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Review article

Geological and mining factors influencing further use of abandoned coal mines – A multi-disciplinary workflow towards sustainable underground storage

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ABSTRACT

The repurposing of abandoned coal mines in Europe presents significant opportunities and challenges for sustainable underground spatial utilization, particularly for energy storage solutions. This study focuses on the geological and mining factors influencing the feasibility of converting these abandoned coal mines into underground storage reservoirs. The study explores various repurposing scenarios, including use as a lower reservoir for an Underground Pumped Storage Hydropower (UPSH) plant, a reservoir for Compressed Air Energy Storage (CAES), heat storage, or geothermal energy.

The initial conditions of coal mines, characterized by heterogeneous rock mass properties and unfavourable permeability, present significant challenges to ensure long-term stability and suitability for reuse after closure. This study uses the Prosper-Haniel hard-coal mine in North Rhine-Westphalia, Germany as a case study for developing a comprehensive 3D geological model that integrates and visualizes stratigraphy, tectonic structures, and mining data. The 3D model can be readily used as a tool for informed decision-making by offering a detailed overview of available geological background data before further exploration.

Based on the literature, scenario opportunities and challenges for UPSH, CAES, heat storage and geothermal production are evaluated from a geological perspective, and key requirements for each application are outlined. A decision tree is proposed to guide the decision-making process, considering the stability of the reservoir, plant efficiency, and compliance with local environmental and safety regulations. The integration of geological and mining data in the Prosper-Haniel subsurface provided a comprehensive assessment of the potential geological conditions of abandoned mines. The paper discusses and identifies key geological and mining datasets essential for conducting feasibility studies for UPSH, CAES, heat storage and geothermal production.

The research underscores the necessity of interdisciplinary collaboration, advanced data analytics, and detailed cost-benefit analyses to fully harness the potential of abandoned coal mines as sustainable energy storage solutions. This study's findings contribute to the broader understanding of the complex interplay between geological conditions and the practical aspects of repurposing abandoned coal mines, aiming to support the transition towards a more resilient and sustainable energy infrastructure.

1. Introduction

There are over 50 coal mining regions in Europe, spread across 17 countries, which have seen a substantial decline in coal usage and subsequent mine closures. In 2018, 90 coal mines were in operation in 11 countries in Europe (Poland, Germany, Bulgaria, Roumania, Spain, Czech Republic, Greece, Slovakia, Hungary, Slovenia, and Italy) [1]. Historically, the use of coal has decreased by 42 % in the last 25 years, leading to the closure of many mines. The current coal phase-out in Europe is affecting several regions including North Germany, Ukraine, Western Poland, and the North of Spain [2]. The increasing need for renewable energy storage, driven by fluctuating supply and demand, currently focuses on research on the potential use of available underground spaces for applications such as UPSH, heat storage, and CAES.

The potential reuse of closed mines can directly address local economic challenges, for example, the cessation of fossil energy production

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and replacement by green energy, existing and potentially upcoming underground stability issues, existing and future land subsidence in former mining districts or environmental challenges including mine water exchange and mine gas migration. The predominant repurposing of mines, particularly metal production mines, encompasses agricultural, recreational (e.g., museum, outdoor recreation), and industrial applications, as well as research sites [3]. Additionally, a notable secondary application involves utilizing underground mines and caverns (mainly granite, slate or salt) as oil or gas storage reservoirs [4,5] or for hydrogen storage and heat storage in the future [6,7]. In addition, three commercial CAES plants are currently operating in Germany, the USA and Canada using salt caverns [8]. Numerous initiatives focus on leveraging warm mine water for heat production or using abandoned mining spaces as thermal energy storage reservoirs, as examples are presented in Table 1. However, coal mines are today in limited use due to their complex geology and heterogeneity in rock mass properties. Coal-related formations often exhibit low rock strength and unfavourable permeability, factors that contribute to underground mine instability and facilitate water circulation within the rock mass.

Various feasibility studies and papers identify the requirements and challenges associated with reusing abandoned mines (69; 40) [16,17]. However, there is a notable gap in the literature regarding the decision-making process involved in selecting the most suitable reuse options. This decision-making process should be based primarily on a preliminary analysis of the available data, without necessitating extensive exploration. This paper provides a workflow that outlines key requirements for energy storage in abandoned mines and provides guidelines for conducting a pre-feasibility study by highlighting key datasets to facilitate informed decision-making. The following questions will be addressed: What are the critical mining and geological requirements for repurposing a coal mine as a reservoir for heat storage, geothermal energy, CAES, and UPSP? Additionally, what existing mine data are essential for conducting a feasibility study on converting the mine into a reservoir for these energy storage systems? By addressing these questions, the paper provides a clear framework for evaluating the suitability of abandoned mines for energy storage projects.

2. Methodology

We present a systematic approach to investigate and assess the feasibility of repurposing abandoned coal mines for energy storage applications, building upon existing geological data and safety protocols established in similar studies and case examples [18,19] (e.g. Bonte, 2011; Cerfontaine, 2018). To test the potential conversion to the real conditions of a coal mine, we use the hard coal mine "Prosper-Haniel" situated in North Rhine-Westphalia (Germany) as a study case that offers a large dataset [20–22]. The workflow applied starts with the collection of comprehensive geological and mining data of the Prosper-Haniel mine. It includes information on rock mass characteristics, mining support systems, hydrogeology, and historical mining activities. Then, data have been extracted from the mining operator modelling software, sorted and formatted to fit the modelling software. These data were used for the development of a detailed 3D geological model incorporating stratigraphic information, tectonic structures, and mining data into the model. In addition, geological parameters influencing the feasibility of repurposing the mine have been listed based on key requirements influencing the stability of the infrastructure, environmental and human safety and productivity of the plant established in the literature, analysis of the founded on the key requirements [17]. Finally, key data sets were identified to enhance the geological and structural understanding of the mine, improving accuracy in site characterization and application feasibility.

Table 1
Examples of mine reuse for thermal production and storage in Europe.

Type of reuse	Projects and reused mines
Warm mine water production	• Mijnwater-project in Heerlen, Netherlands • Abandoned coal mine layout was accessed through directional drilling technology [9] • Zeche Zollverein in Essen, Germany • 28 °C warm coal mine water originating from the mine drainage [9] • Robert Müser colliery in Bochum, Germany • 20 °C warm coal mine water originates from the mine drainage (depth of −570 m [9] • 7 operational coal mine water utilization plants in Saxony (e.g. West Saxon University of Zwickau), Germany • Shallow geothermal reservoirs [9]
Thermal energy storage	• St- Maximim, France • Shallow mine (10 m depth) [10] • Mustikkamaa caverns, Finland • Former oil caverns [11] • Avesta, Sweden • Rock cavern [12] • MineWater 2.0, Netherlands • Coal mine [13] • Sèvres, France • Limestone mine [14] • Mons, Belgium • Chalk mine [15]

3. Data and model building

The 3D geological model, used as a template in this study, is from the coal mine Prosper-Haniel, located in the Ruhr area, Germany (Fig. 1), which closed in 2018. The model integrates various geological and mining data providing a comprehensive overview of rock properties and other subsurface features potentially influencing a reuse of the abandoned mine for UPSP, CAES, heat storage and geothermal production.

