The reuse of abandoned coal mines: Geological and mining aspects from decision-making to the operation phase.

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Abstract

The research presented in this thesis explores the innovative utilisation of abandoned coal mines for energy storage and production. This addresses the energy storage needs driven by intermittent renewable energy sources and the challenges associated with repurposing former mining sites. First, a focus has been placed on the reuse of the mine as a lower reservoir for Underground pumped Storage Hydropower (UPSH), and has been enlarged to have a larger view of the potential use of the mine as a reservoir for Compressed Air Energy Storage) CAES, heat storage and geothermal use.

The reuse of these mines is an opportunity because the closure of coal mines across Europe has resulted in numerous underground spaces with potential for alternative uses. However, these abandoned mines present significant challenges due to the degradation of mine structures, including weathering, dissolution, hydration, leaching, subsidence, and other post-mining processes. These factors complicate the stability, safety, and feasibility of using these spaces as lower reservoirs in UPSP systems. Moreover, the complex geological conditions, such as variable rock mass properties, fault zones, and hydrogeological characteristics, further exacerbate these challenges, necessitating a thorough and integrated approach to site evaluation and preparation.

The research highlights the critical processes involved in cyclical pumping and discharge within UPSPs, including hydraulic discharge processes, cyclic loading, wetting and drying cycles, and thermal stresses. These processes are essential to ensuring the long-term stability and productivity of the storage reservoirs. Detailed simulations and experimental studies previously conducted are compiled in order to understand the mechanical behaviour of the rock mass under these cyclical conditions, providing insights into potential failure mechanisms and mitigation strategies. Furthermore, the study presents various numerical solutions and empirical methods to mitigate these cyclical processes, enhancing the understanding of the interaction between geological conditions and engineered systems.

From an economic perspective, the feasibility of repurposing abandoned mines is examined, with considerations given to favorable rock mass properties, reduced land acquisition costs, and potential revenue from excavated materials. Cost-benefit analyses are performed to evaluate the economic viability of different repurposing scenarios, considering both initial investment and long-term operational costs. The study also explores potential revenue streams from the sale of by-products such as excavated rock and the provision of ancillary services like grid stabilization. The economic model developed in this thesis incorporates various risk factors and sensitivity analyses to provide robust and realistic assessments of project feasibility.

Then, the thesis details the comprehensive workflow developed to address these challenges, incorporating advanced geological modelling, stability assessments, and economic analyses. A key component of the study is the development of a 3D geological model that visualizes the stratigraphy, tectonic structures, and mining data of the Prosper-Haniel mine. This study example provides a multi-disciplinary approach to understanding the geological, hydrological, and engineering factors critical to transforming abandoned coal mines into effective energy storage reservoirs.

In addition, this model aids in assessing the stability of underground tunnels and serves as a foundational tool for further exploration and decision-making processes. The model integrates data, including historical mining records, geological surveys, and seismic surveys, to provide a detailed and dynamic representation of the subsurface conditions.

The study underscores the importance of interdisciplinary collaboration and advanced data analytics in optimizing the repurposing process, aiming to support the transition towards a more resilient and sustainable energy infrastructure. Collaborative efforts between geologists, engineers, economists, and policymakers are crucial to overcoming the multifaceted challenges associated with repurposing abandoned mines.

In summary, this thesis contributes to the broader understanding of utilizing abandoned coal mines for energy storage, offering a detailed examination of the geological and engineering challenges and presenting practical solutions to enhance the viability of such projects. The findings emphasize the potential of abandoned mines to play a crucial role in the future of sustainable energy storage, promoting the effective reuse of existing underground spaces and supporting the integration of renewable energy sources. The research provides a valuable framework for policymakers, industry stakeholders, and researchers, highlighting the strategic importance of repurposing former industrial sites in the context of global energy transitions and environmental sustainability.

Kurzfassung

Die in dieser Dissertation vorgestellte Forschung untersucht die innovative Nutzung aufgegebener Kohleminen zur Energiespeicherung und -produktion. Dies adressiert den Bedarf an Energiespeicherung, der durch intermittierende erneuerbare Energiequellen entsteht, sowie die Herausforderungen im Zusammenhang mit der Umnutzung ehemaliger Bergbaustätten. Zunächst liegt der Fokus auf der Wiederverwendung der Mine als Unterbecken für Untergrund-Pumpspeicherkraftwerke (UPSK) und wurde erweitert, um das Potenzial der Mine als Speicher für Druckluftenergiespeicherung (CAES), Wärmespeicherung und geothermische Nutzung zu betrachten.

Die Wiederverwendung dieser Minen bietet eine Gelegenheit, da die Schließung von Kohleminen in ganz Europa zahlreiche unterirdische Räume mit Potenzial für alternative Nutzungen hinterlassen hat. Diese verlassenen Minen stellen jedoch erhebliche Herausforderungen dar, da die Bergbaustrukturen durch Verwitterung, Auflösung, Hydratation, Auslaugung, Senkung und andere Nachbergbausprozesse degradiert sind. Diese Faktoren erschweren die Stabilität, Sicherheit und Machbarkeit der Nutzung dieser Räume als Unterbecken in UPSK-Systemen. Zudem verschärfen komplexe geologische Bedingungen, wie variable Gesteinseigenschaften, Störungszonen und hydrogeologische Charakteristika, diese Herausforderungen und erfordern einen gründlichen und integrierten Ansatz zur Standortbewertung und -vorbereitung.

Die Forschung hebt die entscheidenden Prozesse im Zusammenhang mit zyklischem Pumpen und Entladen innerhalb von UPSK-Systemen hervor, einschließlich hydraulischer Entladeprozesse, zyklischer Belastung, Nässe- und Trocknungszyklen sowie thermischen Spannungen. Diese Prozesse sind entscheidend, um die langfristige Stabilität und Produktivität der Speicherbecken zu gewährleisten. Frühere detaillierte Simulationen und experimentelle Studien werden zusammengefasst, um das mechanische Verhalten des Gesteins unter diesen zyklischen Bedingungen zu verstehen und Einblicke in potenzielle Versagensmechanismen und Minderungsstrategien zu geben. Darüber hinaus stellt die Studie verschiedene numerische Lösungen und empirische Methoden vor, um diese zyklischen Prozesse zu mildern und das Verständnis der Wechselwirkungen zwischen geologischen Bedingungen und technischen Systemen zu verbessern.

