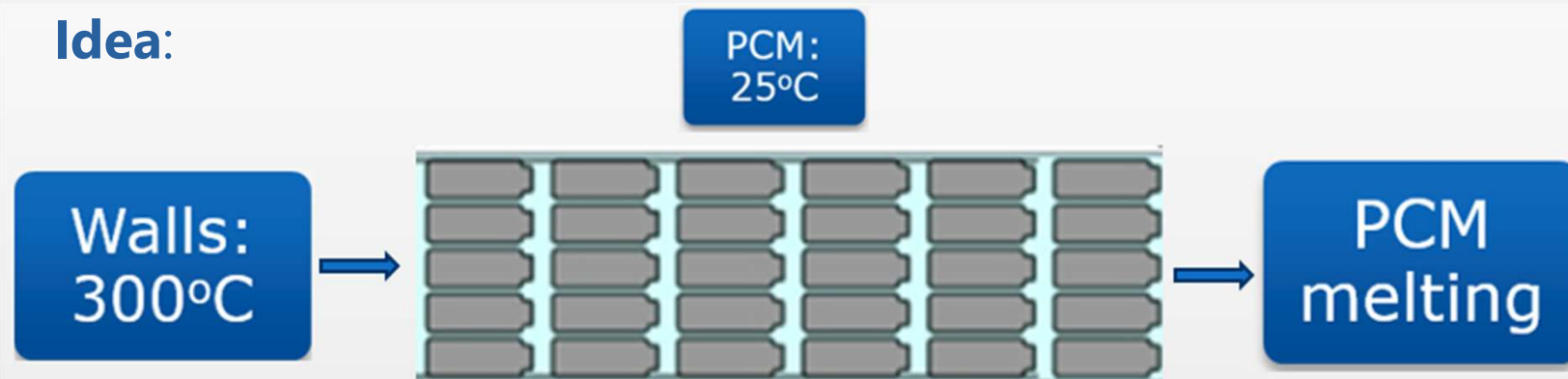
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Variant 1

Simulation conditions:

- 2D model of a packed bed of aluminum bottles filled with PCM
- Initial bottles temperature: **25°C**
- Temperature boundary condition (wall): **300°C**
- PCM material: **Solar Salt (NaNO₃–KNO₃)**

Idea:



- Melting temperature range:

$$T_{\text{solidus}} = 220^{\circ}\text{C}$$

$$T_{\text{liquidus}} = 225^{\circ}\text{C}$$

Material properties		Value	Unit
ρ	Density	1275	kgm^{-3}
C_p	Specific heat	1518	$\text{Jkg}^{-1}\text{K}^{-1}$
β_{th}	Thermal expansion coefficient	0,000384	K^{-1}
η	Dynamic viscosity	0,00326	$\text{kgm}^{-1}\text{s}^{-1}$
λ	Thermal conductivity coefficient	0,55	$\text{Wm}^{-1}\text{K}^{-1}$
L_f	Latent heat of fusion	115000	Jkg^{-1}



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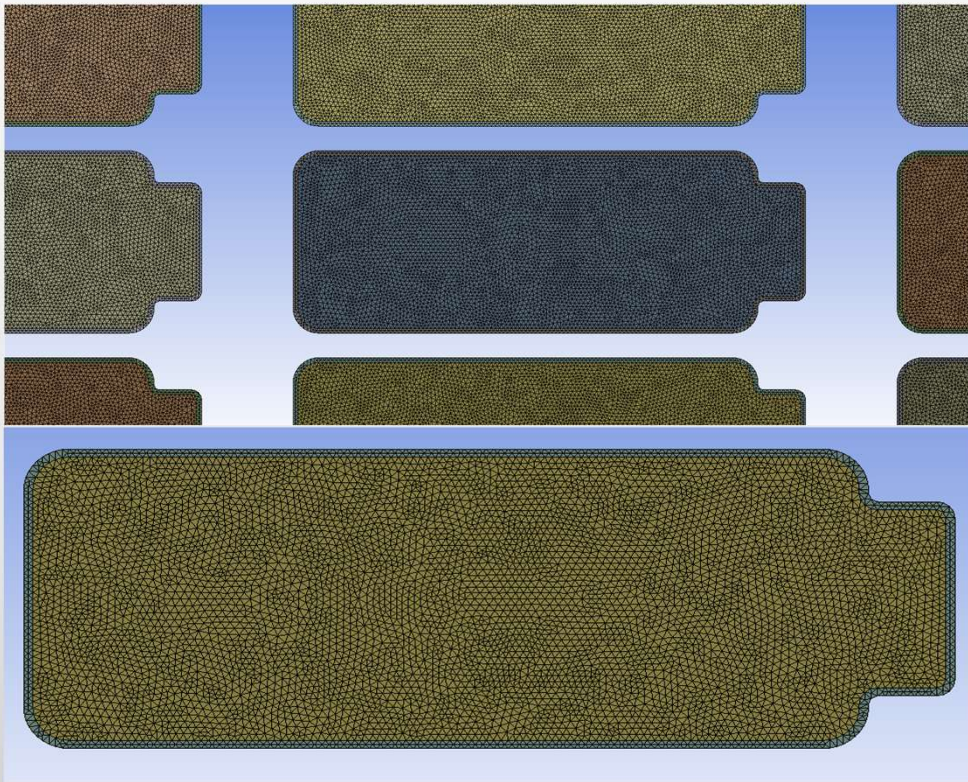


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Variant 1 - results

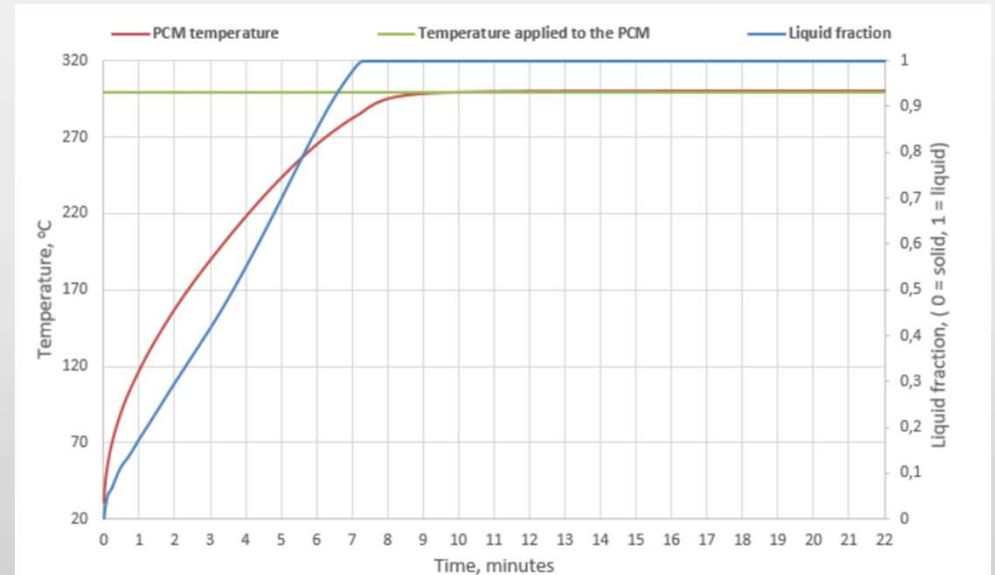
Mesh:

- Type of mesh: tetrahedrons
- Number of elements: 374 890



Results:

- The PCM is heated from all sides by a constant temperature.
- After about 7 min. the PCM is fully melted
- After 10 min. the temperature stabilises.



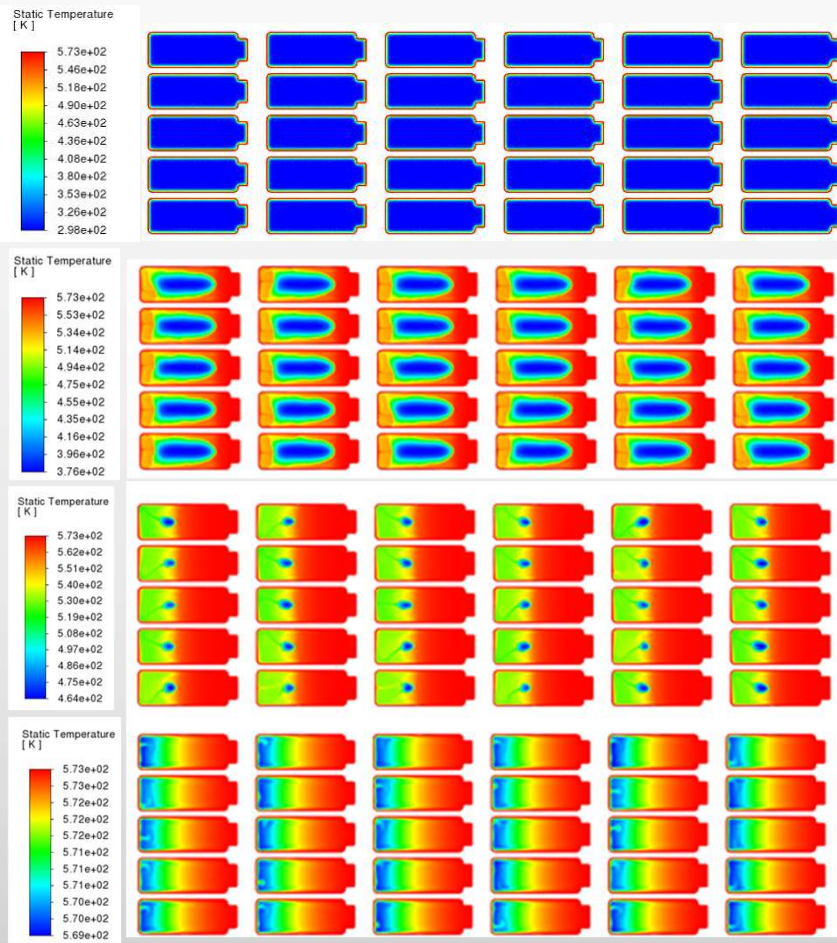
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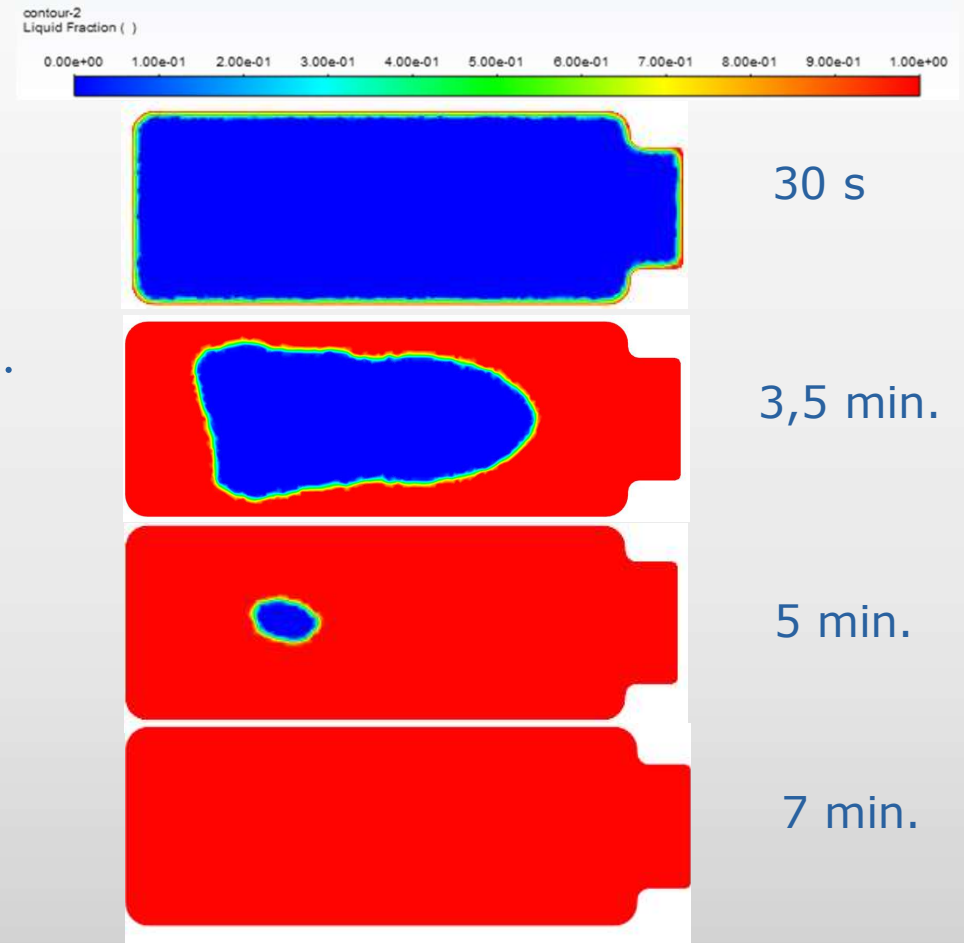
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Variant 1 - results

Static temperature:



Liquid fraction (0=solid, 1=liquid):



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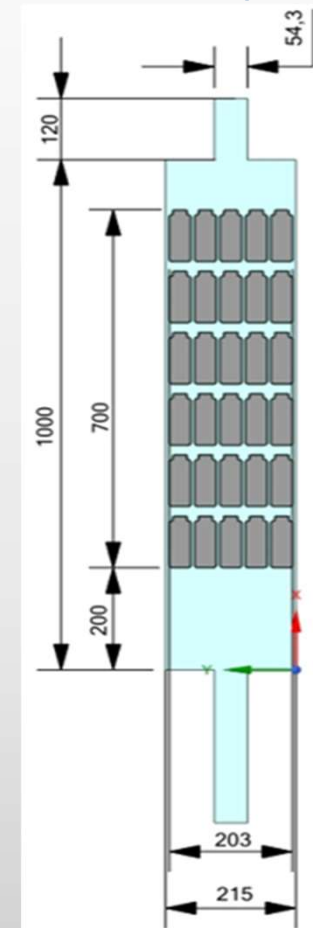
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Variant 2

Simulation conditions:

- 2D model of a packed bed of aluminum bottles filled with PCM in a TES column
- PCM material: **Solar Salt ($\text{NaNO}_3\text{--KNO}_3$)**
- Inlet:
 - Fluid: air
 - Velocity inlet **0,5 m/s**
 - Temperature inlet: **500°C**
- Initial temperature: **25°**
- Outlet: (pressure outlet)
- Bottles walls: (coupled)
- Column walls: heat flux = 0 (adiabatic)

Geometry:



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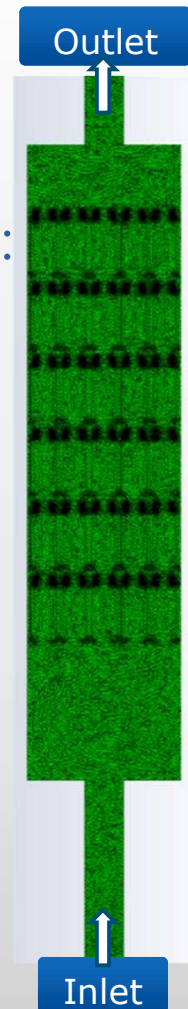


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Variant 2 - results

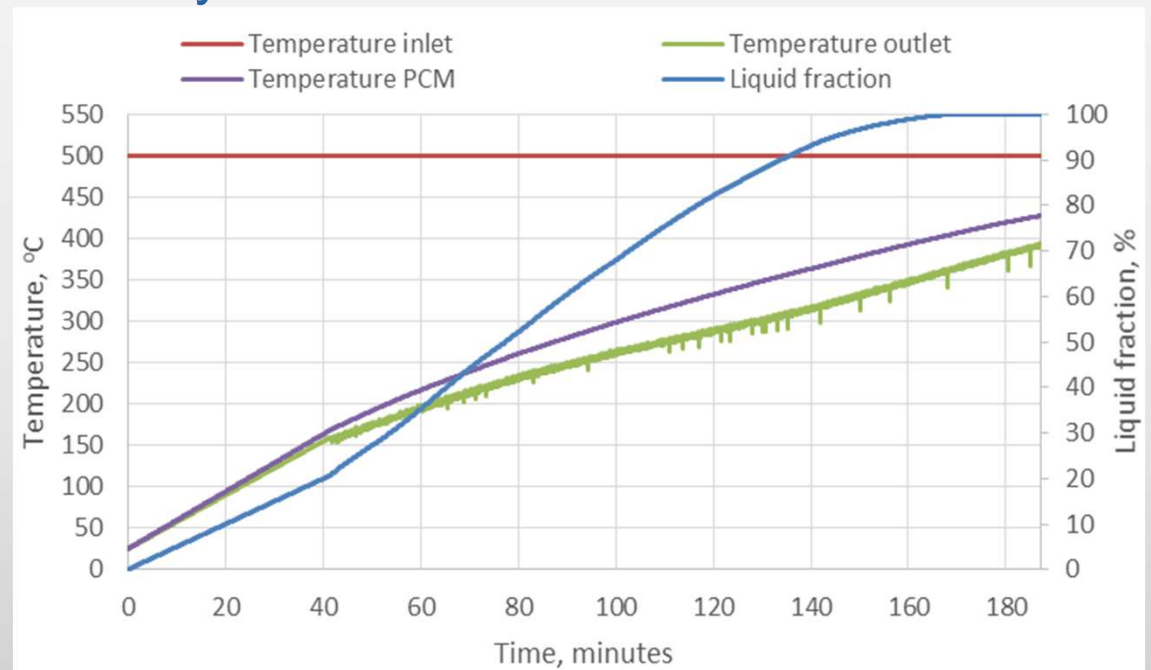
Mesh:

- Type of mesh: tetrahedrons
- Number of elements: 873 423



Results:

- 500°C air flows through a bed of bottle-shaped bodies at the inlet
- The average PCM temperature rises to 420°C
- PCM fully melts 165 min.



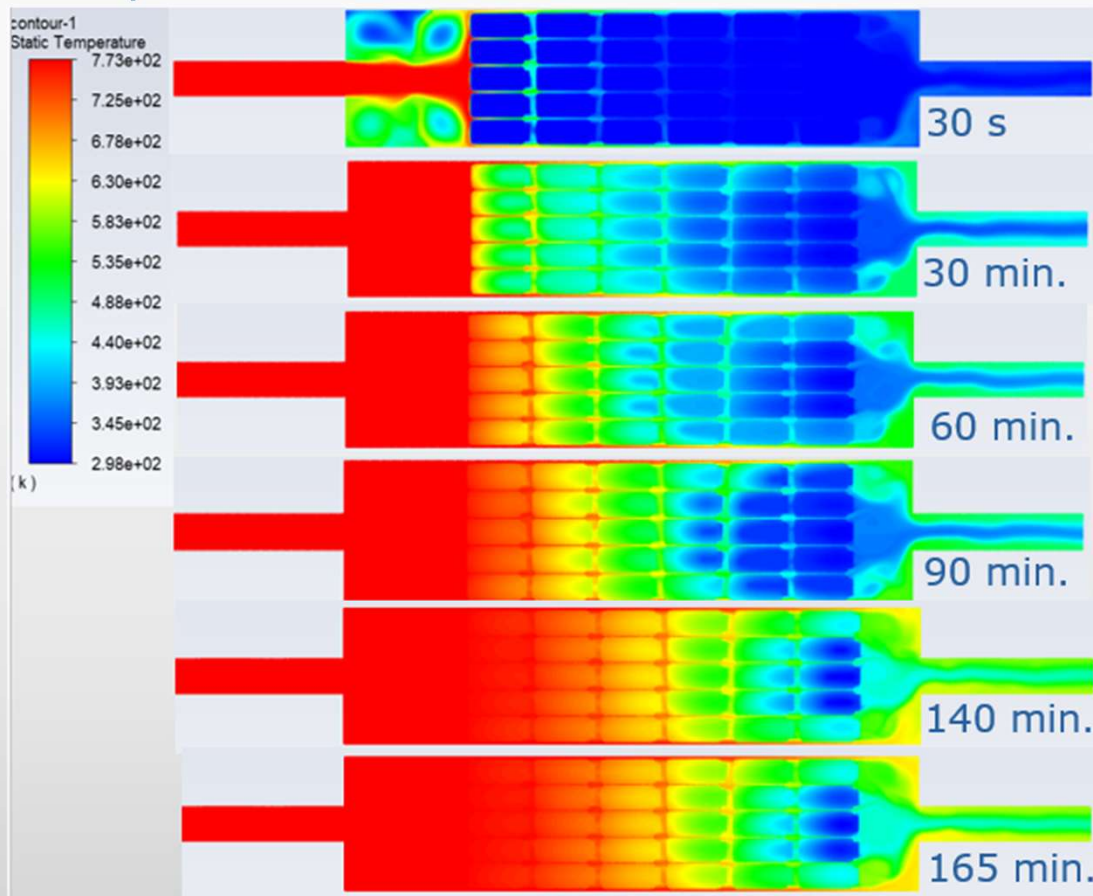
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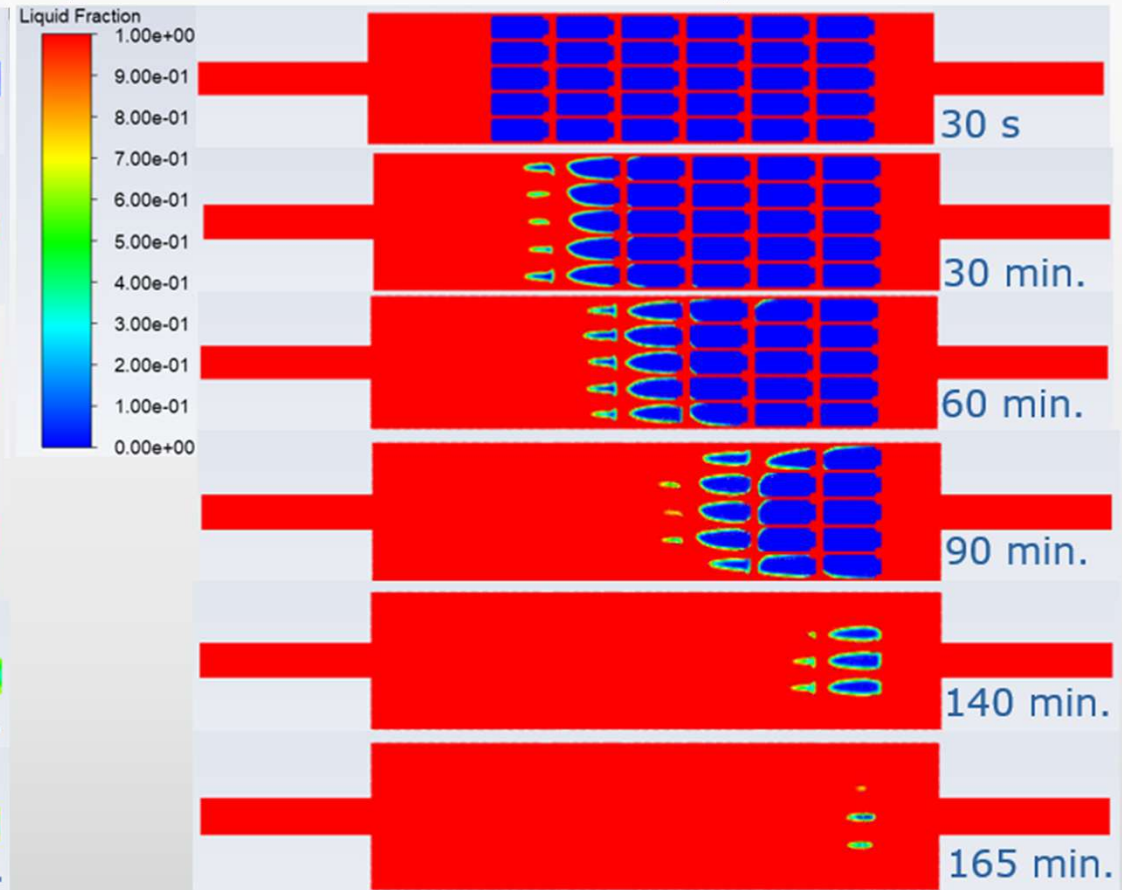
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Variant 2 - results

Temperature distribution



Liquid fraction (0=solid, 1=liquid):



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Summary

- Simplified model: PCM melts quickly and uniformly (**~7 min**) under **constant wall temperature**.
- Detailed model: Realistic airflow causes slower, non-uniform **melting (~165 min)** with gradual temperature rise.
- Liquid fraction visualizations clearly show **melting progression** and **temperature distribution**.
- CFD is an effective tool for analyzing thermal and phase-change behavior in latent heat storage systems and can be used for **visualisation PCM melting** processes that **cannot be observed in real insulated systems**.



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ul. Zamkowa 1, 41-803 Zabrze, Poland,
tel. (+48) 32 271-00-41

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TECHNICAL PARAMETERS OF THE EXAMPLE UNDERGROUND WATER RESERVOIR MODEL

Marcin Lutyński, Konrad Kołodziej

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26



Co-funded by
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The work presented on the poster was performed as part of the HESS project (Hybrid energy storage system using post-mining infrastructure) grant no. 101112380 supported by the EU RFCS.



The project is co-financed by the Polish Ministry of Education and Science under the program entitled International Projects Co-financed Agreement No. 5462/FBWIS/2023/Z

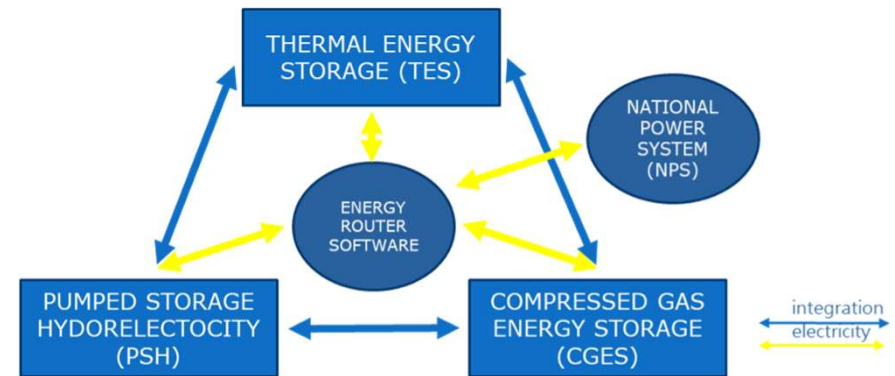
Projekt HESS



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

Project goal

- develop a Hybrid Energy Storage System (HESS) using post-mining infrastructure, parallel energy storage in:
 - Pumped Storage Hydroelectricity system (PSH)
 - Compressed gas – Air/CO₂ Energy Storage system (CGES) and Thermal Energy Storage system (TES).
- **ASSUMPTION: energy storage capacity min. 30 MWh**
- thermal and mechanical integration of the entire system
- integration of the energy router to manage energy exchanges with the national power grid for the intake of low-cost green energy and peak energy production



Project consortium:

Institute of Energy and Fuel Processing Technology (ITPE)



KOMAG Institute of Mining Technology
Silesian University of Technology



Premogovnik Velenje D.O.O.



VSB - Technical University Of Ostrava



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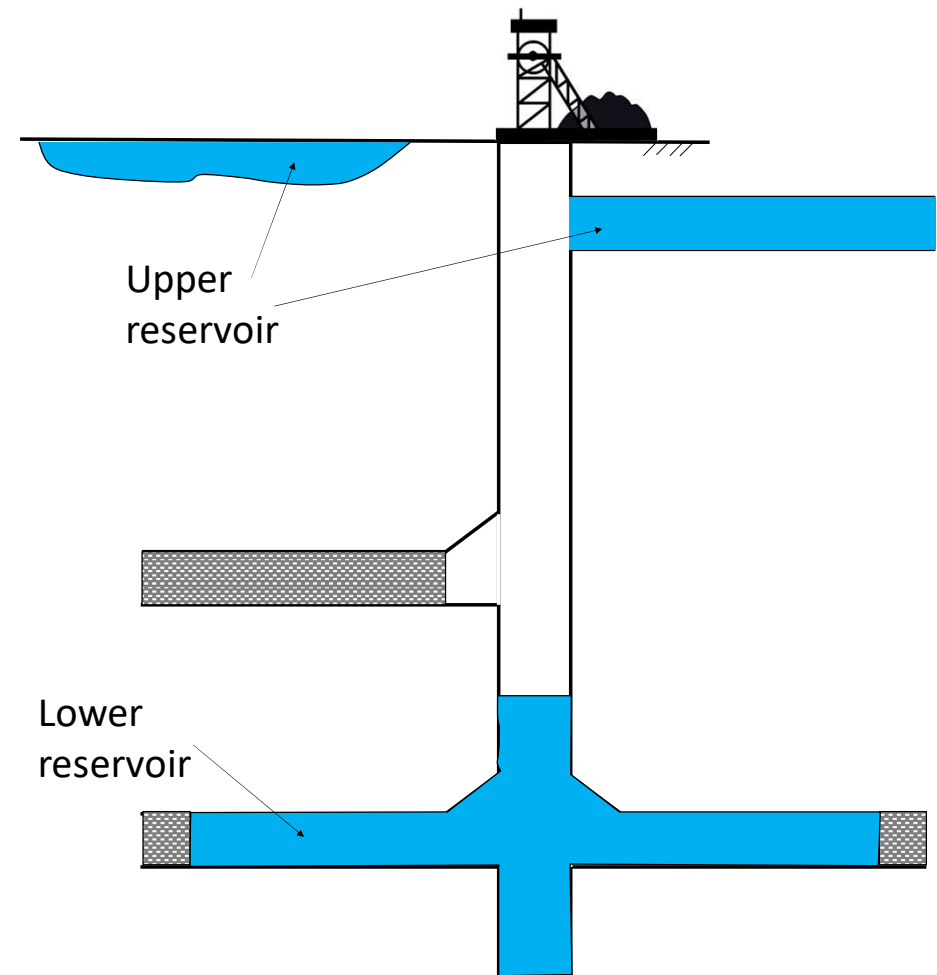


Goal of the work

select potential locations for USPS
where headings near the shaft stations
will serve as a lower reservoir

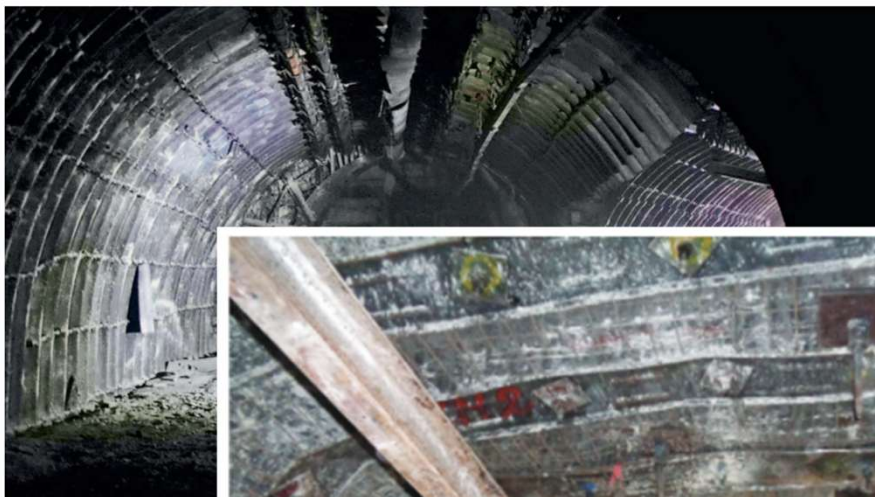
3 Important considerations

Energy storage phase	• Corrosion • Constant load (rockmass) • Cyclic loading (water pressure) • Convergence • Abbrasion from particles suspended in water
Operation phase	• Corrosion • Rather constant load • Convergence



Theory vs. Reality

4



a)



b)



c)



d)



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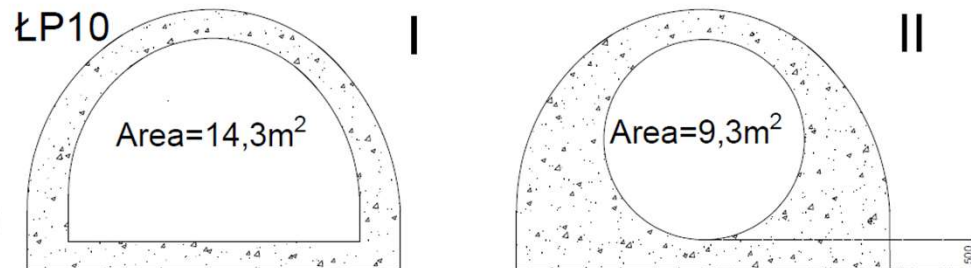
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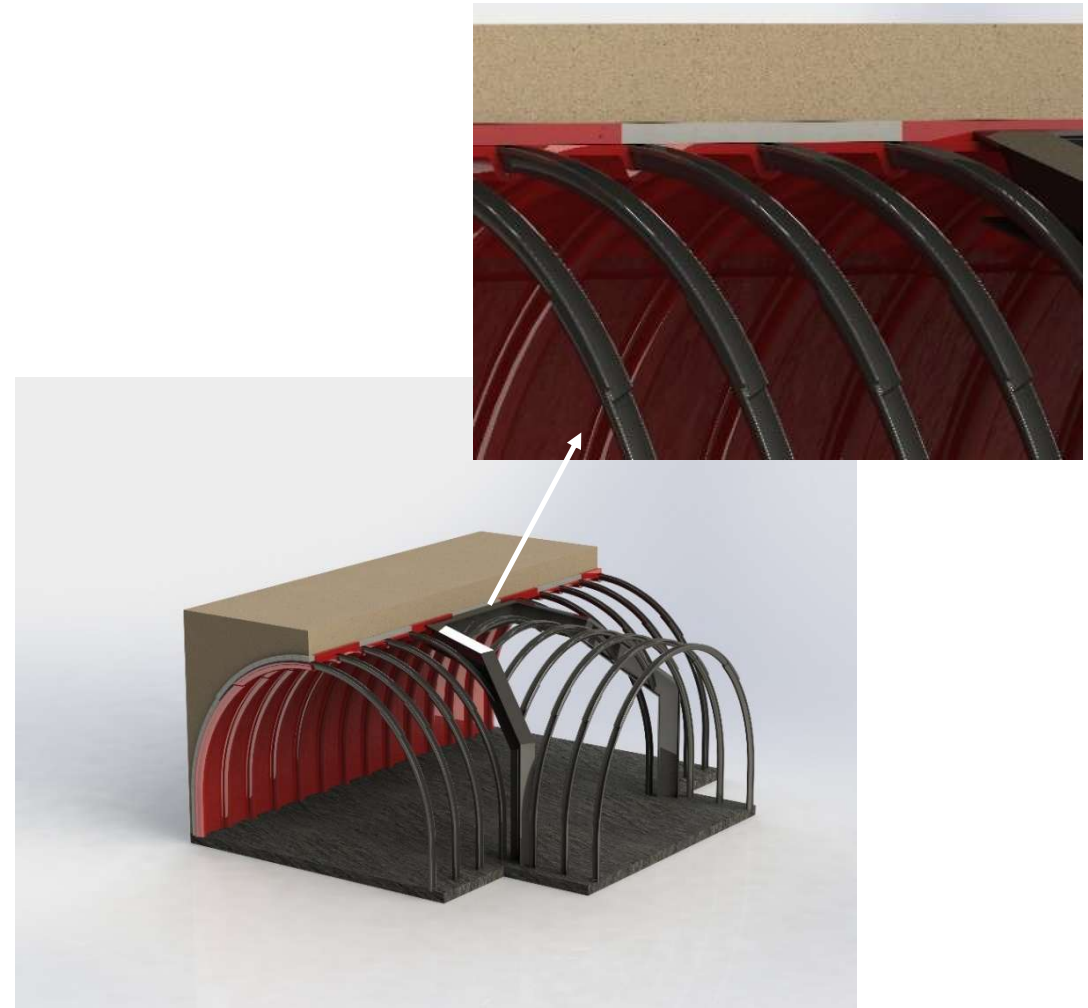
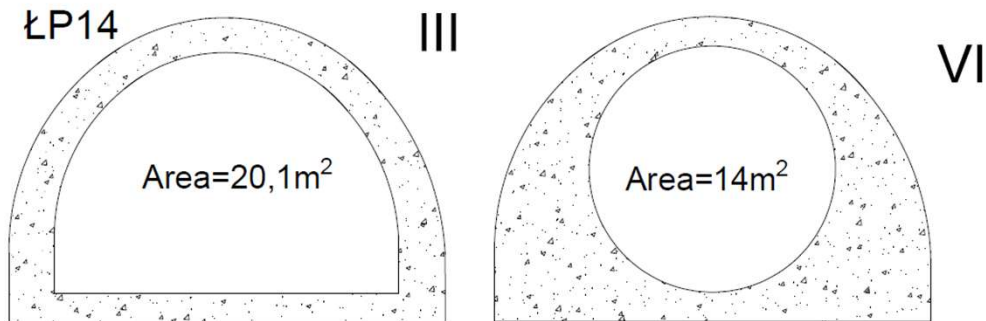
Solution?

- Additional support
- Sealed liner

Initial cross-section: 23.1 m³



Initial cross-section: 32.3 m³



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Identification of shafts and underground excavations

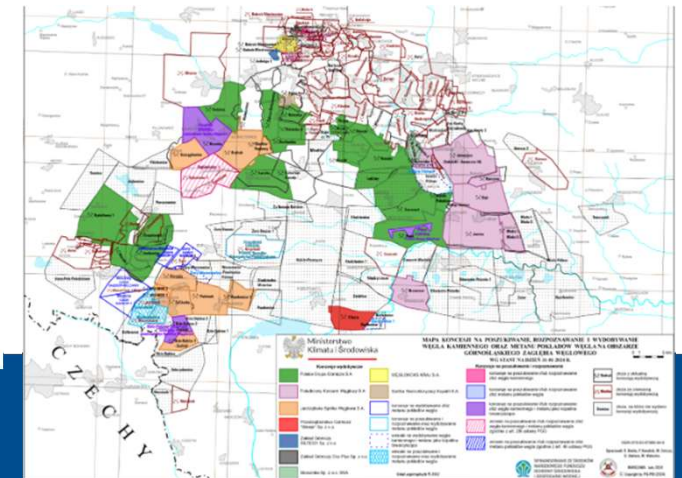
Countries:

Poland, Czechia and Slovenia

- The underground infrastructure of the mine, its equipment, dimensions and depth, and the surroundings of the shafts were verified
- Based on the requirements of the adopted hydroelectric power plant concept, its requirements were determined from the point of view of hydrogeology and geoengineering.
- system for comprehensive assessment of the possibility of using corridor excavations as lower reservoirs of pumped-storage power plants was developed

The data-base includes the number of shafts belonging to each mine. The description of each shaft includes:

- name of the mine shaft,
- function of the shaft,
- shaft diameter,
- shaft depth,
- change in diameter with depth,
- height of shaft collar,
- other information and comments such as: type of shaft lining, other shaft cross-section, levels connected to the shaft, equipment, etc.,
- information on shafts under construction, flooded and decommissioned.



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Multi-criteria decision analysis (MCDA) for assessing shafts as potential USPS

Shaft assessment criteria

Shaft depth $E_p = H_u \cdot Q_p \cdot t_p \cdot \rho \cdot g$

Volumes of the lower reservoir V_z relative to the net head in the turbine (shaft depth) H_u and the points assigned to them.