3.1. Layout and geology of Prosper Haniel mine

The Prosper-Haniel coal mine covers an area of approx. 165 km^2 and can be accessed by a total of five sinking shafts and one inclined shaft (Table 2), and through 7 levels of roadways (Table 3). The coal mine stopped production in 2018 with the closure of level 6 [23].

Since the closure in 2018, the mine water drainage has been reduced and the underground water level will rise from approximately 1200 mbsl (meters below sea level) at present to 580 mbsl by 2035 [24]. This coal mine has previously been subject to feasibility assessments concerning its further utilization either as the underground reservoir for a UPSH [25,26] or as a repository for heat storage [27]. However, since its closure in 2018, no further research has been carried out to investigate a further reuse.

The oldest coal bed in Prosper-Haniel is from the Namurian C period. There was a peak in the accumulation of organic plant matter in the Westphalian A and B periods, before waning in the Westphalian C [20]. The geological successions encountered in Prosper-Haniel start from the Bochum-Formation (Westfalian A) at the base, an alternating sequence of sandstones and sandy siltstones with subordinate intercalation of mudstones and coal beds. The basal part contains hardly any coal seams. The overlying Essen-Formation is characterized by coal seams intercalated with fine-grained rock and rare sandstones (91). The Horst Formation above contains more sandstones, while the Dorsten Formation at the top comprises claystones, siltstones, and thick fluvial sandstone layers [28]. The sandstones from the Upper Carboniferous in the Prosper-Haniel coal mine are generally fine-grained (92; 93) with a mean porosity of 6 % [29,30] and a permeability of <10–18 m^2 [31].

Upper Cretaceous sedimentary strata unconformably overlay the Carboniferous units (Fig. 2), with a slight northward tilt and increasing thickness [30,32]. In Prosper 1, the Cretaceous/Upper Carboniferous boundary lies around 135 m below sea level (−135 m), dropping to −304.5 m near shaft 10 (Fig. 3).

Tectonic compression during the late Carboniferous deformed the

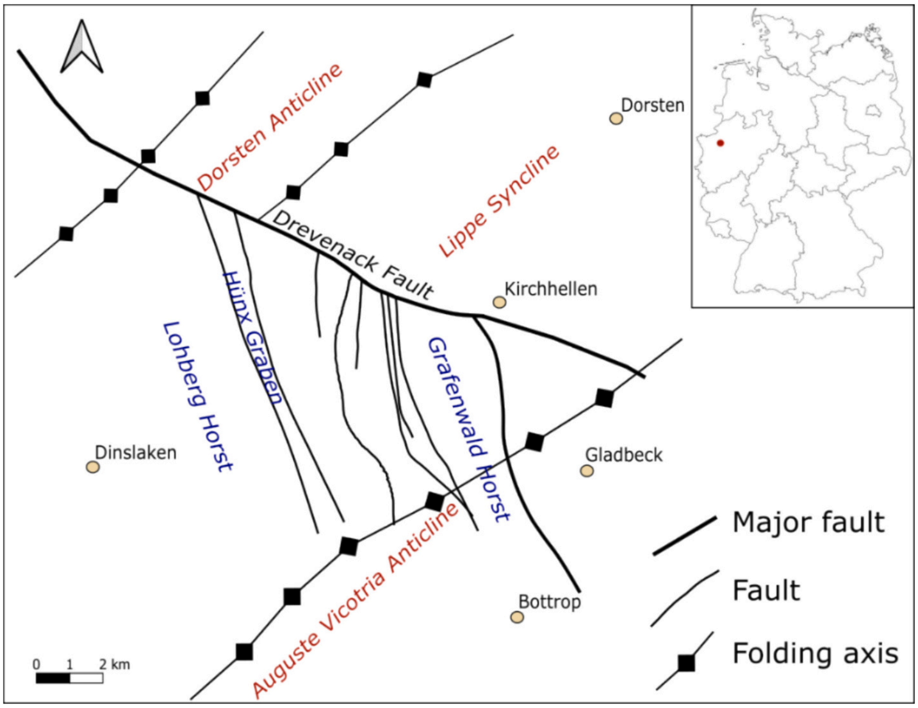


Fig. 1. Simplified structural map of the Prosper-Haniel coal mine area highlighting the structural framework including folds and faults.

Table 2
List of the shafts in the Prosper-Haniel coal mine [21].

Shaft	Depth (mbsl)	Length (m)	Width (m)	Connected tunnels	Approx. volume (m^3)
Haniel 1	530,7	600,1	6	3	16,967
Haniel 2	1007,8	1077,3	6,5	3,5,6	35,748
Prosper 9	960,5	1013,4	7,25	6	41,836
Prosper 10	1246,5	1316	8	4,5,7	66,174
Hünxe	1364	–	8	4,5	–
Förderberg	705,3	–	21,7	5	–

Table 3
List of the level of the roadway in the Prosper-Haniel coal mine (data from [21]. Level 1 is the oldest and level 7 is the youngest level of production.

Levels	Depth (mbls)	Length (km)	Open in 2018
Level 1	–	–	No
Level 2	358 to 349	3	No
Level 3	492 to 484	2,8	No
Level 4	588 to 527	5,5	Partly
Level 5	923 to 723	5,7	Partly
Level 6	932 to 898	30	Yes
Level 7	1211 to 930	?	Partly

pre-existing rock units, resulting in the formation of synclines, anticlines, and thrust faults primarily oriented southwest-northeast (Figs. 1, 2 & 3) [20]. Post-Carboniferous faults intersect these structures, creating horst and graben structures predominantly oriented northwest-southeast. Stress measurements have been previously conducted [31,33,34], and static 3D geomechanical models were developed for prediction of the spatially continuous distribution of undisturbed in situ stress states and for the evaluation of the reactivation risk of major fault zones, with findings indicating that the major horizontal stress is oriented NW-SE.