Aus wirtschaftlicher Perspektive wird die Machbarkeit der Umnutzung aufgegebener Minen untersucht, wobei günstige Gesteinseigenschaften, reduzierte Grundstückskosten und potenzielle Einnahmen aus ausgegrabenem Material berücksichtigt werden. Kosten-Nutzen-Analysen werden durchgeführt, um die wirtschaftliche Tragfähigkeit verschiedener Umnutzungsszenarien zu bewerten, wobei sowohl Anfangsinvestitionen als auch langfristige Betriebskosten berücksichtigt werden. Die Studie untersucht auch potenzielle Einnahmequellen aus dem Verkauf von Nebenprodukten wie ausgegrabenem Gestein und der Bereitstellung von Zusatzdiensten wie Netzstabilisierung. Das in dieser Dissertation entwickelte Wirtschaftsmodell berücksichtigt verschiedene Risikofaktoren und Sensitivitätsanalysen, um robuste und realistische Bewertungen der Projektmachbarkeit zu liefern.

Dann beschreibt die Dissertation den umfassenden Arbeitsablauf, der entwickelt wurde, um diese Herausforderungen zu bewältigen, einschließlich fortschrittlicher geologischer Modellierung, Stabilitätsbewertungen und wirtschaftlicher Analysen. Ein wesentlicher Bestandteil der Studie ist die Entwicklung eines 3D-Geologiemodells, das die Stratigraphie, tektonischen Strukturen und Bergbaudaten der Prosper-Haniel-Mine visualisiert. Dieses Studienbeispiel bietet einen multidisziplinären Ansatz, um die geologischen, hydrologischen und technischen Faktoren zu verstehen, die für die Umwandlung aufgegebener Kohleminen in effektive Energiespeicherreservoirs entscheidend sind.

Darüber hinaus hilft dieses Modell bei der Bewertung der Stabilität unterirdischer Tunnel und dient als grundlegendes Werkzeug für weitere Erkundungen und Entscheidungsprozesse. Das Modell integriert Daten, einschließlich historischer Bergbauberichte, geologischer Untersuchungen und seismischer Erhebungen, um eine detaillierte und dynamische Darstellung der Untergrundbedingungen zu bieten.

Die Studie unterstreicht die Bedeutung interdisziplinärer Zusammenarbeit und fortschrittlicher Datenanalysen zur Optimierung des Umnutzungsprozesses, mit dem Ziel, den Übergang zu einer widerstandsfähigeren und nachhaltigeren Energieinfrastruktur zu unterstützen. Zusammenarbeit zwischen Geologen, Ingenieuren, Ökonomen und Politikern ist entscheidend, um die vielfältigen Herausforderungen im Zusammenhang mit der Umnutzung aufgegebener Minen zu überwinden.

Zusammenfassend trägt diese Dissertation zu einem umfassenderen Verständnis der Nutzung aufgegebener Kohleminen zur Energiespeicherung bei, indem sie eine detaillierte Untersuchung der geologischen und technischen Herausforderungen bietet und praktische Lösungen zur Verbesserung der Machbarkeit solcher Projekte präsentiert. Die Ergebnisse betonen das Potenzial aufgegebener Minen, eine entscheidende Rolle in der Zukunft der nachhaltigen Energiespeicherung zu spielen, fördern die effektive Wiederverwendung vorhandener unterirdischer Räume und unterstützen die Integration erneuerbarer Energiequellen. Die Forschung bietet einen wertvollen Rahmen für politische Entscheidungsträger, Branchenbeteiligte und Forscher und hebt die strategische Bedeutung der Umnutzung ehemaliger Industrieflächen im Kontext globaler Energiewenden und ökologischer Nachhaltigkeit hervor.

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CHAPTER 1
INTRODUCTION

1.1. Context

In the past decades, there has been a consistent decrease in both the production and use of coal within the European Union due to coal mines closure and coal use phasing out for power generation. At the same time, as Europe initiated an energy transition under the framework of an Energy Union, based on clean energy, efficiency, and innovation, various regions face a series of challenges (Kapetaki & Ruiz, 2020). There is today a determined effort to repurpose former energy production regions for future economic development in Europe. Reclaiming mining sites mitigates environmental impacts and boosts local economies through new facilities like recreation centres, museums, and science centres. Although employment should diversify across sectors, the energy sector can still drive regional development (Alves Dias et al., 2018).

As part of the energy transition, renewable energy generation is becoming increasingly important. Since some renewable sources, such as solar and wind, are naturally more variable than fossil fuels, the transformation of the energy system will necessitate more powerful, decentralized energy storage systems (Hunt et al., 2009; Madlener and Specht, 2013). Compared to other technologies, pumped storage power plants are an efficient and technically mature form of energy storage (European Commission, 2012, Cai et al., 2022).

There are currently few technologies that can be used to store energy in corresponding quantities. These include, in particular, pumped storage hydropower (PSH), compressed air energy storage (CAES), hydrogen and methane storage, or heat storage. So far, PSH is the main technology used on an industrial scale covering more than 90% (power installed) (European Commission, 2020).

However, PSH technology has some limitations. The primary disadvantage associated with pumped storage plants is their extensive surface footprint requirements, which necessitate substantial differences in altitude. These locations often consist of areas previously not used by industrial development, leading to resistance from both the population and political entities. In most cases, such utilization is unwelcome due to environmental concerns (Luick, 2013). One alternative possibility for implementing pumped storage facilities close to production and consumption sites is underground constructions such as existing mines or new excavations specifically designed for a pumped storage facility (Turgeon et al., 2011; Matos et al., 2019). The concept of constructing parts of the pumped storage plant below ground level has been studied since the early 20th century and increasingly since the end of the 20th century, in most cases with a positive tendency with a significant increase of interest the last decades in parallel of the increase of intermittent energy production (Fessenden, 1910; Harza, 1962; Pickard, 2012). Therefore, we are investigating the potential of repurposing coal mines for energy storage to sustain energy production in industrial areas. This approach ensures that mining regions continue to play a significant role in the energy transition, contributing to sustainable energy solutions.

1.2. General research aim and objectives

This research was conducted as part of an interdisciplinary project titled "Cyclical Processes related to Underground Pumped Storage Power Plants (UPSP) using Abandoned Mines" (Project number 449163970), a collaboration between RWTH Aachen University and China University of Mining and Technology (CUMT). The project investigates the cyclical processes affecting the stability and operation of underground pumped storage plants (UPSP), integrating expertise from mining surveying, geology, geomechanics, hydrodynamics, and aerodynamics. This thesis contributes to the project by focusing on the geological aspects pertinent to UPSP in abandoned coal mines. Additionally, it explores the potential reuse of abandoned coal mines for other energy storage technologies such as Compressed Air Energy Storage (CAES), heat storage, and geothermal energy, providing a comprehensive overview of various energy transition possibilities for abandoned mines.