Lower reservoir volume [m³]															
H _u [m]	1000	950	900	850	800	750	700	650	600	550	500	450	400	350	300
V _z [m³]	5246	5523	5829	6172	6558	6995	7495	8071	8744	9539	10493	11659	13116	14990	17488
Score	10	10	9	8	8	7	6	5	4	3	1	0	-3	-6	-10

Area for the construction of the upper water reservoir

7 Scoring – availability of the area for the construction of upper water reservoir	
available	2
not available	-2

Scoring for shaft configuration

Scoring depending on the shaft configuration (location)	
neighboring shaft selected as the CAES	5
2 connected neighboring shafts	2
2 connected remote shafts	0
single shaft	-5



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Multi-criteria decision analysis (MCDA) for assessing shafts as potential USPS

Shaft assessment criteria

Hoisting devices

Scoring for the availability of hoisting devices

hoisting tower with man/material hoisting machine at least in one shaft	2
adaptation for the installation of an auxiliary emergency and inspection mine hoist	0
lack of hoisting equipment	-2

Methane hazard

Scoring depending on the methane hazard

Non-methane coal mine(<0.1 CH ₄ /t coal _{daf})	5
Category I (0.1-2.5 m ³ CH ₄ /t coal _{daf})	-1
Category II (2.5-4.5 m ³ CH ₄ /t coal _{daf})	-2
Category III (4.5-8.0 m ³ CH ₄ /t coal _{daf})	-3
Category IV >8.0 m ³ CH ₄ /t coal _{daf})	-4

Water drainage of workings

Number of points depending on the requirements of water drainage

≤ 0 m ³ /min	3
0 m ³ /min ≤ 1 m ³ /min	3
1 m ³ /min and ≤ 3 m ³ /min	0
> 3 m ³ /min	-3

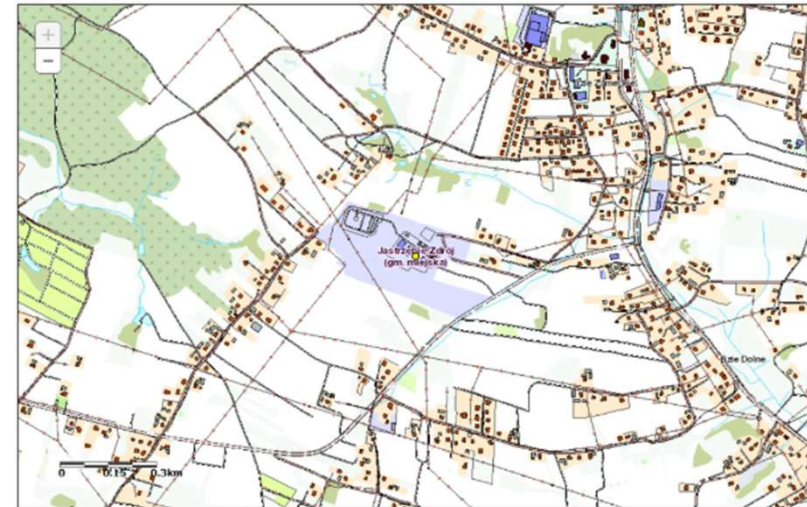


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Multi-criteria decision analysis (MCDA) for assessing shafts as potential USPS

Weights for individual evaluation criteria	
lower reservoir volume (V_z)	50%
uUpper tank area	10%
shaft configuration	10%
hoisting devices	10%
methane hazard	10%
water drainage	10%
total weight	100%



JSW coal company, Division „Bzie” – location of „Bzie-1” (Jan-Paweł) shaft



Multi-criteria decision analysis (MCDA) for assessing shafts as potential USPS

RESULTS

159 shafts in Poland, 12 shafts in Czechia and 12 shafts in Slovenia were assessed



Poland

No.	Company	Mine	Division	Shaft	Depth [m]	Diameter [m]	Total score
1	2	3	4	5	6	7	8
148	SRK	Oddział CZOK	PS Centrum	Budryk	982,26	7,60	5,9
168	Bogdanka	LW "Bogdanka"		2.2	1018,25	7,50	5,8
165	Bogdanka	LW "Bogdanka"		1.3	1030,15	7,50	5,6
169	Bogdanka	LW "Bogdanka"		2.1	1097,74	7,50	5,6
135	SRK	Oddział CZOK	PS Pstrowski	Gigant	874,55	8,00	5,4
146	SRK	Oddział CZOK	PS Śląsk I	I	1081,00	8,00	5,4
47	PGG	KWK ROW	Marcel	II (Antoni)	1011,28	5,50	5,3
164	Bogdanka	LW "Bogdanka"		1.2	995,00	6,00	5,3
166	Bogdanka	LW "Bogdanka"		1.4	995,82	7,50	5,3
11	JSW	KWK Borynia-Zofiówka-Bzie	Bzie	1-Bzie Jan Paweł	1164,00	8,00	5,3



Czechia

No.	Company	Mine	Division	Shaft	Depth [m]	Diameter [m]	Total score
1	2	3	4	5	6	7	8
1	OKD	ČSM	ČSM Sever	Sever (exhaust ventilation)	1005,0	7,5	5,7
2	OKD	ČSM	ČSM Sever	Sever (intake)	1104,4	7,5	6
3	OKD	ČSM	ČSM Jih	Jih (exhaust ventilation)	972,1	7,5	5,2
4	OKD	ČSM	ČSM Jih	Jih (intake)	1103,9	7,5	5,7



Slovenia

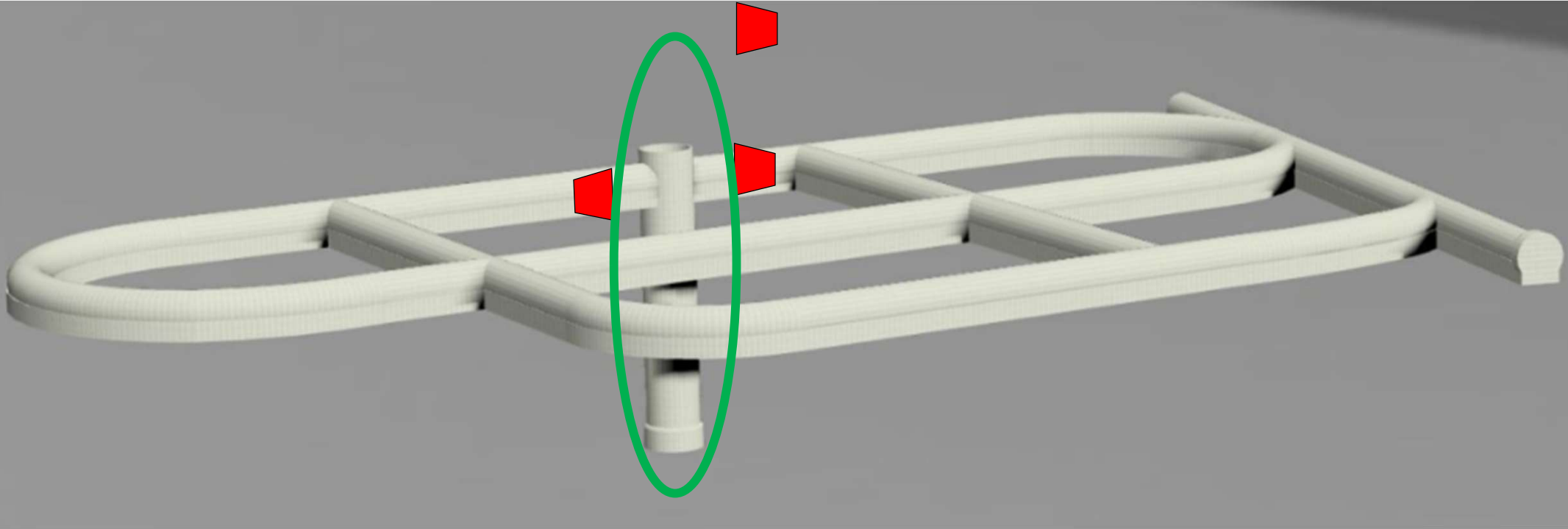
No.	Company	Mine	Division	Shaft	Depth [m]	Diameter [m]	Total score
1	2	3	4	5	6	7	8
1	Premogovnik Velenje, d. o. o.	Velenje	-	Transport shaft Nove Preloge (A)	416,42	7,2	-2,1
2	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Nove Preloge (A)	390,7	6,15	-2,4
3	Premogovnik Velenje, d. o. o.	Velenje	-	Ventilation shaft Pesje (A)	141,76	4	-4,4
4	Premogovnik Velenje, d. o. o.	Velenje	-	Intake shaft Šoštanj II(A)	332,57	5	-4,4



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Selected part of mine for lower reservoir USPS

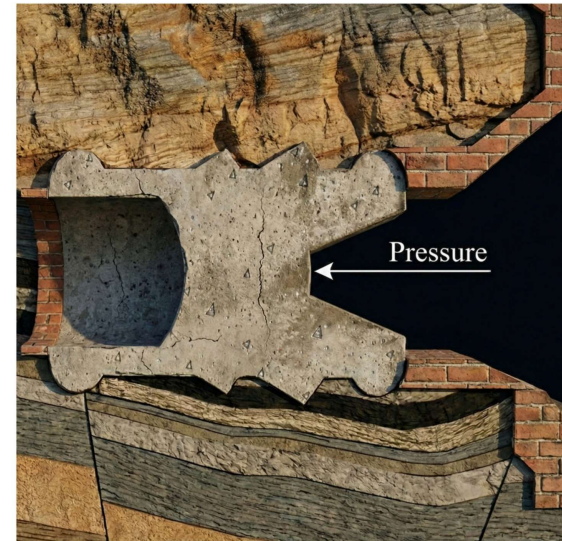


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Thinks to do

- Shaft inlets plugs
- Coating system



12

TECHNICAL AND COST PARAMETERS: LOWER WATER RESERVOIR (SHAFT II)

EXCAVATION DIMENSIONS:

- Width: 7.8 m
- Height: 5.5 m
- Cross-section: 42.9 m²

LEVEL 1050 m (2 dams - E & W):

- Water pressure: 1.45 MPa
- Dam thickness: 1.60 m
- Volume: 75 m³ concrete / dam

LEVEL 1158 m (1 main dam - W):

- Water pressure: 2.51 MPa
- Dam thickness: 2.30 m
- Volume: 110 m³ concrete

COST ESTIMATE (CAPEX):

- Mat: 260 m³ concrete + PUR
- Labor: 1309 man-hours
- Total: 627,818 PLN net

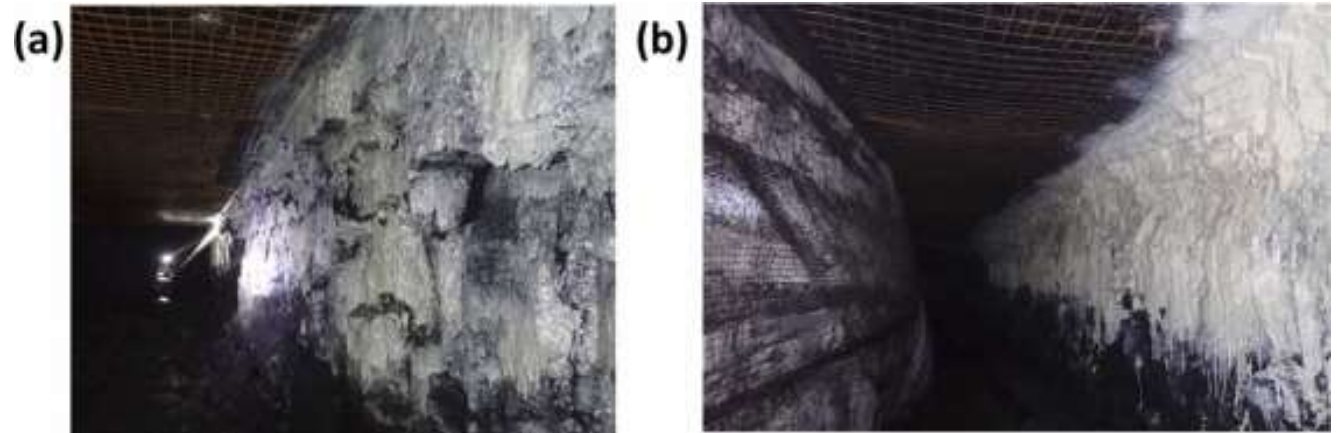


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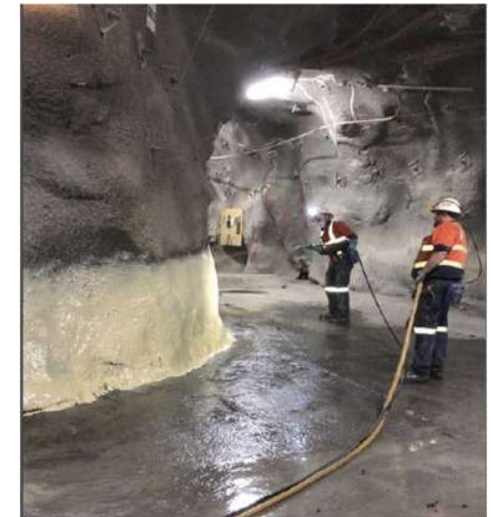
Thinks to do

- Shaft inlets plugs
- **Coating system**



Summary of Costs and Resources (Nanobanan Pro Edition)

Table 1. Category and Specification	Shaft I	Shaft II	TOTAL
FINANCIAL COSTS (NET IN PLN)			
Primer Skagard P 770 (72.22 PLN/kg)	815,771.84	767,883.48	1,583,655.32
Coating WallCoat T (63.75 PLN/kg)	672,090.75	632,637.15	1,304,727.90
TOTAL MATERIAL COST	1,487,862.59	1,400,520.63	2,888,383.22
RESOURCE REQUIREMENTS (UNPRC)			
Mass of P 770 primer (kg)	11,295.65	10,632.56	21,928.21
Mass of WallCoat T coating (kg)	10,642.60	9,923.72	20,566.32
Working shifts (Washing + Spraying)	116	190	226
Man-hours (RSG)	3,488	3,812	6,800
Water consumption [m³]	262	247	509
TOTAL ENERGY CONSUMPTION (kW)	23,958	22,701	46,659



Conclusions

- A multi-criteria decision analysis (MCDA) system was developed to assess the potential of mine shafts and underground workings for Underground Pumped Storage Power Systems (USPS)
- **183 shafts were assessed across Poland, Czechia, and Slovenia, identifying promising candidates for USPS deployment**
- Key assessment factors included shaft depth, reservoir volume potential, shaft configuration, hoisting infrastructure, methane hazard, and water drainage
- 14 • **Detected two main construction challenges to do; -inlet shaft Plugs, coating liner**
- The method bridges theoretical USPS concepts with practical mining infrastructure realities, supporting effective post-mining land use and renewable energy integration
- The results contribute to the broader goals of the HESS project, advancing hybrid energy storage using post-mining infrastructure



THANK YOU!

Project co-financed by the European Commission within the framework of the Research Fund for Coal and Steel – RFCS program under the contact no. 101112380 (RFCS-2022) titled „Hybrid Energy Storage System using post-mining infrastructure” (HESS) and by the State Subsidy within the framework of the program „Co-financed International Projects” (PMW) established by the Minister of Science and Higher Education.

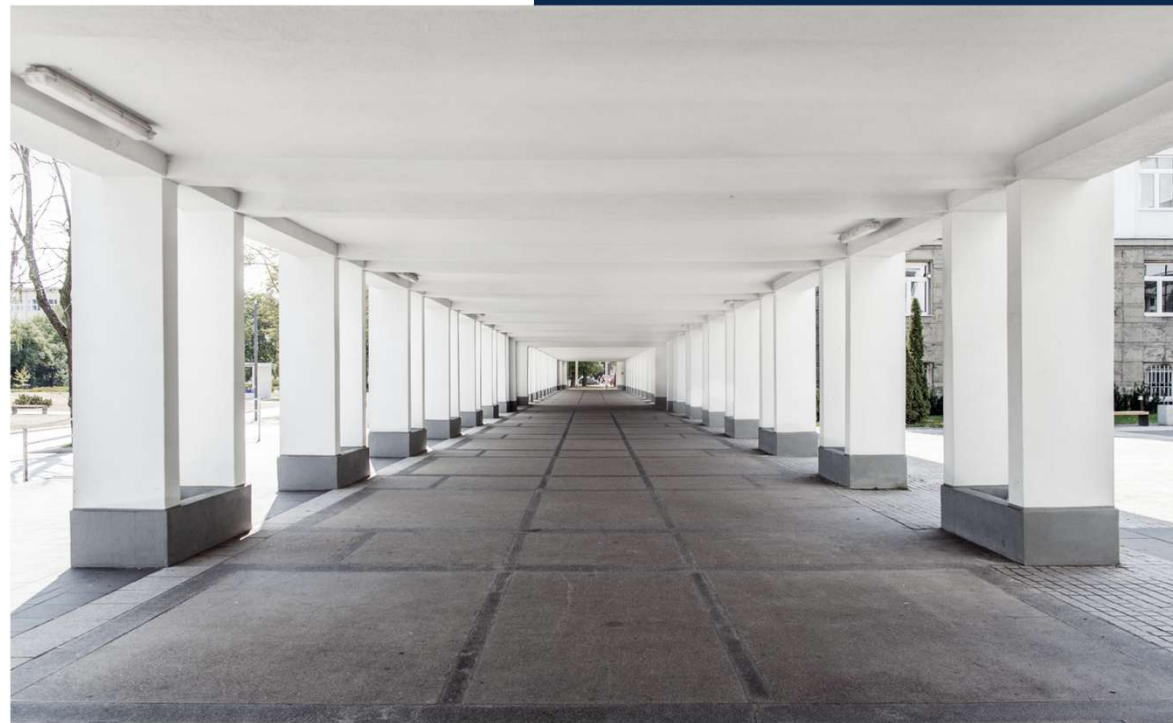


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The work presented on the poster was performed as part of the HESS project (Hybrid energy storage system using post-mining infrastructure) grant no. 101112380 supported by the EU RFCS.

The project is co-financed by the Polish Ministry of Education and Science under the program entitled International Projects Co-financed Agreement No. 5462/FBWIS/2023/2



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FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

The pumped storage systems in mine shafts

PhD Eng. Piotr Matusiak,

PhD Eng. Daniel Kowol

LAUREAT KONKURSU



TERAZ POLSKA

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The pumped storage systems in mine shafts

Deliverable 3.1 The pumped storage systems in mine shafts

During the previous work package (WP2), a review of mine shafts was carried out and a multi-criteria assessment system was developed to evaluate the suitability of shafts for energy storage applications.

The following shaft pair was selected for further calculations:

- shaft Budryk II for the **PSH** system,
- shaft Budryk III for the **CGES** and **TES** energy storage system

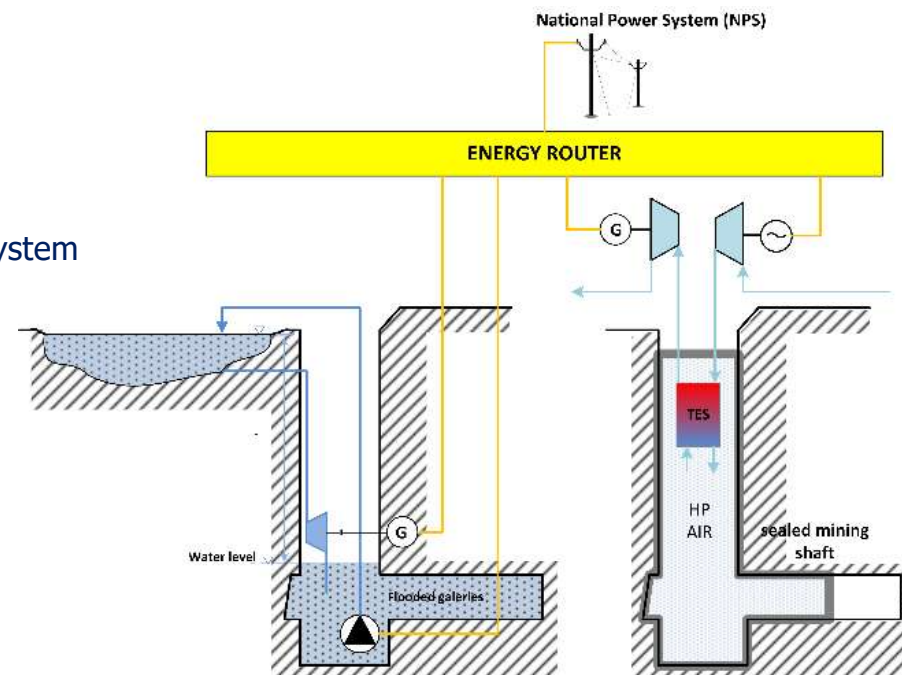


Fig. 1. Schematic diagram of PSH, CGES and TES energy storage systems installed in a mine shaft



HESS project has received funding from the Research Fund for Coal and Steel (RFCS) under GRANT AGREEMENT No. 101112380
Project co-funded by the Polish Ministry of Science and Higher Education under the program entitled „Co-financed International Projects”.

The pumped storage systems in mine shafts

The pumped storage system in mine shaft is built from four main elements:

1. System of the hydro turbine and generator with the shaft reservoir.
2. Water pumping system.
3. Upper reservoir.
4. Platform assembly.



HESS project has received funding from the Research Fund for Coal and Steel (RFCS) under GRANT AGREEMENT No. 101112380
Project co-funded by the Polish Ministry of Science and Higher Education under the program entitled „Co-financed International Projects”.

HESS Hybrid Energy Storage System Using Post-mining Infrastructure No. 101112380

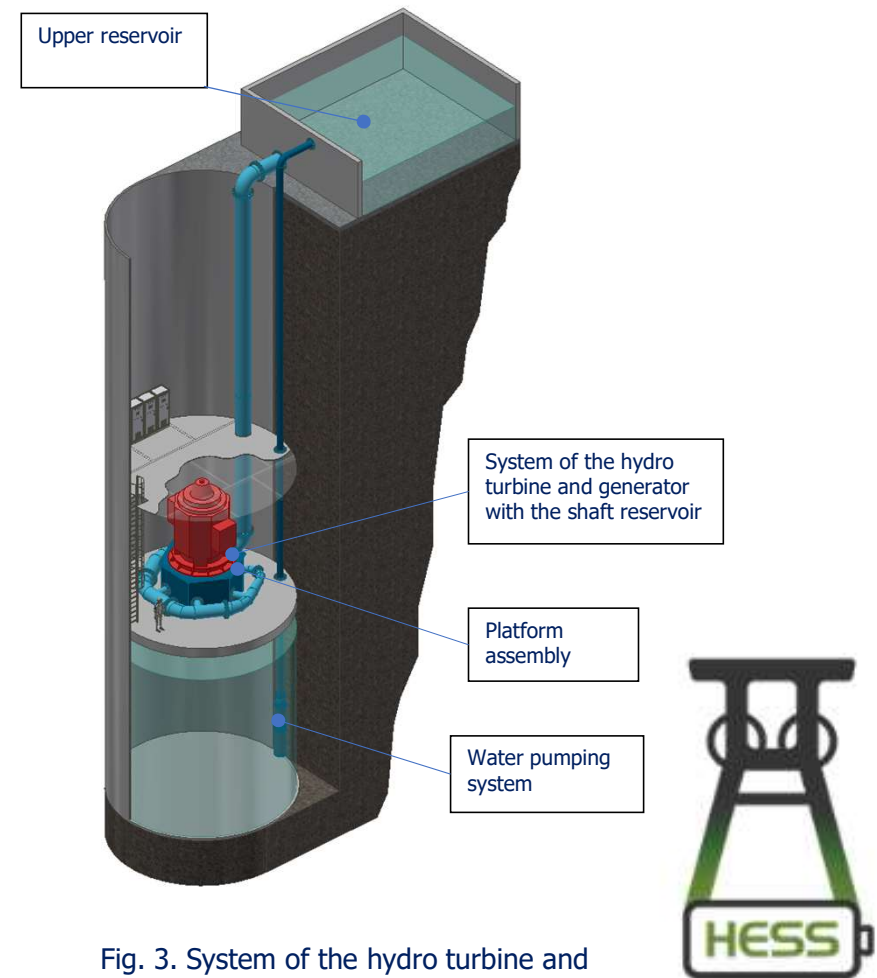


Fig. 3. System of the hydro turbine and generator with the shaft reservoir

1. System of the hydro turbine and generator with the shaft reservoir

PSH System components include:

1. Vertical Pelton turbine.
2. Turbine housing with distribution manifold.
3. Control nozzle with deflector.
4. Synchronous generator.
5. Inlet pipe.
6. Support pipe.
7. Support structure.
8. Pipe section.
9. Gland-type expansion joint.
10. Guiding support.
11. Supply pipe - penstock.
12. Ball valve DN400, PN100.
13. Hydraulic power unit.

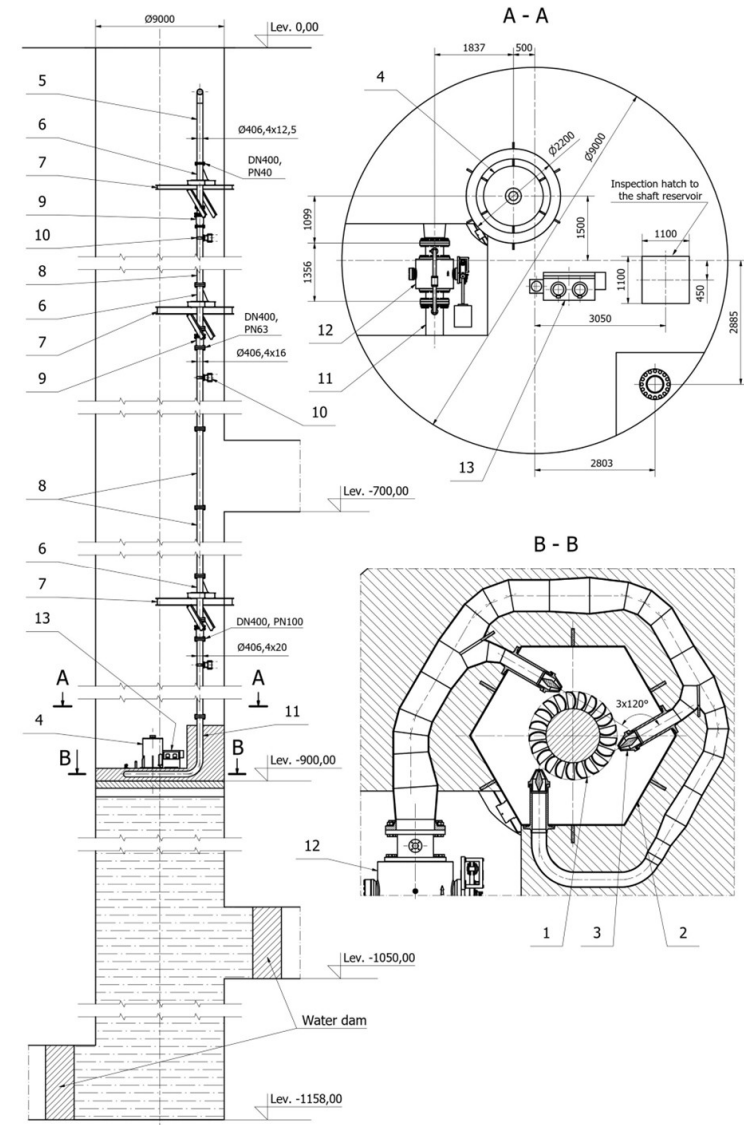


Fig. 4. System of the hydro turbine and generator with the shaft reservoir

1. System of the hydro turbine and generator with the shaft reservoir

Table 1. Technical Parameters of the PSH Energy Storage System:

Parameter	Value
Rated gross head	900 m
Rated net head	837.81 m
Penstock diameter	DN400 mm
Pressure at turbine inlet	8.22 MPa
Rated discharge	0.71 m ³ /s
Runner diameter	790 mm
Runner bucket width	160 mm
Number of nozzles	3
Nozzle diameter	175 mm
Generator rated power	5800 kW
Power factor cos ϕ	0.9
Rated turbine power	5287 kW
Generator rated voltage	6.3 kV
Frequency	50 Hz
Rated turbine efficiency	90.82 % (Q = 0.71 m ³ /s)
Max turbine efficiency	91.39 % (Q = 0.5 m ³ /s)
Rated turbine speed	1500 rpm
Turbine overspeed	2786 rpm
Valve design pressure	100 bar
Governor system pressure	max. 12 MPa
Insulation / Temp. rise	F / B

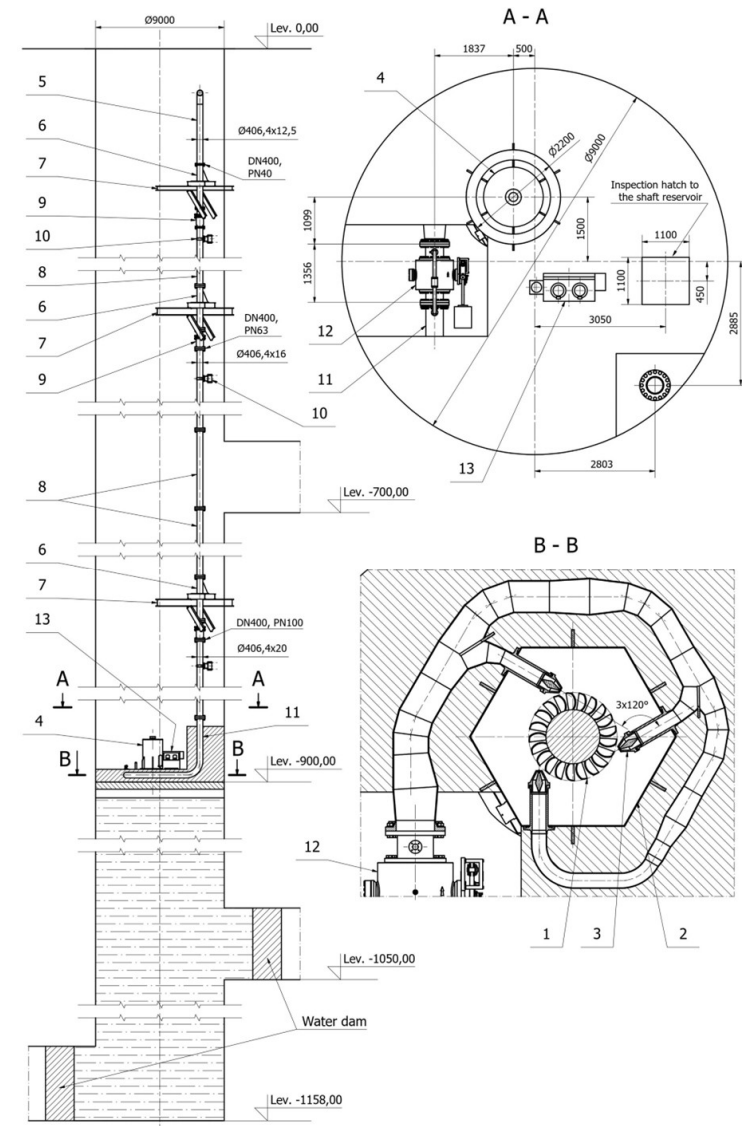


Fig. 4. System of the hydro turbine and generator with the shaft reservoir

1. System of the hydro turbine and generator with the shaft reservoir



As part of the task implementation, a turbine-generator unit consisting of a Pelton turbine and a generator with a rated power output of 5.8 MW was selected.

The Pelton turbine is optimal for the designed power plant in the mine shaft, as it operates most efficiently under very high heads and relatively low flow rates ($H \approx 900$ m, $Q \approx 0.71$ m³/s), which precisely corresponds to the project conditions.

As an impulse turbine, it is practically immune to cavitation and allows a wide range of power regulation through needle-controlled nozzles and deflectors, maintaining high efficiency even under partial loads

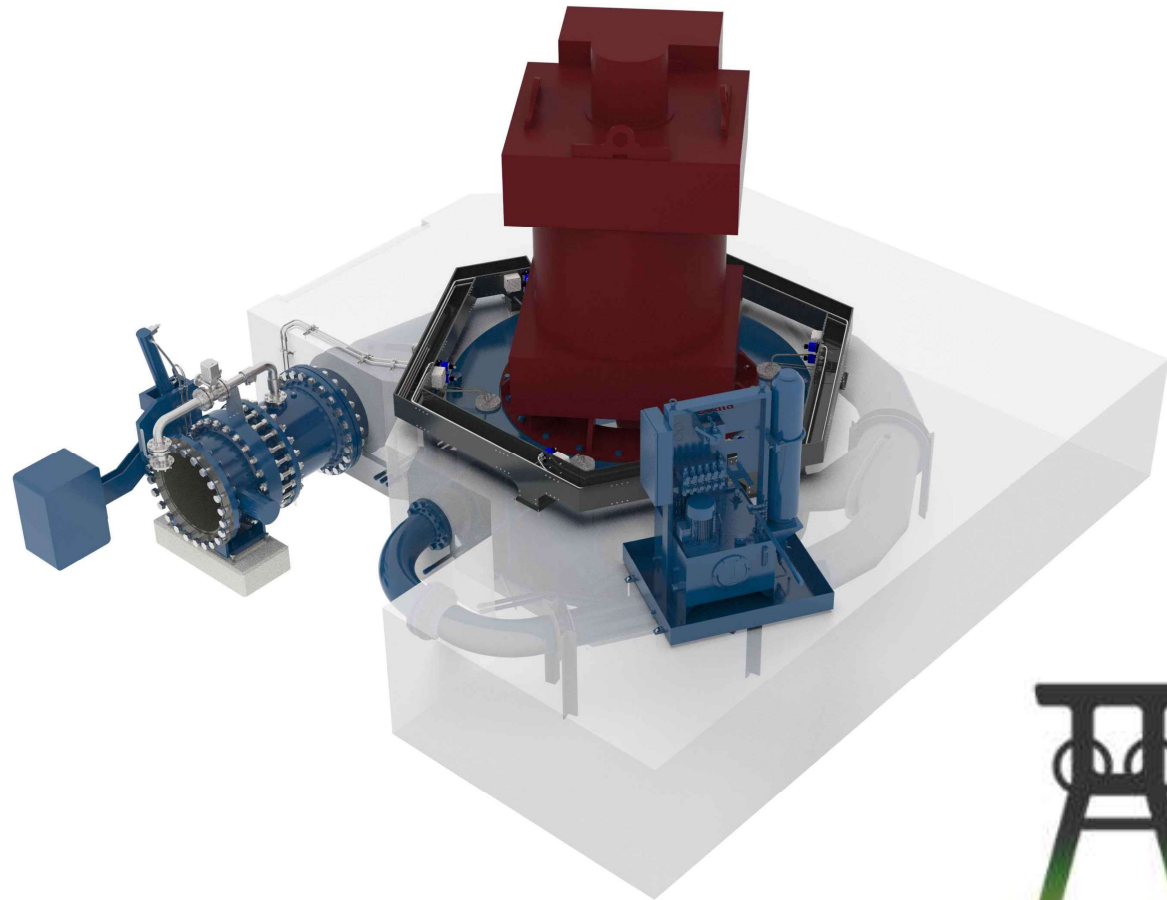


Fig. 5. Pelton turbine and generator set with a rated power output of 5.8 MW

1. System of the hydro turbine and generator with the shaft reservoir



1.1 Pelton turbine runner

The Pelton turbine runner is a key component of the designed pumped-storage hydropower plant, responsible for converting hydraulic energy into mechanical energy.

The proposed solution employs a vertical runner mounted on a shaft directly coupled to a 6.3 kV synchronous generator.

The runner diameter and the number of buckets were selected based on the operating parameters of the system (approximately 900 m head and 0.71 m³/s flow rate) in accordance with the characteristics of the PV3i-790/160 Pelton turbine.



Fig. 6. Pelton turbine runner

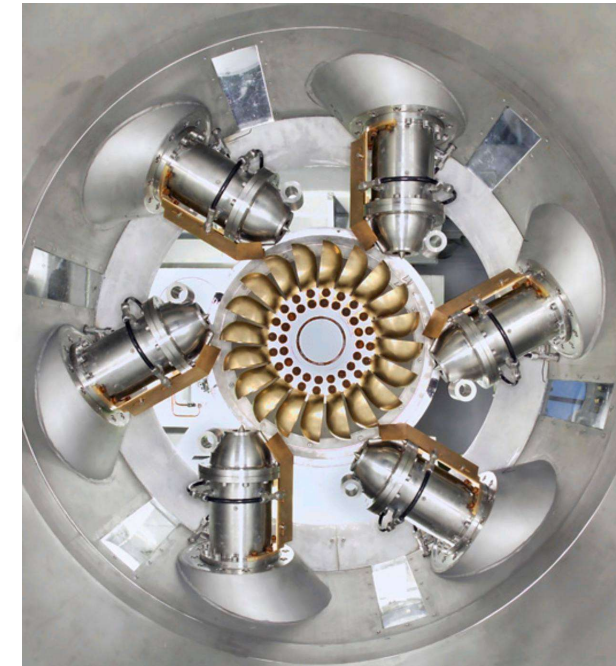


Fig. 7. Pelton runner bucket.



1. System of the hydro turbine and generator with the shaft reservoir



1.2 Synchronous generator

In the designed pumped-storage power plant, the generator constitutes an integral part of the turbogenerator assembly and is directly coupled with the vertical Pelton turbine.

A synchronous generator with a rated voltage of 6.3 kV has been applied, designed to operate at a rotational speed of 1500 rpm, corresponding to the synchronous speed of a four-pole system at a grid frequency of 50 Hz.

The generator's rated power has been selected to match the turbine's hydraulic power of approximately 5.3 MW, with an appropriate margin to ensure thermal and dynamic stability.

The designed synchronous generator is equipped with an IC81W cooling system based on forced air circulation with water-cooled heat exchangers

Synchronous Generator		
Mounting	V1 - vertical	
Output power	5800	kVA
Speed	1500	rpm
Runaway speed	2786	rpm
Nominal current	Tbd	A
Frequency	50	Hz
Power factor	0,9	
Voltage	6300	V
Enclosure	IP44	
Insulation / Temperature rise	F / B	
Ambient temperature	40	°C
Cooling system	IC81W	
Bearings type	Sleeve Bearing	
Bearing cooling	Water	
Altitude	tbd	
Mass of generator	tbd	kg
Natural generator inertia (I)	tbd	kgm ²
Noise level	tbd	dBA



Fig. 8. Synchronous generator

1. System of the hydro turbine and generator with the shaft reservoir



1.3 The other main components:

As part of the PSH system design, we also designed other auxiliary components, including:

- the turbine supply manifold,
- jet deflector.



Fig. 9. Jet deflector (symbolic picture of 4-nozzle unit) [1].



Fig. 10. Cross-section of the casing with a view of the turbine supply manifold



1. System of the hydro turbine and generator with the shaft reservoir

1.3 The other main components:

As part of the PSH system design, we also designed other auxiliary components, including:

- needle-type regulating nozzle,
- spherical shut-off valve - DN400 and a design pressure of PN100 (10 MPa) .



Fig. 11. Needle-type regulating nozzle for a Pelton turbine

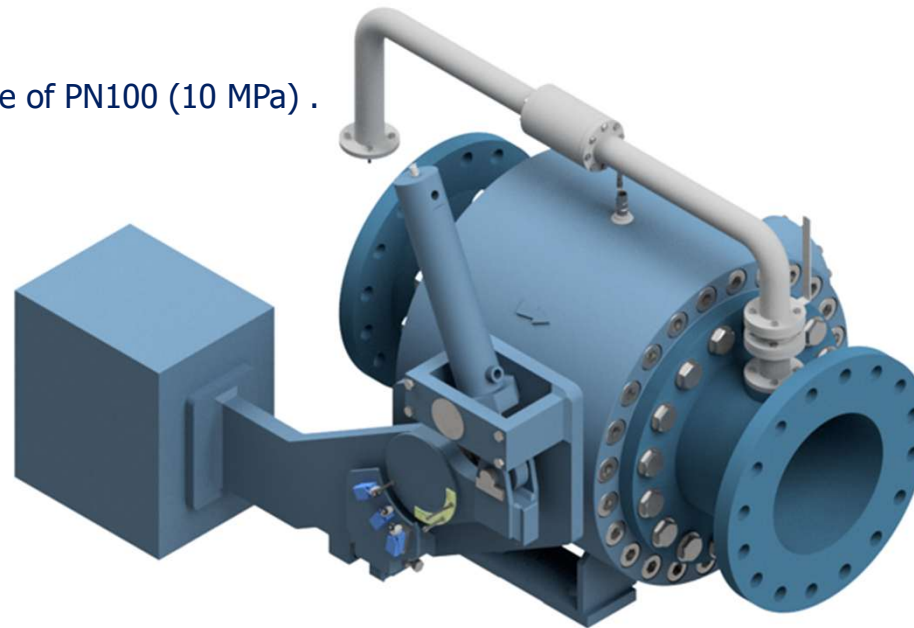


Fig. 12. Spherical shut-off valve [1].



1. System of the hydro turbine and generator with the shaft reservoir



1.4 The penstock :

The penstock transports water from the surface reservoir to the Pelton turbine located at a depth of approximately 900 m. It has a segmented steel construction, facilitating transportation and installation within the mine shaft.

Support structures are installed at intervals of approximately 80 m, with pipe sections about 6 m long located between them.

The stability of the pipeline and the compensation of thermal expansion and dynamic loads are ensured by guide supports and axial expansion compensators.

The penstock has a nominal diameter of DN400 (Ø406.4 mm) and is divided into three pressure zones with different wall thicknesses:

- PN 40 bar (from 0 to -326.5 m) – wall thickness 12.5 mm,
- PN 63 bar (from -326.5 m to -570.0 m) – wall thickness 16 mm,
- PN 100 bar (from -570.0 m to -900.0 m) – wall thickness 20 mm.

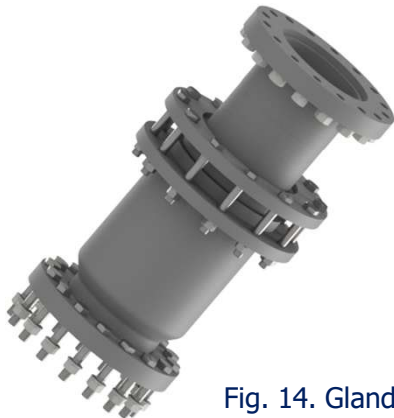


Fig. 14. Gland-type expansion joint

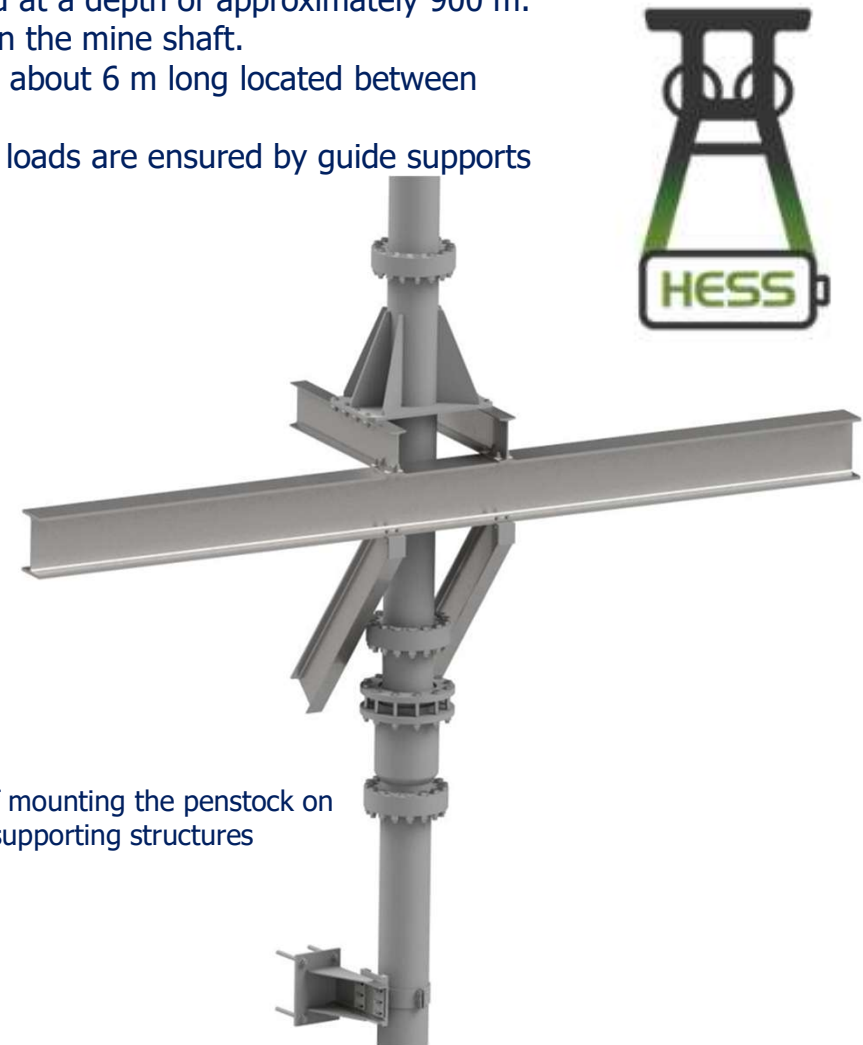


Fig. 13. Method of mounting the penstock on one of the supporting structures

2. Water pumping system

The pumped-storage power plant system installed in the shaft of the Budryk coal mine utilizes the mine's main drainage system infrastructure to pump water from the lower reservoir to the upper reservoir.

The main drainage pumping station (fig. 15), located at the 700-meter level, is equipped with five stations, each operating OWH-200/10 pumps. Alternatively, OWH-200M/10Ex pumps can be used. The nominal capacity of each pump is 315 m³/h.

Two water reservoirs are located adjacent to the pumping station. Taking into account water distribution, the working capacity of the waterways is 1,332 m³ for moderately saline water and 1,236 m³ for brine.

Water is discharged from the pumping station to the surface through two Ø350 mm discharge pipelines.

Water pumping is carried out in three stages:

- Stage I – pumping water from level 1158 m to level 1050 m,
- Stage II – pumping water from level 1050 m to level 700 m,
- Stage III – pumping water from level 700 m to the surface.

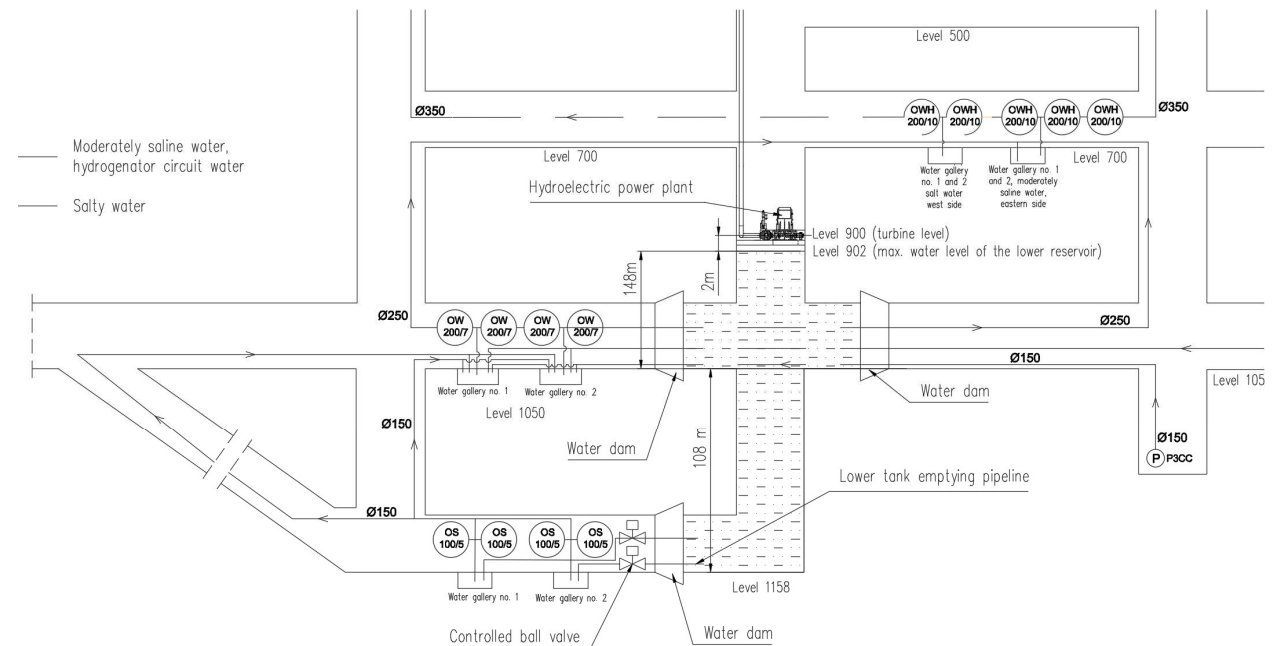


Fig. 15. Schematic diagram of pumping water from the lower reservoir



3. Upper reservoir

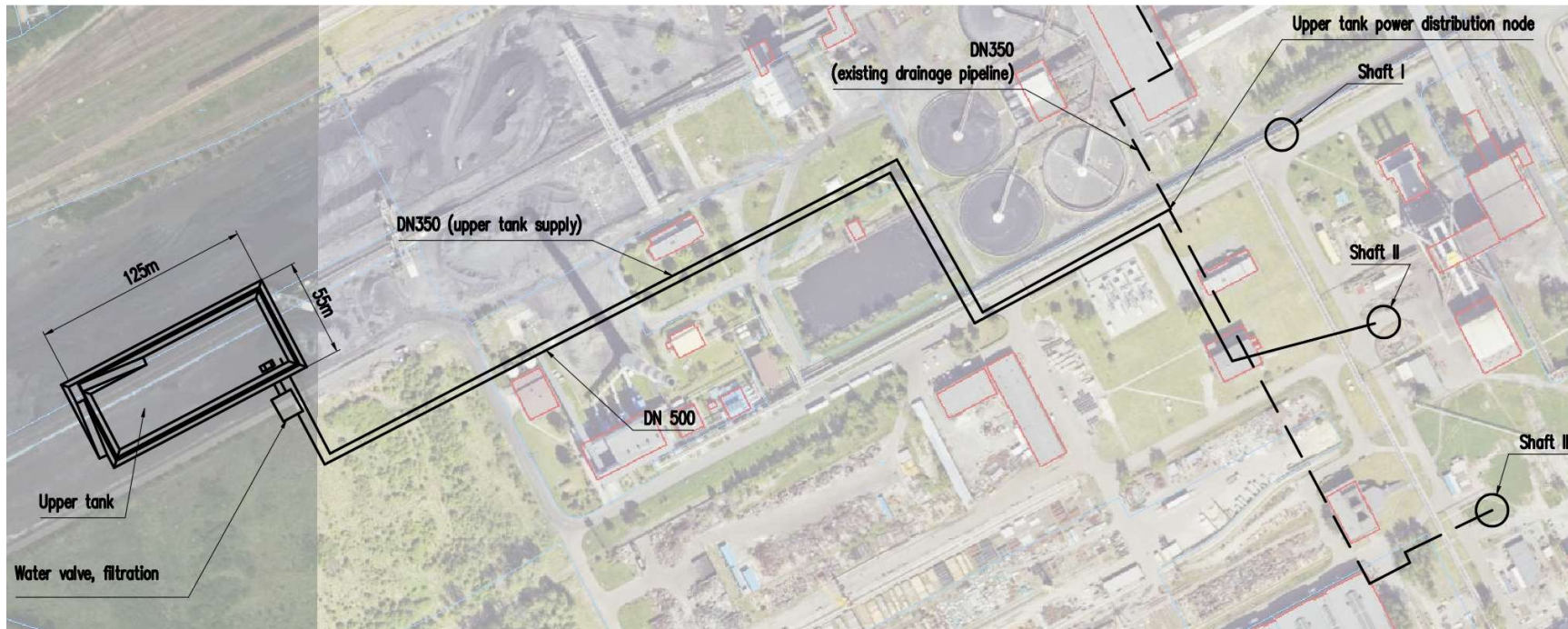


Fig. 16. Location of the upper reservoir

The upper reservoir is a key component of a pumped-storage power plant, serving as a storage facility for potential energy. During periods of surplus electrical energy in the system, water is pumped from the lower reservoir into the upper reservoir. During periods of increased power demand, energy is recovered through turbines, into which water flows under gravity.