3.2. Database

The 3D model was constructed from data from RAG Deutsche Steinkohle AG (RAG) and includes:

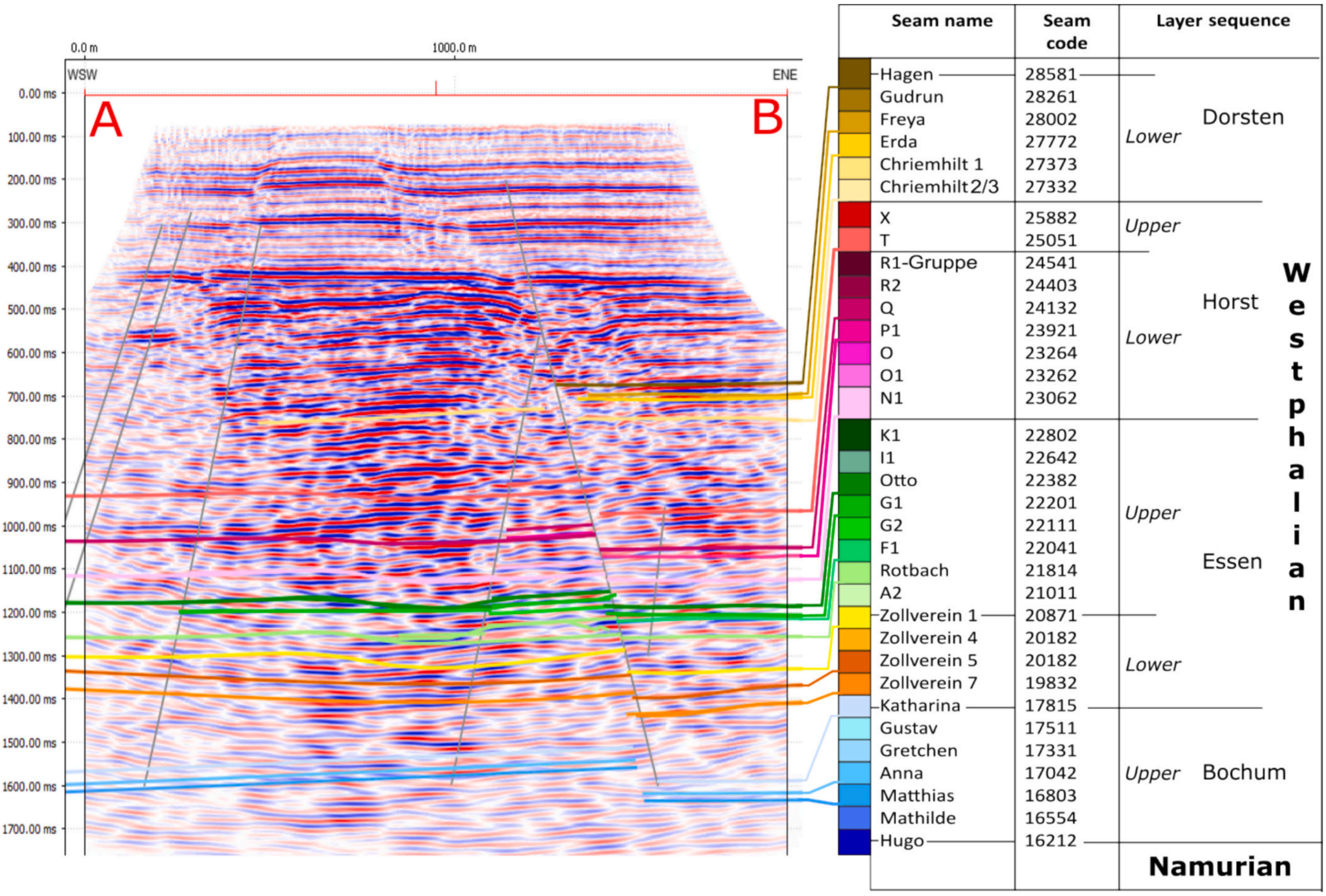
- 173 coal meshes (TIN Format): Meshes of 34 coal seams, spanning from the base of the Upper Bochum Formation (Westphalian A2) to the top of the Lower Dorsten sequence (Westphalian C1).
- 230 Fault Planes (TIN Format): Minor and major fault planes.
- XYZ Point Data: Levels 2, 3, 4, and 6, along with segments of levels 5 and 7, were incorporated to give a detailed overview of the underground mining environment (Table 3, Fig. 3).
- 1113 Exploration Boreholes: Ranging from a few meters to over a kilometre in depth, these data include detailed petrology information.

Additionally, the model integrated a representative 2D seismic-reflection line (from DMT GmbH), collected in 1983 and reprocessed in 2016.

3.3. Model construction

The geological model was developed using Petex 3D MOVE to visualize, analyze, and enhance the available data. To ensure compatibility with the software, the original formats of the coal seams and fault planes were modified. The coal seam plans were grouped, extended, and homogenized according to their stratigraphic codes (seam code) and surrounding tectonic structures (see Fig. 4). From the original 230 fault planes, 38 primary faults were selected to represent the main tectonic structures (see Fig. 3). Additional localized fault planes can be incorporated into the model anytime later for more detailed exploration.

Exploration boreholes, along with their petrological data, were sorted and simplified to highlight four rock groups: sandstone, claystone, coal, and others. The 3D model of this study highlights the types of data available, which are primarily qualitative and derived from exploration along various mine tunnels, boreholes, and seismic-reflection data. While homogenization provides a broad view, it may result in a loss of



Seam name	Seam code	Layer sequence		
Hagen	28581	Lower	Dorsten	Westphalian
Gudrun	28261			
Freya	28002			
Erda	27772			
Chriemhilt 1	27373			
Chriemhilt2/3	27332			
X	25882	Upper	Horst	
T	25051			
R1-Gruppe	24541	Lower		
R2	24403			
Q	24132			
P1	23921			
O	23264			
O1	23262			
N1	23062			
K1	22802	Upper	Essen	
I1	22642			
Otto	22382			
G1	22201			
G2	22111			
F1	22041			
Rotbach	21814			
A2	21011			
Zollverein 1	20871	Lower		
Zollverein 4	20182			
Zollverein 5	20182			
Zollverein 7	19832			
Katharina	17815	Upper	Bochum	
Gustav	17511			
Gretchen	17331			
Anna	17042			
Matthias	16803			
Mathilde	16554			
Hugo	16212			
		Namurian		

Fig. 2. Seismic-reflection profile across the Prosper-Haniel coal mine. List of coal horizons available in Prosper-Haniel with their related stratigraphic sequence of the Bochum- to Dorsten-Formations in the Westphalian A-C stratigraphic interval.

accuracy at a local scale.