The primary objective of this thesis is to examine the geological considerations necessary from the feasibility study phase to the operational phase of underground pumped storage plants. The specific aims are (1) to review the multifaceted challenges and cyclical processes associated with utilizing abandoned mines as lower reservoirs for UPSP, (2) to compile geological and mining requirements for converting an abandoned coal mine into a UPSP, CAES, heat storage, or geothermal energy facility (3) to integrate geological and subsurface data for constructing 3D models of the subsurface, providing a comprehensive assessment of the condition of abandoned mines, (4) to identify key geological and mining datasets essential for conducting feasibility studies for these technologies.

Key questions tackled by this study are:

Q1. What are the geological and mining challenges and cyclical processes associated with employing abandoned mines as lower reservoirs for a UPSP influencing the stability, productivity or safety of the operation?

Q2. What are the numerical solutions existing to comprehend and mitigate cyclical processes in abandoned mines?

Q3. Regarding the different challenges associated with an abandoned coal mine, is the reconversion of the mines as UPSP economically sustainable?

Q4. What are the critical mining and geological requirements for repurposing a coal mine as a reservoir for heat storage, geothermal energy, CAES, and UPSP?

Q5. What existing mine data are essential for conducting a feasibility study on converting the mine into a reservoir for heat storage, geothermal energy, CAES, and UPSP?

1.3. Methods and data

This work is based on the construction of a 3D geological model of the hard coal mine Prosper-Haniel (Germany). The model integrates datasets and contains predictions of the subsurface including lithology and fault zone geometry and underground infrastructures based on RAG data. With the help of a literature review, data evaluation of mine data and the interpretation of 2D seismic lines, a stratigraphic and facies model of the subsurface is constructed.

Our methodology outlines the systematic approach to investigate and assess the feasibility of repurposing abandoned coal mines for sustainable energy storage applications, building upon existing geological data and safety protocols established in similar studies and case examples:

1. Data Collection and Acquisition:

- Collection of comprehensive geological and mining data of the Prosper-Haniel mine. Including information on rock mass characteristics, support systems, hydrogeology, and historical mining activities.
- Compilation of data on safety measures implemented during mine operation and ongoing monitoring practices post-mining, including gas pre-drainage, degassing equipment installation, and environmental monitoring.

2. Geological Modeling:

- Extraction of data from the mining operators' modelling software. Sorting and formatting of the data.
- Development of a detailed 3D geological model of the mine site using available data. Incorporate stratigraphic information, tectonic structures, and mining data into the model.

3. Comprehension of the operation phase and associated cyclical processes:

- Compilation from the literature of insights from cyclical processes to establish criteria for successful mine repurposing.

4. Building the base for feasibility study and risk assessment:

- Evaluation of strategies for mitigating mine gas risks during and after repurposing.
- Analysis of the geological parameters influencing the feasibility of repurposing the mine, such as rock stability, permeability, and hydrogeological conditions.
- Assessing the potential for conversions of the mine such as underground pumped storage power plants (UPSP), compressed-air energy storage (CAES), heat storage, and geothermal application.

5. Recommendations and future research:

- Identifying existing key data to enhance geological and structural understanding of the mine, improving accuracy in site characterization and application feasibility.

1.3.1. Study area

The Prosper-Haniel mine was created in 1974 by merging the Prosper, Franz Haniel and Jacobi mines. Today, the approximately 165 km² minefield is developed by a total of five shafts and one inclined shaft (winding shaft). Prosper 4 (shaft 9) is located in the Grafenwald district of Bottrop, 5.3 km north of the city centre. Prosper 5 (shaft 10) is located in the Holthausen district of Bottrop, approx. 9.2 km north-northwest of the city centre and approx. 2.7 km west of the Kirchhellen settlement (Figure 1.1).

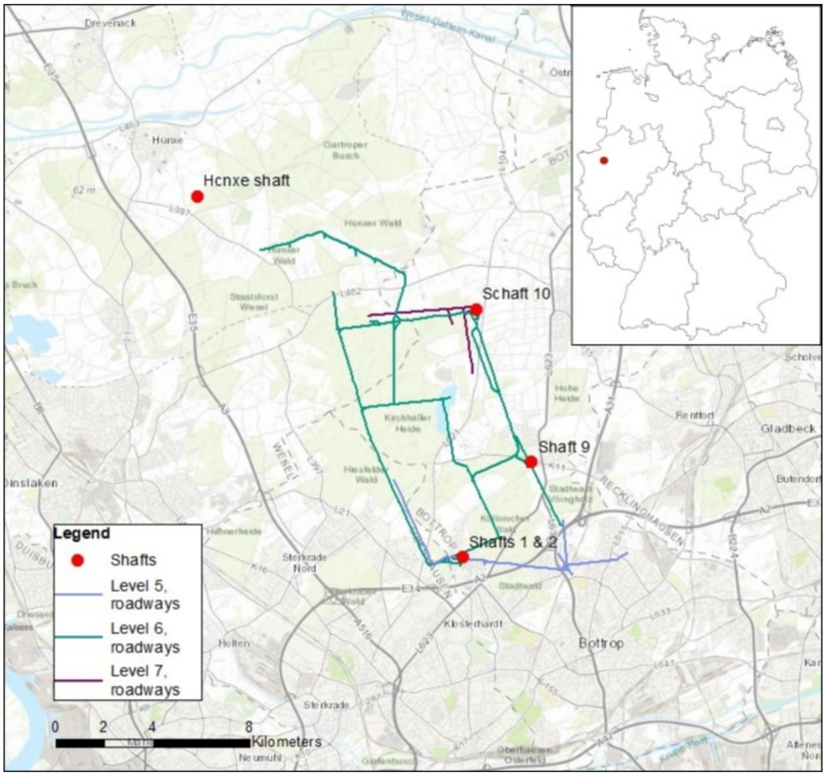

Figure 1.1. Location of the Prosper Haniel mines with the roadways and shafts open before its closure (in 2018).