The upper reservoir of the pumped-storage power plant installed in the mining shaft is located in the western part of the Budryk coal mine area, next to the stockpile area for coal slurry concentrate No. 3 (fig. 16).



3. Upper reservoir

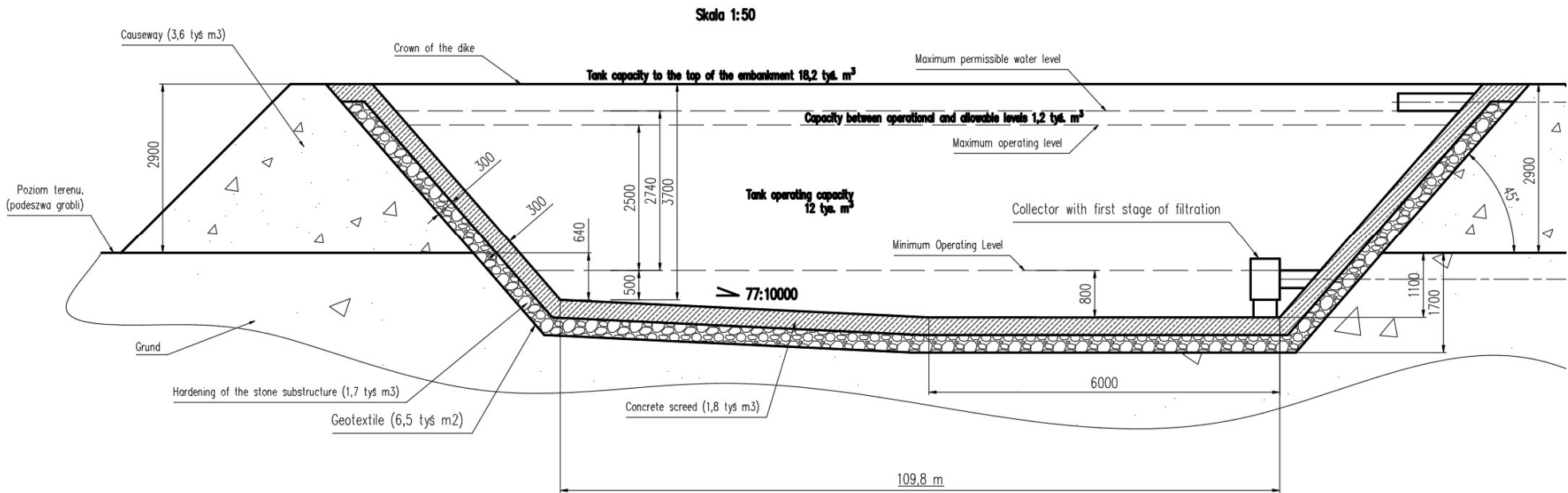


Fig. 17. Cross-section of the upper reservoir

The reservoir has been partially excavated into the ground, to a maximum depth of 1.1 m.

The bottom of the reservoir slopes eastwards, towards the water intake. In the sections of the reservoir situated above ground level, the reservoir is surrounded by an embankment, with the crest located at an elevation of 2.9 m.

The embankment slopes and the bottom of the reservoir consist of three layers (fig. 17).



4. Platform assembly

Technical service platforms:

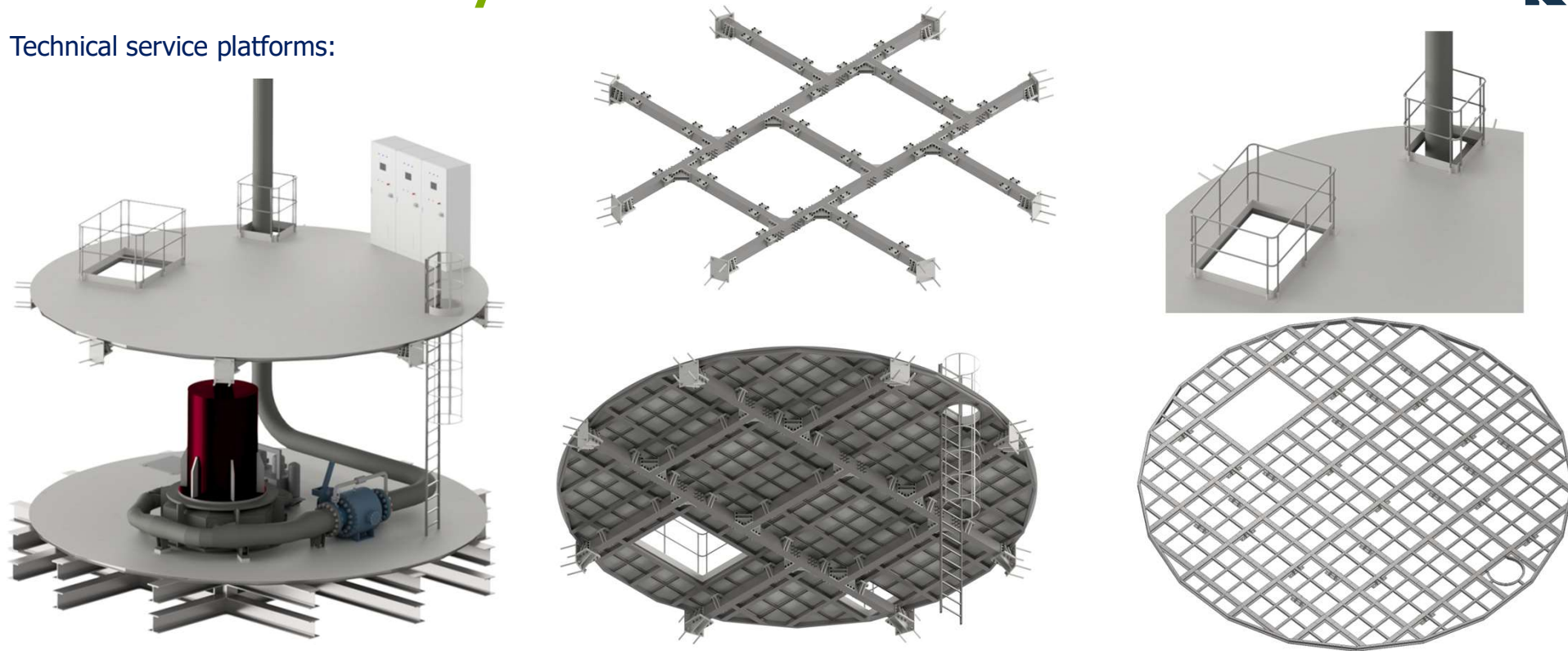


Fig. 18. Original design with a steel lower-platform structure

The upper platform (fig. 18) frame is executed as a welded structure. The outer ring of the frame is made of U100 channels, while the steel grillage consists of HE100B beams. Additionally, to stiffen the structure, cross-members made of U100 channels are welded between the grillage beams.

Checker plates are bolted to the frame structure to form the platform floor surface. The plates are installed using bolted connections fastened to the steel grillage and the cross-members.

HESS Hybrid Energy Storage System Using Post-mining Infrastructure No. 101112380



4. Platform assembly

Technical service platforms:

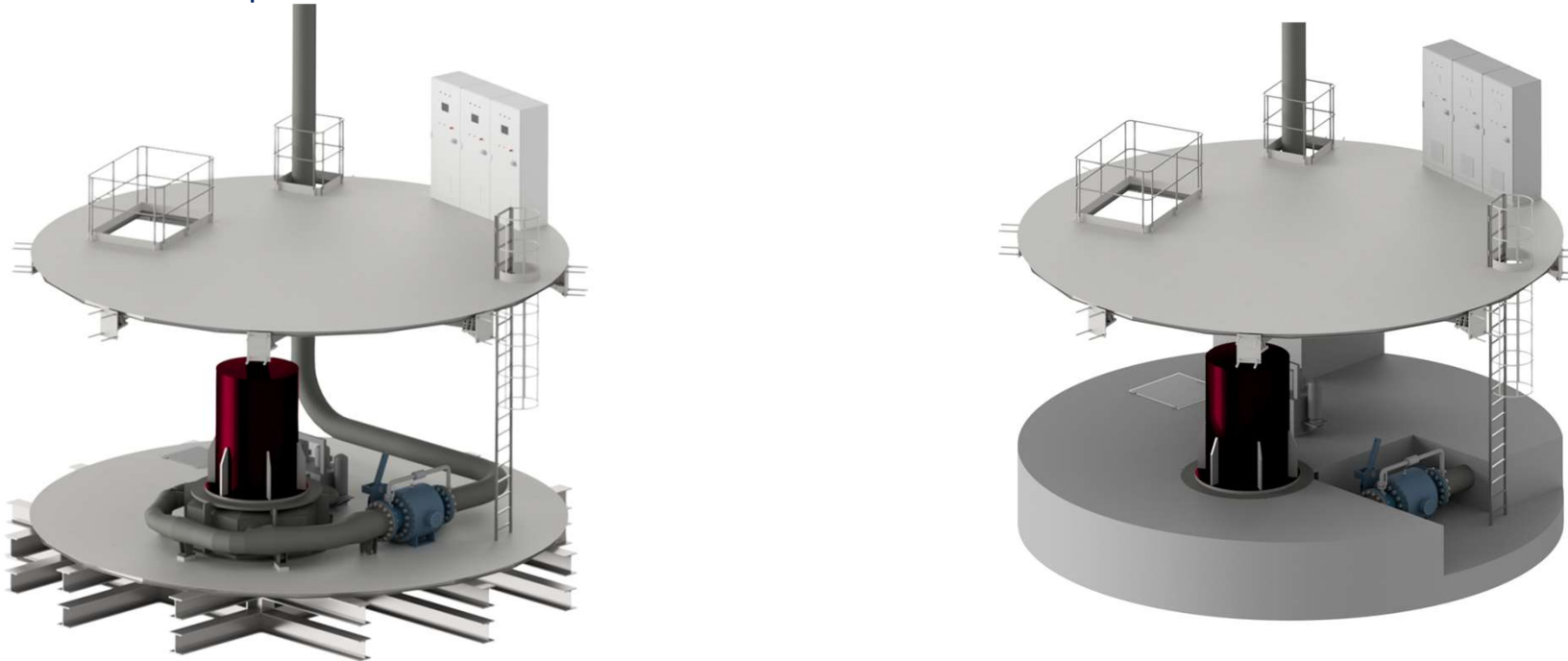
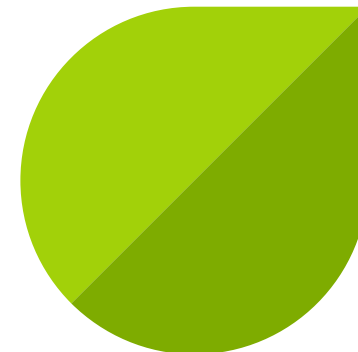
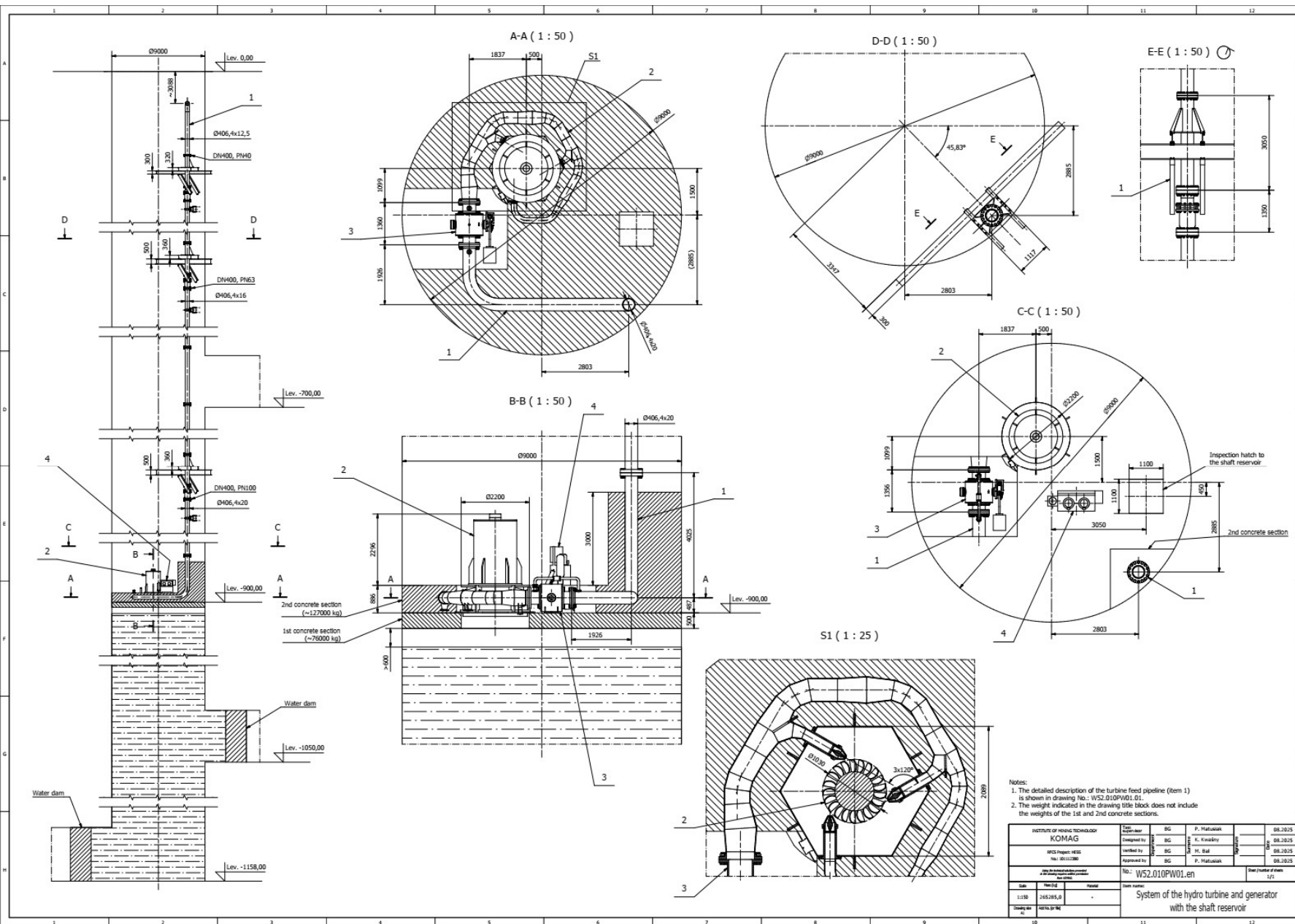
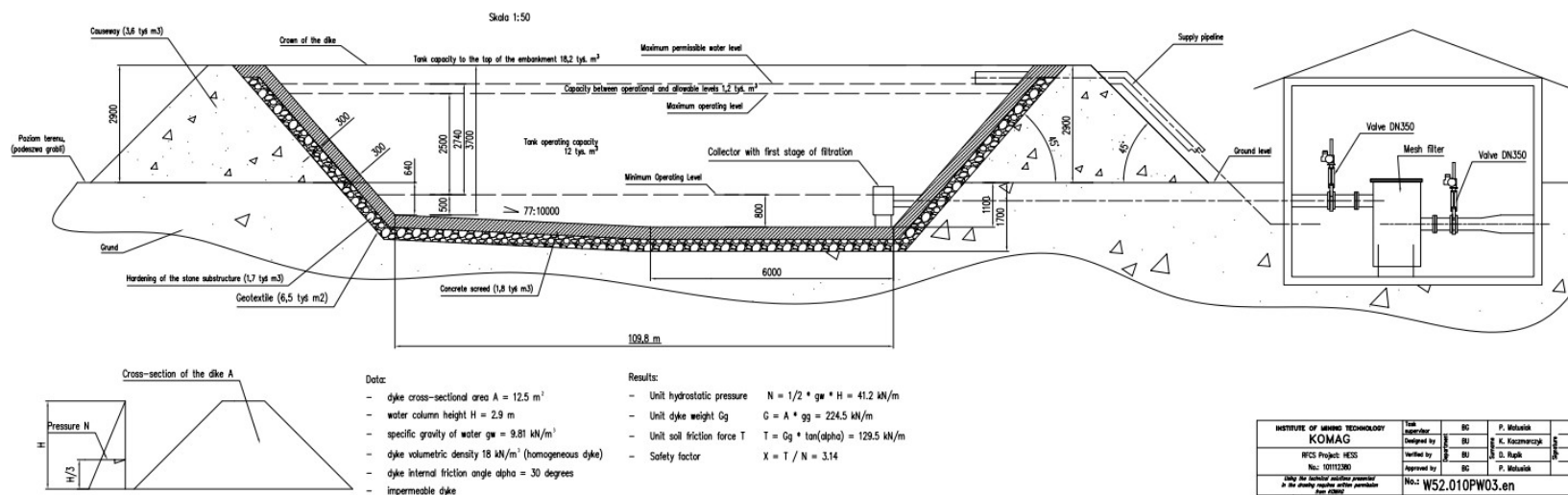
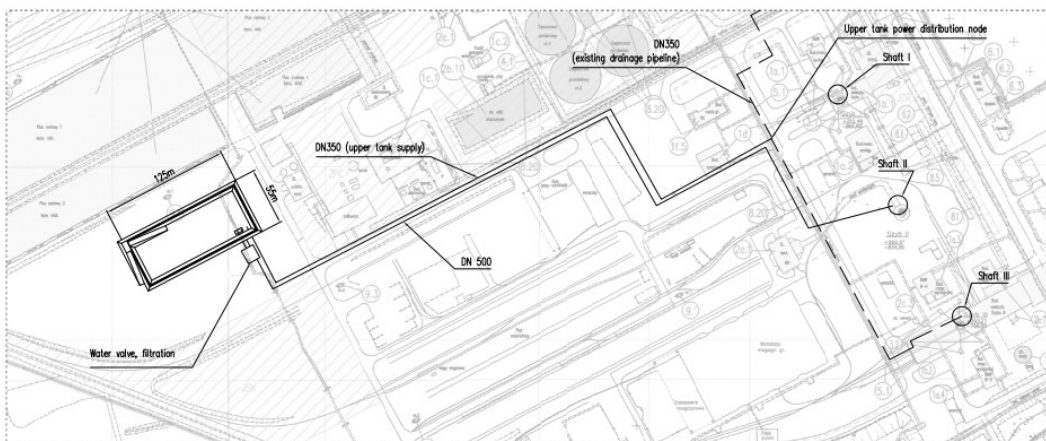


Fig. 19. Lower and upper service platform levels installed in the shaft using a massive concrete structure

Initially, a segmented steel structure was considered due to its ease of prefabrication and installation within the mine shaft. However, following an analysis of the turbogenerator's impact, it was determined that the vibrations and dynamic loads generated during operation required the use of a massive concrete structure, providing improved vibration damping and greater operational stability. In addition, the concrete foundation enhances system durability, improves load distribution, and facilitates the integration of auxiliary equipment.



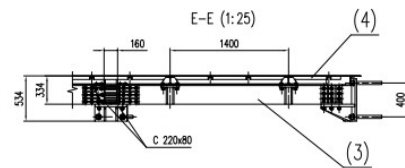
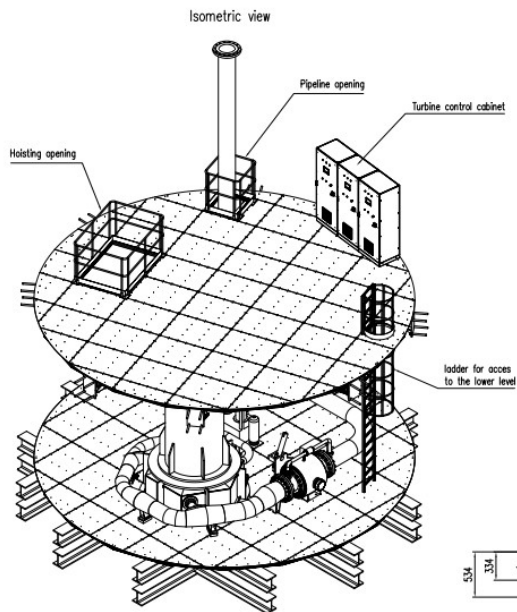
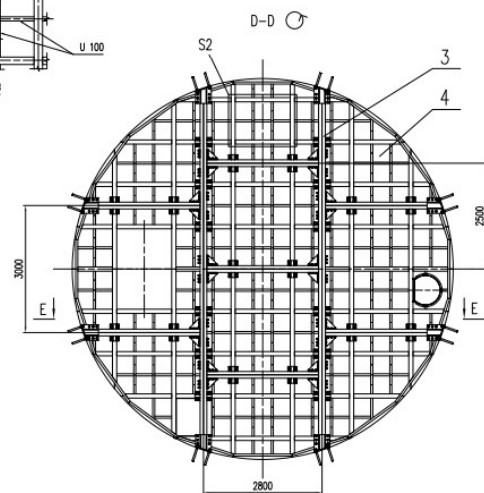
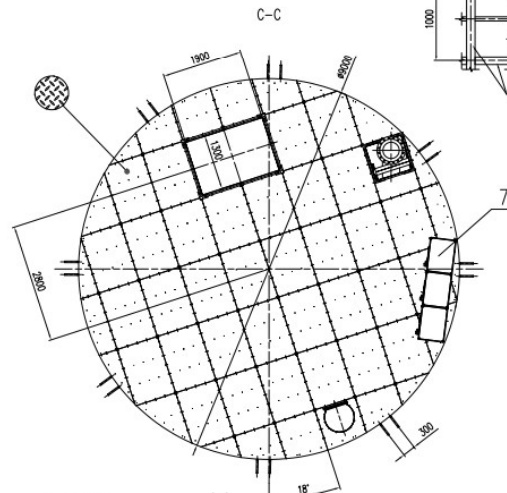
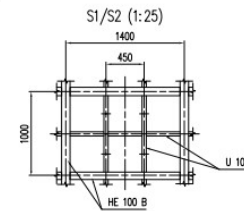
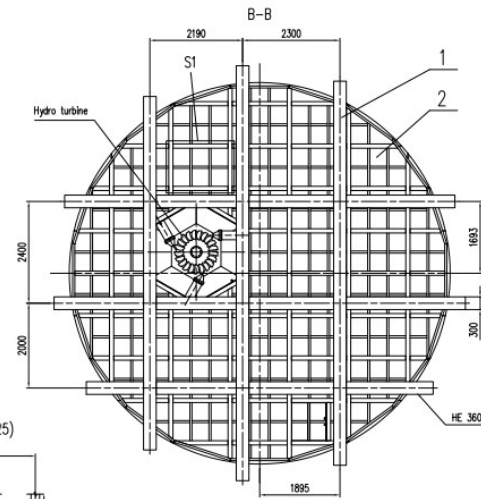
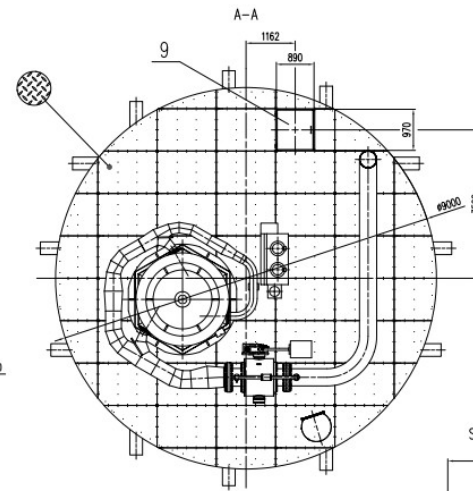
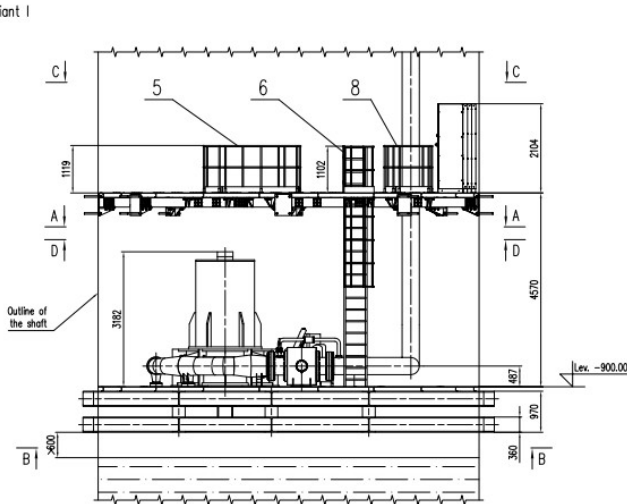
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INSTITUTE OF ANIMAL TECHNOLOGY		Task	BC	P. Mutulak	07.2025
KOMAG		Designed by	BC	A. Kucmanovic	07.2025
WGS Project: HESS		Verified by	BC	G. Hajduk	07.2025
No.: 10113280		Approved by	BC	P. Mutulak	07.2025
Using the technical solution presented in the drawing requires written permission from KOMAG		No.: WS2.010PW03.en			Maximum of sheet 1/1
Scale	1:2000	Sheet No.	Upper reservoir		
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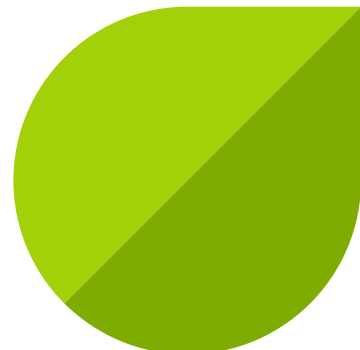


Variant I



- Notes:
1. There are two variants of the assembly: variant I – shown on the sheet 1 with the lower level platform made of steel structure, and variant II – shown on the sheet 2 with the lower level platform made of concrete sections. The mass of variant I assembly is 29855 kg. For variant II assembly, the mass is 9698 kg and does not include the mass of concrete sections.
 2. The platform floor must be made of chequered steel plate for anti-slip surface.

INSTITUTE OF MARINE TECHNOLOGY		Task supervisor	RS	P. Matusiak	10.2025
KOMAG		Designed by	RS	P. Matusiak	10.2025
WCS Project WESS		Verified by	RS	P. Matusiak	10.2025
No. 10112380		Approved by	RS	P. Matusiak	10.2025
Using the technical solution presented in the assembly requires further permission from KOMAG		No. 1 W52.010PW04.en			
Scale	1:50	Notes	Platform assembly		
Drawn by	RS	100 No. for file			

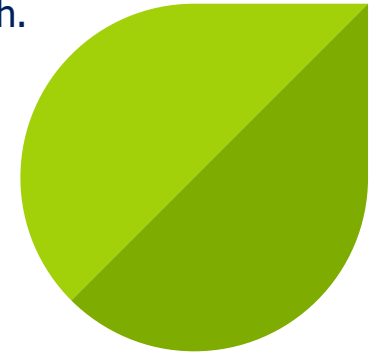


Basic Technological Parameters



The most important parameter of the designed PSH module is the energy storage capacity of 23.06 MWh. This value was determined based on the lower reservoir volume, hydraulic head, and hydropower unit efficiency.

The input parameters adopted for the design of the PSH module are presented in Table 2.



No	Parameter	Value
1	Total shaft depth	1157.45 m
2	Shaft diameter	9 m
3	Lower reservoir depth	200 m
4	Maximum geometrically available useful head	950 m
5	Conservative design head adopted for calculations	900 m
6	Lower reservoir capacity	12 719 m ³
7	Operational working volume	12 000 m ³
8	Hydropower unit efficiency	0.7
9	Gravitational acceleration	9.81 m/s ²
10	Water density	1 kg/dm ³
11	Energy storage capacity	23.06 MWh



Table 2 Input parameters adopted for the design of the PSH module.



Cost of the PSH Energy Storage System Installed in a Mine Shaft

The table below presents the estimated costs of the PSH energy storage system installed in a mine shaft Budryk II

No	Item	Mass [kg]	Cost [EUR]
1	System of the hydro turbine and generator with the shaft reservoir		9 136 901
	Vertical Pelton turbine type PV3i-790-160 5.8 MW with synchronous generator 5800kVA 6300V 1500rpm	19 630	1 676 056
	Pipelines	245 655	3 459 930
	Mine shaft sealing - 32 740 m ² (500 zł per m ²)		3 842 723
	Mine shaft sealing plug - 3 pcs		158 192
2	Water pumping system		9 191 125
	Pipelines	603 570	8 500 984
	Pumps (5pcs OW200/10; 4 pcs OW200/7; 4 pcs OS100/5)		690 141
3	Upper reservoir		1 034 366
	Excavation		131 455
	Embankments		76 056
	Geotextile		12 207
	Compacted crushed stone subbase (dolomite aggregate, assumed bulk density 1.5 t/m ³)		215 493
	Concrete screed C35/45		211 268
	Transport and installation		387 887
4	Platform assembly		555 563
	Upper platform	9 200	173 850
	Lower platform	20 200	381 714
Total Cost [EUR]			19 917 956



Table 3 The estimated costs of the PSH

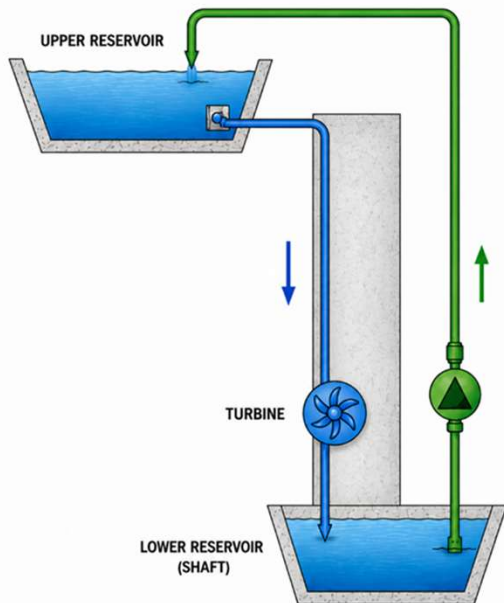
HESS Hybrid Energy Storage System Using Post-mining Infrastructure No. 101112380



Cost of dewatering

Using a three-stage dewatering system to pump 12,000 m³ requires a total energy consumption of 64 MWh per day.

Pumping out 12,000 m³ takes approximately 10 hours.



Parameter	OS-100/5	OW-200/7	OWH-200/10
Pumping stage	1158 m → 1050 m	1050 m → 700 m	700 m → surface
Capacity, Q	81 m ³ /h	300 m ³ /h	315 m ³ /h
Head, H	145 m	420 m	800 m
Nominal power	47.5 kW	490 kW	981 kW
Number of operating pumps	4	1	1
Installed/available power in operation	190 kW	490 kW	981 kW
Effective capacity	324 m ³ /h	300 m ³ /h	315 m ³ /h
Pump load range	50–80%	54.0–86.4%	51.4–82.3%
Pumping power range	95.0–152.0 kW	264.6–423.4 kW	504.5–807.2 kW
Pumping energy	7,037 kWh	19,600 kWh	37,371 kWh

Table 4 Evaluation of the energy efficiency of the lower reservoir pumping process



Fig. 20 Schematic diagram of PSH module operation.

HESS Hybrid Energy Storage System Using Post-mining Infrastructure No. 101112380



Energy storage discharge



Full energy storage discharge capacity – 23 MWh

Discharging 12,000 m³ of water from the upper reservoir to the lower reservoir in the shaft at an optimal power of 5.8 MW takes approximately 4 hours.

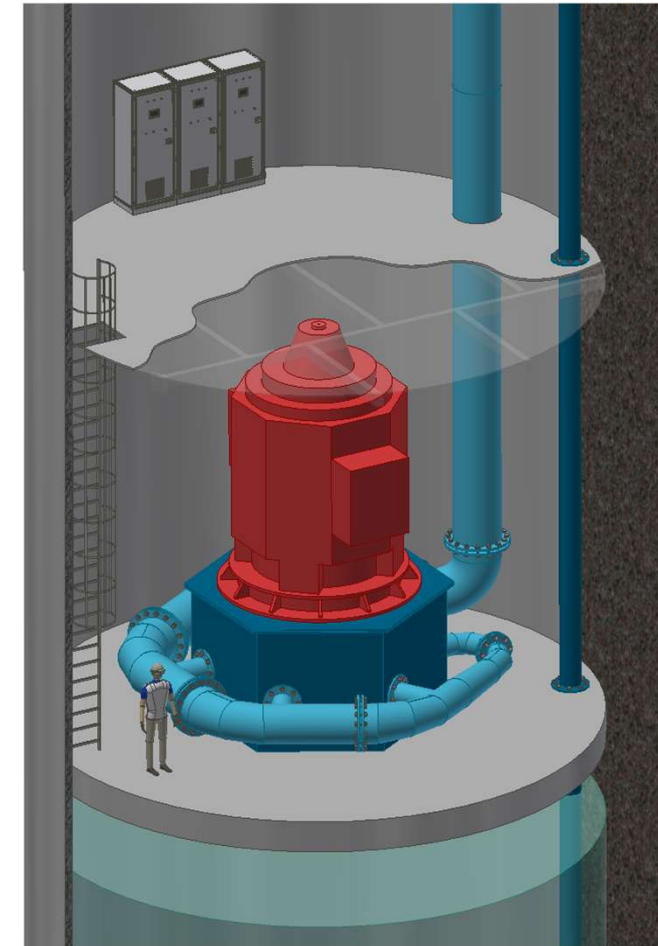
Table 3 Operating parameters of the PSH module

No.	Energy storage capacity [MWh]	Operating time [h]	Turbine power [MWh]	Water flow rate [m ³ /s]
1	23,06	2	11.5	1.77
2		3	7.7	1.18
3		4	5.8	0.88
4		5	4.6	0.71
5		6	3.8	0.59
6		7	3.3	0.50
7		8	2.9	0.44
8		9	2.6	0.39
9		10	2.3	0.35



Summary and Conclusions

1. A review of mine shafts was carried out, based on which the **Budryk II shaft** was selected as the location for the PSH energy storage system. Thanks to its depth of **1,158 m** and diameter of **9 m**, it is possible to achieve a lower reservoir volume of approximately **12,000 m³**, exceeding the minimum project requirements.
2. A **Pelton turbine coupled with a 5.8 MW generator** was selected for the system, and detailed designs were developed for key infrastructure components, including the **DN400 penstock, service platforms, upper reservoir, and drainage system**.
3. The designed PSH system provides an **energy storage capacity of 23 MWh** and a **full discharge duration of approximately 4 hours**, meeting the objectives of the **HESS project**.
4. The estimated construction cost of the PSH system is approximately **EUR 20 million**.
5. The obtained results confirm the **technical feasibility of implementing a PSH energy storage system in an existing mine shaft** and demonstrate the potential of utilizing post-mining infrastructure for **large-scale energy storage applications**.



LAUREAT KONKURSU



TERAZ POLSKA



KOMAG

Thank you for your attention

pmatusiak@komag.eu

dkowol@komag.eu

HESS PROJECT WEBSITE - <http://www.itpe.pl/en/hess/>

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Project co-funded by the Polish Ministry of Science and Higher Education under the program entitled „Co-financed International Projects”.

HESS Hybrid Energy Storage System Using Post-mining Infrastructure No. 101112380



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SELECTION OF LINING MATERIALS FOR SEALING MINE SHAFTS IN HESS APPLICATIONS AND ASSESSMENT OF THEIR GAS PERMEABILITY PROPERTIES

Konrad Kołodziej
Marcin Lutyński

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26



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The work presented on the poster was performed as part of the HESS project (Hybrid energy storage system using post-mining infrastructure) grant no. 101112380 supported by the EU RFCS.

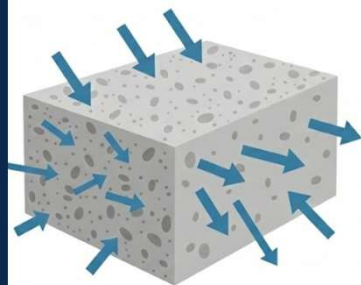


The project is co-financed by the Polish Ministry of Education and Science under the program entitled International Projects Co-financed Agreement No. 5462/FBWIS/2023/Z

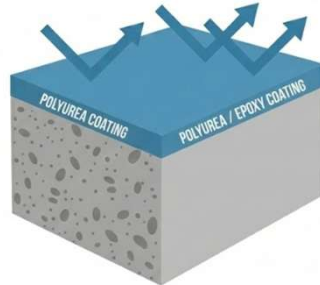
PROTECTION OF CONCRETE AGAINST GASES

HIGH GAS PERMEABILITY

LOW GAS PERMEABILITY



UNPROTECTED CONCRETE



PROTECTED CONCRETE

Purpose and scope of Deliverable 4.3

This deliverable reports the measured gas-permeabilities of candidate shaft-lining materials - coating systems, together with the test methodology and datasets needed for engineering use in HESS.

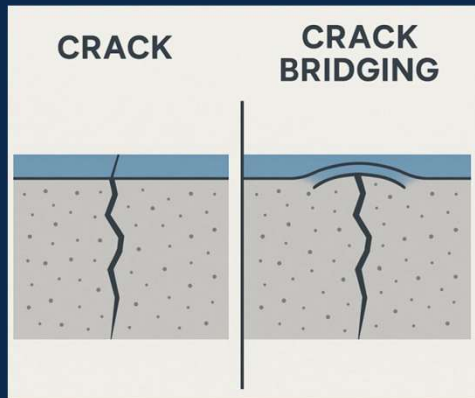


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Materials



Concretes

C20/25 – representative for older shafts

C40/45 – reference for modern deep shafts

Sealing systems

Epoxy thin coating (WallCoat T)

Polymeric membrane (Sikagard® M 790 – Xolutec®)

Material concept	Thickness	Function
Epoxy coating	thin	diffusion barrier
Xolutec® membrane	thick	barrier + crack bridging



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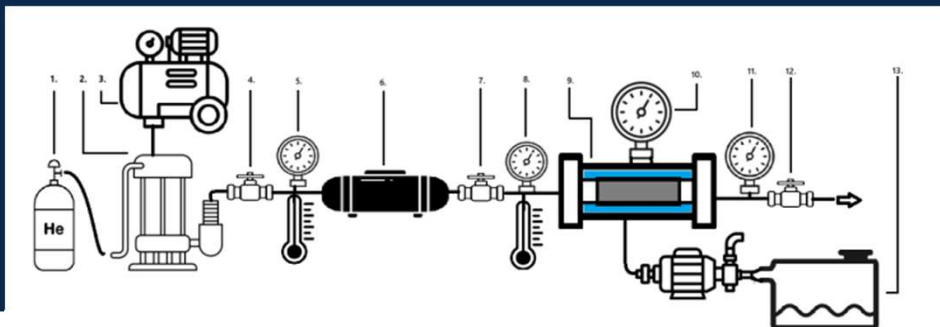
Test Gas, Method & Laboratory Setup

Test gas - Helium (He)

Selected as a non-adsorbing reference gas providing the highest sensitivity for intrinsic permeability at very low flow rates.

Pressure conditions – corrected explanation

The two pressure gradients (60→atm and 60→50 bar) were selected to distinguish material-controlled permeability from boundary-condition effects, by comparing a large driving force representative of worst-case leakage with a reduced gradient representative of quasi-isobaric shaft operation.



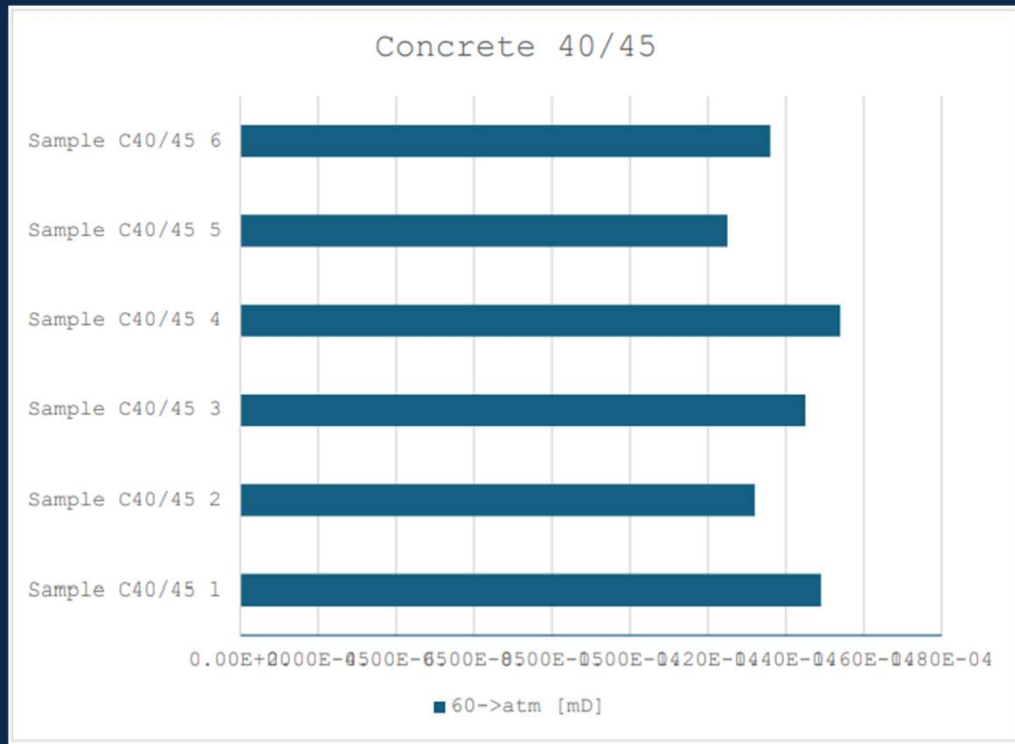
Parameter	Value
Test gas	Helium (He, 99.999%)
Inlet pressure	60 bar
Outlet pressure (case 1)	1 atm
Outlet pressure (case 2)	50 bar
Pressure gradient	60 → atm / 60 → 50 bar
Temperature	20 °C ± 0.1 °C
Specimen size	Ø25 mm × 30 mm
Confining pressure	90 bar ± 2



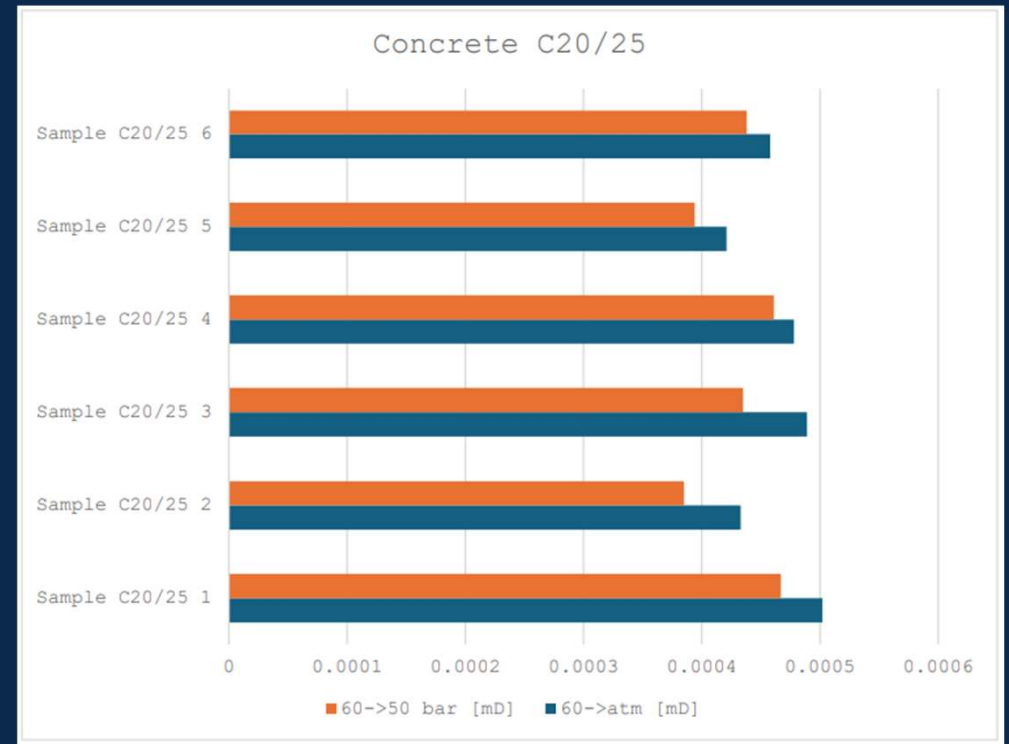
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Permeability results for raw concrete.