Several large geological structures form the boundaries of the 3D structural geological model of the Prosper-Haniel area: the northern boundary is the intersection of the Drevenack strike-slip fault; in the west is the Hünx Graben the model border; the model is bound in the east by the Grafenwald Horst; and finally in the southwest by the edge of the Auguste-Victoria Anticline (Fig. 1). Location data for individual coal seams are available from depths between −350 m and −1600 m.

3.4. Model description

The Prosper-Haniel mine is located in the Lippe syncline. In the model area, the upper Essen horizon ranges in depth from 1355 m in the central part of the syncline to 610 m at the syncline's edge. NNW/SSE faults create a Horst and Graben system where the Grafenwald Graben dips eastward, reaching depths of 1100 to 1170 m for the Essen formation (Figs. 3 & 4).

The top horizon of the Essen layer deepens from 445 m at the syncline's edge to 1100 m in its central region and a maximum depth of 1415 m in the Hünxe graben. The base horizon of the upper Horst layer varies from 480 m to 975 m in the syncline, reaches a depth of 1210 m in the Hünx graben and dips from 510 m to 810 m in the Grafenwald horst. Lastly, the top horizon of the Horst layer is situated at depths ranging from 410 m at the Lippe Syncline edge to 760 m in its central region (Fig. 4).

The development of a 3D geological model significantly enhances the visualization of stratigraphic, and tectonic structures and mining data. The model also serves as a tool for assessing the stability of existing underground tunnels. Additionally, it provides a foundational basis for further exploration, particularly in scenarios involving the extension of the current tunnel network.

4. Mine repurposing – parameters

We propose that key characteristics of coal mines might be similar across different abandoned coal mines, which is potentially important for subsequent repurposing. Depending on the intended reuse, different key criteria may necessitate consideration. However, distinct key parameters serve in all cases as key elements in decision-making processes, including the flooding status of the mine, its accessibility, the stability of underground infrastructure, the permeability of the rock mass, as well as the depth and volume of the mine. It is therefore important to list how those parameters influence the decision to reuse an underground coal mine for UPSH (Table 1), CAES (Table 2), heat storage (Table 3) and geothermal production (Table 4).

Compiling the main criteria allows building a decision tree that provides a clear guideline on which technologies are possible to use for a targeted mine for a specific repurposing (Fig. 5). Several main parameters must be considered:

- Flooding condition: the current water level, plans to raise the water table and the degree of inundation - whether the mine is fully or partially flooded.
- Accessibility of the mine: factors such as ongoing maintenance, worker access, and the functionality of the ventilation system.
- Volume: the volume of the mine and its geometry must also be evaluated, including whether there is sufficient existing volume if the

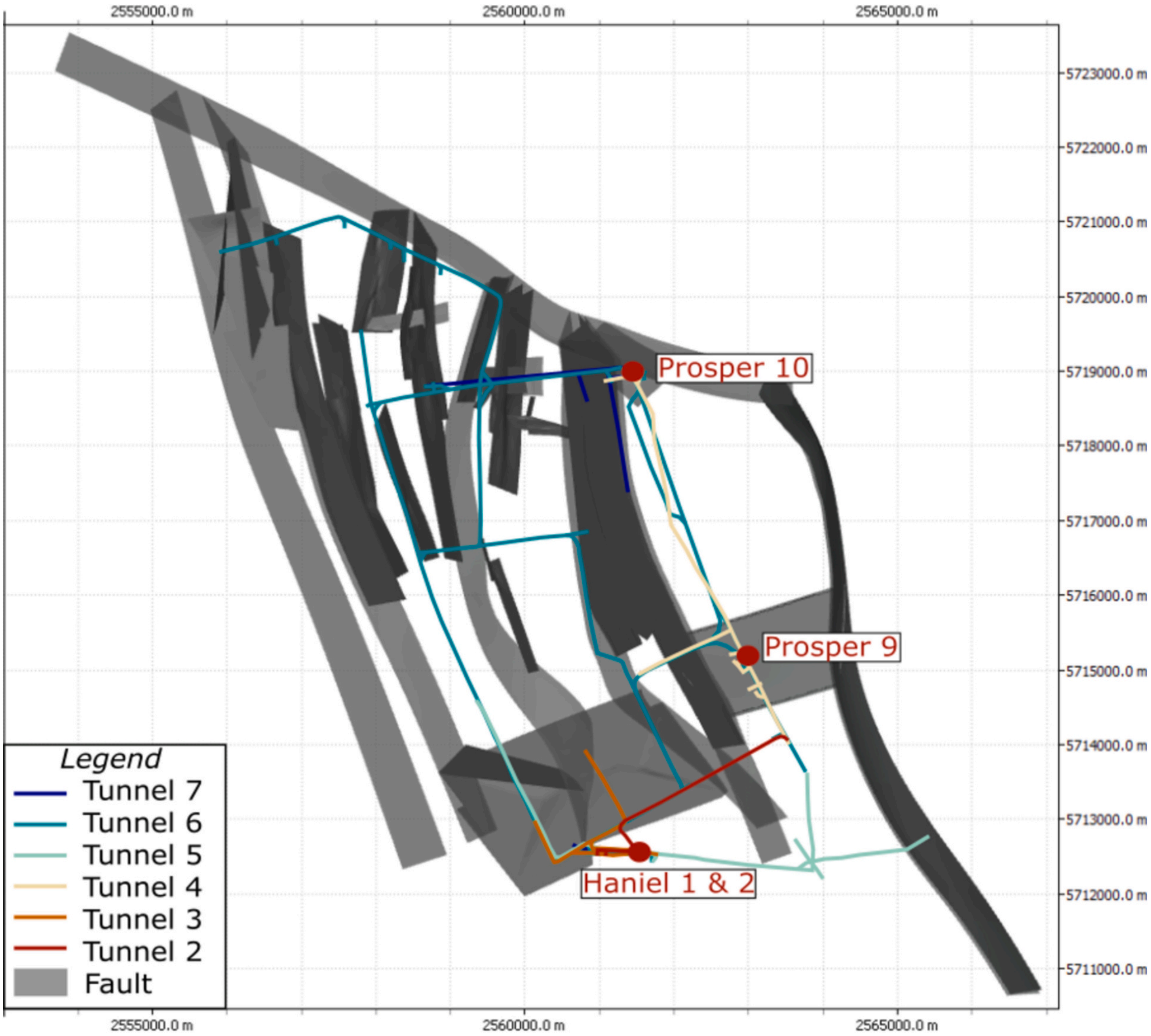


Fig. 3. 3D-view from the top onto majors faults, the tunnel system and the shafts opened in 2018 in Prosper-Haniel coal mine.

measurements of volume and geometry are known and how they can be accurately measured.