Prosper Haniel is composed of 7 roadway levels (Table 1.1) accessible with different shafts (Figure 1.1). The roadway tunnel in Prosper-Haniel is horseshoe-shaped and supported by steel arch sets.

Table 1.1. Roadways information.

ROADWAY LEVELS	DEPTH	LENGTH	OPEN IN 2018
LEVEL 1	?	?	no
LEVEL 2	~358m	~3km	no
LEVEL 3	~427m	~2,8kn	no
LEVEL 4	~583km	~5,5km	partly
LEVEL 5	~727m	~5,7km	partly
LEVEL 6	~932-960m	~30kn	yes
LEVEL 7	~1247m	limited	partly

The Prosper Haniel mine stopped operation in 2018 with the sealing of the shafts. With the closure, the pumping of the underground water used to keep the mine unflooded is reduced. Therefore, the underground water level is progressively rising from 1200mbsl (below the level 6) to 580mbsl. In parallel, gas drainage continues to be operated after the closure. RAG AG's closure plan includes vent lines for shafts 2 and 9 to control degassing, accounting for the rising mine water level and end of ventilation. Monitoring follows guidelines, including regular gas content and pressure measurements at former shafts (Imgrund and Orzol, 2020).

1.3.2. Digital data

To construct the geological model of Prosper-Haniel (Table 1.2), we integrated data from RAG AG and the geological survey. The stratigraphy of the model is based on 41 coal seams, derived from 204 meshes, from the base of the upper Bochum sequence (Westphalian A2) to the top of the lower Dorsten sequence (Westphalian C1). The meshes were merged and standardised to ensure continuous seams that align with the tectonic settings of the area.

Based on these coal seams, four stratigraphic horizons were established: the base of the upper Essen Formation, the top of the Essen Formation, the base of the upper Horst Formation, and the top of the Horst Formation. Additionally, the fault set includes over 223 fault planes in the Prosper-Haniel area. These faults were sorted, snapped, and truncated to create a coherent fault system. Of these, 38 primary faults were selected to represent the major fault system of Prosper-Haniel.

The model also incorporated the shafts 1, 2, 9, and 10 (location, depth)(Figure 1.1.) and the geometry (point clouds of the bottom line of the tunnel) of the open roadways as of 2018. This includes levels 6, and parts of levels 7 and 5, encompassing approximately 40 km (Figure 1.1). Additionally, 1063 exploration boreholes with petrological data were integrated. The rock descriptions along these wells were simplified into six categories: sandstone, claystone, fault zone, coal, and others, and no data.

Table 1.2. Coordinate table of the model (Gauss-Kruger zone 2).

BOUNDARIES	COORDINATES
NORTH-WEST	X:2553904m; Y:5723380m
NORTH-EAST	X:2563574m; Y:5719027m
SOUTH-WEST	X:2558490m; Y:5712378m
SOUTH-EAST	X:2565306m; Y:5712713m

1.4. Thesis layout

This thesis consists of an introduction, two main chapters in the form of research papers and a comprehensive summary chapter.

Chapter 1 provides a general introduction and outlines the objectives of the research.

Chapter 2 (entitled "Overview of converting abandoned coal mines to underground pumped storage systems: Focus on the underground reservoir"). This chapter explores the potential of repurposing abandoned mines, particularly coal mines, as lower reservoirs for UPSPs through a multidisciplinary analysis of the different boundary conditions that the mine is facing from the feasibility study to the operational phase. It firstly addresses the challenges posed by the limited knowledge of the mines' current state due to post-mining processes like weathering, leaching, subsidence, and corrosion. Secondly, chapter 2 examines the processes related to cyclical pumping and discharge, including hydraulic discharge, cyclic loading, and thermal stress. The chapter thirdly presents numerical solutions to understand and mitigate these cyclical processes. Finally, chapter 2 assesses the economic feasibility, considering factors such as rock mass properties, land acquisition costs, permanent water pumping, and potential revenue from excavated rock.

Chapter 3 (entitled "Geological and mining factors influencing further use of abandoned coal mines – focus on energy storage and production"). This chapter explores the multifaceted considerations surrounding the repurposing of abandoned mines for energy storage, with a focus on Underground Pumped Storage Power (UPSP), Compressed Air Energy Storage (CAES), heat storage, and geothermal applications. It documents, highlights and discusses characteristics, geological parameters and processes influencing the success of implementing such technologies, including flooding conditions, accessibility, volume, depth, permeability, and the stability of underground infrastructure. In chapter 3 we use as a study example the Prosper-Haniel hard-coal mine in Germany. The construction of the 3D geological model of Prosper Haniel aids in visualizing the compilation of the stratigraphy and tectonic structures and mining data and enhances insights into the essential datasets for assessing the technical feasibility of repurposing coal mines into energy storage reservoirs. This facilitates the estimation and quantification of the extent to which a mine meets the requirements for accommodating specific energy storage technologies.

Chapter 4 comprises a comprehensive summary of the key results and conclusions from the topics covered in Chapters 2 and 3. Additionally, it provides an outlook on future research possibilities.

1.5. Publications

1.5.1. Peer-reviewed papers

Colas, E., Klopries, E. M., Tian, D., Kroll, M., Selzner, M., Bruecker, C., ... & Amann, F. (2023). Overview of converting abandoned coal mines to underground pumped storage systems: Focus on the underground reservoir. Journal of Energy Storage, 73, 109153.

Colas, E., Kukla, PA., Amann, F., & Back., S (in review 06/2024): Geological and mining factors influencing further use of abandoned coal mines – a multi-disciplinary workflow towards sustainable underground storage, Journal of Energy Storage

1.5.2. Conference contributions

Colas, E., Back, S., & Kukla, P. (2024). Future underground spatial utilization–The role of geological criteria in the repurposing process of former coal mines (No. EGU24-8284). Copernicus Meetings.

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CHAPTER 2
OVERVIEW OF CONVERTING ABANDONED COAL MINES TO UNDERGROUND PUMPED STORAGE SYSTEMS: FOCUS ON THE UNDERGROUND RESERVOIR

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2.1. Abstract

The utilization of Underground Pumped Storage Power Systems (UPSP) addresses the growing need for energy storage in the face of increasing intermittent energy sources. Simultaneously, the closure of mining activities has resulted in vast underground spaces potentially becoming available for alternative purposes. This paper explores the potential of repurposing abandoned mines, particularly coal mines, as lower reservoirs for UPSPs.