Permeability results for C40/45 concrete.

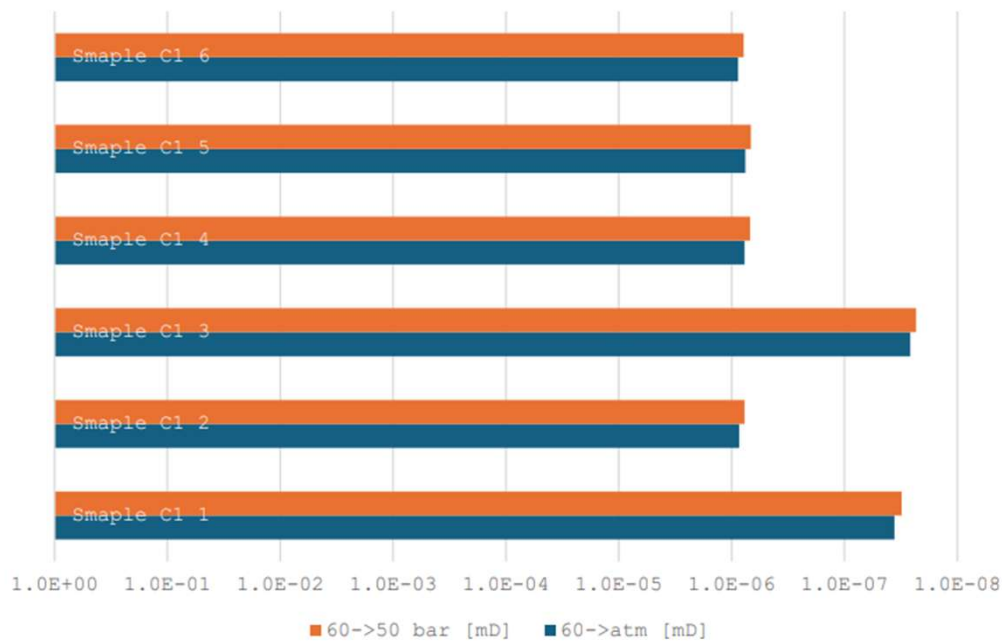


Permeability results for C20/25 concrete under two gradients: 60→atm and 60→50 bar



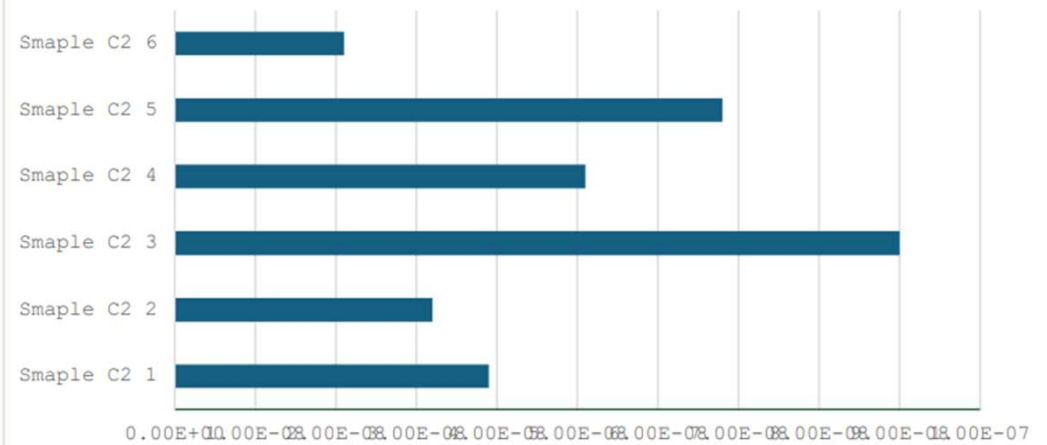
Permeability results for concreto +lining.

Sikagard® M 790



Permeability results for coating system under 60bar to atm and 50-60 bar

WallCoat T



Permeability results for coating system under 60bar to atm.

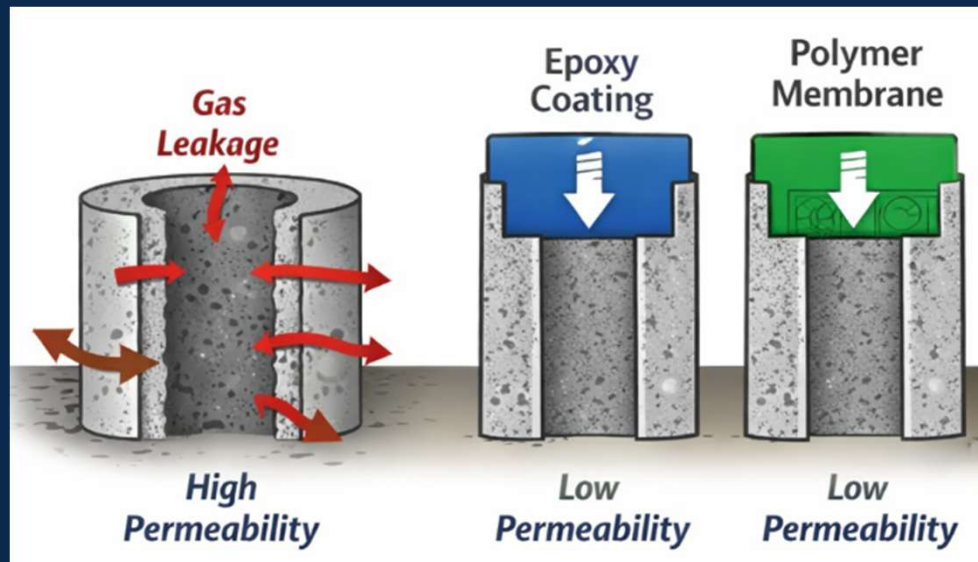


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Results



Engineering significance

Gas permeability is a **limiting parameter for ACAES** operation

Protective coatings are mandatory for shaft adaptation

Measured data enable quantified leakage assessment at system scale

Summary

Uncoated concrete shows measurable gas permeability
Higher concrete class reduces k but does not ensure gas-tightness
Both coating systems reduce permeability by **3–4 orders of magnitude**



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THANK YOU!

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Hybrid Energy Storage System Using Post-Mining Infrastructure (HESS)

Durability and transport properties of concrete and protective coatings for HESS

Krzysztof Supernok, Agata Czardybon,
Szymon Dobras, Tomasz Spietz

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

WP3 – Energy storage in pumped storage systems

T3.2 - Construction and operation of underground reservoirs of pumped storage power plant (PSH)

- Corrosion tests of construction materials in presence of chloride, magnesium and sulphate salts, acid and mine water;
- Erosion tests of construction materials under water and mine water;
- Penetration depth of construction materials;
- Leaching characteristics of pressurized liquids into construction materials.



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**„Hybrid energy storage system using post-mining infrastructure“ (HESS)
No. 101112380 (RFCS-2022)**

Corrosion tests of construction materials

- Corrosion test were carried out by continuous immersion of concrete samples in corrosive solutions:

5% NaCl; 5% MgSO₄, 5% Na₂SO₄, 5% HCl and mine water* (an environment similar to operating conditions)

- The concretes tested were **C20/25** and **C35/45** in the **raw state** and **protected** with **Sikagard® M790** and **WallCoat T** coatings
- The samples were stored in closed cointainers and maintained at **30°C** coirresponding to the temperatures similar to operating conditions.
- Exposure time was **14 - 180 days**.
- After completing the tests, the samples were rinsed with water, dried and assessed for changes in:
 - **mass change,**
 - **compression strength,**
 - **pH,**
 - **structure.**



C20/25



C20/25+ M790



C20/25+ WallCoat T



The samples immersed in corrosive agents

*Mine water composition

Ions	Concentration [mg/L]
Na ⁺	36 000
K ⁺	300
NH ₄ ⁺	1,11
Ca ²⁺	3 286
Mg ²⁺	705
Cl ⁻	61 791
SO ₄ ²⁻	2 492
HCO ₃ ⁻	88
NO ₃ ⁻	1,45

*refers to Lewkiewicz-Małysa A., Winid B. Wybrane problemy związane z zagospodarowaniem wód kopalnianych. *Wiertnictwo Nafta Gaz* 2005, 22(1), 217-224.



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**„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)**

Corrosion tests results

Sample	Corrosive agent		Compressive strength change [%]				Mass change [%]		
		Exporusre time [days]							
			28	90	180		28	90	180
C20/25	NaCl		32,7	6,6	12,0		-0,5	-1,6	-2,7
	MgSO ₄		38,0	-17,5	31,3		-0,3	-0,6	-0,3
	Na ₂ SO ₄		20,1	18,9	16,8		-0,6	-1,2	-1,0
	HCl		-34,7	-16,6	-50,9		-5,9	-4,9	-6,9
	Mine water		-6,9	-1,5	-3,9		-1,4	-0,3	-0,1
C35/45	NaCl		7,3	-1,5	-5,9		-0,2	-1,3	-1,9
	MgSO ₄		-4,3	-7,1	-11,5		0,3	-0,3	-1,6
	Na ₂ SO ₄		2,3	1,7	-0,6		0,0	-1,2	0,8
	HCl		-15,9	-35,8	-38,0		-5,2	-5,7	-5,4
	Mine water		0,0	-3,5	-21,6		-0,7	0,2	0,2
C20/25 + M790	NaCl		-7,6	-10,7	-14,2		0,1	0,2	0,4
	MgSO ₄		-9,5	-5,8	-4,0		0,2	0,5	0,4
	Na ₂ SO ₄		-11,0	-10,9	-5,7		0,1	0,9	1,4
	HCl		-0,4	-0,2	0,9		0,0	0,0	0,3
	Mine water		-10,7	-6,0	-4,6		0,1	0,2	0,2
C35/45 + M790	NaCl		3,1	-6,7	-11,0		0,0	0,1	0,3
	MgSO ₄		0,9	4,2	-0,7		0,3	0,5	0,4
	Na ₂ SO ₄		-6,5	-9,2	-8,9		0,5	0,2	1,4
	HCl		-4,1	-2,1	-3,8		0,1	0,1	0,3
	Mine water		3,7	-5,6	-11,0		0,1	0,5	0,8
C20/25 + WallCoat T	NaCl		-11,2	-4,6	-0,7		0,1	-0,3	0,6
	MgSO ₄		1,7	4,8	2,9		0,8	1,0	0,9
	Na ₂ SO ₄		-9,6	-5,7	1,3		1,4	0,6	1,1
	HCl		-0,1	-5,4	-18,1		0,2	0,7	0,8
	Mine water		-6,1	-18,9	-13,1		0,1	-0,3	0,9
C35/45 + WallCoat T	NaCl		-1,6	-8,3	-14,2		0,8	0,6	0,7
	MgSO ₄		-15,0	-12,3	-10,2		0,5	0,4	1,1
	Na ₂ SO ₄		-3,9	-1,8	-0,5		0,9	0,9	1,6
	HCl		-3,8	-4,8	-7,8		0,1	-0,8	0,6
	Mine water		-2,1	1,0	1,5		0,5	-0,4	0,6



Test stand for compressive strength



Concrete sample after compressive strength test



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„Hybrid energy storage system using post-mining infrastructure“ (HESS)
No. 101112380 (RFCS-2022)

Results of tests on the corrosion under the influence of inorganic salt solutions

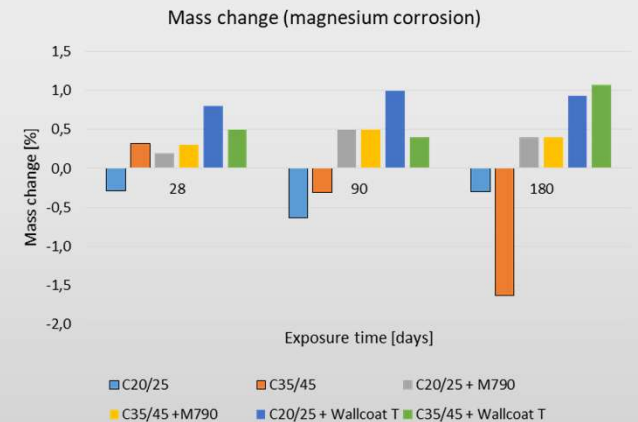
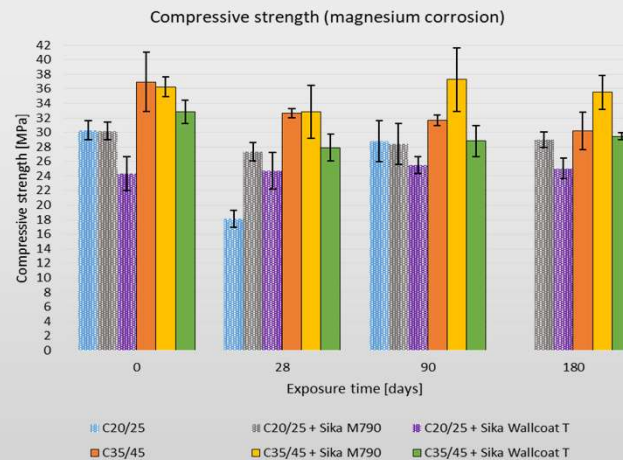
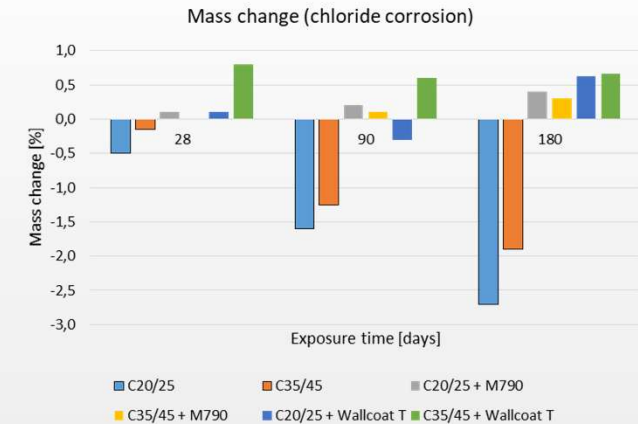
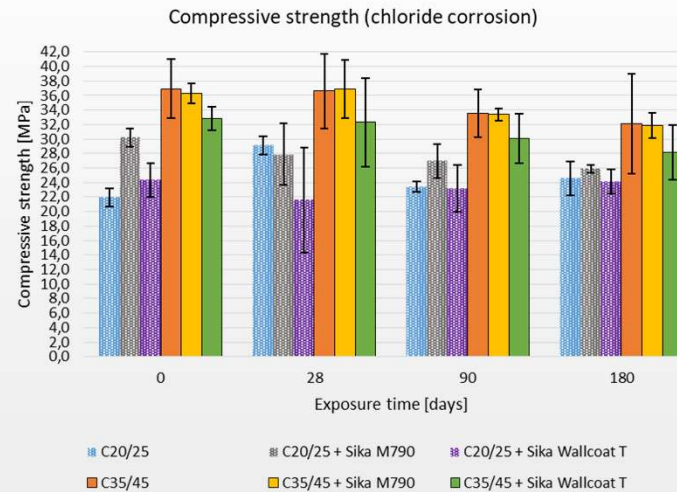
The inorganic salt environment demonstrated moderate aggressiveness towards concrete. The impact depended on the concrete class and coatings.

NaCl

- **C20/25 (raw)**: increase in strength by 33% after 28 days (hydration), then decrease and stabilization
- **C35/45 (raw)**: slight 7% increase after 28 days, then decline to 6% after 180 days.
- **Concretes coated with M790 and WallCoat T**: moderate changes in concrete strength – up to 14% after 180 days.

Summary

- No rapid degradation of concrete after 180 days.
- The changes in concrete mass were relatively small (maximum -2.7% for raw concrete).
- Sikagard® coatings reduce the impact of chlorides, with effectiveness depending on the concrete class (maximum change in mass: 1% with no loss).



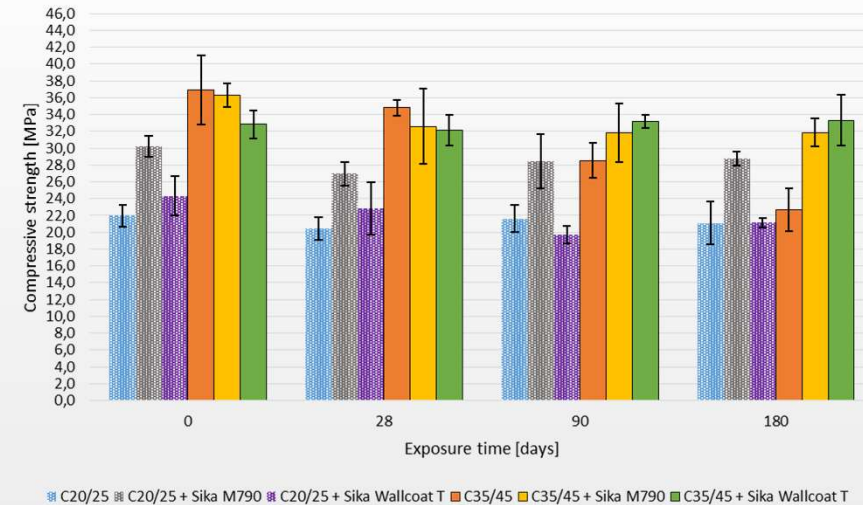
The influence of mine water on changes in the mechanical strength and mass of concrete

- Mine water (comprises of Na^+ , K^+ , NH_4^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , HCO_3^- , NO_3^-) were used to compare the behavior of selected materials in an environment similar to operating conditions.
- **C20/25 concrete** – slight changes in CS (-1.5% to -6.9%), no significant degradation, slight weight changes after 28 days (1,4%), then stabilization
- **C35/45 concrete** – a significant decrease in CS after 180 days (-21.6%), slight weight changes after 28 days (0,7%), then stabilization
- **Sikagard® M790 coating** - effective protection for both classes of concrete, slight strength drops of up to 4.6-11.0%
- **Sikagard® WallCoat T coating** - varied effectiveness depending on the concrete class: C20/25 - decrease by 13–19%; C35/45 - minimal decrease (~0–2%).

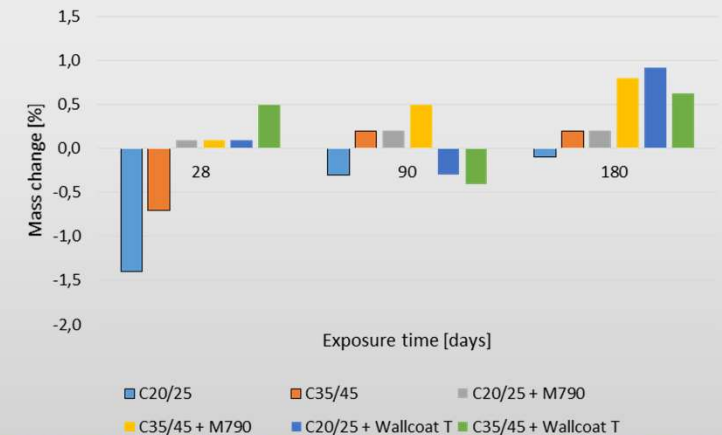
Summary

- **Mine water exhibits moderate aggressiveness towards the tested concretes.**
- The effectiveness of concrete protection depends on both the type of coating used and the concrete grade – **M790 provides stable and effective protection**, while WallCoat T exhibits variable effectiveness, particularly for C20/25 concrete.
- **The observed fluctuations in results, especially for C20/25 concrete, are primarily due to its greater porosity, heterogeneity, and differences in hydration behavior.**

Compressive strength (mine water corrosion)



Mass change (mine water corrosion)



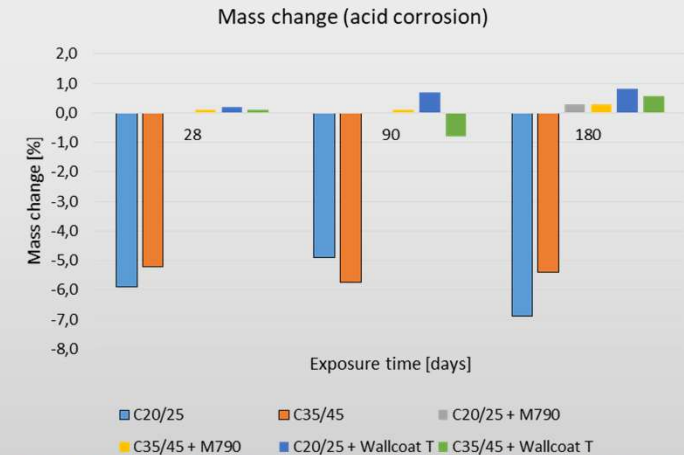
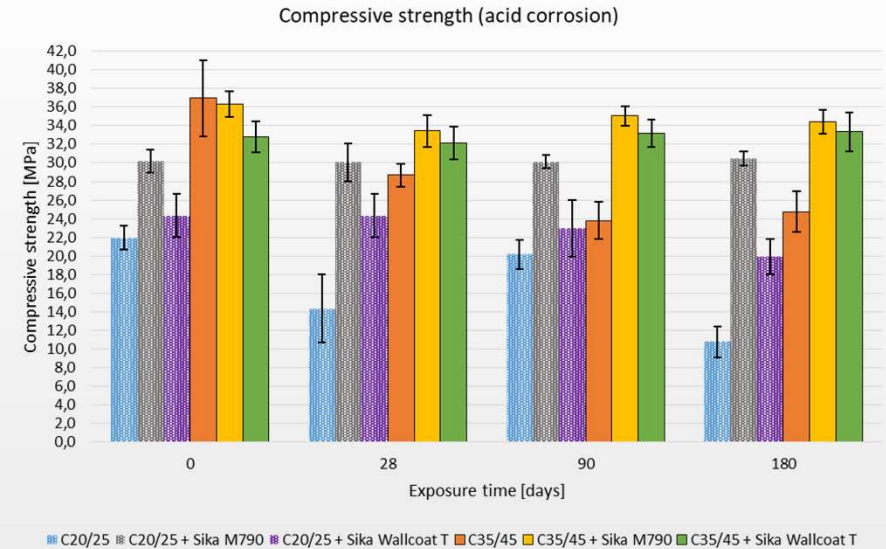
The influence of an acid environment on changes in the mechanical strength of concrete

5% HCl – the most aggressive environment among analyzed

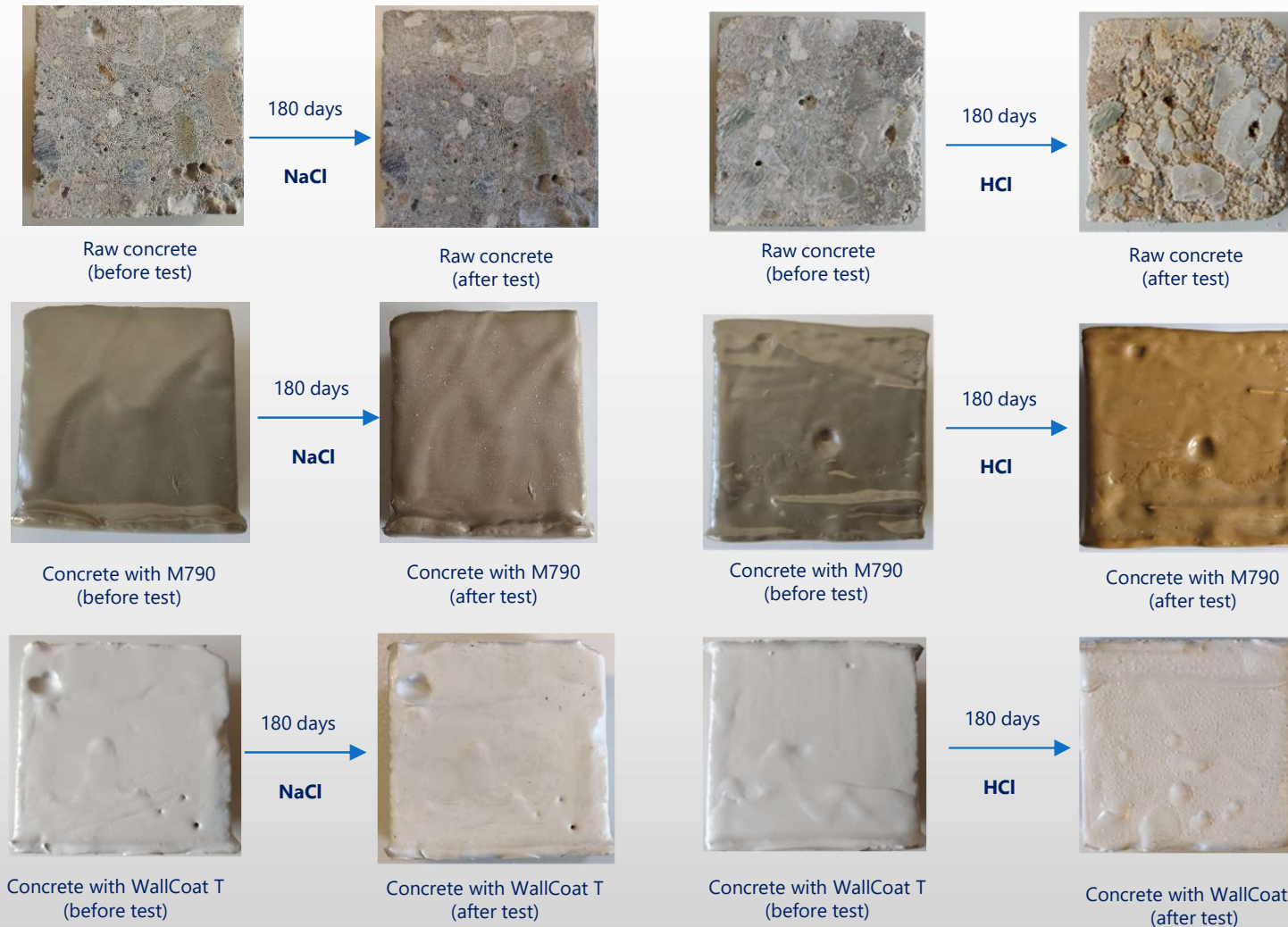
- **C20/25 raw concrete** – compressive strength drop to 51% after 180 days
- **C35/45 raw concrete** – compressive strength drop to 38 % after 180 days
clearly visible degradation of the cement matrix (weight loss)
- **Sikagard® M790 coating** - very high protection efficiency for both concretes (up to 4%)
- **Sikagard® WallCoat T** – reduced protection
- C20/25: compressive strength drop by 18 % (180 days)
- C35/45: moderate decrease in compressive strength (8%), effectiveness decreases over time.

Summary

- A 5% **hydrochloric acid** environment is very aggressive, **causing significant degradation of unprotected C20/25 and C35/45 concrete.**
- In a 5% HCl environment, the **cement matrix dissolution mechanism dominates, leading to concrete mass loss** (the highest mass loss was **5–7% after 180 days**).
Degradation of concrete due to reaction $\text{Ca(OH)}_2 + 2\text{HCl} \rightarrow \text{CaCl}_2 + 2\text{H}_2\text{O}$
- The use of **Sikagard® coatings significantly improves the durability of concrete. M790 provides the highest level of protection**, while WallCoat T offers only partial, short-term protection..
- Sikagard® M790 – very high efficiency, light weight changes ($\leq 0,3\%$)
- Sikagard® WallCoat T – limitation of losses, partial protection.



The influence of corrosive environment on changes in the structure of concrete



Conclusions:

- **No significant structural changes in chloride, magnesium, sulfate, and water mine environments** (applies to both concrete classes).
- **Acid environment (5% HCl)** - visible impact on the concrete surface, partial dissolution of the surface layer, and exposure of the grain structure.
- **Sikagard® M790** - no damage or defects to the coating, uniform structure maintained; color change (from gray to olive).
- **Sikagard® WallCoat T** - visible changes to the coating structure after just 28 days (for acid), blistering, swelling, localized loss of adhesion to the substrate, no degradation of the concrete beneath the coating.



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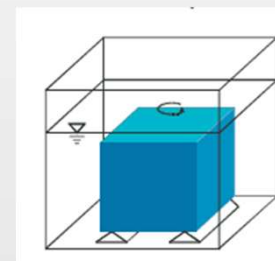


„Hybrid energy storage system using post-mining infrastructure“ (HESS)
No. 101112380 (RFCS-2022)

Leaching characteristic of construction materials

Ions concentration after 30 days, mg/L								
	pH	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	F ⁻	Cl ⁻	SO ₄ ²⁻
C35/45	7,56	18,50	0,01	17,00	67,00	1,01	3,10	53,00
C20/25	7,28	32,90	0,02	26,00	40,00	0,58	6,50	133,00
C20/25 + WallCoat T	6,12	1,10	0,16	0,09	0,08	0,90	0,40	0,74
C35/45 + WallCoat T	5,95	0,70	0,17	0,08	0,10	0,87	0,36	0,52
C20/25 + M790	5,91	0,52	0,11	0,03	0,02	0,67	0,40	0,21
C35/45 + M790	5,82	0,45	0,09	0,04	0,04	0,61	0,33	0,10
Ions concentration after 90 days, mg/L								
C35/45	8,22	16,40	0,02	31,00	131,00	1,57	3,30	53,00
C20/25	8,05	20,70	0,01	40,00	72,00	1,20	6,90	117,00
C35/45 + WallCoat T	6,15	1,70	0,23	0,11	0,08	1,06	0,48	0,68
C20/25 + WallCoat T	5,99	1,50	0,22	0,14	0,25	1,27	0,60	0,76
C20/25 + M790	6,07	0,70	0,15	0,21	0,17	0,77	0,47	0,41
C35/45 + M790	6,01	0,60	0,15	0,29	0,13	0,76	0,32	0,27
Ions concentration after 180 days, mg/L								
C35/45	8,49	6,30	0,02	7,77	97,39	1,28	3,63	65,00
C20/25	8,29	23,90	0,03	10,19	62,32	1,32	7,35	130,00
C35/45 + WallCoat T	6,22	1,20	0,20	0,69	0,26	2,08	0,41	0,45
C20/25 + WallCoat T	6,39	1,02	0,23	0,66	0,15	1,99	0,47	0,69
C20/25 + M790	6,12	0,89	0,18	0,62	0,05	1,07	0,45	0,42
C35/45 + M790	6,07	0,87	0,15	0,65	0,04	1,24	0,35	0,30
Demi water (ref.)	5,60	0,00	0,00	0,01	0,04	<0,1	0,17	0,17

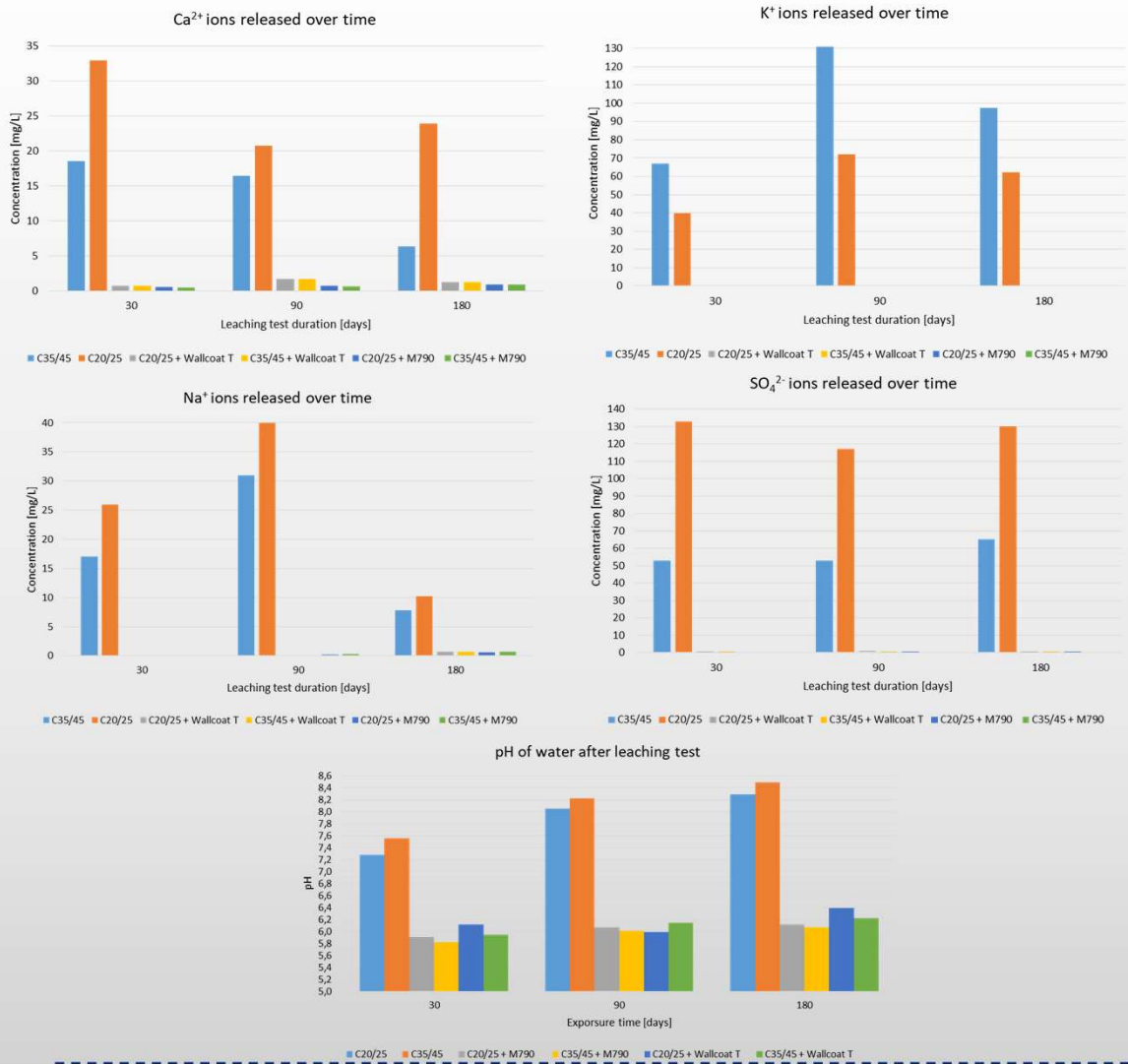
- Immersion in demi water
- Based to **EA NEN 7375:2004 ***
- Immersion time : **30, 90 and 180 days**
- pH, ion concentration : **Ca²⁺, Mg²⁺, Na⁺, K⁺, F⁻, Cl⁻, SO₄²⁻**
- **Water composition analysis** - Dionex ICS5000 ion chromatograph (conductometric detection), HACH DR6000 spectrophotometer and atomic absorption spectrometer (ASA) **for analysis of trace amounts of ions.**



Leaching performance at the beginning and after 180 days

*EA NEN 7375:2004 „Leaching characteristics of moulded or monolithic building and waste materials. Determination of leaching of inorganic components with the diffusion test. The Tank Test”

Leaching characteristic of construction materials



Summary of the leaching tests:

- For concretes in the raw state C20/25 and C35/45 the highest concentrations of ions in the solution were recorded for: Ca²⁺, Na⁺, K⁺, SO₄²⁻, which indicates intensive leaching of the cement matrix components
- With the extension of the exposure time (from 90 to 180 days) changes in ion concentrations were observed, including a partial decrease in Ca²⁺ resulting from earlier leaching, while maintaining high mobility of Na⁺, K⁺ ions, which confirms the progressive decalcification of the cement matrix.
- In the case of the M790 coating, the lowest ion concentrations in the solution were recorded, which proves the effective limitation of leaching of the cement matrix components and the highest tightness and effective protection of the concrete.
- The WallCoat T coating reduces the leaching of components compared to uncoated samples, but the eluate is characterized by higher ion concentrations than in the case of M790, indicating its lower protective effectiveness.
- A clear effect of concrete class was observed. C20/25 shows greater susceptibility to leaching (higher concentrations of Ca²⁺ and SO₄²⁻).
- In the case of unprotected concretes, a significant increase in the eluate pH was observed from 5.6 to 8.5 after 180 days, which indicates intensive leaching of alkaline components and progressive leaching of the cement matrix.
- The use of protective coatings significantly limited this effect – the pH value did not exceed 6.4, which confirms the effective limitation of water contact with concrete and inhibition of degradation processes.



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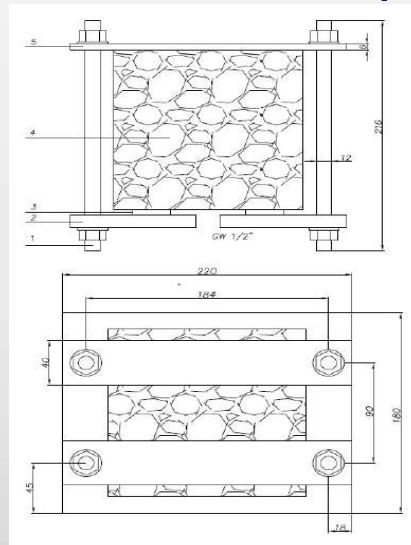
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No. 101112380 (RFCS-2022)

Testing the penetration depth of pressurized liquids into concrete

- The test stand was prepared in accordance with **PN-EN 12390-8***
- **Concrete blocks** (150x150x150 mm) were placed **between two steel plates**
- Water (or mine water) was supplied from the bottom of the block using a hydrophore at a **constant pressure $6 \pm 0,5$ bar at 20°C**
- **C20/25 and C35/45 concretes (raw) and protected with Sikagard® M790 and WallCoat T were tested.**
- Test duration: **72 hours, 2 months**
- **After the test**, the samples were divided and the **maximum liquid penetration depth was measured**



Test stand and scheme for testing the penetration depth



The samples after cracking for the determination of PD



The samples prepared for testing the penetration depth

* Badanie betonu – Część 8: Głębokość penetracji wody pod ciśnieniem



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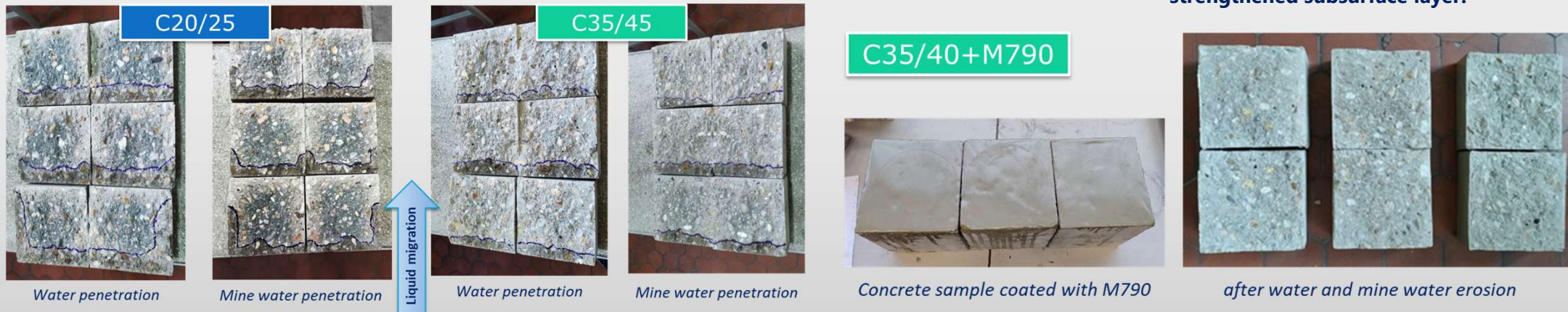
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Testing the penetration depth of pressurized liquids into concrete

Concrete sample	Medium (exposure time)	Max. penetration depth [mm]			Avg. penetration depth [mm]
		Sample I	Sample II	Sample III	
Raw samples					
C35/45	Water (72 hrs)	26	33	28	29
C35/45	Mine water (72 hrs)	28	31	30	30
C20/25	Water (72 hrs)	35	37	37	36
C20/25	Mine water (72 hrs)	32	24	31	29
Samples coated with Sikagard®					
C35/45+Sikagard® M 790	Mine water (72 hrs)	0	0	0	0
C35/45+Sikagard® WallCoat T	Mine water (72 hrs)	0	0	0	0
C35/45+Sikagard® M 790	Mine water (2 months)	0	0	0	0
C35/45+Sikagard® WallCoat T	Mine water (2 months)	0	0	0	0

Summary of the tests:

- Tests showed that **average water permeability was higher for C20/25 concrete.**
- Tests of **mine water permeability** through uncoated concrete **yielded similar results for both concrete grades.**
- **Tests revealed no liquid penetration** (water or mine water) **after two months through concrete samples protected** with Sikagard M790 and WallCoat T coatings.
- **Both tested coatings** provide an effective protective barrier for concrete. Furthermore, **they require greater force to break**, indicating increased resistance **and a strengthened subsurface layer.**



Erosion tests

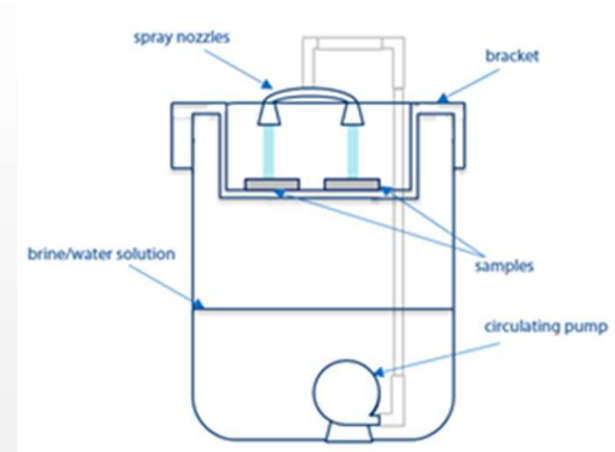
Assumptions:

- **Continuous flow of erosive medium**
- Erosive medium: **water and mine water**
- **Flow rate: approx. 950 l/h**
- Test duration: **60 days**

Sample	Mass change [%]	
	Water	Mine water
C20/25	-0,2	-0,4
C35/45	-0,2	-0,3
C20/25 + M790	0,1	0,1
C35/45 + M790	0,1	0,1
C20/25 + WallCoat T	0,1	0,1
C35/45 + WallCoat T	0,1	0,1

Summary:

- **No significant surface degradation was observed** – only slight surface smoothing was observed on the uncoated concretes.
- **Sikagard coatings demonstrate high erosion resistance** in both water and mine water environments.