- Depth: attention to the most favourable depth for future reuse and assessing temperatures at different depths.
- Permeability: issues such as infiltration/exfiltration can compromise stability or alter the volume of dry tunnels. On the other side, understanding water circulation can facilitate efficient heat flow within the system for thermal production or storage.
- Stability: the stability of the underground infrastructure, particularly the strength of the rock mass, fault stability, and the support system conditions are paramount for ensuring the safety and longevity of any reuse endeavour.

5. Reuses and their requirements

5.1. Underground pumped storage hydropower (UPSH)

The successful installation of UPSH firstly relies on the accessibility and the stability of underground facilities, the low permeability of the surrounding rock mass and a significant available total volume (Table 4). As described in Colas et al., [17] the main challenges are stability issues due to changes in humidity and stress re-distribution impacting the stability of tunnels (through processes like weathering, subsidence, and corrosion), hazards including gas accumulation and water contamination, long-term productivity decrease due to variations in water height, pressure, and hydrodynamic conditions affecting the discharge performance of hydropower systems and risks from water surges and hammer effects that can jeopardize the operation of the entire plant.

UPSH installation in a former mine additionally requires a competent and homogeneous rock and a good understanding of the 3D distribution of the rock mass properties, fault system and potential weathered zones [35]. The rock mass susceptibility to variations in humidity also needs a comprehensive understanding (water sensitivity, slacking, or swelling) [17,21,36].

In addition, a detailed understanding of the hydrogeology of the area is necessary (permeability of the rock mass) and geological discontinuity (interbeds, fractures, faults) is necessary to map hydraulic paths and barriers [17,35,40].

Productivity is the economic factor influencing decision-making in UPSH projects. Critical considerations include determining the potential volume capacity of the underground reservoir and its depth and ensuring accessibility for workers. The choice of the existing mining tunnels will highly depend on their slope orientation towards the shafts [21,45]. The available surface footprint, its morphology, the access to a water source to fill the upper reservoir and the infrastructure at the

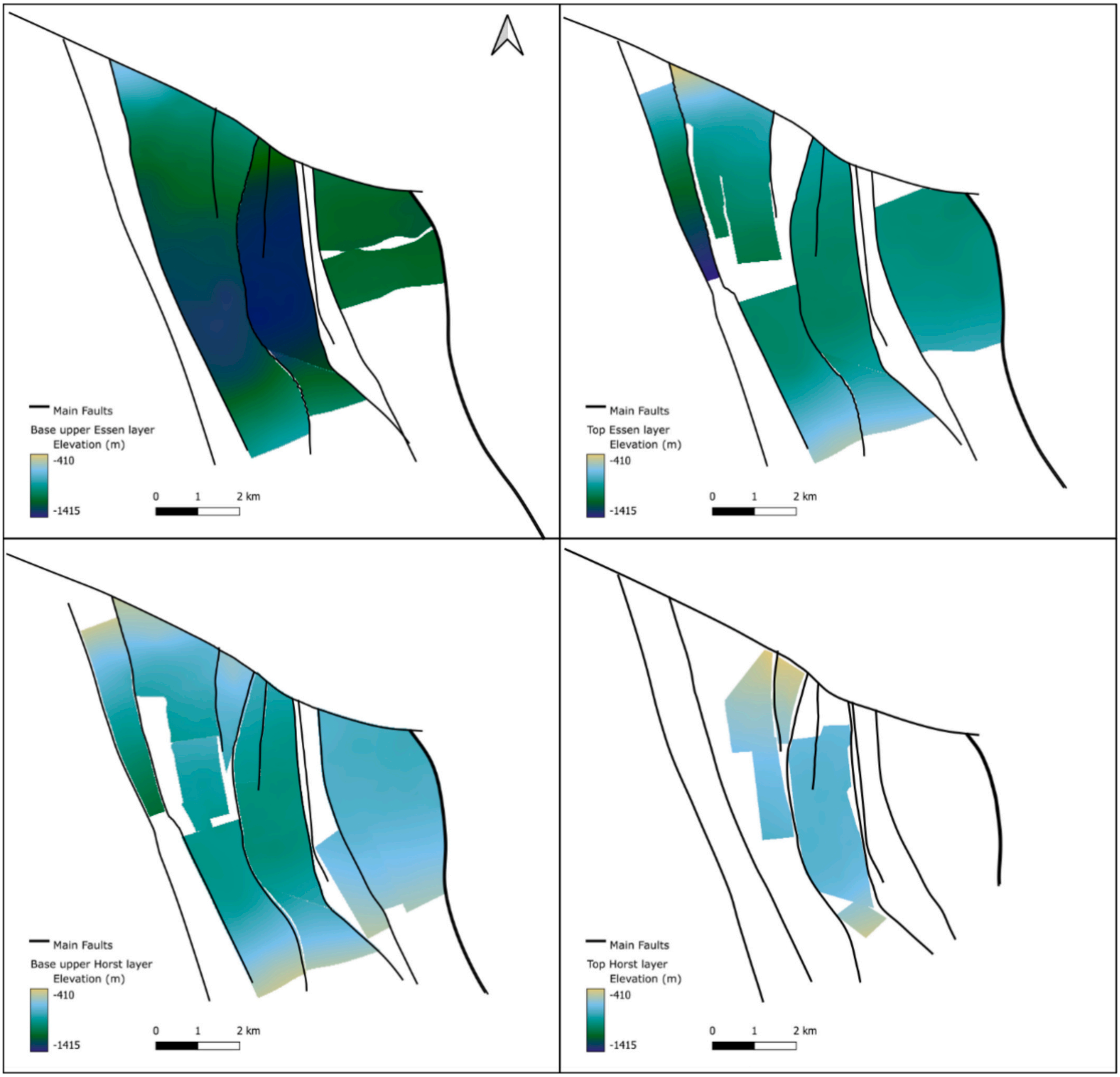


Fig. 4. Depth map of the base of the Upper Essen layer (top left), the top of the Essen layer (top right), the base of the Upper Horst layer (bottom left) and the top of the Horst layer (bottom right).

surface such as energy grid connectivity, proximity to energy producers and consumers or transport access during the construction phase also influence the attractiveness and feasibility of the mine conversion to an energy storage plant [21]. Other aspects need to be considered for the long-term success of the installation, including for example the ventilation system of the underground reservoir [46], the groundwater chemistry and hydrochemical effects [47] or mine gas-related issues [17].