The challenges associated with employing abandoned mines as lower reservoirs are multifaceted. The foremost challenge stems from limited knowledge about the current state of the mines due to post-mining processes, such as weathering, dissolution, hydration, leaching, swelling, slacking, subsidence, creeping along faults, gas migration, and precipitation, along with corrosion and deterioration of the support elements. This study documents and discusses the various processes related to cyclical pumping and discharge within the context of UPSPs, encompassing hydraulic discharge processes, cyclic loading, dry and wet processes, as well as fatigue and thermal stress. These processes significantly impact the safety, productivity, and stability of the lower reservoir.

To address these challenges, the paper presents different numerical solutions available to comprehend and mitigate cyclical processes in abandoned mines. Finally, it explores the economic feasibility of repurposing mines as lower reservoirs and the conditions required are examined, including favourable rock mass properties, reduced land acquisition costs, the necessity of permanent water pumping, and the potential income from excavated rock as a revenue source in case of new excavations.

This research contributes to the understanding of utilizing abandoned mines for UPSPs, highlighting the challenges associated with the use of coal mines as lower reservoirs and presenting several main processes to prevent safety and productivity issues.

Keywords: Cyclical processes, Reservoir stability, Storage capacity, Mining reservoir, Hydraulic processes

2.2. Introduction

In response to the imperative of reducing carbon emissions, many countries are currently undergoing an energy transition to mitigate their environmental impact. This transition involves a growing reliance on renewable energy sources like solar and wind power, which exhibit great variability. Consequently, to address the challenge of temporal matching between energy supply and demand, various energy storage technologies have emerged as potential solutions (Ausfelder et al., 2017). Among these, pumped-storage hydroelectricity (PSH) stands out as the predominant storage system, accounting for approximately 99% of global storage capacity (Geth et al., 2015). PSH systems have gained recognition for their extended operational lifetimes, high reliability, and remarkable efficiency (Allen et al., 1984).

On the other side, the global closure of underground mines has presented a promising prospect for future underground spatial utilization (Figure 2.1). The growing ecological and economic concerns, including the pressures associated with surface footprint, have heightened the interest in utilizing these underground cavities (Stacey et al., 2010; Kretschmann et al., 2017). The closure of coal mines worldwide has raised significant apprehensions related to local economic development, such as the cessation of energy production (Stacey et al., 2010; Kretschmann et al., 2017), underground stability issues, subsidence (Brücker and Preuße, 2019; Lu et al., 2020), and environmental challenges including mine water exchanges and mine gas migration (Krzemień et al., 2016; Duda and Krzemień, 2018).

Therefore, Underground Pumped Storage Power Plants (UPSP) offer a viable solution that capitalizes on the utilization of abandoned underground spaces and effectively circumvents topographical constraints and limitations associated with surface footprint (Andrews, 2017; Kretschmann et al., 2017). Furthermore, UPSP presents an opportunity for revitalizing energy production following the closure of coal mines (Montero et al., 2013; Kretschmann et al., 2017; Schultz et al., 2023).

The concept of utilizing underground cavities as lower reservoirs was initially introduced in the early 20th century (Fessenden, 1910). However, it was not until 2006 that the first pumped storage system with an underground storage expansion was constructed and operationalized at the Nassfeld plant in Austria (Madlener and Specht, 2020). Subsequently, the Socorridos pumping and water storage facility emerged as a prominent example of a fully realized UPSP, situated in the Madeira Islands, where the lower reservoir was excavated in volcanic rocks (Brito et al., 2010).

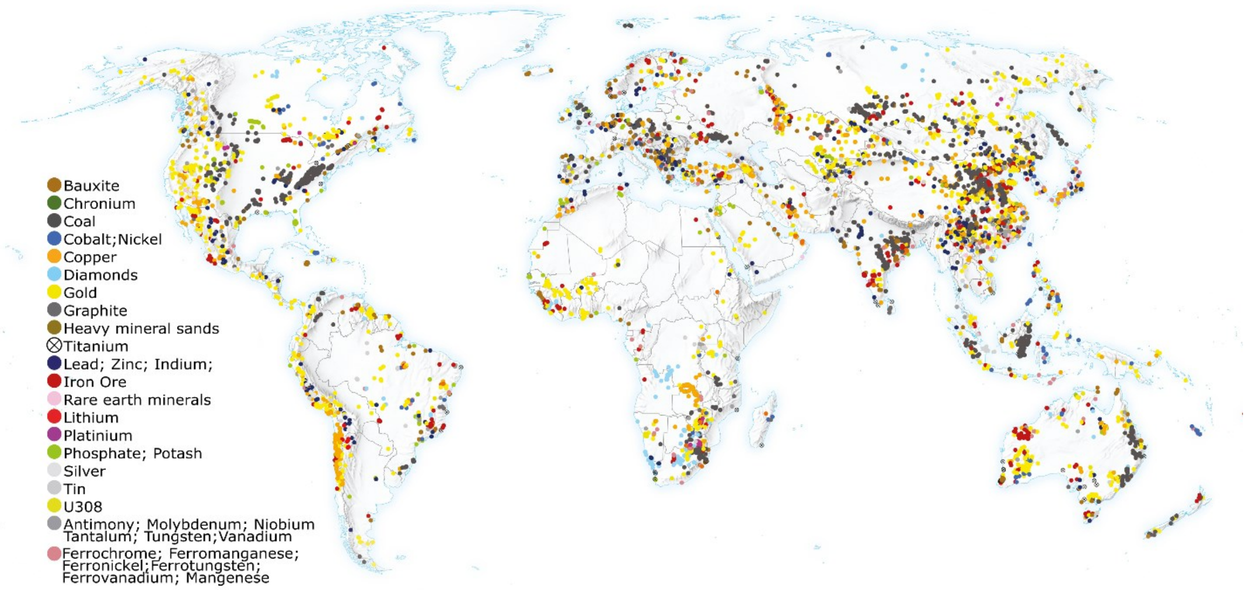
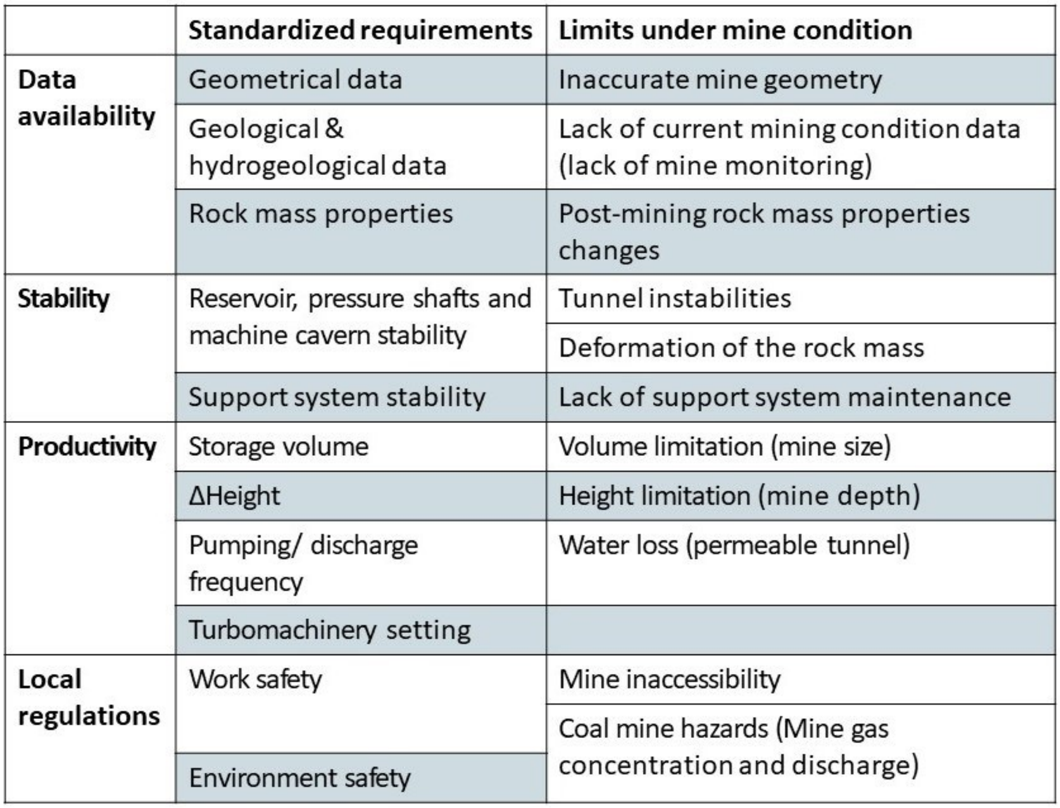