C20/25 raw sample



C20/25 after water erosion



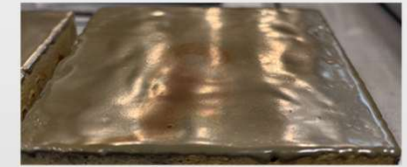
C20/25 after mine water erosion



C20/25 + Sikagard M790



C20/25 + Sikagard M790 after water erosion



C20/25 + Sikagard M790 after mine water erosion



C20/25 + Sikagard WallCoat T



C20/25 + Sikagard WallCoat T after water erosion



C20/25 + Sikagard WallCoat T after mine water erosion



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WP4 – Energy storage in compressed gas systems

T4.2 - Compressed CO₂ energy storage in mine shaft

Corrosion tests under CO₂ in a pressure tank



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No. 101112380 (RFCS-2022)**

Corrosion tests under CO₂ in a pressure tank

Assumptions:

- Maintain concrete samples in gaseous CO₂ at 6 bar
- Combination of CO₂ with water, inorganic salts and mine water on mass loss and compressive strength were investigated
- Test duration: 60 days

Sample	C20/25		C35/45		C20/25 + M790		C35/45 + M790		C20/25 + WallCoat T		C35/45 + WallCoat T	
	MC [%]	CS / MPa	MC [%]	CS / MPa	MC [%]	CS / MPa	MC [%]	CS / MPa	MC [%]	CS / MPa	MC [%]	CS / MPa
Raw	-	28,9	-	36,9	-	25,3	-	34,5	-	24,3	-	32,8
Water+ CO ₂	-0,9	29,3	-0,4	39	<0,2	23,5	<0,1	30	<0,1	23,7	0,1	34,9
Chloride + CO ₂	-0,2	23,7	-0,1	38,8	<0,2	23,7	<0,1	29,2	<0,1	22,5	0,1	32,1
Magnesium + CO ₂	0,1	26,8	-0,1	32,8	<0,2	21	<0,1	33,7	<0,1	26,4	0,1	31,8
Sulphate + CO ₂	-0,2	19,9	-0,2	27,8	<0,2	23,7	<0,1	32,6	<0,1	21,1	0,1	29,7
Mine water+ CO ₂	-0,6	21,5	-0,4	26,5	<0,2	18,8	<0,1	32,3	<0,1	21,6	0,1	29,9

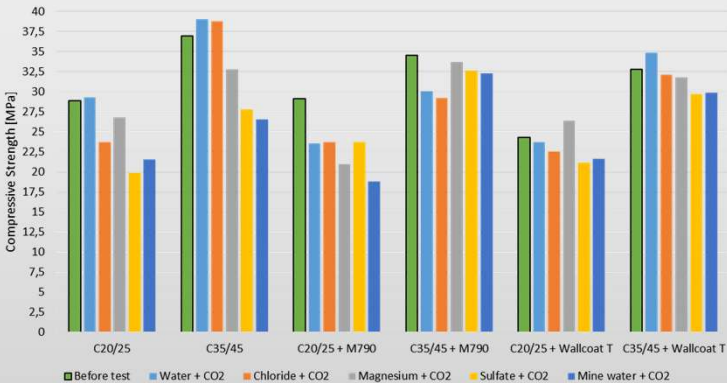
Conclusions:

- The sample **weight loss was recorded for uncoated concrete (higher for C20/25 concrete).**
- The **largest compressive strength drop** was observed for CO₂ combined with sulphate and mine water (approximately 9 MPa).
- Sikagard®-coated concretes showed increased resistance to weight and strength loss compared to uncoated concrete.



Stand for testing the corrosion of construction materials in the presence of CO₂ under pressure

Compressive strength of samples after corrosion with presence of CO₂ in water solutions (after 60 days)



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Summary of the work

- **Both Sikagard® protective systems effectively limit liquid penetration, reduce ion leaching and improve concrete durability** compared to uncoated samples.
- For environments **with increased chemical aggression, especially acidic environments**, and where maximum sealing and reduced leaching of concrete components are required, **Sikagard® M790 should be the preferred solution**. This coating has **demonstrated the highest chemical resistance, the best barrier properties, and the highest effectiveness** in limiting ion migration and reducing the alkalinity of concrete.
- **Sikagard® WallCoat T** can be recommended **for moderately aggressive environments** where prolonged exposure to strongly acidic media is not a concern, and where chemical resistance and barrier requirements are lower. While Sikagard® WallCoat T provides concrete protection, its effectiveness under **long-term chemical exposure is lower than that of the Sikagard® M790 system**.
- **Sikagard® M790 is a more flexible** coating with crack-bridging properties, **which increases its long-term durability**. It also provides greater reliability in structures prone to cracking.
- **Sikagard® M790 shows high adhesion to the concrete**, even at increased humidity, **which enables its use in less favorable application conditions**.
- **Compared to Sikagard® WallCoat T, Sikagard® M790 is approximately three times thicker and has a unit price that is approximately 30 times higher**.



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**INSTITUTE OF ENERGY
AND FUEL PROCESSING TECHNOLOGY**

ul. Zamkowa 1, 41-803 Zabrze, Poland,
tel. (+48) 32 271-00-41

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since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

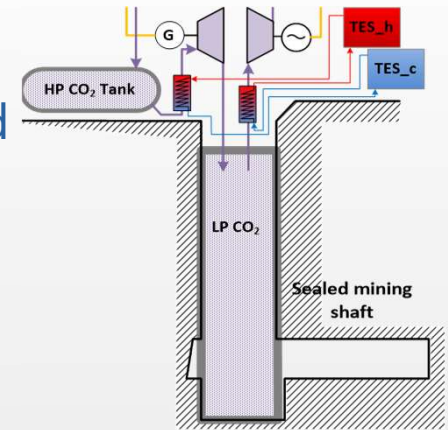
Analysis of the CO₂ compression and purification for the CCES system

Tomasz Spietz, Szymon Dobras, Tadeusz Chwoła,
Lucyna Więclaw-Solny, Magdalena Dobras, Agata Czardybon

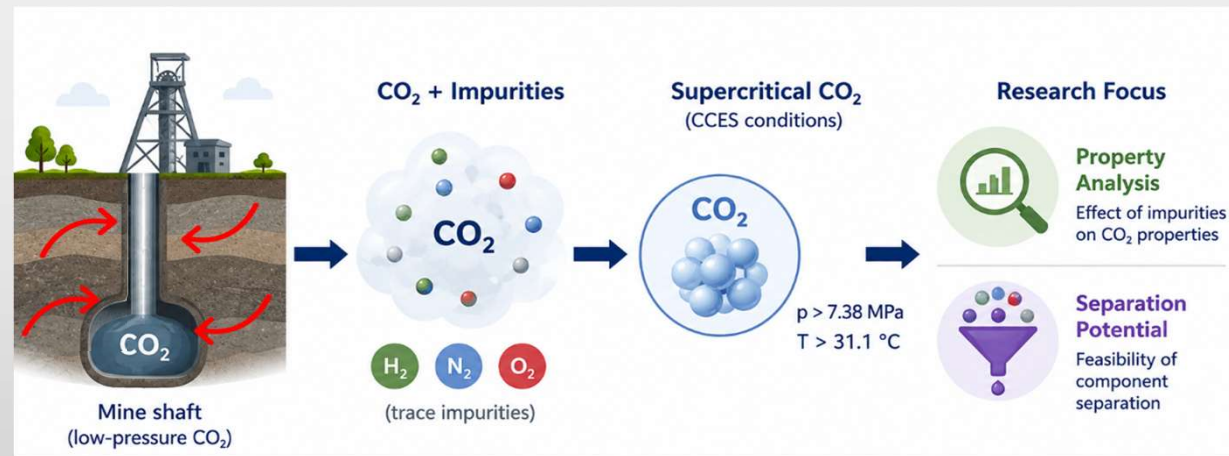
FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

Research Objectives - WP4 (Task 4.2)

- Evaluation of the effects of impurities (such as H_2 , N_2 , O_2) in CO_2 stream
- Investigation of the potential for component separation within CO_2 -based gas mixture
- Experimental studies conducted under conditions representative of CCES systems i.e., supercritical CO_2 ($p > 7.38$ MPa, $T > 31.1^\circ C$)



Gaseous impurities from the surrounding rock formation may diffuse through the sealed mine shaft wall and enter the circulating CO_2 stream



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Test rig components

Constant-temperature control section

- Uniform column heating through a full-length heating jacket
- Temperature control accuracy: $\pm 0.1^\circ\text{C}$
- Thermal insulation minimizes heat losses and temperature gradients

Gas supply module

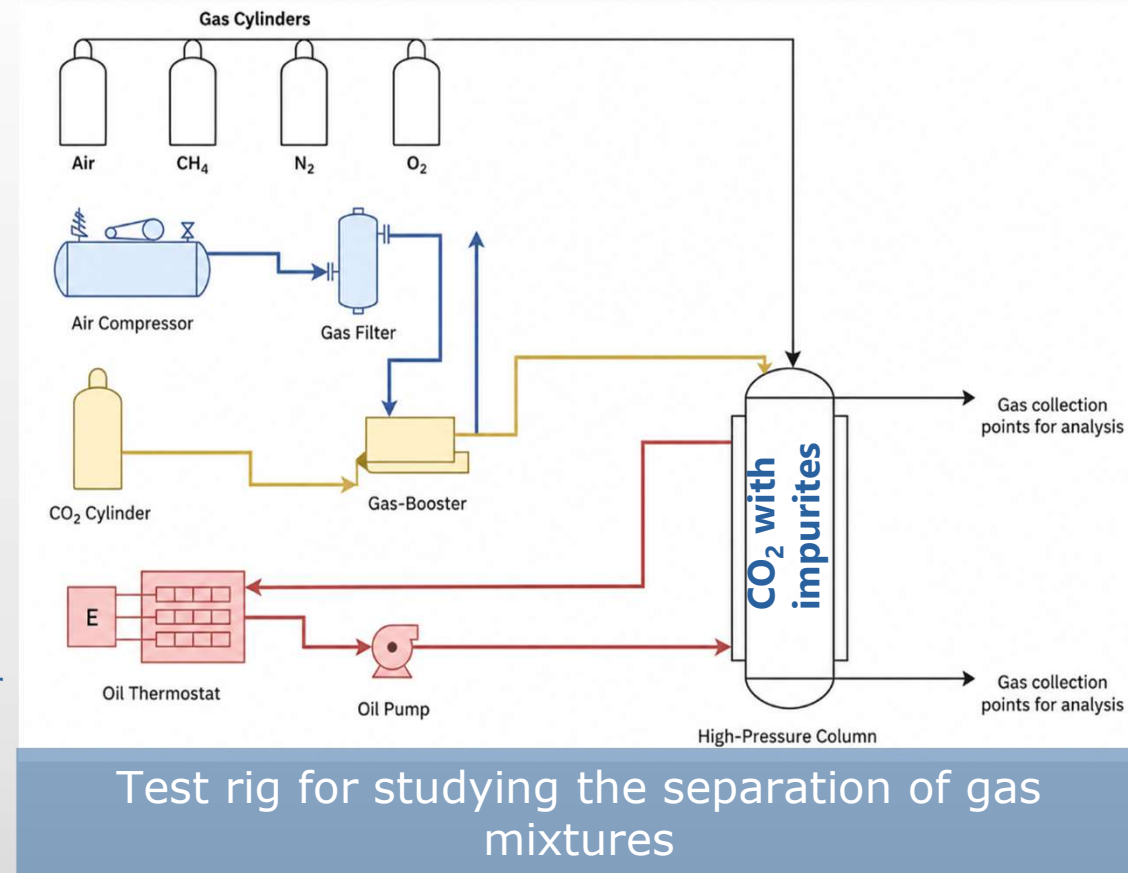
- Controlled dosing of N_2 , O_2 , CH_4 and air
- Individual pressure regulators
- High-pressure stainless-steel piping ensures leak-tight operation

CO_2 dosing module

- Pneumatic gas-booster for CO_2 compression above 100 bar
- Controlled and gradual pressurization of the reactor

High-pressure column

- Stainless steel, volume: 3 L
- Maximum operating pressure: 160 bar
- Pressure monitoring and gas sampling ports



Test rig components



CO₂ gas-booster



High-pressure column

Test rig with
thermostat



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Experimental methodology

1. System Preparation

- Leak testing and purging of the column with CO₂ before each experiment

2. Gas Mixture Preparation

- Impurities (N₂, O₂, CH₄ or air) are introduced up to 5 or 10 bar
- CO₂ then injected up to 100 bar

3. Experimental Conditions

- Total pressure: 100 bar and temperature 40°C
- Stabilization time: 20 h (time to sample collection)

4. Gas Sampling and analysis

- Gas collected from the top and bottom sections of the column
- Tedlar bags used for sample collection and GC analysis
- Determination of CO₂, N₂, O₂ and CH₄ concentrations
- Each sample analyzed in duplicate to ensure data reliability

The gas separation coefficient **S** was used to quantify gas distribution along the column height

$$S = \frac{C_{top}}{C_{bottom}}$$

C_{top} , C_{bottom} – concentration of a component in the sample collected from the top or bottom of the column, respectively



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Reference test with pure CO₂

- Test performed to verify the installation and sampling procedure
- Reactor filled with CO₂ to 100 bar and stabilized at 40°C for 20 h
- GC analysis showed high CO₂ content: **99.63%** at the **top** and **99.44%** at the **bottom**
- Trace gases were treated as measurement background
- Results confirmed **proper system operation** and **no significant concentration gradient**

Analyzed Compound	$C_{top\#1}$	$C_{top\#2}$	C_{top} Average	$C_{bottom\#1}$	$C_{bottom\#2}$	C_{bottom} Average
O ₂	0.26	0.24	0.25	0.23	0.25	0.24
N ₂	0.08	0.12	0.10	0.32	0.30	0.31
CH ₄	0.02	0.02	0.02	0.01	0.01	0.01
CO ₂	99.64	99.62	99.63	99.44	99.44	99.44

C_{top} , C_{bottom} in % vol.



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Other tests

- CH₄ 10 bar, and then CO₂ charged to 100 bar
- Air 5 bar, and then CO₂ charged to 100 bar
- Air 10 bar, and then CO₂ charged to 100 bar

Conditions: pressure 100 bar and temperature of 40°C

Air 5 bar

Compound	C _{top} , average	C _{bottom} , average
O ₂	0.71	0.78
N₂	3.16	3.46
CO ₂	96.14	95.77

- The highest separation effect was observed for N₂, based on the highest $\Delta C = 1.01\%$
- Differences in concentration (top/bottom) are low
- The lower concentration, the weaker the separation
- Separation of impurities is limited

Air 10 bar

CH₄ 10 bar

Compound	C _{top} , average	C _{bottom} , average
O ₂	0.25	0.23
N ₂	0.20	0.21
CH₄	5.19	4.70
CO ₂	94.35	94.86

Compound	C _{top} , average	C _{bottom} , average
O ₂	0.93	0.67
N₂	4.15	3.14
CO ₂	94.92	96.19



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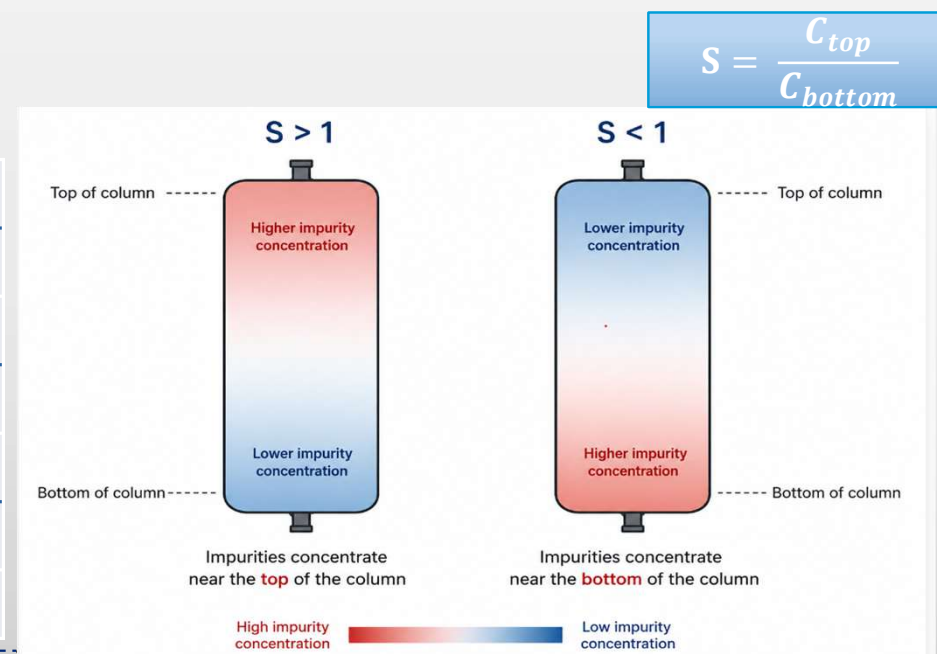


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Summary of the experimental results

- Gas separation is limited and in an operating CCES system, separation of the components is unlikely to occur
- The limited separation observed in this study is likely a consequence of the high pressure and supercritical conditions.
- Under these conditions, the CO₂-rich mixture forms a dense single phase, which suppresses gravitational separation and promotes a nearly homogeneous composition

Impurity	Gas	S	ΔC [%]	Separation
Air (10 bar)	N ₂	1.32	1.01	High
	O ₂	1.39	0.26	Medium
CH ₄ (10 bar)	CH ₄	1.10	0.49	Low
	N ₂	0.95	0.01	Marginal
Air (5 bar)	N ₂	0.91	0.30	Low
	O ₂	0.91	0.07	Marginal



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Effect of gas impurities

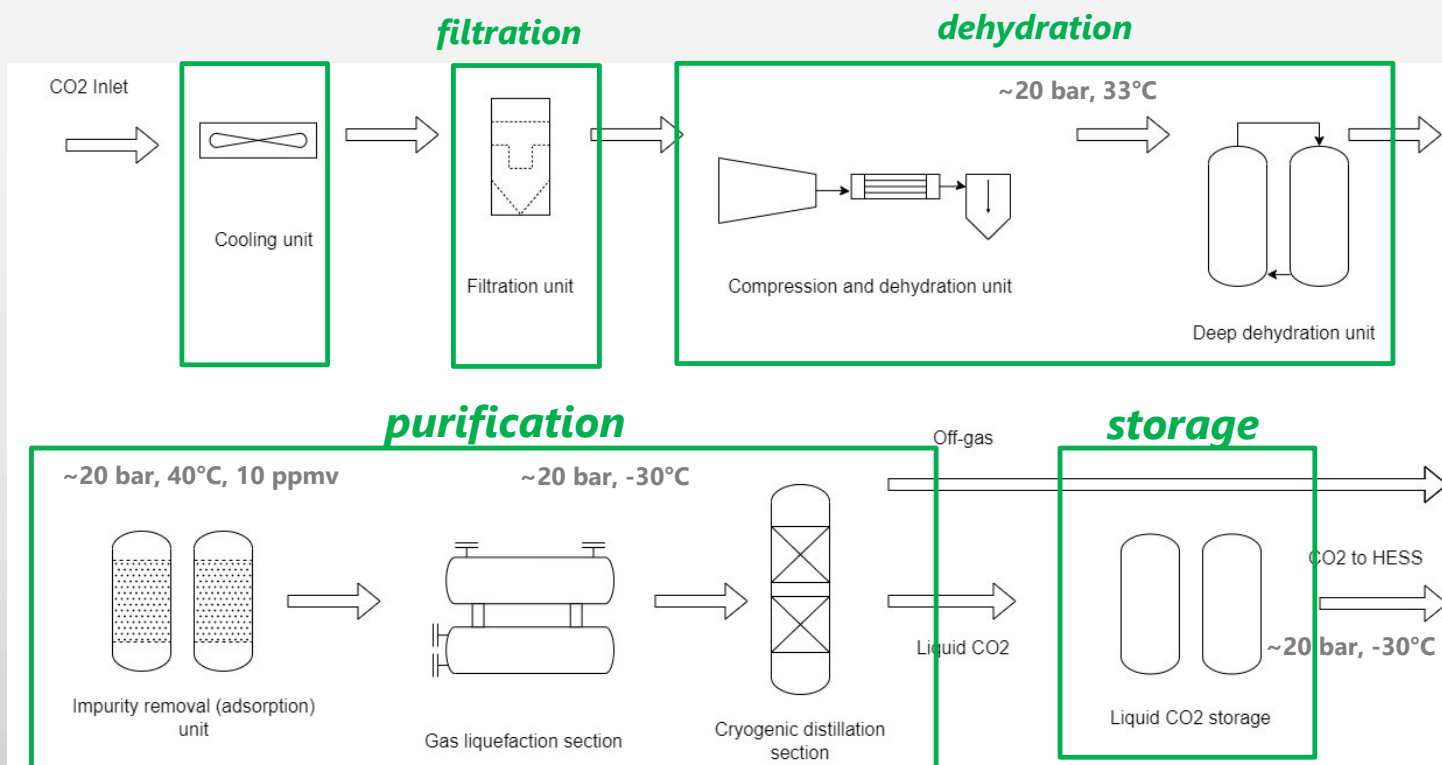
During long-term operation of a CCES system, small amounts of impurities may appear in the CO₂ loop, resulting from factors such as the interaction of the working fluid with system components or micro-leaks in the system. The impurities such as H₂O, CH₄, N₂, O₂, and others can change the properties of CO₂ and lead to corrosion

- May change the thermodynamic properties of CO₂ and shift the stable operating range of the CCES system
- Light gases (N₂, O₂, H₂, and CH₄) reduce the density of CO₂-rich mixtures
- May affect the T_c and P_c of the gas mixture and increase the risk of two-phase flow formation
- Changes in density and viscosity affect pressure drop and compression work
- Water vapor may significantly increase the risk of corrosion



CO₂ cryogenic purification unit

- CO₂ cryogenic purification unit will be integrated with CCES system.
- Cryogenic purification is based on condensation and low-temperature separation
- Allow to remove: H₂O, CH₄, N₂, O₂, others



- CO₂ purity: >99.99%
- Capacity: 1000 kg CO₂/h
- Storage: cryogenic tank, cylindrical, 2x50t, ~20 bar, -30°C.

Purification unit provides an additional safeguard to maintain high CO₂ purity during long-term CCES operation.



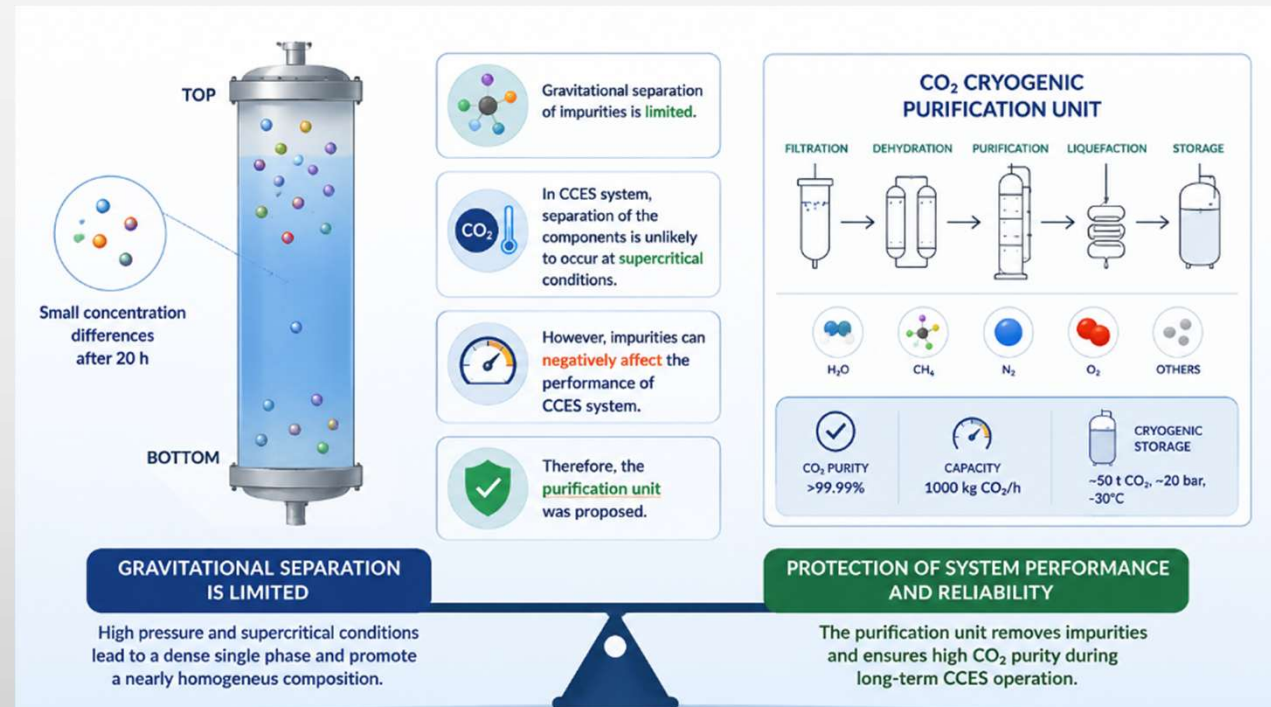
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Summary

- Gravitational separation of impurities is limited
- In CCES system, the separation of the components is unlikely to occur at supercritical conditions
- Impurities can negatively affect the performance of CCES system
- Therefore, the integration of a CO₂ purification unit is recommended.



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MINE SHAFT ADAPTATION FOR HESS: BASELINE REQUIREMENTS AND KEY TECHNICAL CHALLENGES

Konrad Kołodziej Marcin Lutyński

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26



Co-funded by
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The work presented on the poster was performed as part of the **HESS project** (Hybrid energy storage system using post-mining infrastructure) grant no. 101112380 supported by the EU RFCS.

The project is co-financed by the Polish Ministry of Education and Science under the program entitled International Projects Co-financed Agreement No. 5462/FBWIS/2023/2



PRESENTATION OUTLINE

- ✓ Baseline Condition & Structural Repairs
- ✓ Sealing Technology & Performance Results
- ✓ High-Pressure Isolation Dams (Pyramid Design)
- ✓ Service Logistics (Ventilation & Drainage)

Each technical section is followed by CAPEX/OPEX breakdown based on delivered project reports.



TECHNICAL BASELINE

Operational Asset Condition

Currently, the inventoried shafts belong to operational mines. Regular maintenance and safety protocols ensure the concrete lining is in good technical condition.

- **No General Restoration:** Extensive casing rebuilds are not required
- **Continuous Oversight:** Existing management ensures lining integrity
- **Focus:** Strategy is strictly on adaptation rather than rescue



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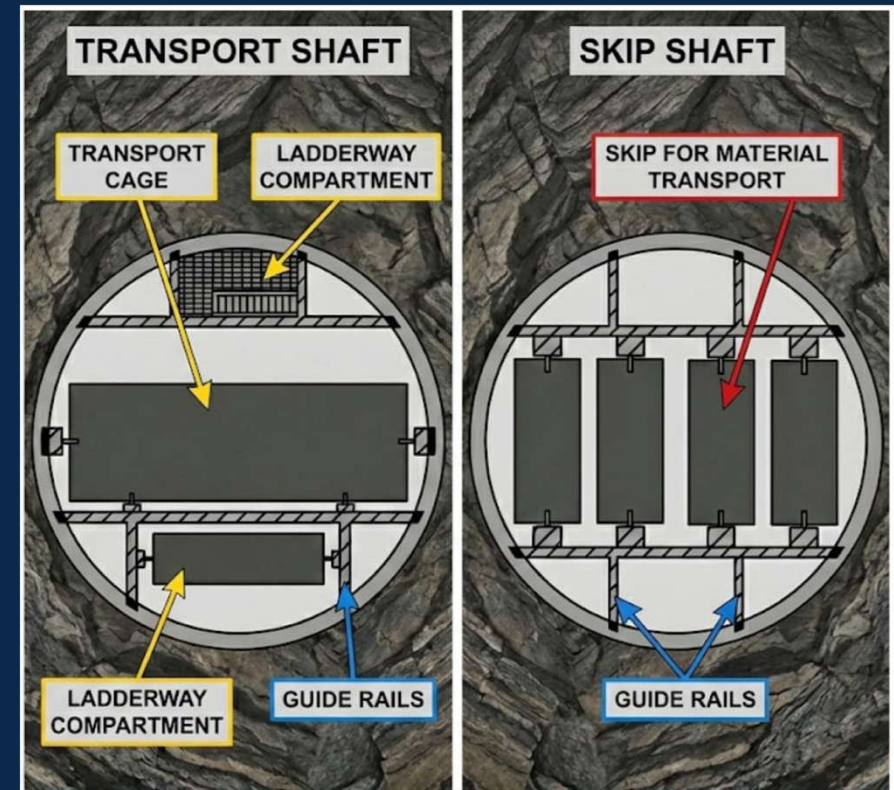
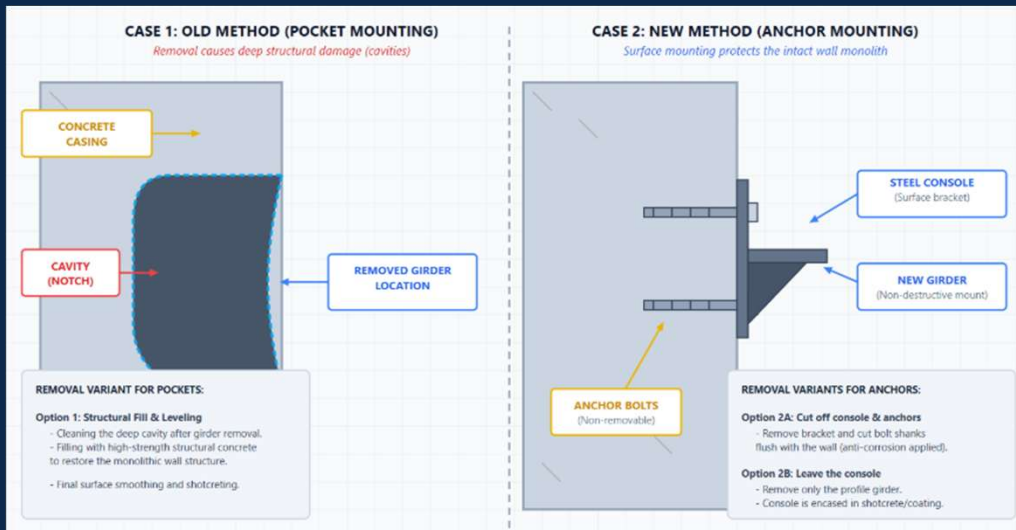


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THE CHALLENGE OF TRANSPORT SHAFTS

THE CHALLENGE OF TRANSPORT SHAFTS

Patching the "Notches" Even in healthy shafts, the removal of transport infrastructure (guides and girders) creates structural gaps or "notches" in the concrete. These local defects must be patched to ensure a smooth, uniform base for the gas-tight coatings.



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SEALING & SECURING

Porous Casing Challenge

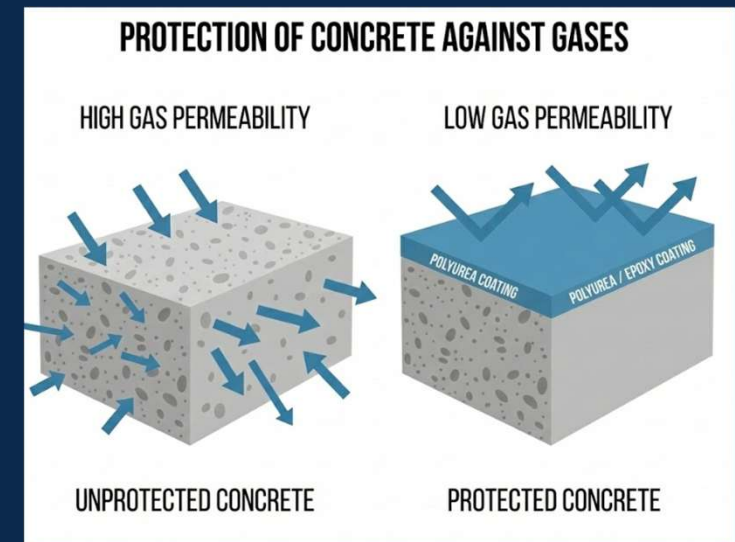
Concrete is naturally permeable. Under **8 MPa operational pressure**, gas molecules migrate through the connected pore network, leading to critical standby energy losses.

Integrated Sealing

Polymer coatings (Epoxy or Xolutec®) reduce surface concrete porosity. These systems create a **molecular-level barrier** that ensures gas retention and reservoir integrity.

Triple Protection

Beyond gas tightness, the seal provides **100% waterproofing** and anti-corrosion protection against aggressive Acid Mine Drainage (AMD), extending asset lifespan.



SYSTEM IMPACT: Barrier coatings reduce pressure-driven leakage by nearly 600 times, ensuring the economic

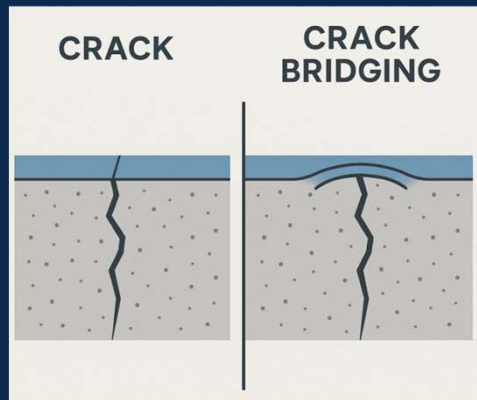


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MATERIALS



Concretes

C20/25 – representative for older shafts

C40/45 – reference for modern deep shafts

Sealing systems

Epoxy thin coating (WallCoat T)

Polymeric membrane (Sikagard® M 790 – Xolutec®)

Material concept	Thickness	Function
Epoxy coating	thin	diffusion barrier
Xolutec® membrane	thick	barrier + crack bridging



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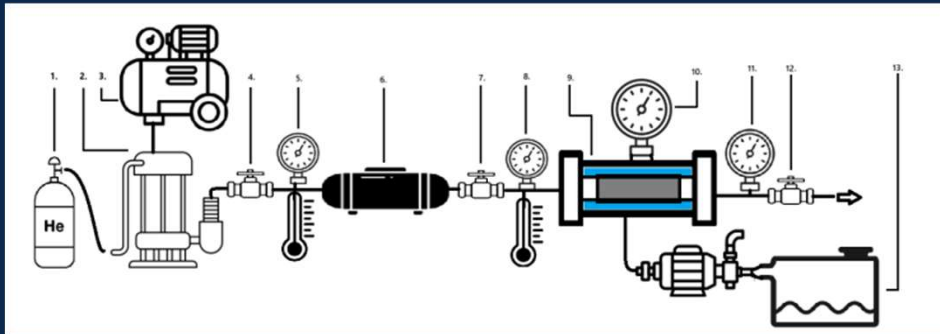
Test Gas, Method & Laboratory Setup

Test gas - Helium (He)

Selected as a non-adsorbing reference gas providing the highest sensitivity for intrinsic permeability at very low flow rates.

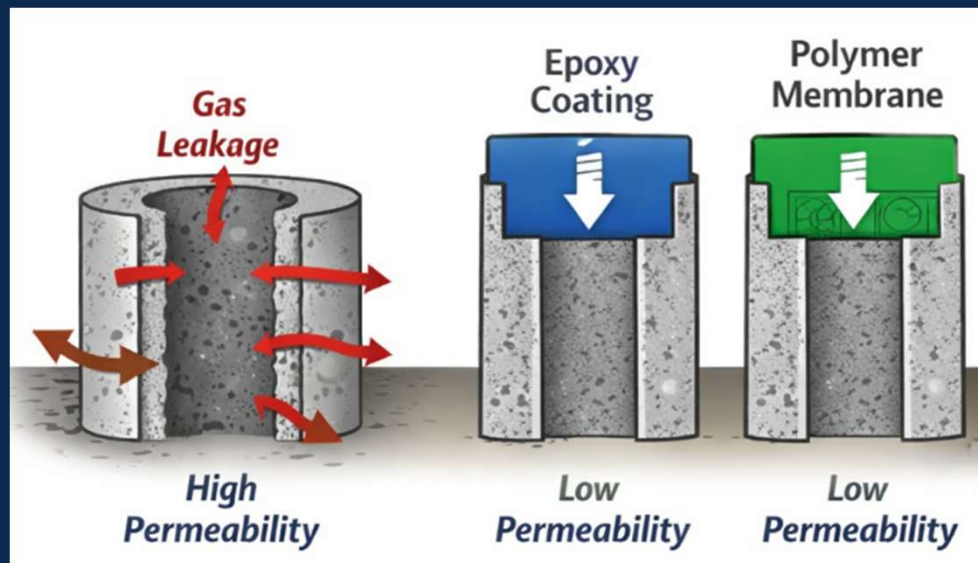
Pressure conditions – corrected explanation

The two pressure gradients (60→atm and 60→50 bar) were selected to distinguish material-controlled permeability from boundary-condition effects, by comparing a large driving force representative of worst-case leakage with a reduced gradient representative of quasi-isobaric shaft operation.



Parameter	Value
Test gas	Helium (He, 99.999%)
Inlet pressure	60 bar
Outlet pressure (case 1)	1 atm
Outlet pressure (case 2)	50 bar
Pressure gradient	60 → atm / 60 → 50 bar
Temperature	20 °C ± 0.1 °C
Specimen size	Ø25 mm × 30 mm
Confining pressure	90 bar ± 2

Results



Engineering significance

Gas permeability is a limiting parameter for ACAES operation
Protective coatings are mandatory for shaft adaptation
Measured data enable quantified leakage assessment at system scale

Summary

Uncoated concrete shows measurable gas permeability
Higher concrete class reduces k but does not ensure gas-tightness
Both coating systems reduce permeability by 3–4 orders of magnitude

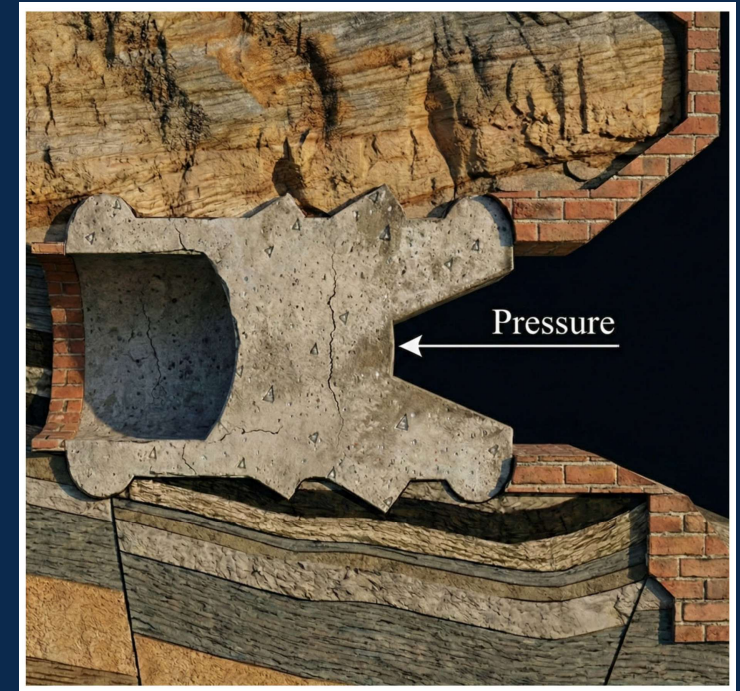


HIGH-PRESSURE SHAFT INLETS DAM

Evolution from Water Dams

Originally designed as massive concrete water dams for flooding protection, these structures have been adapted for HESS gas isolation.

- ✓ **Structural Locking:** The pyramid shape transfers internal gas pressure directly into the rock mass.
- ✓ **Triple Barrier:** Multi-segment construction for fail-safe containment.



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NORMATIVE DAM CALCULATIONS

CONCRETE PYRAMID DAM: THICKNESS DESIGN (EQ. 2)

$$d_t \geq \frac{p_x \cdot r}{2k_c - p_x} + \frac{a^2}{8r} \quad [\text{cite: 18}]$$

 d_t : Dam Thickness, calculated in cm [cite: 18]

 p_x : Concrete Strength (Compressive) [cite: 18]

 r : Inner Radius [cite: 18]
(refer to conditional parameters)

 k_c : Coefficient [cite: 18]

 a : Characteristic Dimension 'a' [cite: 18]
(refer to roadway context)

CONDITIONAL DESIGN PARAMETERS [cite: 18]

 **ROCK STRENGTH**
< 30 MPa [cite: 18]

- Inner Radius r
(Horizontal):
2.0 a [cite: 18]

- Inner Radius r (Vertical):
2.0 b [cite: 18]

- Angle of Inclination ($\alpha/2$)
15° [cite: 18]

 **ROCK STRENGTH**
> 30 MPa [cite: 18]

- Inner Radius r
(Horizontal):
1.5 a [cite: 18]

- Inner Radius r (Vertical):
1.5 b [cite: 18]

- Angle of Inclination ($\alpha/2$)
20° [cite: 18]

CONCRETE PYRAMID DAM: DESIGN CHECKS (EQ. 3 & EQ. 4) [cite: 18]

 d_t : Dam Thickness, calculated in cm [cite: 18]

 p_z : Concrete Strength (Compressive) [cite: 18]

 a : Characteristic Dimension 'a' [cite: 18]

 b : The height of the excavation in the breach, cm [cite: 18]

 l : Dam circuit, $l=2(a+b)$, cm [cite: 18]

 τ : Calculated shear strength value of the dam material according to the standard [cite: 18]

 k_s : Allowable compressive stress for rocks, MPa [cite: 18]

 α : Angle of inclination, radians [cite: 18]

SHEARING CHECK

$$d_t \geq \frac{p_z ab}{2l\tau} \quad [\text{cite: 18}]$$

PRESSURE ON THE ROCK CHECK

$$d_t \geq \frac{p_z ab}{k_s l \sin \frac{\alpha}{2}} \quad [\text{cite: 4}]$$



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Implementation Roadmap

01. Excavation

Mechanical notch cutting in strong rock contacts. No blasting allowed



03. Casting

Rapid pouring of 800m³ C30/37 W12 concrete via high-capacity post-mine cages.



02. Formwork

These heavy-duty structures hold the volume of liquid concrete until it cures.



04. Sealing

High-pressure contact injection after 28-day curing stabilization.



Operational Focus

The sequence minimizes downtime by leveraging Shaft III's superior hoisting capacity, allowing for monolithic casting of the largest seals (110m³) in a single shift.