5.2. Compressed air energy storage (CAES)

The primary prerequisites for the successful implementation of a CAES system require having an airtight, dry and stable underground reservoir (Table 5). The main challenges associated with a CAES use are the structural integrity of the mine and of the seal [48], water ingress, air leakage, and hazards including gas accumulation and potential explosions [8]. Because coal depositional environments do not generally fulfil these requirements, the conversion of coal mines or a section of the mine into CAES facilities necessitates lined tunnels to maintain the necessary tightness. Furthermore, the rock mass must reach sufficient uniaxial compressive strength (UCS) with a favourable thermal capacity and be under favourable in-situ stresses to ensure system stability during static pressure applications and cyclical pressure changes within the tunnels [8,49,50]. Additionally, the rock mass should exhibit low thermal conductivity and possess the capability to withstand thermal stresses, given that tunnel temperatures can reach up to 135 °C [50,51]. Moreover, precautions must be taken to prevent compressed air from being in contact with methane, naturally present in coal beds, necessitating avoidance of tunnels excavated within coal beds [16].

The tunnel or shaft's shape and condition can significantly affect the

Table 4
Key parameters for UPSH lower reservoir installation in abandoned mines from the literature focusing on geological and physical properties.

Criteria	References	UPSH criteria
Flooded	[37]	-Should be installed in mines that are not completely flooded
Access	[38]	-Accessibility guarantees access to the information on the mine geometry and stability
Stability	[17]	-Cyclical processes (wetting and drying, fatigue of the rock mass and thermal-induced stresses) can influence the reservoir's stability.
	[37,39]	-The support system's deterioration might pose a major challenge to tunnel stability, especially with water presence.
	[40]	-Fatigue is critical due to fluctuating water levels and increasing overburden.
	[41]	-Stability issues might happen because of the slaking phenomenon, increasing the presence of discontinuities
Permeability	[42,43]	-Groundwater interactions can influence UPSH operation
Depth & volume	[21,44]	-Critical considerations involve assessing the underground reservoir's volume and depth, with tunnel selection heavily influenced by slope orientation towards shafts.

needed concrete lining volume, concrete bulkheads or steel lining potentially offering cost advantages during construction [50]. Shafts, in particular, are favoured, with a focus on specific criteria such as depth, diameter, collar lining type, water inflow rates, and chemistry to consider [56].

5.3. Heat storage

The successful reuse of coal mines as heat storage reservoirs requires a comprehensive understanding of the hydrogeology in the surrounding flooded area to estimate the volume of the reservoir, mass and heat transport within the reservoir and assessing potential water contamination risks [57,58] (Table 6). The main challenges associated with the reuse of an abandoned coal mine into a heat storage reservoir are heat loss and environmental regulations controlling groundwater contamination [9,59]. The different aquifers in the area and hydraulic paths or barriers must be understood. This involves knowledge of permeable rock formations, the presence of clay and its smearing characteristics (clay deformation or displacement along fault zones), and the properties of the aquifers [27].

Heat storage installations must exhibit stability, with a focus on fault stability, the thermal properties of the rock mass, and its ability to maintain stability with changes in pore pressure and moisture exposures. The initial reservoir temperature influences productivity, potentially reducing the storing heat temperature.

Additional considerations must be addressed when heating shallow underground water, including potential environmental risks near drinking water sources [69], changes in water viscosity [70] and in water chemistry.

5.4. Geothermal

Similar to heat storage, the key factors for converting a coal mine

Table 5
Key parameters for CAES in abandoned mines from the literature focusing on geological and physical properties.

Criteria	References	CAES criteria
Flooded	[16]	-Problems of water inflow and reduction of volume by reusing flooded mines
Access		
Stability	[52]	-Very large deformations can happen in weak rocks via (numerical analysis).
	[53,54]	-Focus on fractured zones, from mining, as they increase permeability and air leakage risk.
	[49,50]	-The rock mass must reach sufficient strength and be under favourable in-situ stresses to ensure stability during cyclical pressure changes within the tunnels.
Permeability	[55]	-The rock permeability might need to be reduced essentially to reduce air leakage during the operation.
	[37].	-It is recommended to target a homogeneous, impermeable rock mass.

Table 6
Key parameters for heat storage in abandoned mines from literature focusing on geological and physical properties.

Criteria	References	Heat storage criteria
Flooded & access	[60] [10]	-The coal mine must be flooded -Efficiency of thermal storage in a partially flooded underground cavity
Stability	[18,60,61]	-Temperature difference between the reservoir and injected water may induce thermal stress in the reservoir and fault reactivation
Permeability	[62,63]	-The mine must exhibit favourable, alongside control of water circulation within the rock mass.
	[64–66]	-An understanding of stratigraphy and fault systems is necessary to map potential hydraulic paths or barriers for estimating regional water circulation.
	[67]	-Shaft stability and permeability to prevent heat loss during injection or pumping.
Depth & volume	[68]	-The tunnel geometry must be known to assess the potential volume of the reservoir

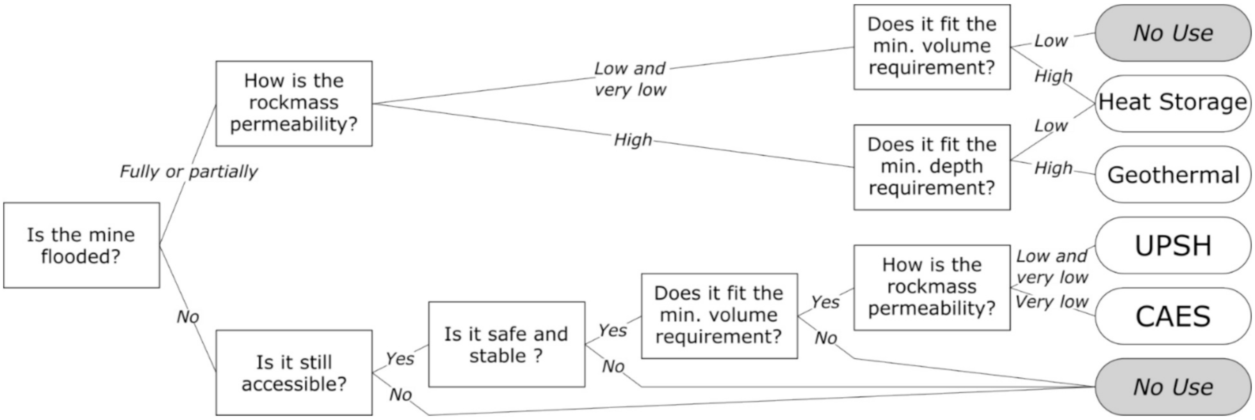


Fig. 5. Simplified decision tree for the main requirements, from the mine properties to its potential future reuse, for heat storage, geothermal, UPSH and CAES technologies.

into a geothermal reservoir are the thermal gradient and the water temperature, the thermal depletion, and the environmental regulations. Therefore, the hydrogeological characteristics of the reservoir constitute the primary criteria (e.g. flooded mine with good permeability and stable fault system) (Table 7).