Figure 2.1. Map of the mining capacity zone of coal and metal mines (Non exhaustive) (Global Coal Mine Tracker, 2023).

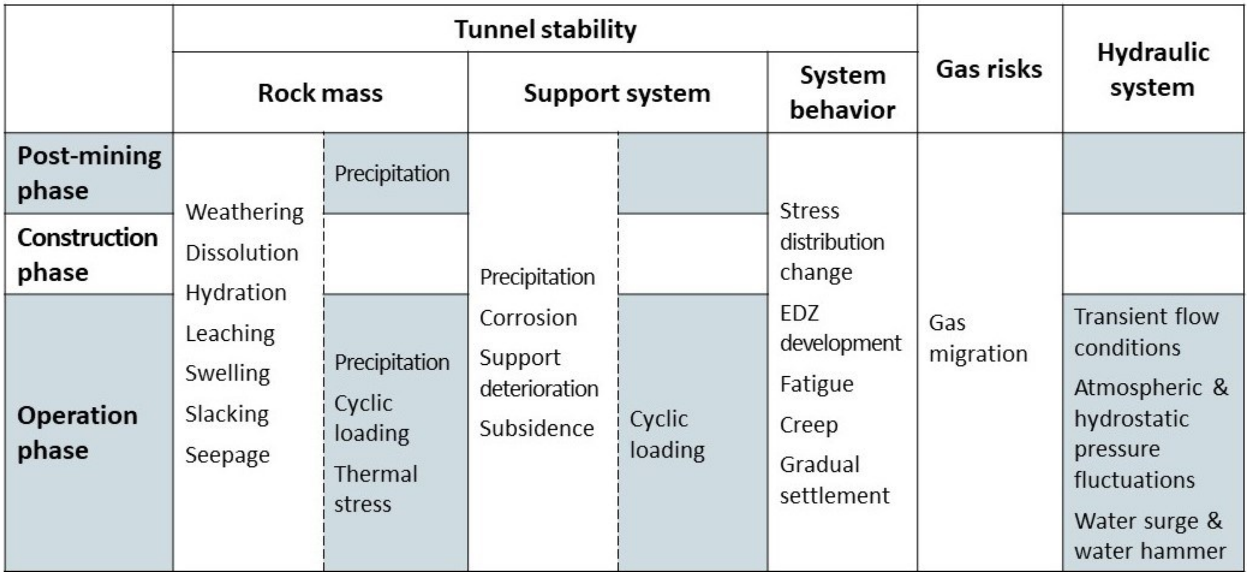
In order to utilize an abandoned coal mine as a lower reservoir for a UPSP, it is crucial to address various challenges that may arise. These challenges revolve around the requirements that need to be addressed throughout the different stages of the feasibility study, including data availability, stability assessments, productivity evaluations, and compliance with local regulations pertaining to work and environmental safety (Figure 2.2). Furthermore, the stability of the underground tunnel is influenced by changing boundary conditions during its lifetime. These boundary conditions vary across different phases, namely the post-mining phase of the abandoned mine and the subsequent construction and operation phase. Tong et al. (2013) highlighted key problems encountered in abandoned mine areas, including issues related to mine gas (such as excessive gas concentration and gas discharge), tunnel instabilities (such as floor instabilities, subsidence, rock burst, pillar failure and roof collapse, including sinkholes and ground fissures caused by mud or water inrush and debris inrush), significant progressive deformation of the surrounding rock (resulting in cavity formation), and support system instabilities (such as lining cracks, spalling, and bending/shearing of steel bars) (Wang et al., 2000; Molinda, 2003; Hoek et al., 2005; Zhang et al., 2017; Sadowski, 2020). Additionally, during the operating phase, new challenges arise concerning cyclic discharge/pumping, hydraulic processes, and tunnel stability, potentially limiting the production of the system (Cerfontaine et al., 2018).