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DAM MATERIALS

Investment Category	Technical Description	Cost [PLN]
Materials	Upregulated C30/37 W12 Concrete + Crystalline Additives	572,000
Logistics & Handling	Cage Hoisting, Underground Pumps, & Steel Formwork	445,000
Civil Works	Mechanical Notching & Specialized Casting Labor	420,000
Injection Systems	High-Pressure Resins & Micro-cement Sealing	540,000
TOTAL CAPEX	Consolidated Sealing Strategy (6 Locations)	1,977,000

TOTAL VOLUME ~800 m³ SEALING POINTS 6 Inlets OPERATING PRESSURE up to 8MPa



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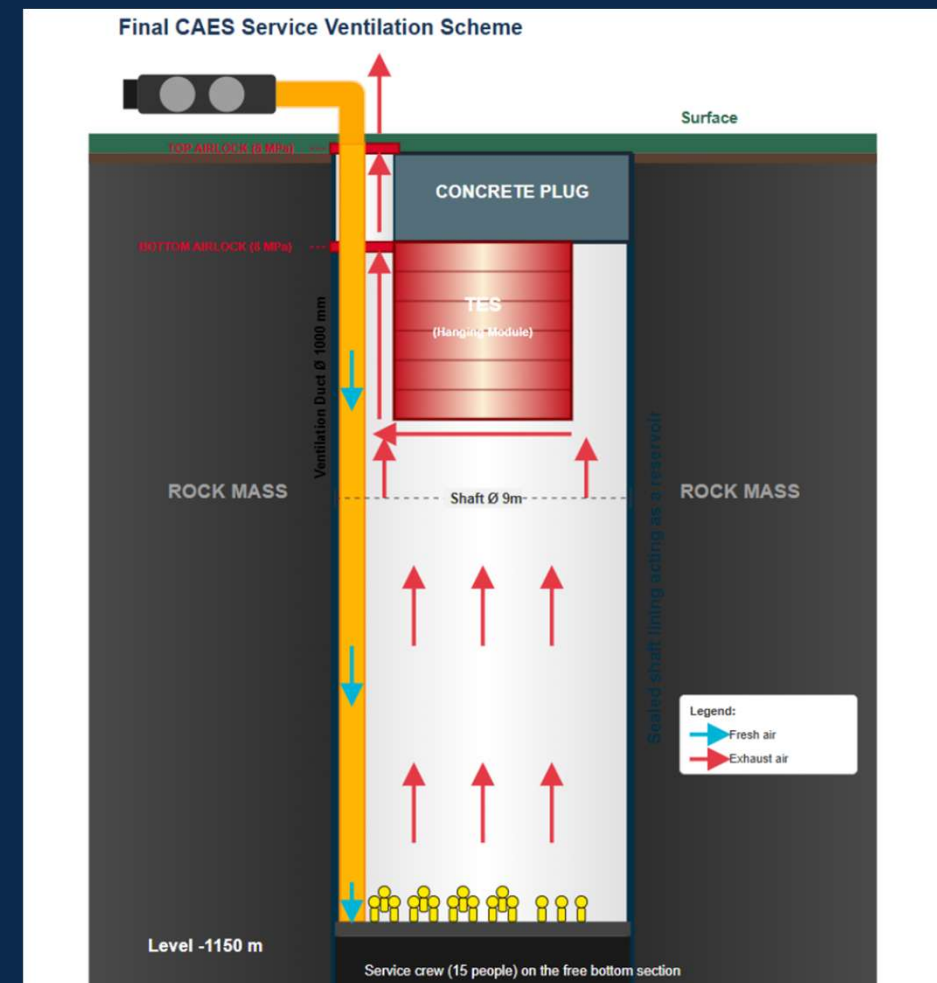
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SERVICE VENTILATION DESIGN

System Purpose & Scope

Designed to support a **15-person specialist crew** at bottom of – shaft during adaptation works of servis work.

- Service Focus:** Providing fresh air for polymer coating application (fumes) and structural work.
- Flow Requirement:** 580 m³/min for O₂ stability and gas dilution.



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CONCLUSION

- Selection sites in advance prevent degradation
- New shaft have izier to remove guide rails
- Concerete plugs are the most expensive and complicated challenges to do
- Coating proces can seal tank, and prevent it from outside hazards
- Ventilation system is temporary, but nesesery for process



THANK YOU!

Project co-financed by the European Commission within the framework of the Research Fund for Coal and Steel – RFCS program under the contact no. 101112380 (RFCS-2022) titled „Hybrid Energy Storage System using post-mining infrastructure” (HESS) and by the State Subsidy within the framework of the program „Co-financed International Projects” (PMW) established by the Minister of Science and Higher Education.



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CURABITUR PULVINAR QUAM





Co-funded by
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FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

Energy router software

Project HESS No. 101112380

Joanna Rogala-Rojek, Marcin Jura, Wiktor Markusik

LAUREAT KONKURSU

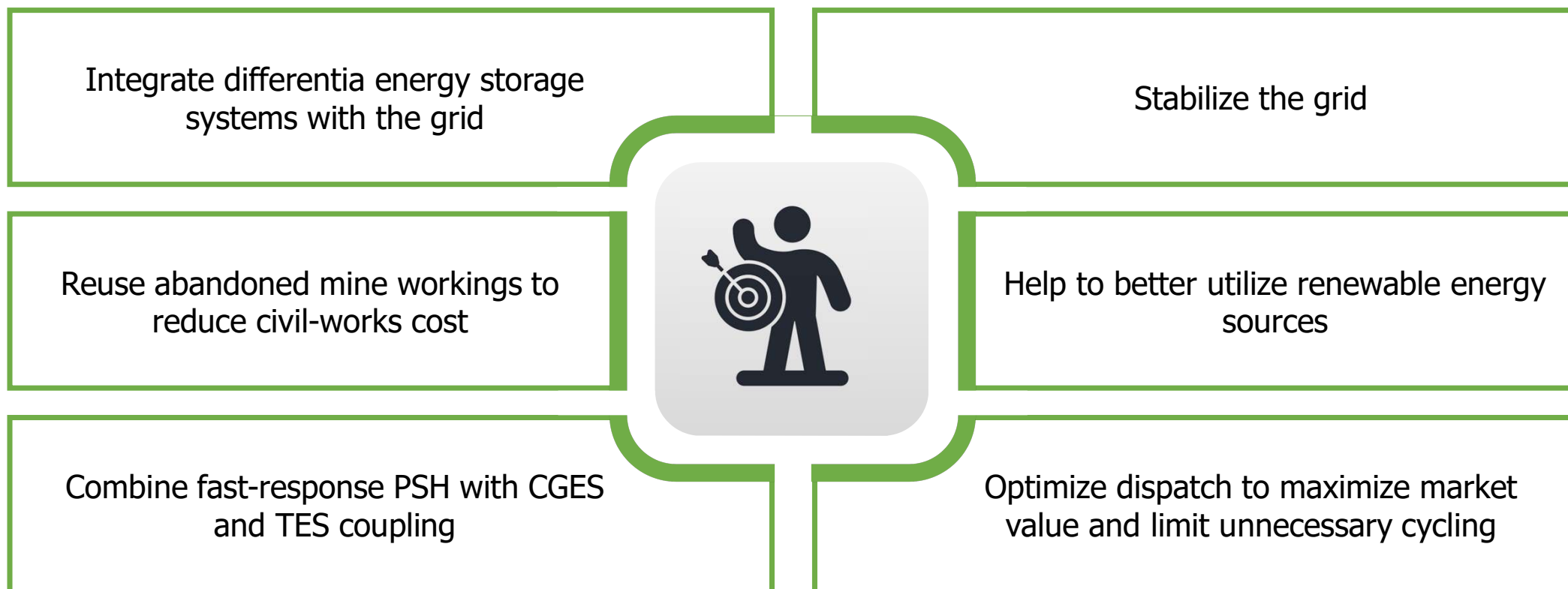


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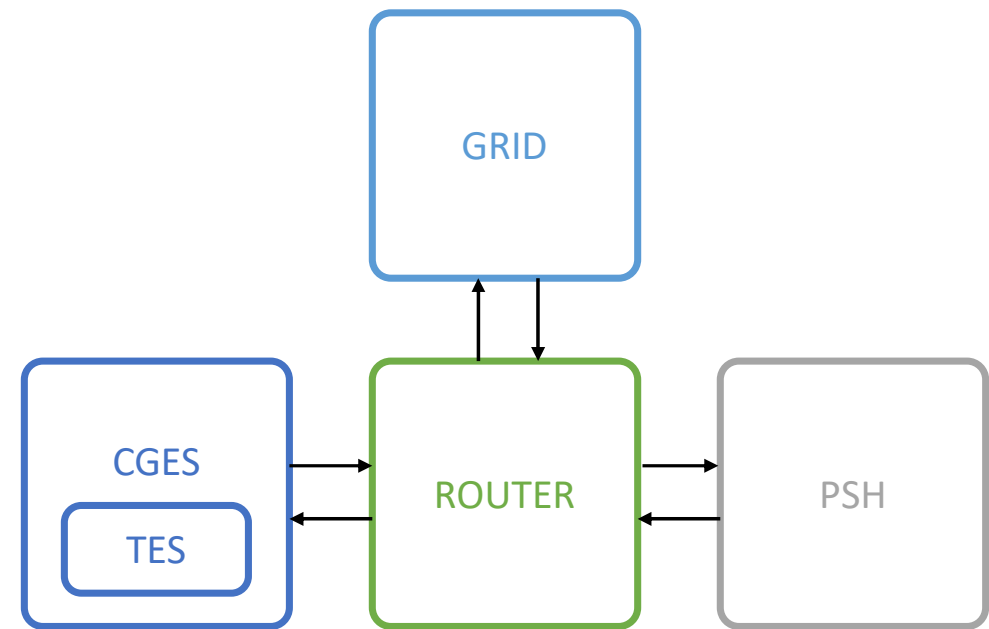


Motivations and goals



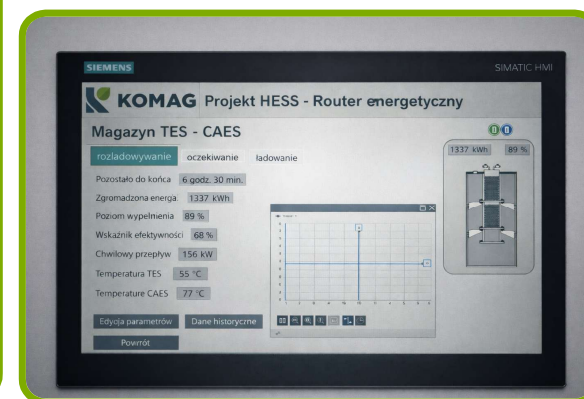
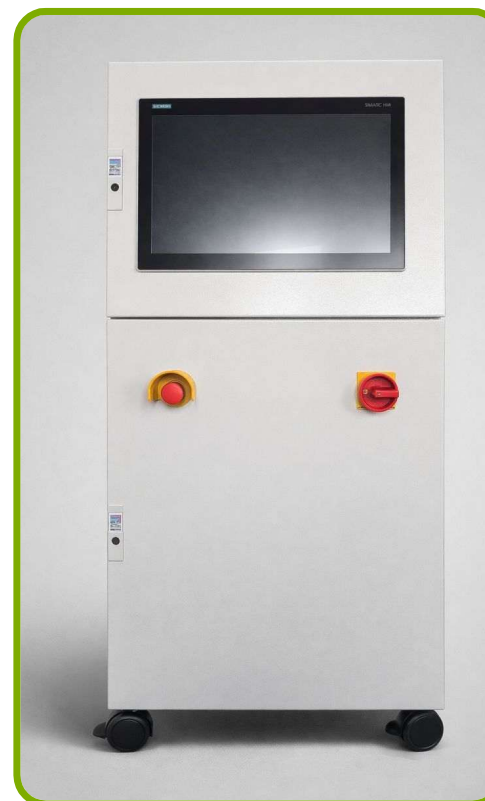
System Architecture

- ❖ Energy router: central control and power-conversion hub coordinating storage assets
- ❖ Storage fleet: PSH (fast), CGES (long-duration) with TES (heat coupling)
- ❖ Supervisory server, PLC, local HMI, and web dashboard for control and monitoring
- ❖ Data flow: market prices → scheduler → execution → monitoring & logging



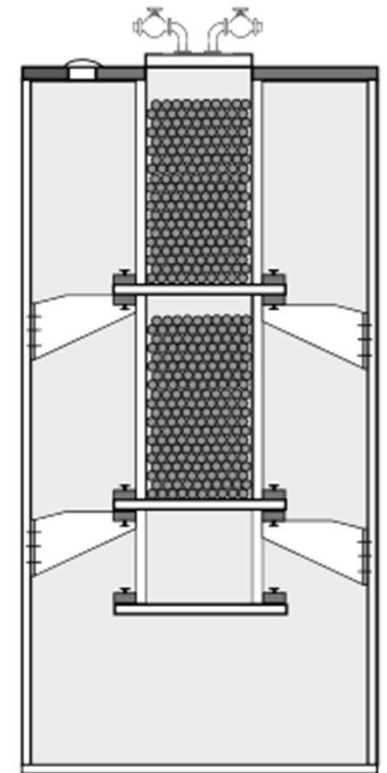
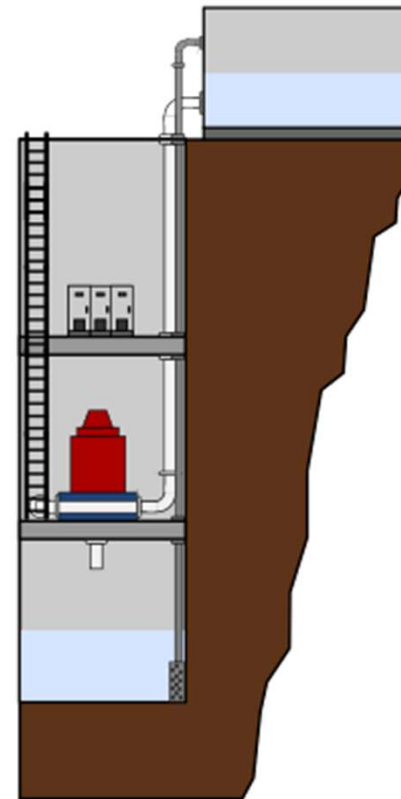
Demonstrator hardware

- ❖ SIMATIC S7-1515F-2 PN PLC: executes control logic and device I/O
- ❖ Supervisory server: simulations and scheduling
- ❖ SIMATIC MTP1900 Unified Comfort panel: local HMI for operator interaction
- ❖ Rittal cabinet with 24 V DC supply, ventilation, main switch, and E-stop
- ❖ Industrial Ethernet (PROFINET / Modbus TCP/IP) to supervisory server and HMI



Simulation overview

- ❖ PSH model: reservoirs, turbines/pumps, simple head–flow relations, partial cycles supported
- ❖ CGES model: reduced-order thermodynamic model for pressure, temperature, and efficiency
- ❖ TES model: captures heat from compression and returns it during expansion to improve round-trip efficiency
- ❖ Software stack: Python orchestrator, control & safety modules, integrator, HMI/API and database



Data acquisition

Primary input: day-ahead hourly prices (DAM) used for next-day scheduling

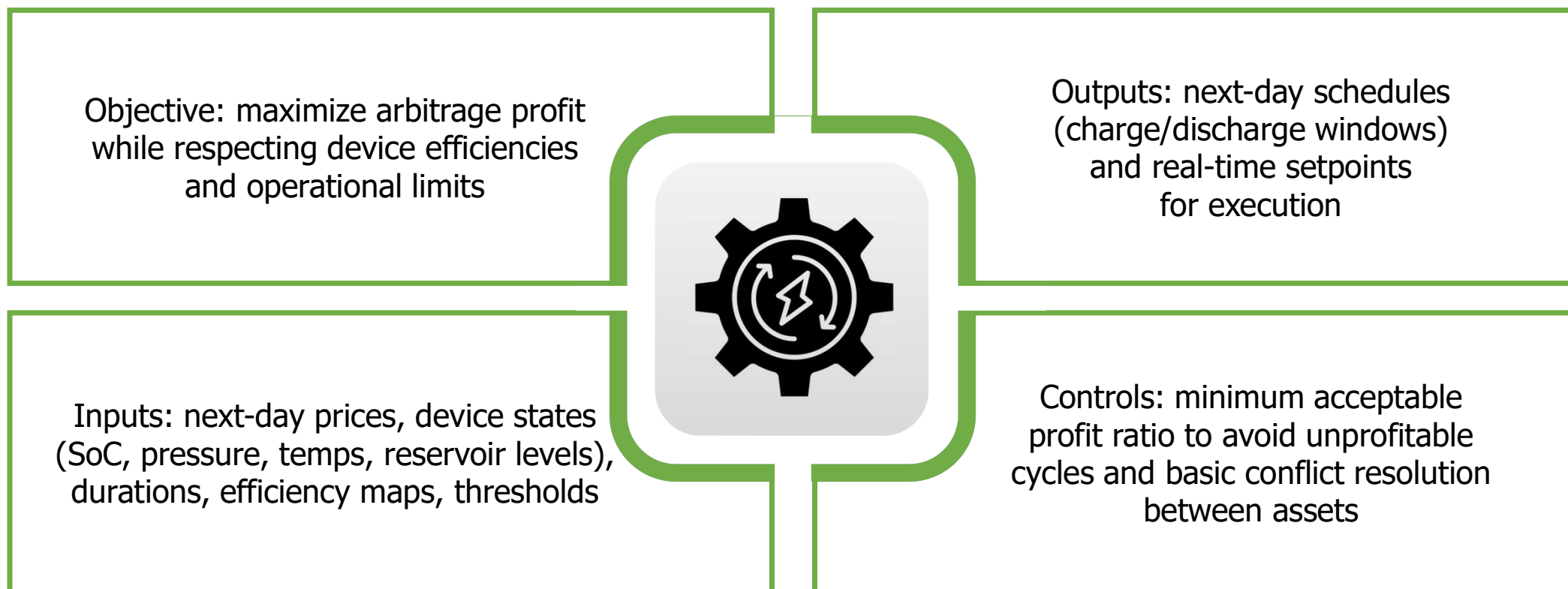
Project approach: manual import of CSV/tabular reports



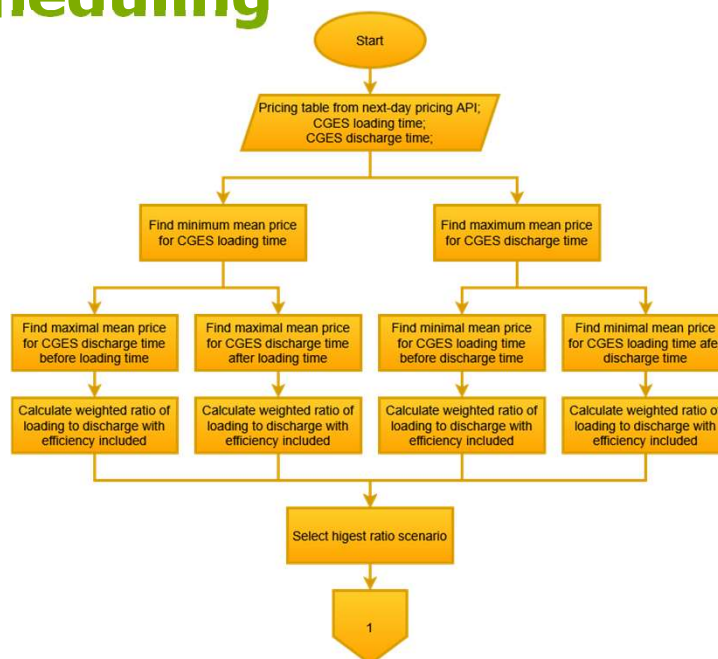
Poland DAM operated by TGE; automated API access requires licensing and data-use agreement

Web scraping only if fully compliant with provider terms; licensing should guide automation choices

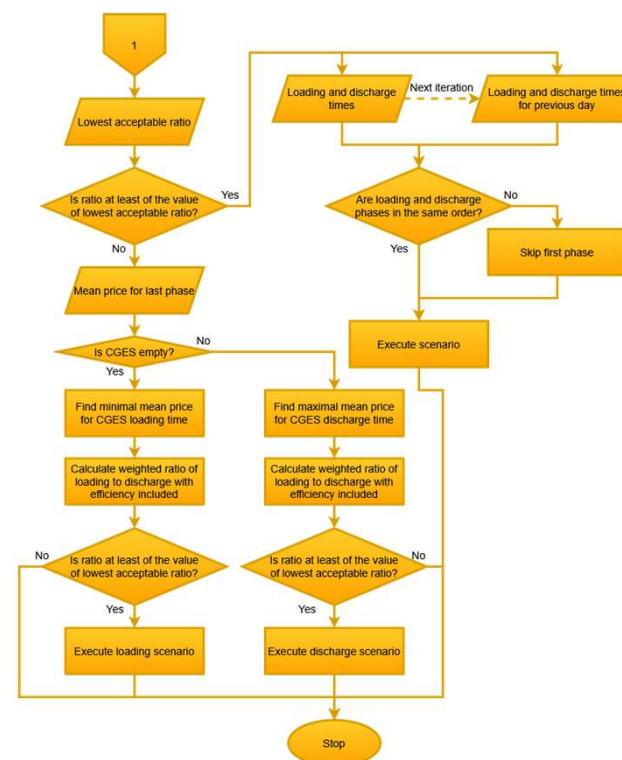
Energy router objectives and inputs



CGES scheduling



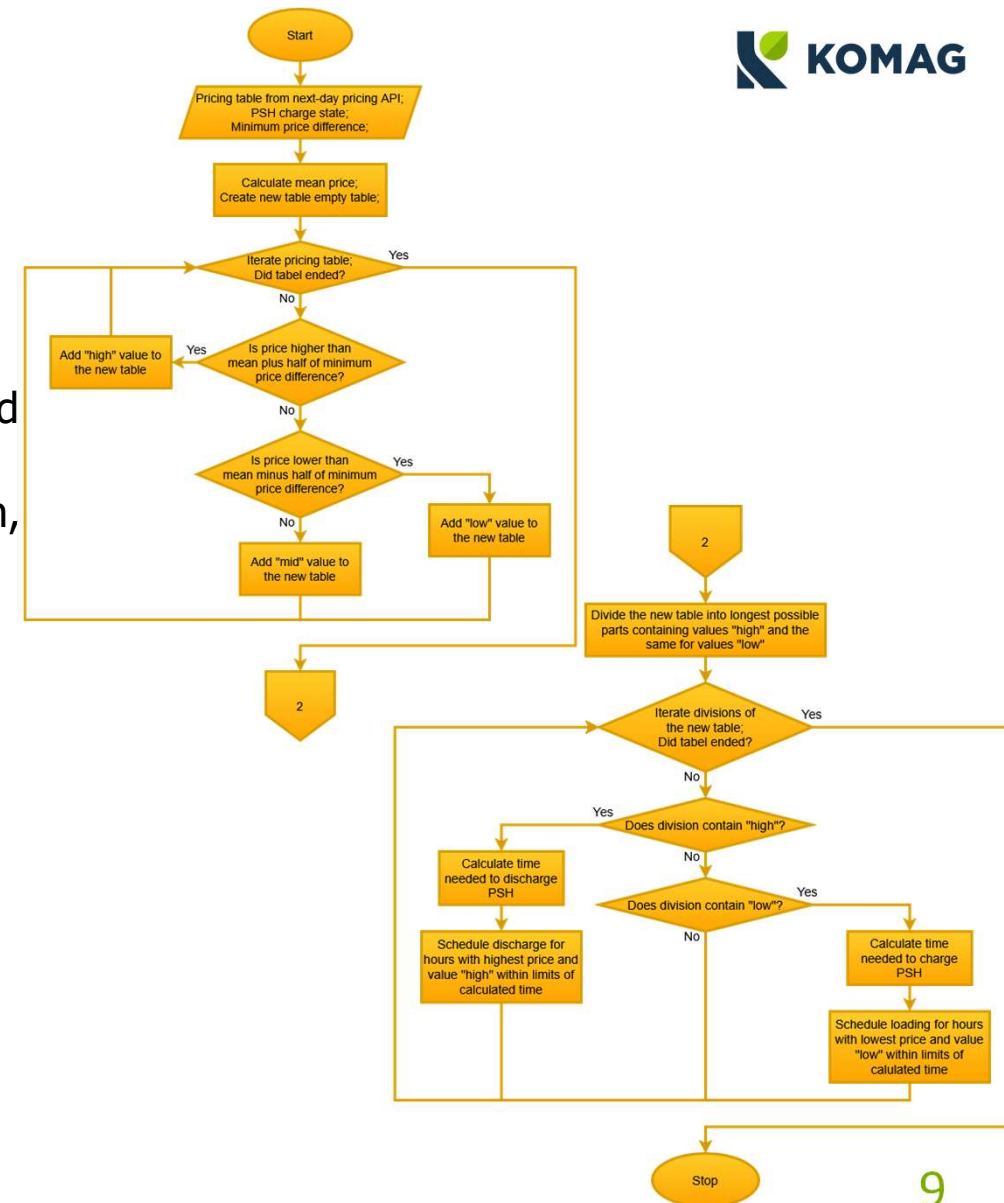
- ❖ Build candidate charge/discharge windows from price extrema and provided durations
- ❖ Compute weighted scenario score = revenue differential × round-trip efficiency – optional cycle costs



- ❖ Select highest-scoring scenario; require score ≥ minimum acceptable ratio to execute
- ❖ Fallback behavior: if no acceptable scenario, schedule minimal-cost charge or maximal-price discharge based on state

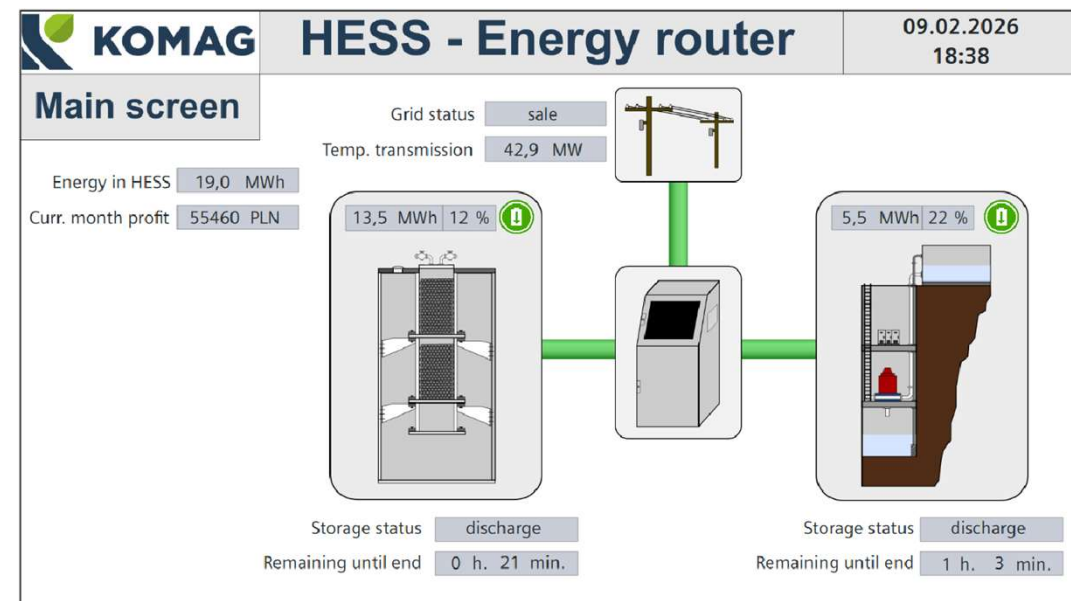
PSH scheduling

- ❖ Compute day mean price and mark each hour as "high", "mid", or "low" using a minimal price-difference threshold
- ❖ Partition hours into maximal contiguous sections of {high, mid} or {low, mid}
- ❖ For high sections: compute discharge duration and pick highest-price hours within limits to schedule generation
- ❖ For low sections: compute charge duration and pick lowest-price hours within limits to schedule pumping
- ❖ Enforce reservoir limits, ramp rates, and avoid overlapping operations



Visualization: HMI

- ❖ Implemented in TIA Portal for MTP1900 operator panel; PLC ↔ server via Modbus TCP/IP
- ❖ Main screen: system schematic, real-time flows, storage fill levels, operating icons, energy balance, and economic metrics
- ❖ Detail screens per unit: TES/CGES (compressor power, heat removed, temperatures), PSH (efficiency, turbine output)
- ❖ Historical charts and monthly summaries available for trend analysis; manual override options provided



Visualization: HMI


HESS - Energy router

09.02.2026
18:38

TES-CGES storage

Selected storage variant **A-CAES.C-800** **Select**

Storage status **discharge**

Remaining until end **0 h. 21 min.**

Accumulated energy **13,5 MWh**

Fill level **12 %**

Enrg. effic. of storage **65 %**

Charging air flow **0,0 kg/s**

C1 compressor power **0,0 MW**

C2 compressor power **0,0 MW**

C3 compressor power **0,0 MW**

Heat dissipated E1 **0,0 MWh**

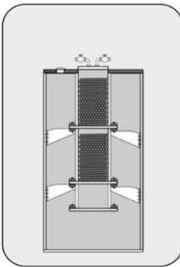
Heat dissipated E2 **0,0 MWh**

Temp. before exchanger E1 **303 K**

Temp. before exchanger E1 **303 K**

Discharge air flow **97,6 kg/s**

Expander power **37,6 MW**



Back **Historical data**


HESS - Energy router

09.02.2026
18:38

Pump storage

Storage status **discharge**

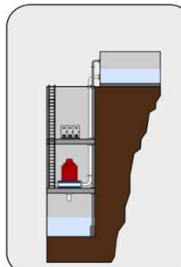
Remaining until end **1 h. 3 min.**

Accumulated energy **5,5 MWh**

Fill level **22 %**

Enrg. effic. of storage **66 %**

Turbine power **5,3 MW**



Back **Historical data**


HESS - Energy router

09.02.2026
18:38

Router settings

Current month profit **55460 PLN**

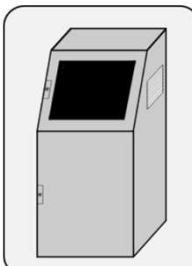
System status **discharge**

Remaining until end **1 godz. 3 min.**

Total energy in HESS **19,0 MWh**

HESS fill level **14 %**

HESS energy efficiency **65 %**



Back **Historical data**


HESS - Energy router

09.02.2026
18:38

Grid settings

Grid status **sold**

Temp. transmission **42,9 MW**

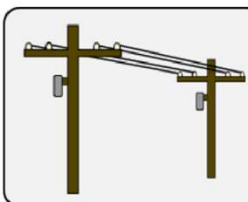
Curr. price per kWh **778 PLN**

Energy purchased this month **1353 MWh**

Avg. purchase price per MWh **447 PLN**

Energy sold whis month **883 MWh**

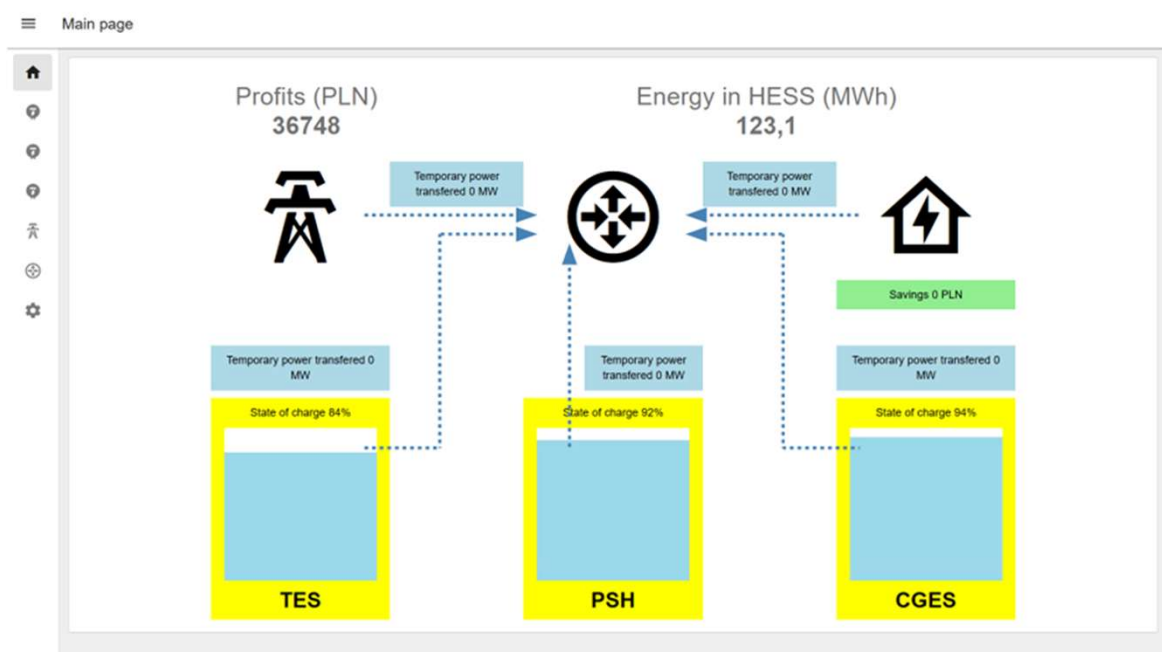
Avg. selling price per MWh **778 PLN**



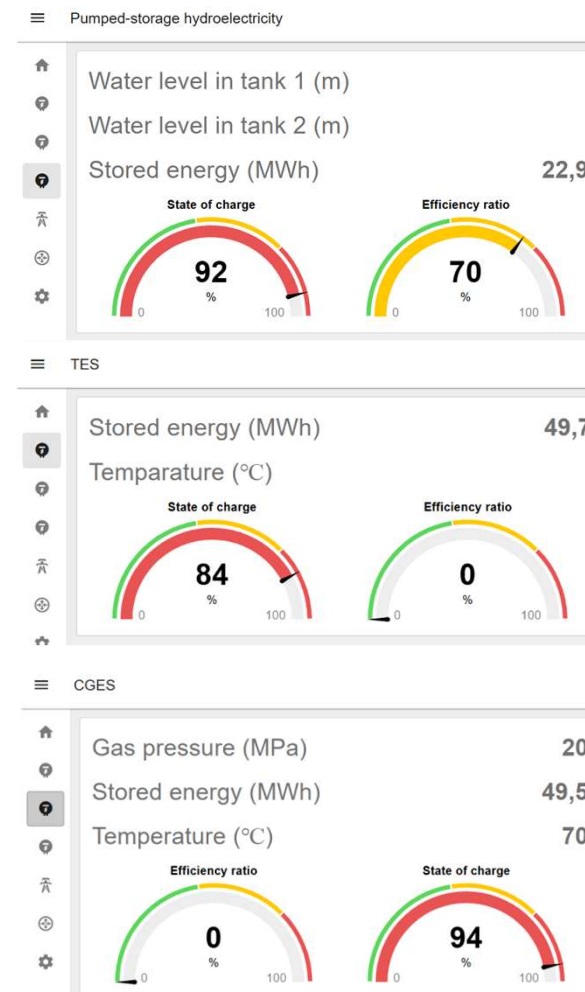
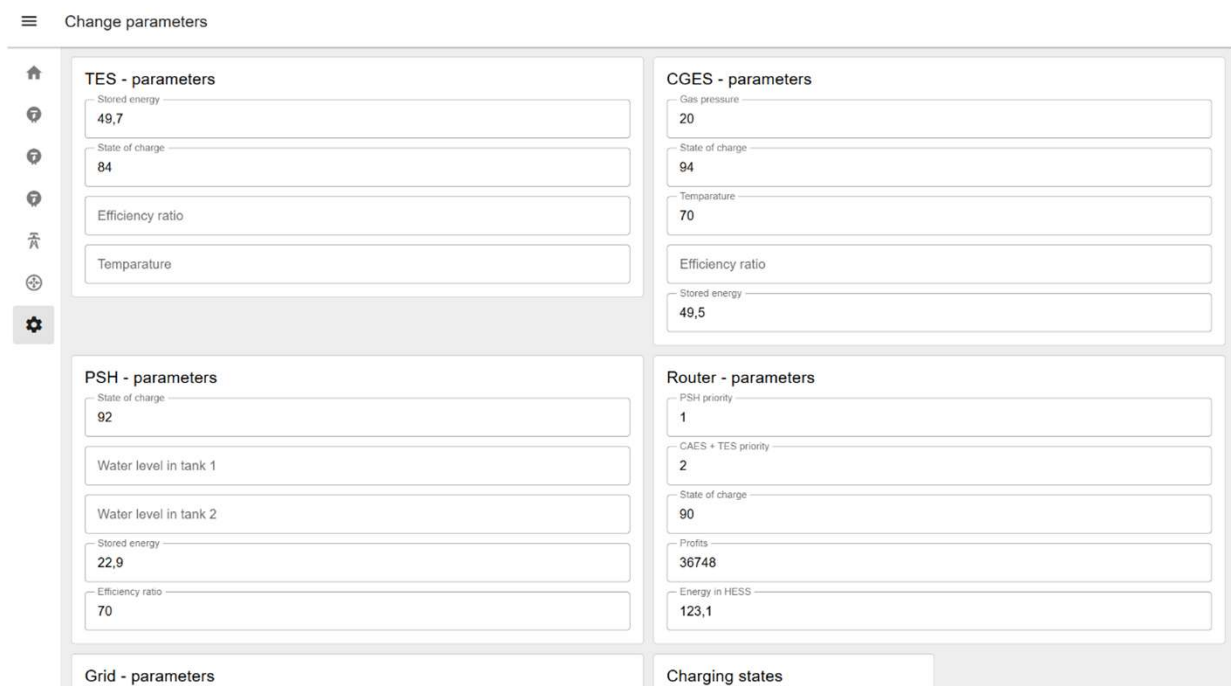
Back **Historical data**

Visualization: web dashboard

- ❖ Node-RED 4.0 backbone with custom Vue 3 components for advanced UI elements
- ❖ Main schematic: grid, router, consumer, storages, directional flow arrows and power indicators
- ❖ Dedicated pages: TES, CGES, PSH with parameters and history; parameters page for manual inputs (current stage)
- ❖ Node-RED handles data flows, calculations and page routing; Vue enables richer interactive components



Visualization: web dashboard



Simulation and algorithm outcomes

Simulations provide runtime efficiency and behavior data used to score scheduling scenarios

PSH: fast response for intra-day price spreads



CGES + TES: enables long-duration storage; TES heat recovery improves effective round-trip efficiency

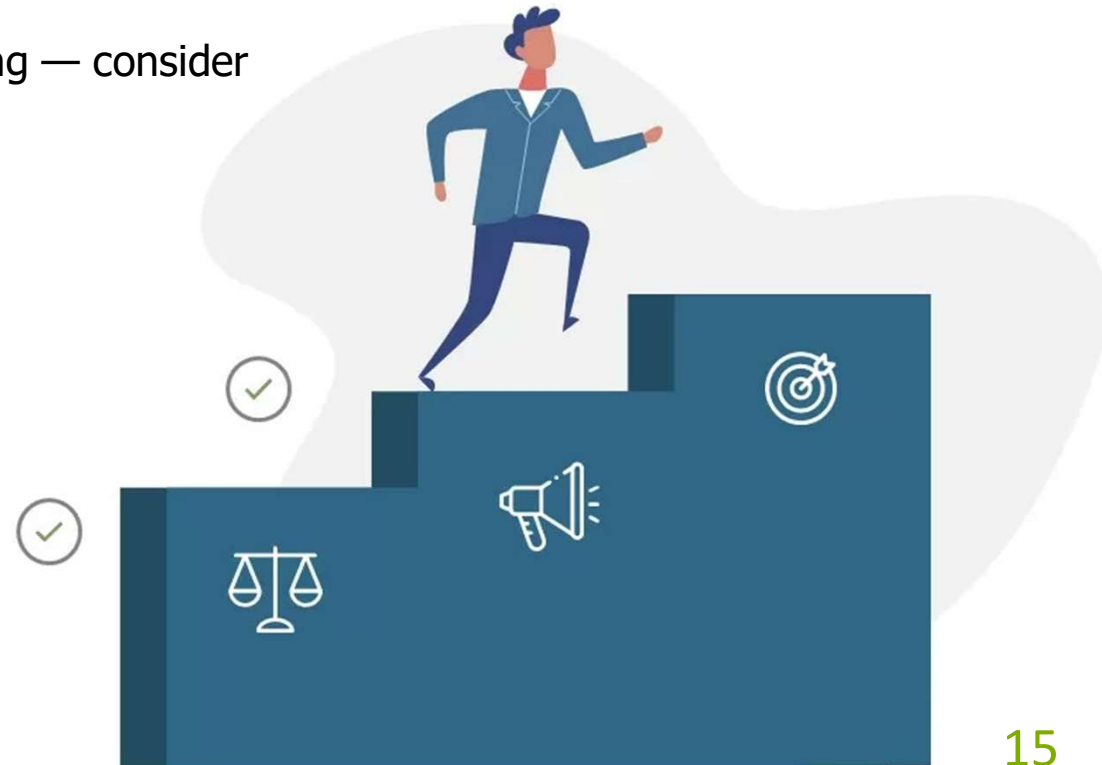
Combined scheduling leverages complementary strengths to increase overall system value

Limitations and future work

- ❖ Current CGES scheduling excludes explicit degradation and maintenance cost modeling — can be added when empirical data will be available
- ❖ Price data automation constrained by TGE licensing — consider formal agreements for live feeds

Next steps:

- ❖ Integrate changes and validate with field hardware
- ❖ Improve visualizations to accept live inputs and automate parameter updates from real Energy storages



Key takeaways

Hybrid energy router in repurposed mines can reduce costs and embodied carbon while enabling storage services

HMI and web visualizations provide both local operator control and remote monitoring for testing and demonstration



Reduced-order models support practical, system-level scheduling without prohibitive computational cost

Incorporating degradation, licensed price feeds, and field validation will strengthen economic and operational realism



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Thank you for your attention

Project co-financed by the European Commission within the framework of the Research Fund for Coal and Steel – RFCS program under the contact no. 101112380 (RFCS-2022) titled „Hybrid Energy Storage System using post-mining infrastructure” (HESS)
and by the State Subsidy within the framework of the program „Co-financed International Projects” (PMW) established by the Minister of Science and Higher Education.