For the geothermal use of the mine, the main focus is the initial reservoir temperature and the heat transport. The reservoir temperature needs to be high enough to be economically sustainable with a significant warm water recharge to ensure the long-term temperature sustainability of the reservoir by modelling various scenarios of heat extraction over time [71,72].

6. Discussion

The synthesis of various datasets from Prosper-Haniel offers a comprehensive understanding of coal mining characteristics. These datasets encompass typical information sourced from mining operators and regional geological surveys. By compiling and weighing these datasets, we ascertain the essential datasets required for constructing a robust geological model (Table 8). Based on analysing feasibility methodologies (e.g. [9,27,56,58,61,74]) for the conversion of coal mines, the dataset has been qualitatively sorted by its relevance for each application. This process facilitates the identification of critical parameters crucial for assessing the coal mine's geological profile.

6.1. Key data for UPSH

The 3D geological model derived from the example Prosper-Haniel dataset provides information on the 3D spatial distribution of rock mass properties, faults and other geological discontinuities of the study area. In the Prosper-Haniel case, the stratigraphy is built with available mining data (coal seams bed) (Figs. 2 & 4), geological exploration borehole data (lithology) and reconnaissance seismic-reflection data (Fig. 2). The available data are combined in a 3D model that can contain properties such as rock strength (UCS), porosity, permeability, or elasticity.

The understanding of the fault distribution allows for mapping high hydraulic conductivity or unstable areas and available inflow data along the tunnel can be implemented to increase the knowledge of the hydrogeology of the area. In addition, rock slope stability in coal-measure rocks is influenced by coal-coated discontinuities, therefore incorporating in-situ stress field data, the friction angle of the discontinuities, the coefficient of lateral pressure and seismic event catalogues would provide insights into the stress field and the stability of faults.

An important task is to include man-made features in the geological 3D model in order to calculate the available volume in line with the geological requirements (avoiding unstable areas). The geometry (size and shape of the tunnels), their connection to shafts, and the slope orientation can be determined in the model. Specifically for Prosper-Haniel, the level 6 of the mine would present a promising UPSH volume in horse-shoe shape (approx. 680,000 m^3) connected to 3 shafts (Haniel 2, Prosper 9 and 10) and with a favourable slope (1 to 2°) dipping towards the shafts [21,25,74] (Fig. 3). However, the Prosper-Haniel mine was closed in 2018 and the accessibility of the mine shaft is no longer available, which today compromises the possibility to use Prosper-Haniel as a lower reservoir for UPSH.

Table 7
Key parameters for geothermal re-use of abandoned mines from literature focusing on geological and physical properties.

Criteria	References	Geothermal criteria
Flooded & access	[37]	-Require flooded mines, which generally have closed >5 years ago
Stability	[73]	-Fault stability can be perturbed by thermal stress and changes in pore pressure induced by geothermal operations, potentially leading to seismic activity
Permeability		
Depth & volume	[71,72]	-The reservoir temperature needs to be high enough to be economically sustainable with a significant warm water recharge to ensure the long-term temperature stability of the reservoir

6.2. Key data for CAES

Incorporated in the 3D geological model of Prosper-Haniel, the tunnel geometry can be used to measure the potential volume available above the current or planned water table (580 mbsl by 2035). In addition, the exploration boreholes, the stratigraphy and the fault system (Figs. 2, 3 & 4) offer a 3D spatial distribution of the nature of the rock and their properties (e.g. permeability and porosity) that would be used to estimate the permeability of the rock mass along the tunnel. The tightness of the reservoir can be estimated thanks to the permeability and porosity data along known horizons and by having a precise fracture network built along the tunnel taking into account the faults system and discontinuities.

Additionally, similar to UPSH utilization of abandoned mines, the 3D representation of Prosper-Haniel, including stratigraphic layers, fault distributions, exploration boreholes, and geometry of tunnels and shafts, serves as a base model for a prospective thermodynamic analysis aimed at evaluating rock fatigue induced by cyclical injection and release of compressed air. Furthermore, 3D coal seam meshes (Figs. 2 & 4) and exploration boreholes are used to mitigate potential fire hazards by avoiding them. Finally, the potential reservoir capacity is deduced through tunnel geometry, and the concrete lining volume can be estimated. However, similar to UPSH, the feasibility of constructing a CAES in an abandoned mine depends on accessibility, which is no longer viable at Prosper-Haniel, rendering the conversion unfeasible.

6.3. Key data for heat storage & geothermal exploitation

Previous feasibility studies of the reuse of Prosper-Haniel for heat storage focused on groundwater modelling with a 3D numerical groundwater flow and heat transport to ensure a lifetime of 40 to 50 years of seasonal heat storage [19,27,75]. The construction of the 3D geological model of this study as a framework for numerical hydrogeological modelling includes data on the stratigraphy, faults system and tunnel geometry (Figs. 2, 3 & 4).

In order to build the groundwater model, hydro-stratigraphic units (Fig. 6) were implemented. In this case, it was important to incorporate the fault system and deformation zones, to characterise the nature of the fault-gauge fill (e.g. clay content) [27,76–79], to analyze the geometry of the faults (e.g. strike, dip, length, with), and to document their connection to permeable formations. Water discharge measurements from fault zones documented over time example rates, were also taken into account in the model.

A similar model is necessary for geothermal production. However, because the area triggers interest in several geothermal projects and because the water recharge needs to be understood, the model needs to analyze on a regional scale the discontinuity connections. Existing studies of the geothermal potential of the area must be taken into account such as the studies of Balcewicz et al. [80] based on lab and field data. In this study, different outcrops highlighted 1068 discontinuities (open fractures without filling, joints, veins filled with calcite, fractures filled with debris deposits) in deeper formations (upper Devonian and lower carboniferous). The understanding of water circulation through discontinuities on a regional scale is necessary to anticipate potential interferences between the different geothermal plants.

A study in the “Zeche Dannenbaum”, a mine near Prosper-Haniel, has shown the presence of pre-stressed faults and thermal connections between different mining levels that could influence on a larger scale the reactivation of faults [61]. The Prosper-Haniel mine reaches a depth of

Table 8
Importance of having access to this dataset type for the feasibility study for each application.