	Standardized requirements	**Limits under mine condition**
Data availability	Geometrical data	Inaccurate mine geometry
	Geological & hydrogeological data	Lack of current mining condition data (lack of mine monitoring)
	Rock mass properties	Post-mining rock mass properties changes
Stability	Reservoir, pressure shafts and machine cavern stability	Tunnel instabilities
		Deformation of the rock mass
	Support system stability	Lack of support system maintenance
Productivity	Storage volume	Volume limitation (mine size)
	ΔHeight	Height limitation (mine depth)
	Pumping/ discharge frequency	Water loss (permeable tunnel)
	Turbomachinery setting	
Local regulations	Work safety	Mine inaccessibility
		Coal mine hazards (Mine gas concentration and discharge)
	Environment safety	

Figure 2.2: Requirements necessary for a UPSP in an abandoned mine and the limits influencing the decision-making.

Therefore, to gain a better understanding of the risks associated with reusing abandoned coal mines for UPSPs, we propose an overview of the various issues and processes involved that may pose challenges to the initial project requirements. The approach aims to simplify this complex problem and provide a description of the main issues, offering a rough overview of the associated risks. The matrix (Figure 2.3) serves as a guideline for the results presented in the following parts and the discussion describing the processes involved at each phase of UPSP life cycle, highlighting their influence on the initial requirements and emphasizing the interactions between rock mass stability, the support system, mine gas risks, and hydraulic management.



	Tunnel stability					Gas risks	Hydraulic system
	Rock mass		Support system		System behavior		
Post-mining phase	Weathering Dissolution Hydration Leaching Swelling Slacking Seepage	Precipitation	Precipitation Corrosion Support deterioration Subsidence		Stress distribution change EDZ development Fatigue Creep Gradual settlement	Gas migration	
Construction phase							
Operation phase		Precipitation Cyclic loading Thermal stress		Cyclic loading			Transient flow conditions Atmospheric & hydrostatic pressure fluctuations Water surge & water hammer

Figure 2.3: Processes matrix influencing the stability, productivity and safety of the lower reservoir in a UPSP based on the different boundary conditions that the lower reservoir will face.

2.3. Pre-operation phase: Insufficient knowledge of the current geometry

2.3.1. Documentation of the geometry

Knowledge of the current situation of an abandoned mine is the first step in a pre-feasibility study of a project. Often the lower reservoir geometry is determined by the geometry of the abandoned mine and cannot be modified to a larger extent without significant monetary costs (Menendez et al., 2020a). Typical structures in abandoned mines that can be used as lower reservoirs are often manifolds of tunnels with sidearms, bifurcations and dead-end passages, forming either a fish-grid network of branches or ring-type roadways (Madlener and Specht, 2020).

The aim of using the original documentation (mine plans) is the estimation of the underground volume accessible for the dimensioning of the UPSP (e.g. storage volume, depth, choice of turbomachinery and plant efficiency). This documentation might be insufficient for the purpose of detailed planning and depend on local regulations (e.g. presence or not of a regulative framework), the date of the operation cease, and the accessibility of the data set. Also, initially, detailed plans may no longer provide a full picture of the mine geometry if structural changes such as settlements or collapses have occurred since the mine was closed (Kratzsch, 1983).

After assessment of these documentations, the initial estimation of the geometry and stability of the mine might be insufficient. A cavity detection survey can be operated with photogrammetry and laser scanning technology to build a reconstruction and visualization of the 3D structure of the cavities (Zlot and Bosse, 2012; van der Merwe and Andersen, 2013; Wang et al., 2014; Gökdemir, 2021; Gurgel and Preusse, 2021).

Due to the expected conditions in an abandoned mine, exploration technology may be mounted on carriers and navigable in these conditions. In non-flooded surroundings, exploration can only be performed if the mine gas situation allows for a safe work environment with regards to personnel and explosion protection. Automated measurements could also be considered as an option. Other methods such as Radar and Sonar remain experimental (Brooker et al., 2005; Pilgram, 2006).

2.3.2. Time-dependent geometrical changes: the rock mass

Stability of the underground space will strongly influence the size of the underground reservoir and the construction cost of the project. Years passed after the excavation, and the condition of the underground space may have changed. The underground space conditions depend on the system behaviour (i.e. rock mass and the support system behaviour). These two elements have faced boundary conditions changes due to, on one side, rock mass deformation, and on the other side support system degradation.

First, the changes in the rock mass properties depend on the initial properties of the excavated rock mass. In a coal mine environment, the most common rocks are coal, sandstone, siltstone, mudstone, shale, carbonates and clay. The nature of these sediments spans in short distance from clay- and mud- rich weak mineral bonds to coarser and stronger sediment rocks. Therefore, the uniaxial compressive rock strength (UCS) can vary from 2MPa for clay shale to 140MPa for sandstone (Molinda and Mark, 1996; Molinda, 2006). Secondly, coal measure rocks are typically heterolithic, with interbedded deposits of sands and muds and reflecting rapidly changing flow regimes. They are subsequently subject to erosion, differential compaction associated with their burial history and the formation of faults and joints that formed during tectonic processes (Molinda, 2006). These discontinuities modify the rock properties, cohesion, and strength in all directions and increase the difficulty of assessing the rock mass strength and behaviour around the mine (Hoek, 1983; Wilson, 1983; Molinda, 2003; Hoek et al., 2005; Ozarslan et al., 2013; Matos et al., 2019; Pikl et al., 2019a).

2.3.2.1. Humidity changes

Rocks in coal mines can be sensitive to high humidity and humidity changes in the mine and might lead to rock mass degradation processes such as weathering, dissolution, hydration, leaching and precipitation (Figure 3) may alter geomechanical properties of the host rock (Wang et al., 2000; Castellanza et al., 2018; Mánica et al., 2020; Wang et al., 2021). These processes can be accelerated with water circulation (e.g. seepage) along fractures (Zhang et al., 2021a). Soluble rocks such as evaporites and carbonate rocks are particularly sensitive to long-term water circulation. Wetting of the rock around the cavities after long-term exposure to atmospheric conditions (including the ventilation) can cause a decreasing strength and stiffness (Broch, 1979; Hawkins and McConnel, 1992; Hawkins et al., 1994; Vasarhelyi, 2003; Vasarhelyi, 2005; Török and Vásárhelyi, 2010). For instance, clay (Wild et al., 2015), siltstone and sandstone (Vasarhelyi, 2003; Erguler and Ulusay, 2009; Junker, 2009) show a strong relationship between total suction and strength/stiffness. Dyke and Dobereiner (1991) demonstrated a decrease of 25-30% of the UCS for sandstones with increasing moisture content. On the other side, carbonate rocks are less sensitive to strength degradation with increasing water content (Figure 2.4).