HESS PROJECT WEBSITE - <http://www.itpe.pl/en/hess/>



since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

Integration of particular components of the HEES

Authors: Krzysztof Głód, Agata Czardybon, Krzysztof Supernok, Janusz Lasek

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26



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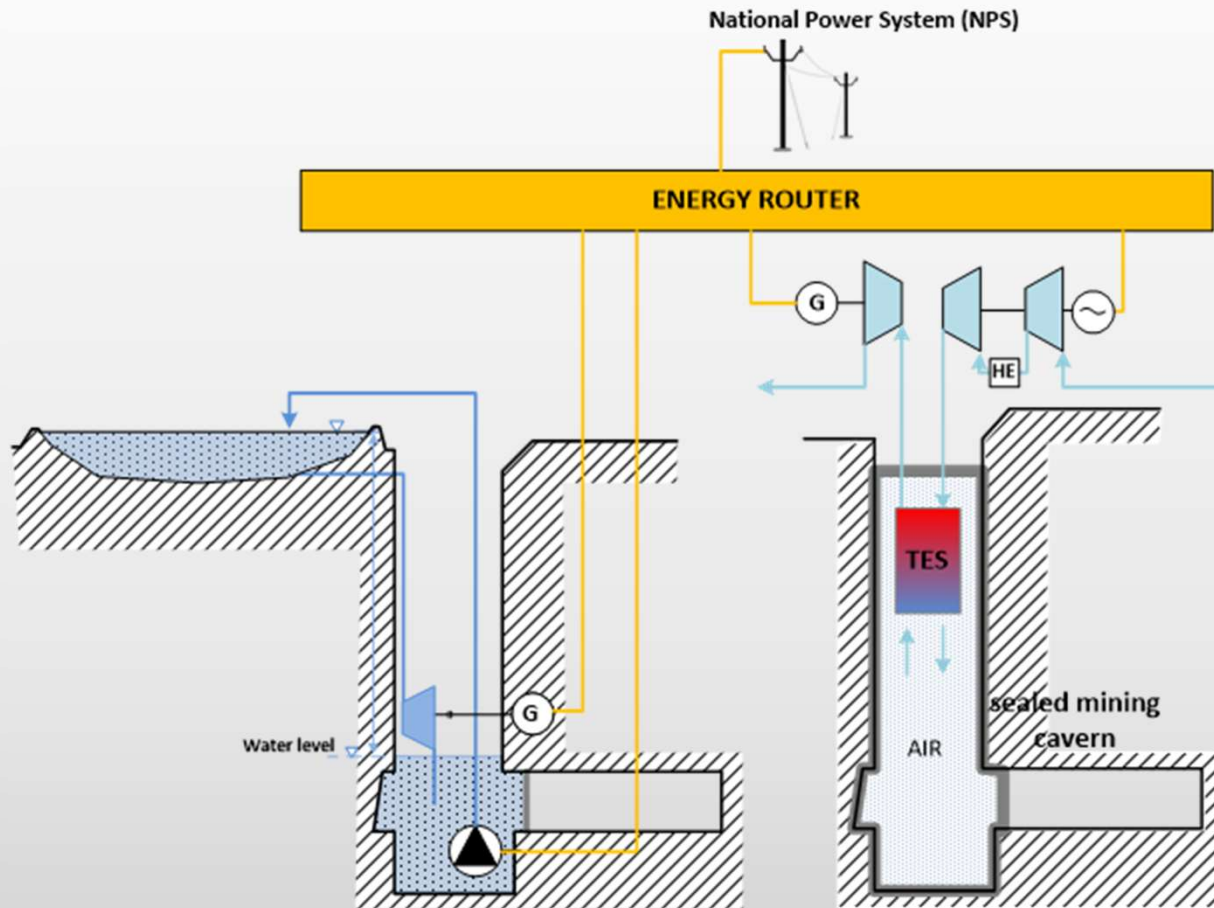


„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

Technology scheme

Hydro

Pumped
storage hydro
power plant,
PSH



Compressed air

Compressed Air
Energy Storage
System, CAES



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

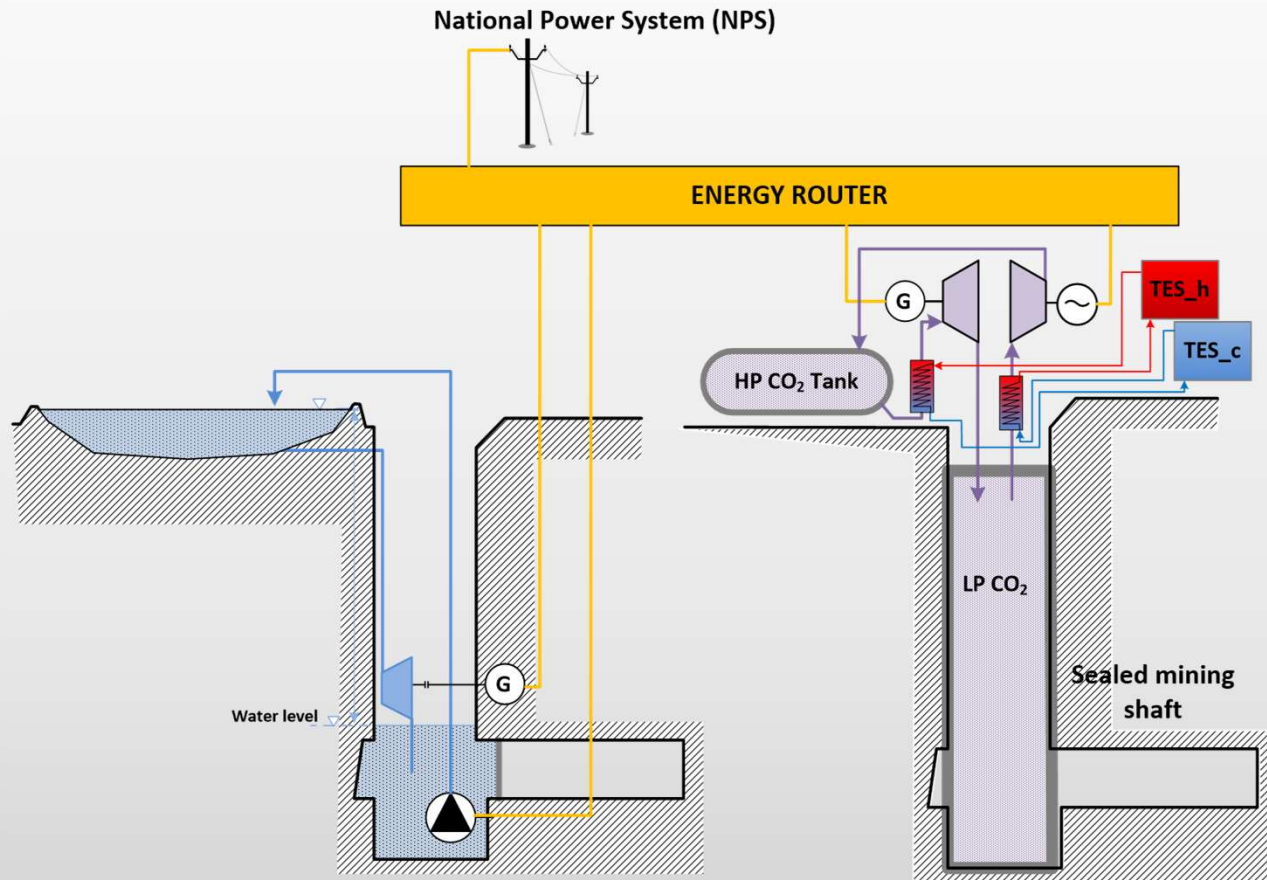
Technology scheme

Hydro

Pumped
storage hydro
power plant,
PSH

CO₂

Compressed
CO₂ Energy
Storage
System

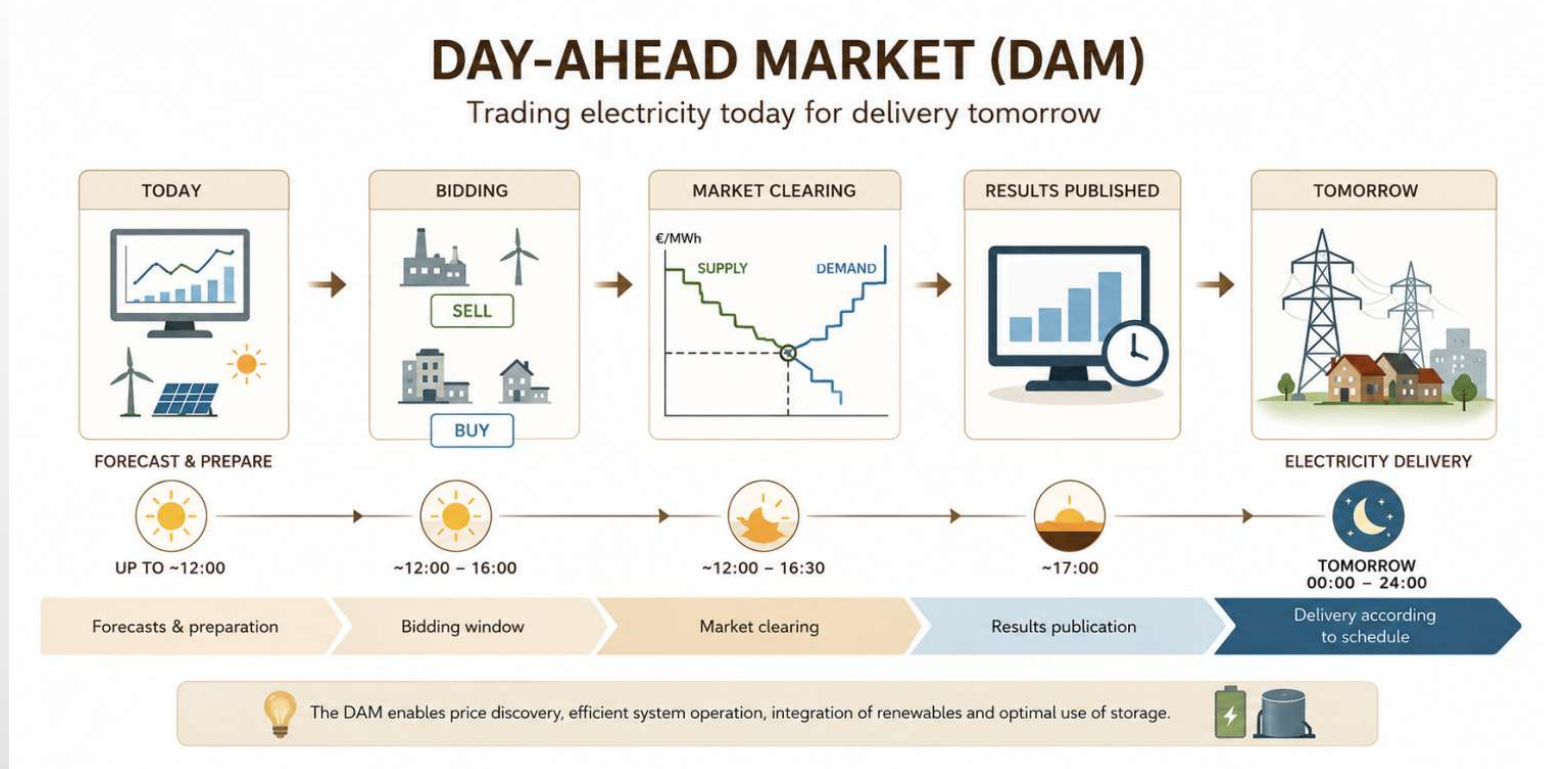


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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

DAM definition



Day-Ahead Market (DAM) – is a spot market for electricity where buyers and sellers trade energy for delivery on the next day, typically via hourly auctions, in order to balance generation and demand for the following 24-hour period.

Analysis

Analysis of changes in RDN (DAM) electricity prices (2025), average values

Time	January	February	March	April	May	June	July	August	September	October	November	December
0:00	447,5	544,1	481,2	454,4	507,1	524,3	536,3	459,9	446,3	361,2	405,3	414,1
1:00	404,3	502,8	430,4	413,3	451,6	445,9	463,0	418,0	406,5	351,5	402,8	412,3
2:00	380,8	494,8	426,1	409,2	440,7	431,8	452,4	408,5	394,7	335,3	394,4	399,3
3:00	365,2	475,1	406,2	386,2	415,4	404,0	424,7	390,1	383,3	333,6	390,4	388,8
4:00	352,9	465,3					407,5	376,2	375,8	335,0	392,6	391,0
5:00	349,0	462,6					405,9	371,9	374,9	342,4	402,8	393,7
6:00	359,4	473,8					404,1	376,4	383,5	383,6	433,8	402,5
7:00	388,4	495,1	435,0	411,5	430,8	392,5	416,7					487,8
8:00	458,3	596,1	531,0	488,6	478,6	436,0	459,7					552,6
9:00	541,1	728,8	555,6	488,6	476,8	419,5	468,3					573,7
10:00	605,6	699,6	466,5	448,6	406,5	322,1	438,0	406,9	513,8	399,9	514,6	517,3
11:00	556,7	575,6	346,8	322,0	291,7	210,6	371,0	314,0	407,5	333,0	487,1	473,5
12:00	483,3	506,7	217,8	218,2	193,3	97,7	304,0	228,7	314,2	326,3	488,1	471,0
13:00	462,3	465,4	151,6	124,8	155,4	51,2	271,9	173,9	247,1	314,8	501,9	477,1
14:00	452,8	444,0	143,1	60,9	145,8	23,7	228,9	142,8	219,0	339,0	547,6	533,8
15:00	472,2	468,4	145,5	28,2	149,3	9,2	221,7	138,3	215,6	382,9	677,8	576,9
16:00	493,4	494,2	192,0	64,0	170,2	23,3	244,6	158,6	264,2	443,2	737,4	602,4
17:00	566,3	563,6	341,5	141,6	220,8	83,2	296,3	230,0	351,7	560,6	821,3	671,8
18:00	603,3	672,0	472,9	254,1	293,5	166,6	375,2	307,5	426,6	669,2	712,9	582,5
19:00	618,8	752,9	599,1	397,2	429,7	336,7	435,9	407,2	561,2	742,2	623,7	566,3
20:00	604,6	736,0	718,5	499,4	548,6	511,6	545,6	510,5	727,8	673,2	589,8	540,9
21:00	583,7	702,5	687,1	654,6	595,0	630,6	692,1	659,8	1108,6	489,1	517,9	491,6
22:00	516,7	640,2	588,0	702,5	857,3	856,8	812,9	743,1	740,7	434,3	447,8	448,7
23:00	458,9	561,6	504,7	522,6	623,2	708,7	673,9	542,4	496,8	415,9	433,3	442,6

<350 PLN/MWh

>550 PLN/MWh

Analysis

Analysis of changes in RDN (DAM) electricity prices

	January	February	March	April	May	June	July	August	September	October	November	December
Average price, zł/MWh												
2021	252,3	250,6	268,2	266,6	297,6	352,4	372,8	374,9	473,0	465,3	-	-
2023	605,2	635,4	579,1	543,2	488,6	541,3	513,2	490,7	499,2	442,2	444,5	349,4
2024	395,5	328,7	326,8	337,3	362,8	449,6	434,4	414,6	392,4	436,4	522,4	459,2
2025	480,23	563,37	418,07	361,81	396,06	343,11	431,28	377,14	452,75	412,71	522,25	574,34
MAX price, zł/MWh												
2021	485	547,4	596,8	448,28	545,1	770,95	673,4	592,6	1037,1	1925,3	-	-
2023	1070,5	1010,7	882,2	884,3	2683,7	914,8	850,8	989,2	1058,4	860,2	783,8	777,9
2024	700,0	604,2	626,0	693,1	674,9	1560,2	1915,5	1975,2	2300,0	1778,1	2719,1	1447,8
2025	1372,17	1263,59	1178,80	1158,47	1491,52	1800,87	1984,13	1238,46	1881,03	1759,78	1988,55	1807,35
MIN price, zł/MWh												
2021	120	74,5	86,5	40,4	96,1	111,8	176,6	135,4	243,7	128,6	-	-
2023	22,0	343,8	106,6	36,7	4,5	44,7	37,3	97,6	0,1	0,0	22,3	-15,2
2024	96,5	43,2	43,1	-157,9	-99,4	-278,2	-186,4	-430,0	-256,2	-395,2	-21,7	-126,3
2025	-307,29	86,77	-138,51	-524,48	-542,00	-559,72	-9,09	-259,00	-246,58	-10,10	-5,68	256,81
Number of hours with prices >550 zł/MWh												
2021	0	0	0	0	0	7	4	7	146	175	-	-
2023	450	464	380	310	175	327	290	223	222	199	175	108
2024	79	7	9	16	39	165	152	146	125	159	270	194
2025	206	306	174	95	114	94	97	70	130	139	139	142
Number of hours with prices <350 zł/MWh												
2021	703	649	688	657	610	364	279	230	50	159	-	-
2023	32	1	8	19	82	54	87	97	78	167	147	366
2024	284	457	518	366	242	175	242	213	282	217	140	198
2025	117	29	180	241	206	277	141	209	127	175	57	123
Number of hours with prices <0 zł/MWh												
2021	0	0	0	0	0	0	0	0	0	0	-	-
2023	0	0	0	0	0	0	0	0	0	0	0	6
2024	0	0	0	17	31	23	25	53	36	19	10	17
2025	11	0	44	82	47	67	5	36	13	18	0	0

Rok	Średnia cena RDN [zł/MWh]
2020	210,11
2021	401,17
2022	796,17
2023	533,62
2024	424,94

>550 PLN/MWh

<350 PLN/MWh

From October 2025, 15-minute billing was introduced.

Analysis

Conditions for technical and economic analysis of the impact of variable configuration of generation equipment.

1. To analyze the operation of the systems, the operating parameters of the devices recommended by project partner were adopted.
2. For comparison purposes, **similar energy storage capacities** were assumed for the obtained indicators. When selecting individual capacity levels for each unit, the starting storage capacity of the CCES unit was assumed to be the maximum capacity of the expanded CO₂ tank.
3. In the case of a **CO₂ compression system**, it is necessary to ensure that a low-pressure storage tank with a capacity of **55 000–60 000 m³** can be installed, as this is the maximum capacity permitted for a mine shaft. The maximum volume of the **Budryk mine shaft in Ornontowice** is around 65 000 m³.
4. **Systems operate only at full charge and discharge cycles** – no possibility of partial charging and discharging of storage facilities, production) for systems with TES (A-CAES and CCES)
5. **Periods with the lowest average price** for the required **charging** cycle length and the **highest average price** for the **production** period were selected for the calculations.

FIRST-STEP ANALYSIS

Analysis

Summary of electricity production efficiency indicators for variable CCES generation equipment configurations

Compressed CO2 storage capacity -HTP, m3	2 030			1 557			1 151	
Storage capacity, MWh	54,8			42			31	
Expanded CO2 storage capacity -LTP, m3	72 847			55 870			41 300	
Production time at max capacity, h	5	5	4	4	4	3	3	3
Charging time at max capacity, h	8	7	6	7	6	5	6	5
Annual energy production, MWh	14797,7	15263	15583	11832,4	11951,5	11924,8	8809	8815,2
Production efficiency, %	78,79	78,77	78,77	78,77	78,77	78,76	78,77	78,76
Number of hours with max. tank filling, h	2032	2310	2631	2347	2631	2761	2761	2761
Number of hours with min. tank filling, h	3989	3942	4150	4150	4150	4307	4307	4307
Number of production cycles,	278	283	285	301	305	284	284	306
Number of charging cycles,	270	278	284	281	284	283	283	283
Amount of energy produced from storage capacity MWh/MWh	270,0	278,5	284,4	281,7	284,6	283,9	284,2	284,4
Amount produced from storage volume (HTP+LTP) MWh/m3	0,198	0,204	0,208	0,206	0,208	0,208	0,208	0,208
Profit from price arbitrage, PLN								
January	-5 057	3 542	20 980	-3 920	2 500	20 573	2 612	2 727
February	17 951	26 659	44 893	17 357	23 882	37 404	19 102	18 052
March	3 860	17 490	54 698	15 802	29 787	52 886	22 462	29 129
April	46 424	66 350	122 212	68 007	82 078	103 374	63 390	66 546
May	181 669	217 984	265 772	158 140	189 759	229 045	143 917	156 923
June	366 618	415 978	522 809	350 210	383 566	438 988	299 428	309 000
July	609 609	662 133	758 981	528 908	563 399	636 430	442 842	453 455
August	617 543	691 646	838 071	570 157	625 644	706 349	491 054	507 435
September	352 749	413 422	557 646	375 613	412 399	468 915	324 310	334 229
October	225 790	267 291	341 288	222 851	244 325	309 341	211 081	212 345
November	292 853	312 666	368 780	249 712	263 896	307 593	211 321	209 737
December	225 894	244 381	288 565	194 022	204 470	237 313	159 855	159 674
Total	2 935 903	3 339 542	4 184 693	2 746 859	3 025 706	3 548 212	2 391 375	2 459 252
Unit profit PLN/MWh	198	219	269	232	253	298	271	279

CO₂

Longer → Shorter

Analysis

Summary of electricity production efficiency indicators for variable A-CAES B generation equipment configurations

Storage capacity –compressed air, m3	31 645			24 165			18 411	
Storage capacity, MWh	55			42			32	
Production time at max capacity, h	5	5	4	4	4	3	3	3
Charging time at max capacity, h	8	7	6	7	6	5	6	5
Annual energy production, MWh	14 847,3	15 314,6	15 635,2	11 820,5	11 939,4	11 912,8	9 070,2	9 076,6
Production efficiency, %	67,65	67,64	67,63	67,64	67,63	67,62	67,63	67,62
Number of hours with max. tank filling, h	2032	2310	2631	2347	2631	2761	2761	2761
Number of hours with min. tank filling, h	3989	3942	4150	4150	4150	4307	4307	4307
Number of production cycles,	278	283	285	285	285	306	309	310
Number of charging cycles,	270	278	284	281	284	283	283	283
Amount of energy produced from storage capacity MWh/MWh	270,0	278,4	284,3	281,4	284,3	283,6	283,4	283,6
Amount produced from storage volume MWh/m3	0,469	0,484	0,494	0,489	0,494	0,493	0,493	0,493
Profit from price arbitrage, PLN								
January	-78 167	-70 632	-53 560	-58 434	-51 841	-39 609	-42 436	-39 660
February	-33 619	-25 650	-8 002	-20 937	-14 192	-7 619	-13 890	-13 388
March	-60 841	-47 729	-13 307	-35 277	-20 553	1 555	-16 873	-8 273
April	-14 287	5 834	63 711	23 157	38 846	56 631	29 572	34 186
May	98 013	137 114	190 576	95 694	131 750	171 993	104 801	120 062
June	284 357	334 610	445 851	285 778	323 496	378 699	263 528	274 826
July	535 611	591 016	693 392	472 315	511 497	583 923	417 731	430 253
August	562 681	638 651	787 872	524 284	584 951	669 699	477 527	497 298
September	301 613	363 070	509 200	334 691	375 581	430 633	303 615	315 935
October	144 000	189 352	263 490	163 046	186 201	245 713	169 792	173 852
November	216 075	237 092	293 512	194 590	209 177	243 995	170 163	172 772
December	151 310	170 677	216 292	140 097	151 548	177 121	119 182	122 743
Total	2 106 748	2 523 404	3 389 027	2 119 006	2 426 462	2 912 734	1 982 711	2 080 606
Unit profit PLN/MWh	142	165	217	179	203	245	219	229

Comp.
air

Analysis

Summary of electricity production efficiency indicators for variable PSH generation equipment configurations

Storage capacity, m3	23 610			18 020			13 750	
Storage capacity, MWh	55			42			32	
Production time at max capacity, h	5	5	4	4	4	3	3	3
Charging time at max capacity, h	8	7	6	7	6	5	6	5
Annual energy production, MWh	15 366,4	15 631	15 636,8	12 014,5	11 934,6	11 906,6	9 085,2	9 085,2
Production efficiency, %	73,93	73,92	73,91	73,92	73,91	73,90	73,91	73,91
Number of hours with max. tank filling, h	2394	2600	2782	2708	2782	2761	2908	2761
Number of hours with min. tank filling, h	3580	3612	4000	3773	4000	4308	4161	4308
Number of production cycles,	280	285	285	287	285	284	297	310
Number of charging cycles,	279	284	284	286	284	283	283	283
Amount of energy produced from storage capacity MWh/MWh	279,4	284,2	284,3	286,1	284,2	283,5	283,9	283,9
Amount produced from storage volume (upper and lower storage) MWh/m3	0,325	0,331	0,331	0,333	0,331	0,330	0,330	0,330
Profit from price arbitrage, PLN								
January	-52 839	-39 886	-7 856	-33 708	-17 006	-2 326	-12 836	-13 375
February	-20 533	-15 028	10 456	-1 2319	-674	20 271	-2 000	6 285
March	-24 404	-10 602	22 069	-3 221	6 373	32 826	3 777	14 764
April	29 089	37 002	99 582	46 598	66 187	85 159	51 024	55 122
May	149 774	188 086	226 386	134 537	158 875	206 368	125 616	146 160
June	265 660	314 550	489 409	282 250	356 604	416 599	289 336	303 853
July	599 880	628 844	714 536	503 617	527 115	615 711	430 140	454 234
August	532 237	579 411	766 276	486 607	567 548	691 690	463 407	514 348
September	366 858	430 589	526 163	356 859	388 160	453 781	313 586	333 453
October	177 242	222 086	303 843	185 706	216 792	284 927	193 731	201 969
November	283 167	303 473	326 709	246 648	234 384	283 831	193 049	200 139
December	192 765	215 546	255 799	174 251	182 380	2146 92	145 696	148 778
Total	2 498 896	2 854 070	3 733 371	2 367 826	2 686 736	3 303 529	2 194 526	2 365 729
Unit profit PLN/MWh	163	183	239	197	225	277	242	260

Hydro

FINAL CASE / ASSUMPTIONS



FINAL CASE / ASSUMPTIONS

Type of storage	PSH	CAES	CCES
Storage capacity, MWh	23.3	108.0	32.6
Storage capacity / pressure tank, m ³	-	62 751	1023
Expanded CO ₂ storage capacity -LTP, m ³	12 700	-	63 300
Production time at max capacity, h	4	3	3
Charging time at max capacity, h	8	5	5
Annual energy production, MWh	7865.3	30656.7	9229.2
Production efficiency, %	60.0	65.0	64.8
Number of hours with max. tank filling, h	2094	2761	2761
Number of hours with min. tank filling, h	4100	4307	4307
Hours of production cycles, h	1365	931	852
Hours of charging cycles, h	2616	1417	1417
Amount of energy produced from storage capacity MWh/MWh	338.3	283.9	283.3
Amount produced from storage volume (HTP+LTP) MWh/m ³	0.155	0.489	0.143
Profit from price arbitrage, PLN			
January	-163 383	-81 320	-50 753
February	-105 933	-2 939	-21 095
March	-81 073	21 175	-17 735
April	-74 044	165 749	26 316
May	-15 302	473 881	109 662
June	47 688	1 021 788	266 701
July	162 396	1 562 442	427 544
August	207 158	1 783 253	498 726
September	179 375	1 150 586	315 393
October	51 285	673 607	166 151
November	18 311	671 517	166 708
December	-22 043	492 418	116 162
Total	204 435	7 932 158	2 003 780
Unit profit PLN/MWh	26	259	217

Conclusions

Conclusions:

1. There has been an increase in fluctuations in electricity prices throughout the day.
2. Shorter charging and electricity production periods are better suited to periods of very low and very high electricity prices.
3. The best results in terms of thermodynamics were obtained in case of compr. air (CAES). The final configuration of individual systems will depend on investment costs.

**„Hybrid energy storage system using post-mining infrastructure”
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Thank you for your attention





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**„Hybrid energy storage system using post-mining infrastructure” (HESS)
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since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

Techno-economic assessment of hybrid energy storage technology in post-mining infrastructure

Tomasz Billig, Agata Czardybon

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26



„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

Economic analysis – CAPEX

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

Accuracy class	Project implementation level [%]	Typical Estimation Goal	Expected accuracy range [%]
Class 5	0% do 2%	Project concept	L: -20% do -50%, H: +30% do +100%
Class 4	1% do 15%	Feasibility study	L: -15% do -30%, H: +20% do +50%
Class 3	10% do 40%	Budget, Permits and Control	L: -10% do -20%, H: +10% do +30%
Class 2	30% do 75%	Control, bidding	L: -5% do -15%, H: +5% do +20%
Class 1	65% do 100%	Checking the estimate, making offers	L: -3% do -10%, H: +3% do +15%



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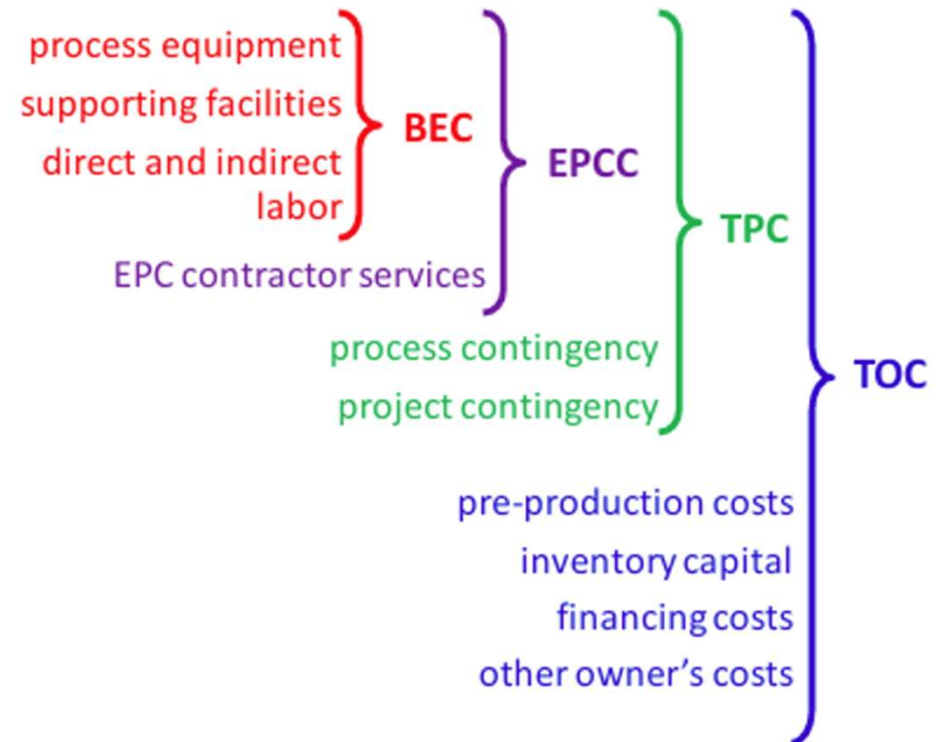


**„Hybrid energy storage system using post-mining infrastructure“ (HESS)
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Economic analysis – CAPEX

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

1. Bare erected cost (BEC) – these include the costs of equipment and devices, as well as the costs of construction, assembly, and installation of equipment, along with other costs directly related to the construction of the installation.
2. Engineering, procurement, and construction cost (EPCC) – these include bare erected cost plus items such as design costs, project management costs, site preparation, and other indirect costs.
3. Total plant costs (TPC) – these include EPCC costs plus items such as process contingency and project contingency.
4. Total overnight cost (TOC) – these are the total construction costs plus pre-production costs, spare parts costs, and other investor costs (legal costs, studies, investor engineering costs, management reserve, etc.).



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Economic analysis – cost assumptions

Engineering, procurement and construction cost (EPCC)

Based on NETL guidelines, EPCM contractor services were estimated at 15 percent of BEC. These costs consist of all home office engineering and procurement services as well as field construction management costs.

Total plant cost (TPC)

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

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

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

Depending on the cost component, 0-15% process contingency was assumed. Based on AACE guidelines, the cost of project contingency for accuracy class 4 was assumed to be 15% of EPCC.

Total overnight cost (TOC)

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

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



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PSH - BEC

Bare erected cost:

1. Process equipment
 - Vertical Pelton turbine with generator
 - Turbine – pipelines, supporting structures
 - Water pumps
 - Pumps – pipelines
 - Auxiliary equipment
2. Supporting facilities, direct and indirect labour
 - Mine shaft water dams
 - Mine shaft sealing
 - Wallcoat
 - Upper reservoir construction
 - Platform assembly
 - Electrical installations
 - Instrumentation
 - Auxiliary installations
 - Civil works (roadworks, land preparation etc.)
 - Labour, materials (proces equipment installation)

Costs Area	Costs, PLN
Pelton turbine	7 140 000
Pumps	2 940 000
Turbine - Pipelines	14 739 300
Pumps – Pipelines	36 214 194
Auxiliary equipment	7 324 019
Total equipment cost	68 357 513
Wallcoat	2 209 982
Mine shaft sealing plug	673 900
Upper reservoir	4 406 400
Platform assembly	2 706 700
Civil works	6 152 176
Auxiliary installations (instrumentation, electrical, services)	47 779 003
Labour, materials (construction, installation etc.)	52 471 339
Bare erected cost (BEC)	184 714 055



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PSH - TOC

Costs Area	Cost, PLN
Pelton turbine	7 140 000
Pumps	2 940 000
Turbine - Pipelines	14 739 300
Pumps – Pipelines	36 214 194
Auxiliary equipment	7 324 019
Total equipment cost	68 357 513
Wallcoat	2 209 982
Mine shaft sealing plug	673 900
Upper reservoir	4 406 400
Platform assembly	2 706 700
Civil works	6 152 176
Auxiliary installations (instrumentation, electrical, services)	47 779 003
Labour, materials (construction, installation etc.)	52 471 339
Bare erected cost (BEC)	184 714 055
Contracting Strategy and EPC Contractor Services	27 707 108
Engineering, procurement and construction cost (EPCC)	212 421 163
Process Contingency	4 298 833
Project Contingency	31 863 174
Total plant cost (TPC)	248 583 170
Preproduction (Start-Up) Costs	1 242 916
Inventory Capital	4 971 663
Other Owner's Costs	37 287 476
Total overnight cost (TOC)	292 085 225



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A-CAES - BEC

Bare erected cost:

1. Process equipment
 - Compressors
 - Expander
 - TES tank
 - Auxiliary equipment
2. Supporting facilities, direct and indirect labour
 - Mine shaft sealing dams
 - Mine shaft sealing cork
 - Wallcoat
 - TES fill
 - Electrical installations
 - Instrumentation
 - Auxiliary installations
 - Civil works (roadworks, land preparation etc.)
 - Labour, materials (proces equipment installation)

Costs Area	Costs, PLN
Compressors	40 934 400
Expander	86 760 000
TES tank	12 000 000
Auxiliary equipment (pipelines, valves, intercooler)	14 750 000
Total equipment cost	154 444 400
Wallcoat	2 086 122
Civil works	22 410 000
Mine shaft sealing dams	2 370 763
Mine shaft sealing cork	45 000 000
TES fill (basalt)	633 500
Auxiliary installations (instrumentation, electrical, services)	99 361 380
Labour, materials (construction, installation etc.)	168 654 120
Bare erected cost (BEC)	494 960 285



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A-CAES - TOC

Costs Area	Cost, PLN
Compressors	40 934 400
Expander	86 760 000
TES tank	12 000 000
Auxiliary equipment (pipelines, valves, intercooler)	14 750 000
Total equipment cost	154 444 400
Wallcoat	2 086 122
Civil works	22 410 000
Mine shaft sealing dams	2 370 763
Mine shaft sealing cork	45 000 000
TES fill (basalt)	633 500
Auxiliary installations (instrumentation, electrical, services)	99 361 380
Labour, materials (construction, installation etc.)	168 654 120
Bare erected cost (BEC)	494 960 285
Contracting Strategy and EPC Contractor Services	74 244 043
Engineering, procurement and construction cost (EPCC)	569 204 328
Process Contingency	8 531 313
Project Contingency	85 380 649
Total plant cost (TPC)	663 116 290
Preproduction (Start-Up) Costs	3 315 581
Inventory Capital	13 262 326
Other Owner's Costs	99 467 443
Total overnight cost (TOC)	779 161 640



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CCES - BEC

Bare erected cost:

1. Process equipment
 - Compressors
 - Expander
 - CO₂ high pressure storage
 - CO₂ purification system
 - TES tanks
 - Heat exchangers
 - Auxiliary equipment
2. Supporting facilities, direct and indirect labour
 - Mine shaft sealing dams
 - Mine shaft sealing cork
 - Wallcoat
 - TES fill
 - Electrical installations
 - Instrumentation
 - Auxiliary installations
 - Civil works (roadworks, land preparation etc.)
 - Labour, materials (proces equipment installation)

Costs Area	Costs, PLN
Compressors	12 370 000
Expander	26 120 000
CO ₂ high pressure storage	2 700 000
CO ₂ purification system	6 624 000
TES tanks	28 720 000
Heat exchangers	9 100 000
Auxiliary equipment (pipelines, valves, intercooler)	15 306 800
Total equipment cost	100 940 800
Wallcoat	2 086 122
Civil works	8 997 200
Mine shaft sealing dams	2 370 763
Mine shaft sealing cork	9 000 000
TES fill (basalt)	280 000
TES fill (thermal oil)	7 840 000
Auxiliary installations (instrumentation, electrical, services)	30 282 240
Labour, materials (construction, installation etc.)	108 624 780
Bare erected cost (BEC)	270 421 905



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CCES - TOC

Costs Area	Cost, PLN
Compressors	12 370 000
Expander	26 120 000
CO ₂ high pressure storage	2 700 000
CO ₂ purification system	6 624 000
TES tanks	28 720 000
Heat exchangers	9 100 000
Auxiliary equipment (pipelines, valves, intercooler)	15 306 800
Total equipment cost	100 940 800
Wallcoat	2 086 122
Civil works	8 997 200
Mine shaft sealing dams	2 370 763
Mine shaft sealing cork	9 000 000
TES fill (basalt)	280 000
TES fill (thermal oil)	7 840 000
Auxiliary installations (instrumentation, electrical, services)	30 282 240
Labour, materials (construction, installation etc.)	108 624 780
Bare erected cost (BEC)	270 421 905
Contracting Strategy and EPC Contractor Services	40 563 286
Engineering, procurement and construction cost (EPCC)	310 985 191
Process Contingency	2 321 313
Project Contingency	46 647 779
Total plant cost (TPC)	359 954 282
Preproduction (Start-Up) Costs	1 799 771
Inventory Capital	7 199 086
Other Owner's Costs	53 993 142
Total overnight cost (TOC)	422 946 281



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Router + grid connection - TOC

Costs Area	Cost, PLN
Energy router	184 000
Step-up transformer	9 570 000
HV switchgear	16 530 000
Total equipment cost	26 284 000
Building	13 050 000
Grounding and lightning protection system	2 610 000
DC power supply system and UPS	3 045 000
Fire protection systems	2 610 000
HVAC and cooling systems	3 915 000
Grid connection infrastructure	9 570 000
Router supporting infrastructure	297 000
Router integration with PSH, CAES, CCES	120 000
Bare erected cost (BEC)	61 501 000
Contracting Strategy and EPC Contractor Services	9 135 000
Engineering, procurement and construction cost (EPCC)	70 636 000
Process Contingency	0
Project Contingency	10 595 400
Total plant cost (TPC)	81 231 400
Preproduction (Start-Up) Costs	406 157
Inventory Capital	1 610 805
Other Owner's Costs	12 184 710
Total overnight cost (TOC)	95 433 072



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
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Case analysis - CAPEX

In Case 1 system consists of:

- PSH
- A-CAES
- Router + grid connection

In Case 2 system consists of:

- PSH
- CCES
- Router + grid connection

Costs Area	Case 1, PLN	Case 2, PLN
Total equipment cost (TEC)	249 085 913	195 582 313
Bare erected cost (BEC)	741 175 340	533 006 960
Contracting Strategy and EPC Contractor Services	111 086 151	79 860 894
Engineering, procurement and construction cost (EPCC)	852 261 490	612 867 853
Process Contingency	12 830 146	9 443 971
Project Contingency	127 839 224	91 930 178
Total plant cost (TPC)	992 930 860	714 242 002
Preproduction (Start-Up) Costs	4 964 654	3 571 210
Inventory Capital	19 844 794	14 271 017
Other Owner's Costs	148 939 629	107 136 300
Total overnight cost (TOC)	1 166 679 937	839 220 530



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Project co-financed by the European Commission within the framework of the Research Fund for Coal and Steel – RFCS program under the contact no. 101112380 (RFCS-2022) titled „Hybrid Energy Storage System using post-mining infrastructure” (HESS) and by the State Subsidy within the framework of the program „Co-financed International Projects” (PMW) established by the Minister of Science and Higher Education.



HESS PROJECT WEBSITE - <http://www.itpe.pl/en/hess/>



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**„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)**



since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

Life Cycle Assessment of the HEES

**Authors: Katarzyna Rychlewska, Radosław Lajnert,
Karolina Wodzisławska-Pasich ITPE**

FINAL HEES SEMINAR, Zabrze, Poland 22.06.26



**„Hybrid energy storage system using post-mining infrastructure” (HEES)
No. 101112380 (RFCS-2022)**

Life Cycle Assessment of the HESS



GOAL: The primary goal is to quantify the life cycle environmental impacts of a developed HESS system, identifying which processes of the life cycle contribute most to the overall impact, as well as highlighting the factors responsible for the greatest impacts. The results are intended to provide insight into the environmental burdens of the adaptation of a mine shaft for the purposes of a hybrid energy storage system based on technological solutions proposed by Partners.

FUNCTIONAL UNIT: Main assumed functional unit is 1 kWh of energy produced annually.

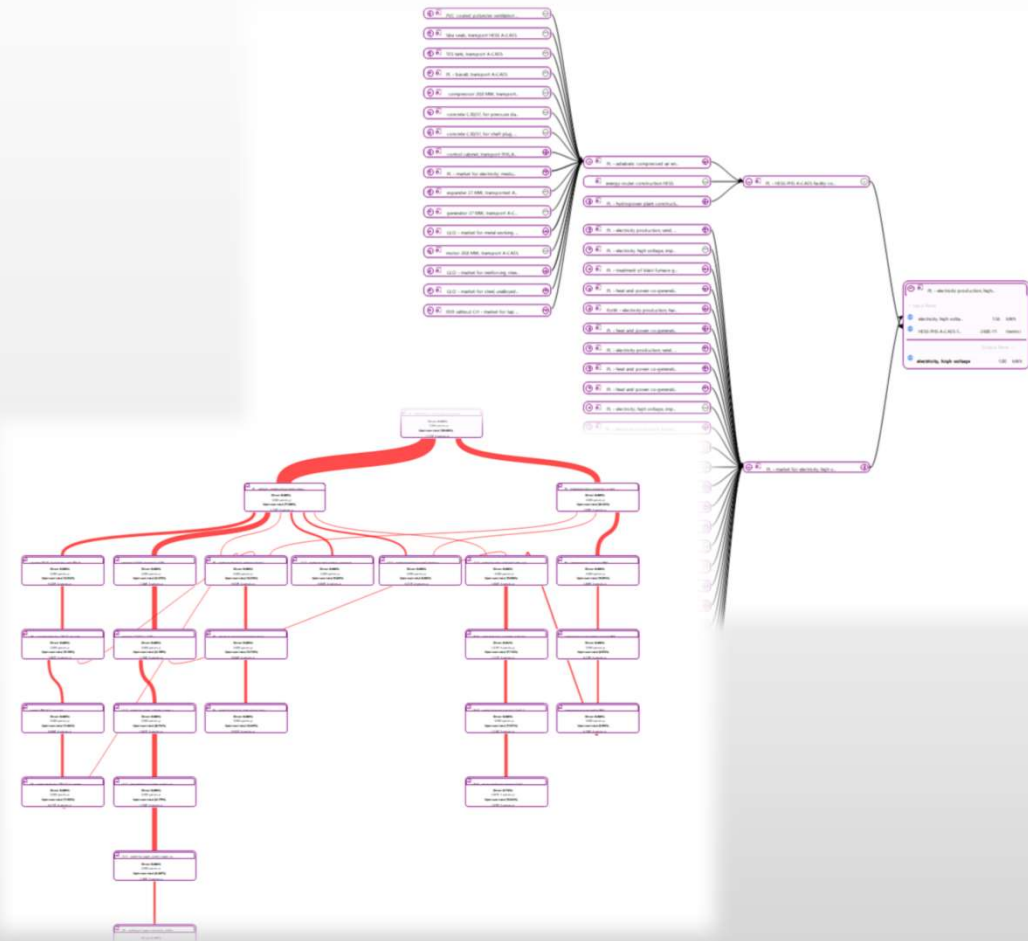
SYSTEM BOUNDARIES: The scope of this study encompassed a “cradle-to-gate” perimeter, which is the most common approach for hydropower plants. The end-of-life stage is generally not included, as the decommissioning of hydropower plants is currently not a common practice and the expected lifetime of hydropower plants is very long. System boundaries covers:

- manufacturing stage - this phase comprises the raw material acquisition and construction of HESS components;
- HESS construction stage – transport to construction site, construction works, adaptation of the shaft;
- operation of HESS system for 1 year.

Life Cycle Assessment of the HESS

For this study, the openLCA software to develop and link unit processes is employed. The ReCiPe impact evaluation method will be used for calculating the lifecycle impact category indicators.

Life cycle inventory of foreground processes is based on reports provided by project Partners and literature data regarding similar projects. ecoinvent v.3.12 database is used for background processes modeling.



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)

Life Cycle Assessment of the HESS



Two systems: HESS PHS A-CAES facility with energy router and HESS PHS CCES facility with energy router.

Each „component” of HESS was modeled separately and individual systems were connected by „facility construction proces”. Electricity production was modeled by separate „electricity production” processes.

HESS PHS A-CAES

Inputs/Outputs - HESS PHS A-CAES facility construction, in mine shafts - PL

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descripti...
adiabatic compr...	HESS PHS A-CAES	1.00000	Item...		none		adia...			
energy router HE...	HESS PHS A-CAES	1.00000	Item...		none		ener...			
hydropower pla...	HESS PHS A-CAES	1.00000	Item...		none		hydi...			

Outputs

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descripti...
HESS PHS A-CAES	HESS PHS A-CAES	1.00000	Item...		none					

Inputs/Outputs - adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descripti...
basalt, transport...	HESS PHS A-CAES	1.00000	kg		none		basal...			
compressor 20.8...	HESS PHS A-CAES	1.00000	Item...		none		com...			
concrete C30/37...	HESS PHS A-CAES	1364.00...	m3		none		conc...			
concrete C30/37...	HESS PHS A-CAES	7972.00...	m3		none		conc...			
control cabinet, L...	HESS PHS A-CAES	1.00000	Item...		none		contr...			Servis v...
electricity, mediu...	D:Electricity, gas, st...	2.27010...	kWh		none		mark...			Electricit...
electricity, mediu...	D:Electricity, gas, st...	2.24273...	kWh		none		mark...			Shaft III ...
expander 27 M...	HESS PHS A-CAES	1.00000	Item...		none		expa...			
generator 27 M...	HESS PHS A-CAES	1.00000	Item...		none		gene...			
metal working, a...	C:Manufacturing/2...	3.25367...	kg		none		mark...			Steel an...
metal working, average for metal product manufacturing			kg		none		mark...			Steel an...
motor 20.8 MW...	HESS PHS A-CAES	1.00000	Item...		none		mot...			
PVC coated poly...	HESS PHS A-CAES	3523.00...	kg		none		PVC ...			
reinforcing steel	C:Manufacturing/2...	4.99142...	kg		none		mark...			For shaf...
reinforcing steel	C:Manufacturing/2...	1.97292...	kg		none		mark...			For shaf...
Sika seals, transp...	HESS PHS A-CAES	2.61556...	kg		none		Sika ...			
steel, unalloyed	C:Manufacturing/2...	1.62683...	kg		none		mark...			Steel an...

Outputs

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descripti...
adiabatic comp...	HESS PHS A-CAES	1.00000	Item...		none					
wastewater, aver...	E:Water supply; se...	2465.52...	m3		none					
Non-hazardous ...	/Inventory indicat...	208.930...	m3		none					Rocks fr...