	Data	UPSH	Heat storage	Geo-thermal	CAES
Stratigraphy	Coal seams horizon	+	–	–	++
	Rock formation horizons	++	+	+	++
	Seismic reflection data	–	+	++	+
	Petrology data in exploration boreholes	++	+	+	++
Tectonic/discontinuities	Fault planes	+	++	++	++
	Discontinuities along wells	–	++	++	++
	Fractured set analysis	+	+	++	++
	DFN model	–	+	+	–
Rock mass properties	Grain size	+	–	–	+
	Permeability	+	++	++	++
	Porosity	–	++	++	++
	Strength	++	+	+	++
	Elasticity	+	+	+	++
	Thermal capacity	–	++	+	++
	Gas content	+	–	–	++
Stress field	In-situ stress data	+	++	++	++
	Seismic event catalogue	–	+	+	+
Mining data	Tunnel geometry: Size	++	+	+	++
	Tunnel geometry: Shape	++	–	–	++
	Tunnel geometry: slope orientation	++	–	–	–
	Shafts geometry (diameter, length)	+	+	+	++
	Support system characteristics	++	–	–	++
	Lining concrete properties (shafts)	+	–	–	++
	Lining concrete properties (tunnels)	++	–	–	++
Hydrogeology	Aquifer locations	+	++	++	+
	Water table level	++	++	++	++
	Reservoir temperature	+	+	++	+
	Groundwater chemistry	++	++	+	–

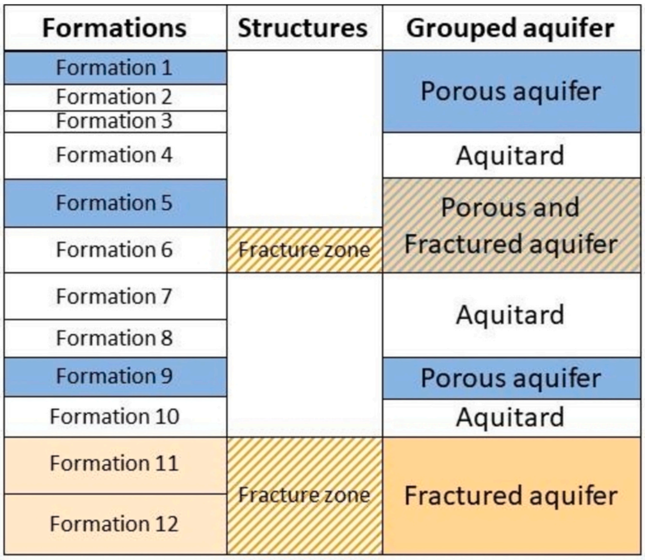


Fig. 6. Schematic representation of formations/rock units, structure and hydrostratigraphic units important for heat storage and geothermal exploitation (modified after [27]).

1013.1 m (Shaft 9) and 1316.5 m (shaft 10) in the Upper and Lower Essen strata. At this depth, a temperature of 45C° is expected [81], while the loading temperature ranges between 90C° to 135C°. Therefore, thermal stress is expected and must be studied. Utilizing the 3D spatial distribution of the fault system, a fault-stability analysis under seasonal heat storage variations taking into account the in-situ stress field [31] must be conducted to assess potential fault reactivation, which may induce seismic events.

For mines like Prosper-Haniel, converting them into heat storage reservoirs or geothermal energy sources represent the most viable options. In this context, the accessibility of the mine or the stability of its roadways is not significant factors in the decision-making process. Instead, feasibility studies should focus on the primary challenges: hydrogeology, thermal performance, and compliance with environmental regulations.

6.4. *Importance of dataset*

We have identified the different key datasets and recommendations critical for repurposing abandoned coal mines as UPSH, CAES, heat storage and geothermal production. It is essential to consider different parameters when evaluating the significance of each dataset for a specific repurposing project. Factors such as data accuracy, reliability, and completeness can additionally impact the credibility of the feasibility study. Therefore, consistency checks, error margin analysis, and a review of the historical reliability of data collection are necessary [82]. Due to extensive exploration by the mining operator, detailed geological data from the study case was available, but changes in rock type (e.g., from claystone to sandstone and coal) increase extrapolation uncertainty and affect rock mass strength calculations. Uncertainty also arises in predicting in-situ stress and fault reactivation risk due to limited stress data. Research on uncertainty estimation (e.g., using information entropy and Bayesian inference) helps reduce these uncertainties, ensuring better decisions for repurposing sites [83]. Additionally, seismic data can help create a stochastic uncertainty model, accounting for data errors, structural complexity, and velocity model errors [84]. Another important pre-requisite is that datasets are up-to-date, especially when concerning environmental regulations or site conditions. Assessing whether the data reflects the project's scale or is adaptable to it will further enhance the quality of the exploration phase. Prioritizing datasets based on these criteria will ensure a comprehensive feasibility study and supports well-informed decision-making. Refined parameters and advanced analytics further improve decision-making, maximizing efficiency and sustainability.

7. Conclusions

We have explored multifaceted considerations surrounding the repurposing of abandoned mines for energy storage, with a focus on

Underground Pumped Storage Power (UPSH), Compressed Air Energy Storage (CAES), heat storage, and geothermal applications. We have identified key parameters for the successful implementation of such technologies, including flooding conditions, accessibility, volume, depth, rock-unit permeability, and the stability of underground infrastructure. Emphasizing the significance of compiling and repurposing relevant geological datasets underscores the necessity of informed decision-making in utilizing abandoned coal mines as energy storage reservoirs or for energy production.

To enhance the use of underground coal mines as energy storage solutions, various efforts are needed in several key areas. Interdisciplinary research should focus on the interaction between surface constraints and underground conditions, incorporating geotechnical, geological, and economic analyses to assess the feasibility and challenges of repurposing abandoned mines. Additionally, research on the optimal positioning and operation of turbomachines is essential, as their placement will significantly impact system efficiency. This involves exploring how to install turbines and compressors in confined spaces, ensuring proper ventilation, and addressing issues related to heat dissipation and maintenance in underground environments.

Enhancing ultimately our understanding of how underground characteristics influence construction costs is paramount for ensuring the economic viability of energy storage projects in abandoned coal mines. This necessitates conducting detailed cost-benefit analyses that account for factors such as site accessibility, geologic complexity, infrastructure requirements, and the long-term maintenance of turbomachines. Maintenance considerations, such as accessibility for repairs, wear and tear due to the underground environment, and the need for specialized equipment to service turbines and compressors, must be factored into the overall financial planning. By accurately assessing these factors, decision-makers can optimize project budgets and secure funding. By addressing these challenges and leveraging emerging technologies, the full potential of abandoned mines as valuable assets in the transition towards a more sustainable and resilient energy infrastructure can be unlocked.

CRediT authorship contribution statement

Elisa Colas: Writing – original draft. **Peter A. Kukla:** Writing – review & editing. **Florian Amann:** Writing – review & editing. **Stefan Back:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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