Life Cycle Assessment of the HESS



Manufacturing stage: raw materials sourcing and construction materials manufacturing (reference unit of 1 item, 1 m³ or 1 kg):

- HESS components manufacturing using different types of steel and other identified materials;
- different types of concrete for CO₂ purification system slabs (C20/25 with CEM II), shaft plugs and pressure dams (C30/37 with CEM III) and water dams/lower platform in PHS (C35/45 with CEM II);
- Sika seals manufacturing based on SDS;
- Therminol VP1 manufacturing;
- Basalt and dolomite quarry;

The screenshot displays the 'Inputs/Outputs' tab for 'Sikagard P770 Part A A-CAES'. The interface includes a left sidebar with a list of materials and components, and a main table with columns for Flow, Category, Amount, Unit, Costs/R..., Uncertai..., Avoided..., Provider, Data qu..., Location, and Descripti....

Inputs Table:

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descripti...
chemical, organi...	C:Manufacturing/2...	478.500...	kg		none		mark...			Approx...
glycerine	C:Manufacturing/1...	55.80000	kg		none		mark...			
hydrated lime, p...	C:Manufacturing/2...	717.700...	kg		none		mark...			
naphtha	C:Manufacturing/1...	55.80000	kg		none		mark...			
non-ionic surfact...	C:Manufacturing/2...	55.80000	kg		none		mark...			Approx...

Outputs Table:

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descripti...
Sikagard P770 ...	HESS PHS A-CAES	3189.7...	kg		none					

Life Cycle Assessment of the HESS



Inputs/Outputs - hydropower plant construction, in mine-shaft HESS - PL

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descripti...
concrete C30/37,...	HESS PHS A-CAES	260.000...	m3		none		con...			
control cabinet, t...	HESS PHS A-CAES	1.00000	Item(...		none		contr...			
electricity, mediu...	D:Electricity, gas, st...	2.39580...	kWh		none		mark...			Electricit...
electricity, mediu...	D:Electricity, gas, st...	4165.56...	kWh		none		mark...			Shaft II ...
hydraulic drive u...	HESS PHS A-CAES	1.00000	Item(...		none		hydr...			
penstock, transport...	HESS PHS A-CAES	1.00000	Item(...		none		pens...			
reinforcing steel	C:Manufacturing/2...	1.17000...	kg		none		mark...			For low...
shut-off valve, tr...	HESS PHS A-CAES	1.00000	Item(...		none		shut...			
Sika seals, transp...	HESS PHS A-CAES	2.43160...	kg		none		Sika ...			
tap water	E:Water supply; se...	2.61928...	kg		none		mark...			Water f...
upper reservoir ...	HESS PHS A-CAES	1.00000	Item(...		none		uppe...			
upper technical ...	HESS PHS A-CAES	1.00000	Item(...		none		uppe...			

Inputs/Outputs - HESS PHS A-CAES facility construction, in mine shafts - PL

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...
adiabatic compressed air energy storage pla...	HESS PHS A-CAES	1.00000	Item(...		none		adia...	
energy router HESS	HESS PHS A-CAES	1.00000	Item(...		none		ener...	
hydropower plant, mine-shaft HESS - PL	HESS PHS A-CAES	1.00000	Item(...		none		hydr...	

Outputs

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...
HESS PHS A-CAES facility, in mine shafts	HESS PHS A-CAES	1.00000	Ite...		none			

System boundaries - construction:

- construction stage – transport of components, transport of concrete and steel to construction site;
- construction works and adaptation of the shaft – application of seals, dams building.



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
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Life Cycle Assessment of the HESS



System boundaries covered - operation stage - electricity production by HESS system for 1 year of its operation.

The screenshot displays the openLCA software interface. The left sidebar shows a list of components for the 'electricity production, high voltage, HESS PHS_A-CAES - PL' process. The main window shows the 'Inputs/Outputs' table for this process.

Inputs/Outputs - electricity production, high voltage, HESS PHS_A-CAES - PL

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descr...
HESS PHS A-CAES facility, in mine shafts	HESS PHS A-CAES	2.59600E-11	Item[...]		none					
electricity, high voltage	D:Electricity, gas, st...	1.56000	kWh		none					

Inputs/Outputs - electricity production, high voltage, HESS PHS_CCES - PL

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descr...
HESS PHS CCES facility, in mine shafts	HESS CCES	5.85000E-11	Item(s)							
electricity, high voltage	D:Electricity, gas, st...	1.60053	kWh							

Inputs/Outputs - electricity production, high voltage, HESS PHS_A-CAES - PL

Flow	Category	Amount	Unit	Costs/R...	Uncertai...	Avoided...	Provider	Data qu...	Location	Descr...
electricity, high voltage	D:Electricity, gas, ...	1.00000	kWh	0.0977...	none					

The bottom of the interface shows tabs for 'Information', 'Inputs/Outputs', 'Documentation', 'Parameters', 'Allocation', 'Social aspects', and 'Direct impacts'.



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Thank you for your attention!

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since 1955



Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

presentation title: Possibilities for implementing the results of the HESS project in the Czech Republic,

Authors: Zbyszek Szeliga (Vysoká škola báňská – Technická univerzita Ostrava)

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

Possibilities for implementing the results of the HESS project in the Czech Republic,

Presentation Outline:

- What was anticipated at the start of the project; status in 2023
- What is the current status in 2026?
- What does the potential application of the HESS project results in the Czech Republic look like?



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**„Hybrid energy storage system using post-mining infrastructure” (HESS)
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Status in 2023, What Was Anticipated at the Start of the Project,

- List of anticipated mines in the Czech Republic within the OKR area that were considered and for which suitability analysis, identification, and evaluation were conducted according to established - multi-criteria analysis.

Entrepreneur	Mining plant	Division	Shaft	Depth [m]	Diameter [m]
1	2	3	4	5	6
OKD	ČSA		Jan	962,2	7,5
			ČSA 2	1049,3	7,5
			ČSA 3	994,8	7,5
	Darkov		Da-1	878,3	7,5
			Mír 5	887,2	7,5
			Mír 4	1011,5	7,5
	ČSM	ČSM Sever	Sever (wylotowy, wentylacyjny)	1005,0	7,5
			Sever (intake)	1104,4	7,5
		ČSM Jih	Jih (wylotowy, wentylacyjny)	972,1	7,5
			Jih (intake)	1103,9	7,5
VKD	Jeremenko		Jeremenko 1	819,0	5
			Jeremenko 2	1062,0	7,5

No.	Entrepreneur	Mining plant	Division	Shaft	Depth [m]	Diameter [m]	Total score tank in shaft
1	OKD	CSM	CSM Sever	Sever (exhaust ventilation)	1005,0	7,5	3,7
2	OKD	CSM	CSM Sever	Sever (intake)	1104,4	7,5	5,5
3	OKD	CSM	CSM Jih	Jih (exhaust ventilation)	972,1	7,5	2,7
4	OKD	CSM	CSM Jih	Jih (intake)	1103,9	7,5	5,2



The Situation in 2023:

The analysis of mine shafts in the Czech Republic included shafts from the CSM, CSA, Darkov, and Jeremenko coal mines.

Except for the CSM mine, the shafts in the other mining operations are either in the process of being filled or have already been designated for filling.

Therefore, only the shafts from the CSM mine were subjected to a multi-criteria analysis.

The CSM mine consists of two parts: "Sever" and "Jih," each containing two shafts: an intake (service and material) shaft and an exhaust shaft (equipped with an extraction skip). Based on the collected data, for the purposes of constructing a pumped storage hydropower plant, the shafts located in the Sever field were selected. An additional argument for choosing these shafts is the selection of one of the Sever field shafts for compressed air energy storage.



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**„Hybrid energy storage system using post-mining infrastructure“ (HESS)
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What is the current situation in 2026 (?)

Black coal mining came to an end at the ČSM Mine - in early February of this year.
(...the last operating hard coal mine in the Czech Republic)
Immediately afterward, OKD began the process of decommissioning the mine.

OKD is building 87 dams to seal off mine tunnels, the last two dams will be completed this July.

Once all the barriers are completed, the company plans to turn off the main fans and backfill both ventilation shafts.

In June, OKD will turn off the main fans in the South area and in September in the North area.
(The former opening pits, intake shaft, will be ventilated separately during the liquidation.)

The alternative solution proposed by HESS was not adopted;
the operator preferred other options ...



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(The backfilling of one of them is planned for August, the other for September.)

The liquidation of the opening pits, intake shaft ... They will be modified so that after the end of coal mining they can be used for pumping methane. Degassing pipelines are being installed in the mine and in the access shafts in preparation for future methane extraction.

... will build a concrete pit plug at the first floor level.

The part below the plug to the bottom of the pit will remain free for the possibility of gas, methane accumulation.

The depth of this part is approximately 600 meters, from the pit plug to the surface the pit will be filled with a cement-ash mixture.

We were unable to convince the operator of the energy storage solution proposed by the HESS project.

The reasons included concerns about methane hazards, the economic viability of the facility's operation, and the relevant technologies ...

At the time the basic information was presented, not all of the project's evaluation results had been finalized.

... a time discrepancy between the project schedule and actual processes ...

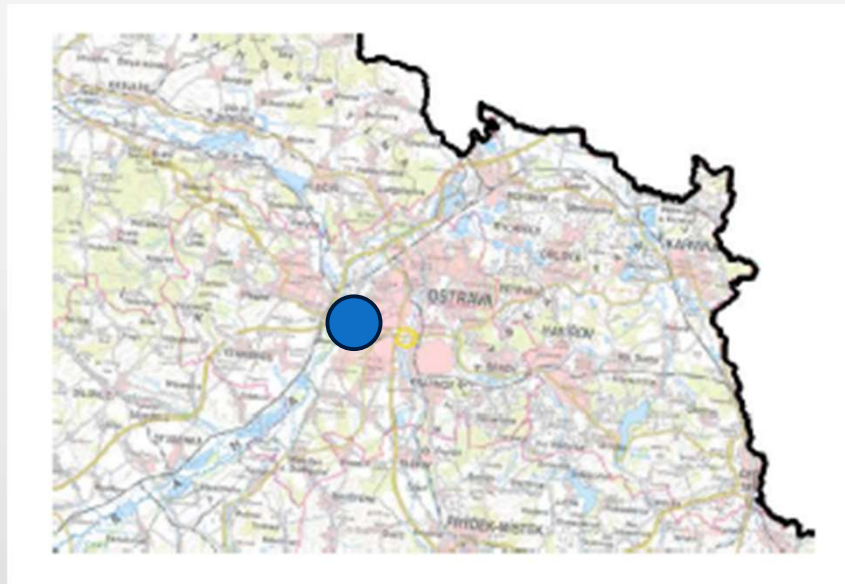


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**„Hybrid energy storage system using post-mining infrastructure“ (HESS)
No. 101112380 (RFCS-2022)**

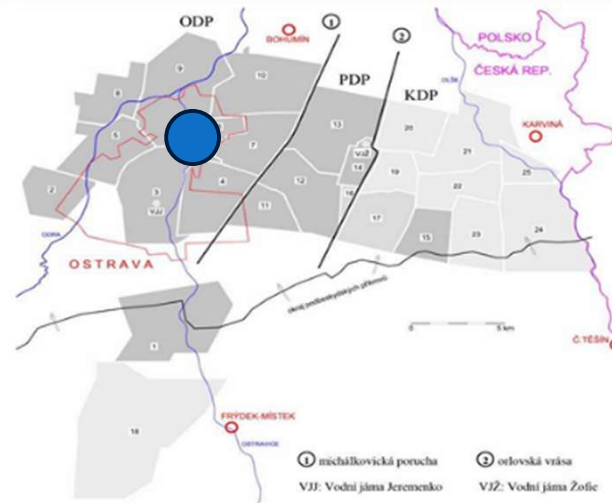
The way forward? ... a return to the concept of energy storage at the Jeremenko Mine (?)



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)



obr. 3: Regionální členění české části Hornoslezské pánve (upraveno dle Dopita et al., 1997 in Malucha, 2013).

Project Title: Research on the Impact of Gradual Flooding of the Karviná Sub-Basin of the OKR with **High-Salinity Mine Water** on the Vulnerability of the Landscape Affected by Coal Mining and the Stability of the HDD



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Mine water is pumped practically continuously from the mine area of the closed Jeremenko Mine at a rate of approximately 160 l/s. The reason for pumping the water is that this mine area is connected to the mine areas of other shafts, which could be at risk if the water level in the Jeremenko Mine rises.

The water is pumped from a depth of approximately 600 m, and its average temperature is 26°C.

The water is discharged into the nearby Ostravice River. This discharge limits pumping during periods of low flow in the Ostravice River and may even result in the suspension of pumping.



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**„Hybrid energy storage system using post-mining infrastructure“ (HESS)
No. 101112380 (RFCS-2022)**

TIRSMPO906 - Výzkum možností využití uzavíraných hlubinných dolů
v ČR pro energetické účely a jako potenciál vodních zdrojů

Objective: To research and validate a new concept for energy storage
using a small underground pumped-storage power plant with a the
nominal power of 650 kW (639 kVA) located at a depth of approximately
600 meters.

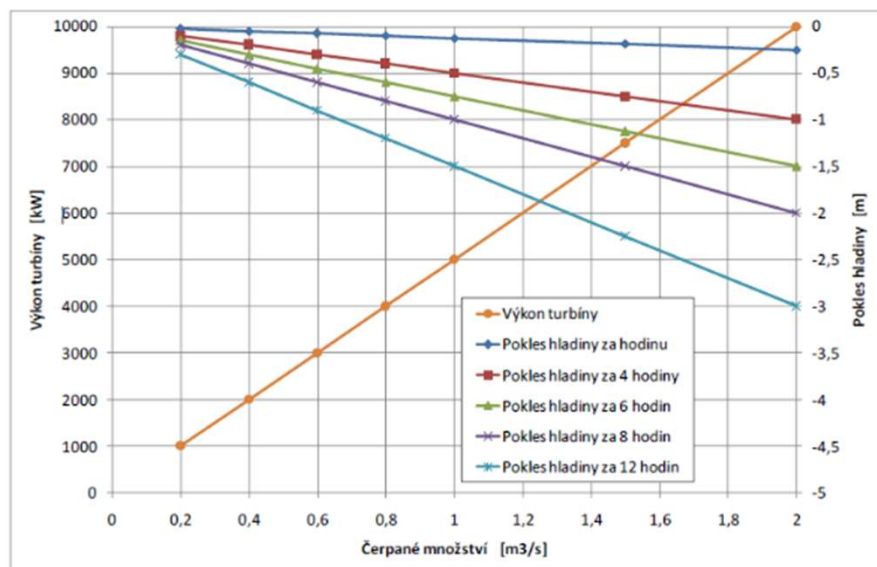
Implementation: The research lasted 4.5 years and began in July 2015.



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**„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)**



Obrázek č. 37: Závislost výkonu turbíny a poklesu hladiny na čerpaném množství a režimu provozu

TIRSMPO906 - Výzkum možnosti využití uzavíraných hlubinných dolů v ČR pro energetické účely a jako potenciál vodních zdrojů

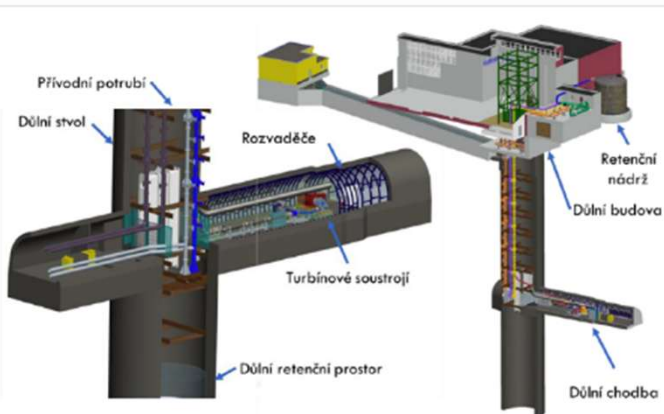
At the maximum considered flow rate and a 12-hour cycle, the water level fluctuation in the mine would reach 3 m. The graph also shows, for comparison, the turbine output, which would be 1 MW at a flow rate of 0.2 m³/s (i.e., at a pumping rate slightly higher than the current one) and would reach 10 MW at the maximum considered flow rate of 2 m³/s.



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)



Důlní přečerpávací elektrárna na VJ Jeremenko (výzkumná, poloprovozní) (Bartoš, 2016)

Because this was a research project, a relatively small hydroelectric power plant with the nominal power of 607 kW was installed underground, and a small storage reservoir with a volume of only 150 m³ was built on the surface, which was sufficient for only about 10 minutes of continuous operation. If there were sufficient water on the surface (or if part of the pumped water were reused), the power plant could operate continuously. During the trial operation, this pumped-storage power plant was tested.

However, certain problems have arisen during the trial operation that would need to be resolved before the system can be used on a permanent and commercial basis. Due to the water's chemical composition, these primarily involved problems with the leaks of individual turbine components, clogging or corrosion of the turbine's metal parts, and the formation of hazardous H₂S (Hydrogen sulfide) dissolved in the water and released into the mine atmosphere when water struck the turbine blades. These problems could be resolved by using a closed-loop system, in which only clean water would circulate within the pumped-storage power plant—that is, mine water would not be used.

Question: Is this the right way?



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„Hybrid energy storage system using post-mining infrastructure” (HESS)
No. 101112380 (RFCS-2022)



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Poljak, Michal
Nove sady 988/2
602 00 Brno
REPUBLIQUE TCHÈQUE

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Primary Examiner
Name: Luc, Rapha
Tel: +49 89 2339 - 4827

Application No. 23 783 298.5 - 1002	Ref. REG2306_PCTEP	Date 27.05.2026
Applicant Vysoká škola Báňská-Technická Univerzita Ostrava, et al		

Communication under Rule 71(3) EPC

1. Intention to grant

You are informed that the examining division intends to grant a European patent on the basis of the above application, with the text and drawings and the related bibliographic data as indicated below

A copy of the relevant documents is enclosed

1.1 Text intended for grant

In the text for the Contracting States:

AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO
PL PT RO RS SE SI SK SM TR

Description, Pages

1-44 filed in electronic form on

01-12-2025

We have been granted a European patent that could be included among the results of the HESS project ...
(?)

Title:

„A modular pumped-storage power plant“



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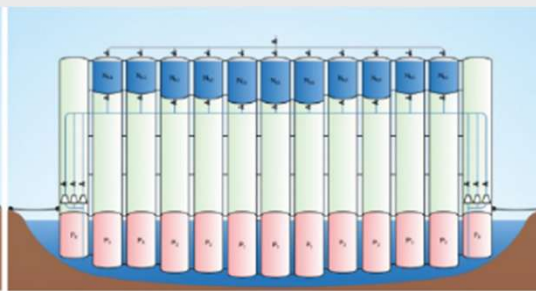
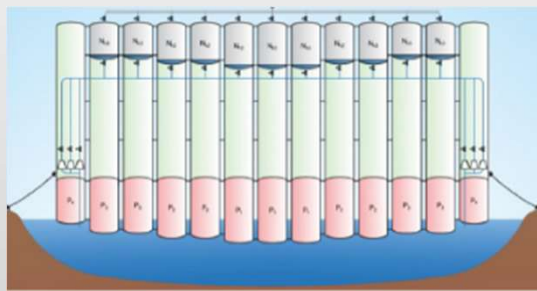
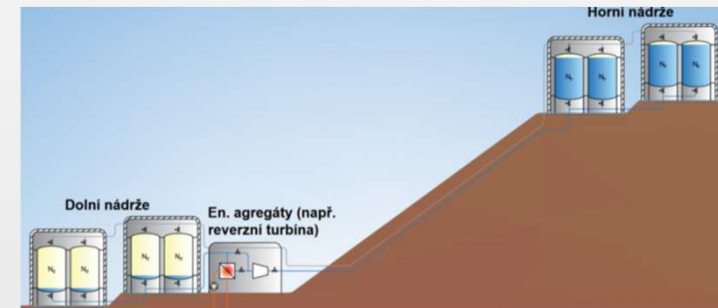
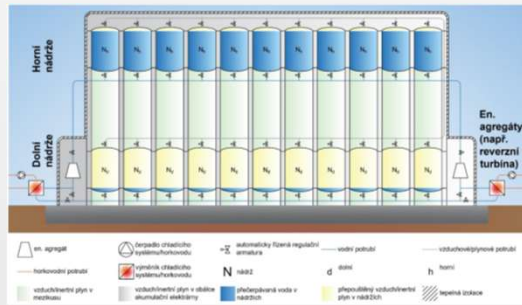
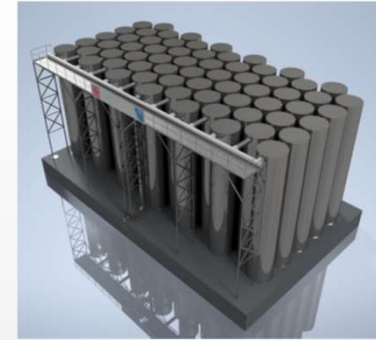


„Hybrid energy storage system using post-mining infrastructure“ (HESS)
No. 101112380 (RFCS-2022)

„A modular pumped-storage power plant“

The upper and lower reservoirs of the pumped-storage power plant are designed as a modular system of storage tanks.

- Above-ground installation.
- As a **floating** power plant. (Here, taking into account the load on the ground, etc.)



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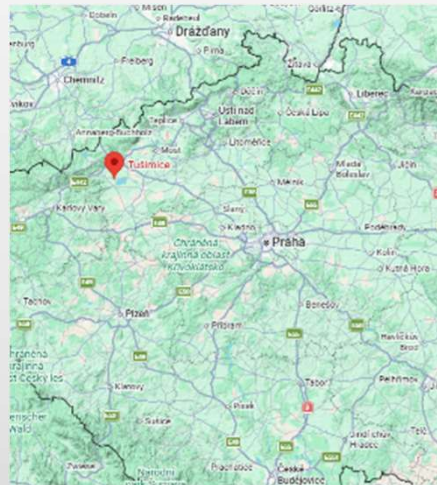


„Hybrid energy storage system using post-mining infrastructure“ (HESS)
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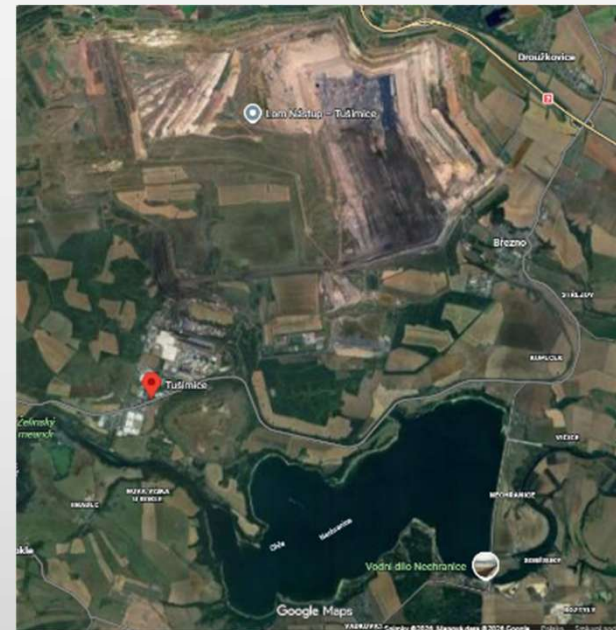
The Tušimice thermal power plant, which burns lignite, will be shut down in the future.
The site is planned for the installation of a modular nuclear power plant.

A pumped-storage hydroelectric plant appears to be a viable option, with the lower reservoir being a flooded open-pit mine.
The proximity of the Nechranice Dam will allow for relatively rapid filling of the reservoir.

It is desirable to find a solution for energy storage...



<https://www.google.com/maps/>



THANK YOU FOR YOUR ATTENTION

Project financed by the European Commission within the framework of the Research Fund for Coal and Steel – RFCS program under the contact no. 101112380 (RFCS-2022) titled „Hybrid Energy Storage System using post-mining infrastructure” (HESS).



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Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

Assessment of the feasibility of HESS implementation in Coal Mine Velenje

Sergej Jamnikar, Coal Mine Velenje (Premogovnik Velenje)

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

HESS for Coal Mine Velenje - Objectives

- Coal Mine Velenje operates in shallower depths, comparing to the Polish and Czech mines.
- HESS Criteria excluded shafts in Coal Mine Velenje (416m, 390m).
- Secondary inspection of mine network data indicated possibility of re-evaluation of case.



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HESS for Coal Mine Velenje - Setting

- **Mine shafts and access roadway network designs included reinforced support system** despite the favourable geologic and geomechanic conditions. The **lifespan** of given objects is estimated to be **long after mine closure**. Due to **vicinity of lakes** and/or existing **surface water reservoirs**, which were used in the past for waste water treatment and are no longer in use, the potential is accessed with additional input data.
- **Water accumulations in Velenje lake or water treatment pools** could be used as surface water reservoirs to supply power generator (turbine) in the shaft. Velenje lake represents near-infinite water source, whereas water treatment pools designs provide approximately 70.000 m³ of potential water storage reservoir.
- According to the HESS project tasks, the assessment of post-mining objects properties, **support quality and overall conditions for energy storage by CO₂ or air compression** show appropriate results that match the project requirements.
- Given the data of shafts properties, the shafts lining and roadway support, the further **analysis of objects suitability for energy storage is justified**.

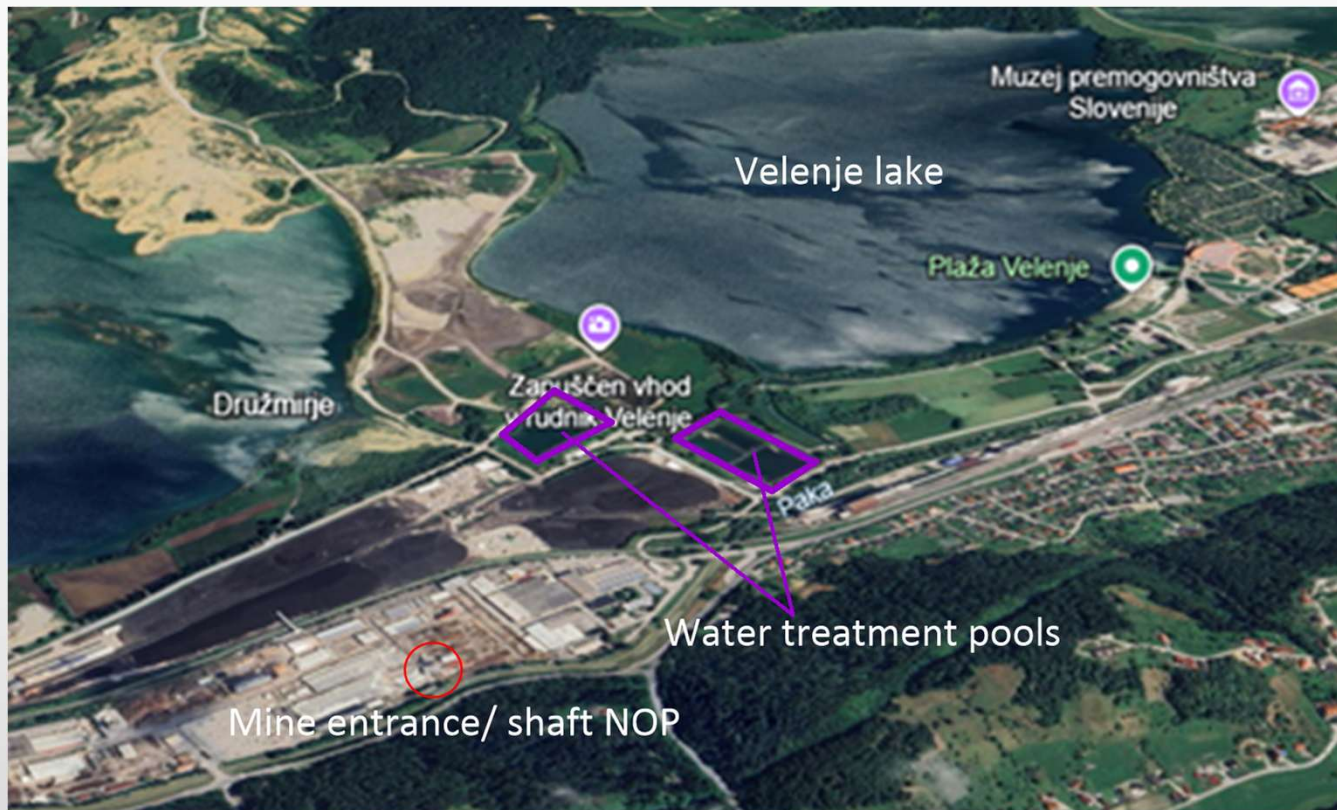


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Coal Mine Velenje - Setting



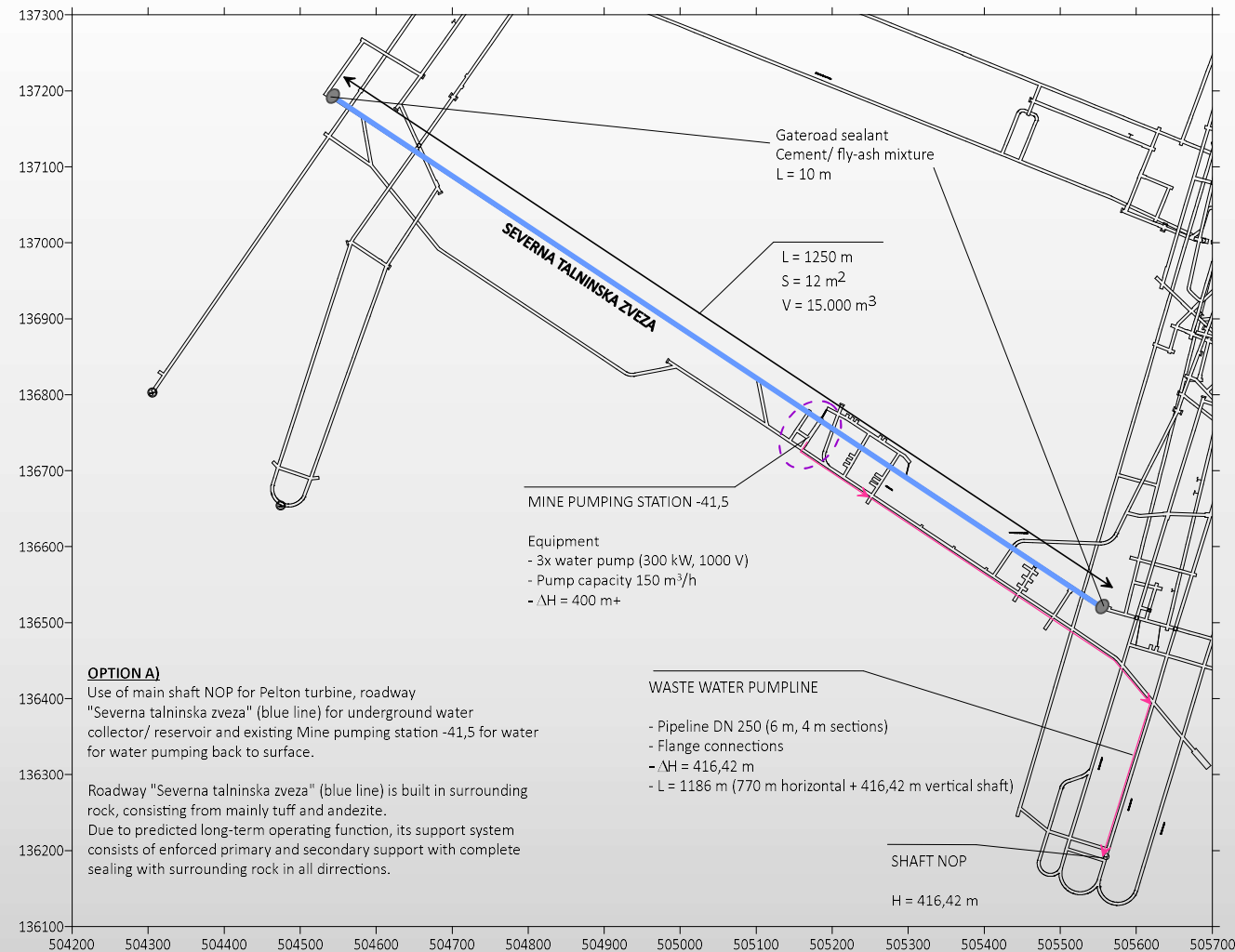
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Coal Mine Velenje - Setting

- Locations of mine objects “Severna talninska zveza” roadway, mine pumping station -41,5, shaft NOP with main parameters.
- The roadway “Severna talninska zveza” is characterised as underground water reservoir with storage capacity of 15.000 m³.



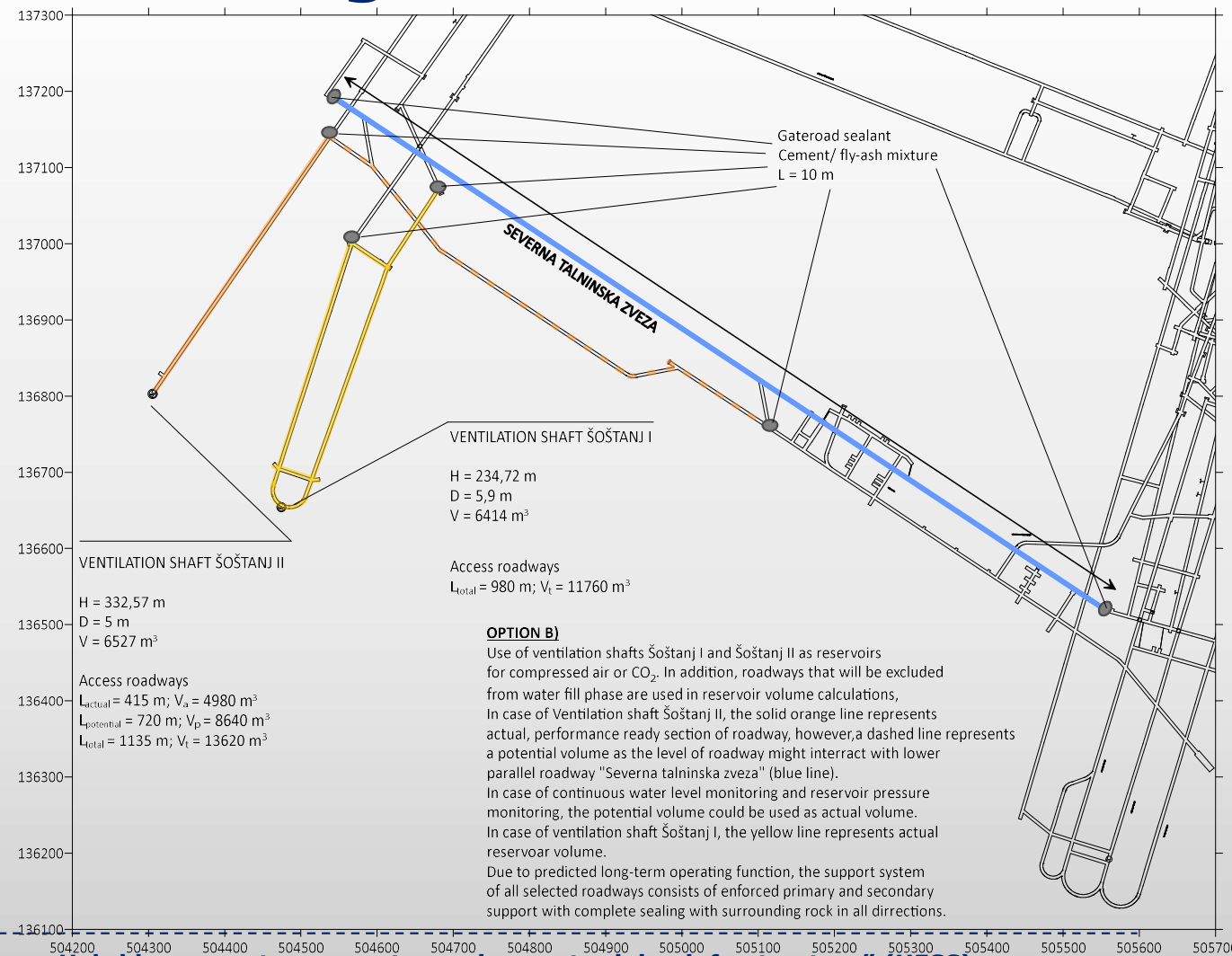
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Coal Mine Velenje - Setting

- Section of mine outline with marked objects for possible compressed air or CO₂ underground storage reservoirs (energy storage).
- Measured objects dimensions and calculated values show theoretical volumes of 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.



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HESS for Coal Mine Velenje - Infrastructure

In case of Coal Mine Velenje, the HESS implementation could include:

- Water accumulations in Velenje lake or water treatment pools could be used as surface water reservoirs to supply power generator (turbine) in the shaft.
- The NOP shaft ($H = 416,42$ m, $d = 7,20$ m) or optional NOP II shaft ($H = 390,70$ m, $d = 6,15$ m), that will remain also for mine closure activities. Both shafts have installed steel arch support, anchoring, mesh and concrete lining ($0,60+$ m)
- Mine pumping station $-41,5$ that will remain due closure works and optionally after the closure works will be completed. The location of pumping station $-41,5$ is in relative vicinity of 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.
- Mine roadway network with total volume of storage capacity of 15.000 m³.
- Shaft Šoštanj I with auxiliary objects in volume capacity 18.174 m³ and shaft Šoštanj II with auxiliary objects in volume capacity from 11.507 m³ to 20.147 m³ for CAES or CCES.



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HESS for Coal Mine Velenje - Calculations

- According to the HESS project tasks, the assessment of post-mining object for energy storage by CO₂ or air compression matches the object properties.
- Given the data of shafts properties, the shafts lining and roadway support, the further analysis of objects suitability for energy storage is justified. 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 give 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.



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Hybrid Energy Storage System Using Post-Mining Infrastructure (HEES)

SWOT Analysis for HESS Project

Sergej Jamnikar, Coal Mine Velenje (Premogovnik Velenje)

FINAL HESS SEMINAR, Zabrze, Poland 22.06.26

SWOT Objectives

- SWOT Analysis includes a collection of various technological, environmental, economical and jurisdictional aspects on HESS project.
- In some cases, the statements may be repositioned under different category.
- It is very welcome to include ideas from different mining communities to compare the ways of understanding alternative use of post-mining infrastructure.



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SWOT

Strengths

- Avoidance of investment costs
- Combining HESS with geothermal potential
- Positive impact for stagnant (post)mining communities and locations

Opportunities

- Environmental impact
- HESS Energy Router and storage capacity
- HESS technology adaptation for metal mines
- Modification of HESS for mine setups with shallower shafts and existing mine network
- Revision of already closed/ in closure mines

Weaknesses

- Limited access to underground objects
- Lack of trained personnel
- Unclear cost preview
- Lack of legislation, Rejection by mining authorities and Technical regulations, requirements and safety measures

Threats

- Unidentified weak underground structures
- Community rejection
- Discrepancy between different mine closure plans and possible HESS
- Surface stability
- Ownership and responsibilities



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Strengths

- **Avoidance of investment costs**

As mine infrastructure already exists, there is no need to invest into construction of objects for HESS System installation. In addition, underground constructions require large investments as they need to be built under strict conditions.

- **Combining HESS with geothermal potential**

It is generally accepted that with depth, the geothermal potential increases. An opportunity is seen in assessment of geothermal potential during the production and storage operations in greater depths, where water of compressed air/CO₂ could be treated as energy medium of carrier.

- **Positive impact for stagnant (post)mining communities and locations**

In many cases, where local communities relied on mining, transition have not succeeded in a way to preserve the community in its growth as mostly young people decided to move to locations with better opportunities. HESS as an advanced system could serve as a guideline for introducing novel, appealing technologies into conservative environment.



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Weaknesses

- **Limited access to underground objects**

Even though HESS system suggests a closed system, a possibility of human access is still present due to monitoring, inspection or remedial works. In cases where access would be needed, additional activities for ventilation, access corridors, material and equipment transport may occur.

- **Lack of trained personnel**

Mining has been decreasing for decades and as a result, the number of trained personnel has been decreasing. The HESS System would require a reasonable great amount of trained personnel and experts from various field with connection to underground operations.

- **Unclear cost preview**

HESS System installation plan may show a certain stage of uncertainty as actions, or the scope of work could not be identified entirely. The risk of limited access during investigations of underground objects (properties, conditions) should be taken into the account by cost planning. Prior the decision of HESS installation, a coherent analysis of all aspects is mandatory with a critical view on all stages of the system. Any unidentified operations (sealing, shaft/ roadway casing repair, etc...) may lead to significant cost increase.

Weaknesses

- **Lack of legislation, Rejection by mining authorities and Technical regulations, requirements and safety measures**

Every country has its own national mining legislation with safety measures. In some cases, rules are strict and they limit any new technical approaches apart from defined in law or technical requirements. Some countries' legislation has additional option, where special technical committee assesses alternative solutions. Mining authorities could also recognize different kinds of potential risks in HESS technology, as new and alternative approaches are introduced. Working in a joint project group with authorities might improve the level of acceptance. Generally, mining regulations do not include pressurized reservoirs in underground structures as they were prepared for active mines. In most cases, revision of regulations would be needed and updated for alternative (post-mining) use of infrastructure.



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Opportunities

- **Environmental impact**

Mining is generally recognized as environmental threatening activity. If the post-mining infrastructure could be used as “green” energy production or/and storage facility, then the acceptance factor is improved. Switching from undesired environmental impact towards means of water driven energy generation with re-cycle possibilities represents major improvement.

- **HESS Energy Router and storage capacity**

In cases of power surpluses (specially of photovoltaic in summer periods), those could be combined with HESS system solutions. More cases of coal transition regions offer the remediated land as a brownfield for power generation and photovoltaic panel installations. These cases could be used as pilot fields for power generation – storage cycle in both, compressed air/CO₂ or thermal storage options.



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Opportunities

- **HESS technology adaptation for metal mines**

Metal mines generally operated in stable rock formations, where stability issues have not been recognized as obstacles. Shafts and other access infrastructure represent objects of great interest as they are in self-carrying rock. The suggestion is that objects in closed mines should be inspected and accessed with an emphasis on possible leakage zones and possibilities of technical solutions to establish HESS system.

In case of successful technology transfer, the HESS system could be recognized as business model for different environments.

- **Modification of HESS for mine setups with shallower shafts and existing mine network**

In cases of shallower mines and consequently shallower shafts, underground mine roadways network should be studied carefully for potential reservoirs. In cases of good stability conditions with good sealing properties in access network, these objects may be used as underground reservoirs.

Revision of already closed/ in closure mines

Many cases of closed mines or mine in the process of closure might still be appropriate to divert the plans into HESS technology installation. In closed and water submerged mines the possibilities are rather limited, however in the support system is still in good condition, is worth considering

Opportunities

- **Revision of already closed/ in closure mines**

Many cases of closed mines or mine in the process of closure might still be appropriate to divert the plans into HESS technology installation. In closed and water submerged mines the possibilities are rather limited, however in the support system is still in good condition, is worth considering pumping water and revisioning the objects.



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Threats

- **Unidentified weak underground structures**

In cases, where mine infrastructure was built in weak geological formation with possible water presence, there could be potential risk of weaker zones, where contact between support and formation is reduced. Given zones represent hazard for structure stability when additional pressure is applied.

To avoid given risk, a time and cost consuming methodology is available, such as various geo-seismic, geo-radar or geo-acoustic methodologies. Pilot or investigative drilling is due to large areas of interest less acceptable, however it may be useful in cases of remedial works (cement injection).

- **Community rejection**

A possible community rejection can show in given situations where people would not accept the HESS System on a base of weak information and introduction. Technologies that are unknown could mobilize the community into rejection behaviour.



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Threats

- **Discrepancy between different mine closure plans and possible HESS**

Mines in process of closure usually focus on stability issues, prevention of sudden subsidence and water level management. In case of HESS, some parameters may interact with water level management if not studied carefully or technically directed separately. In worst cases, rising water columns in geological formations may interrupt shafts or mine access network by water leakage of support stability issues.

- **Surface stability**

In cases, where mining caused surface subsidence, additional and more careful monitoring should be obtained to detect any undesired land/slope movements that might cause structural damage on the shaft casing and in case of compressed CO₂ energy storage, potential CO₂ leakage.

- **Ownership and responsibilities**

Mines that have undergone the full closure process are according to national mining law appointed by the national government. It is not likely to national government to accept the HESS system installation as the priority.



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