Rock mass degradation's processes lead also to changes in hydraulic properties of the rock such as permeability, hydraulic conductivity and porosity. They can enhance seepage (e.g. exfiltration, infiltration) with the surrounding rock (Coates, 1983; Bodeux et al., 2016; Bodeux et al., 2017; Cerfontaine and Collin, 2018).

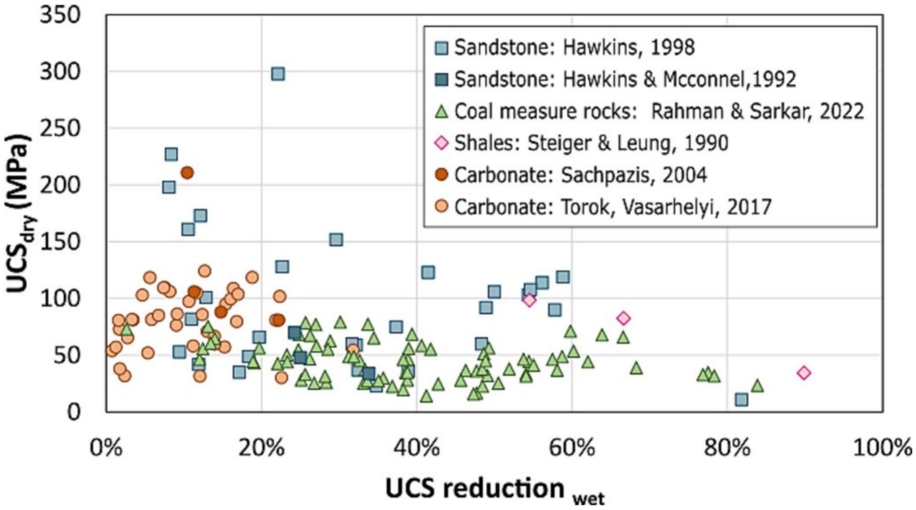


Figure 2.4. Percentage of UCS loss for wet rock samples compared to dry samples (Steiger and Leung, 1990; Hawkins and McConnel, 1992; Hawkins, 1998; Sachpazis, 2004; Török and Vásárhelyi, 2010; Rahman and Sarkar, 2022).

In addition, The phenomenon of swelling (Figure 2.3) is a time-dependent process commonly observed in soft-rock masses surrounding coal mine tunnels, including mudstone, clay rock, shale, and coal measure strata, as defined by the Society for Rock Mechanics (ISRM) (Bonini et al., 2009; Tang and Tang, 2012; Junying et al., 2019). Under humid conditions, the excavation and unloading of the tunnel can trigger mechanisms such as stressed-dilatation and physicochemical swelling, leading to stress redistribution and deterioration of the rock mass (Kie, 1983; Steiner, 1993; Junying et al., 2019).

Furthermore, rock formations containing clay fractions can undergo a slaking process (Figure 2.3) when subjected to alternating wetting and drying cycles resulting from variations in humidity. Slaking occurs as a result of differential pore pressure between air-filled and water-filled voids, leading to the breakdown of the rock structure (Bell, 2007; PINEDA et al., 2014; Wild et al., 2017). It is important to note that slaking can only take place if the rock was previously dry and the severity of slaking increases with the presence of discontinuities, such as fractures (Phien-Wej et al., 1995). This process is well-documented in the context of coal mines and has been associated with potential roof instabilities (Cummings, 1987; Sasaoka et al., 2016).

2.3.3. Time-dependent geometrical changes: the support system

Support structures in underground tunnels were initially designed to withstand the stresses and strains associated with mining activities. However, their suitability for long-term use and their current condition can often be uncertain due to a lack of data or the gradual degradation of the support system over time due to a lack of maintenance (Figure 2.3). The deterioration of the support system's original condition over the long term poses a significant challenge to the overall stability of the tunnel, particularly in the presence of water (Tong et al., 2013; Menendez et al., 2019b; Zhang et al., 2021a).

Corrosion phenomena (Figure 2.3) pose a significant risk to the stability of tunnels, as they can lead to premature failure of crucial support elements such as steel roof supports, wire ropes, and rock bolts. Premature rock bolt failures in coal mines are often attributed to stress corrosion cracking, while environmental cracking, including hydrogen cracking mechanisms, and corrosion fatigue can also contribute to support failures (Hebblewhite et al., 2004; Bylapudi et al., 2015; Craig, 2018; Guo et al., 2019; Bylapudi et al., 2020). Corrosion in underground coal mines can be categorized into two types: atmospheric corrosion, resulting from humidity and pollutants in the ventilation, and aqueous corrosion, caused by groundwater present in the mine (Roy et al., 2016; Aritan and Can, 2019; Bylapudi et al., 2020).

Multiple parameters influence corrosion processes. The composition and corrosivity of mine water, which is primarily responsible for steel corrosion in coal mines, can vary (Roy et al., 2016; Chen et al., 2018; Craig, 2018; Aritan and Can, 2019). The acidity of mine water can be attributed to pyrite oxidation, the presence of peaty acids, and bacteria (Craig, 2018). Other factors such as high humidity (>90%), temperature (around 30°C), airborne dust, in-situ stress, and the coal itself significantly influence corrosion (Rawat, 1976; Gardiner and Melchers, 2002; Gardiner and Melchers, 2003; Craig, 2018). The most common forms of corrosion encountered are uniform corrosion, pitting corrosion (which poses challenges in detection and can lead to sudden failure of ground support elements), and stress corrosion (particularly relevant to pre-stressed supports or those subjected to loading and straining after installation) (Roy et al., 2016).

Corrosive groundwater containing salts, sulfuric acid root ions, chloride ions, and bicarbonate ions can cause concrete damage and cracks due to its interaction with the tunnel structure. This erosion can occur on a micro to macro scale, leading to spalling and flaking of shafts and tunnels (Ghafari, 2013; Liu et al., 2015; Zhou et al., 2019b).

Finally, mineral precipitation (Figure 2.3) resulting from the dissolution of surrounding rock in water can lead to the deposition of minerals on the support system, potentially compromising its stability (Pujades et al., 2019).

As previously discussed, reinforcing or renewing the support system is crucial for ensuring tunnel stability. However, estimating the support requirements presents challenges in identifying and predicting the hydro-mechanical properties, dimensions of the tunnel (e.g., shape, size), ventilation-associated pumping/discharge, and hydrogeological conditions of the abandoned mine (Hawkins et al., 1994; Wojtkowiak and Didier, 1999; Bianchi Fasani et al., 2011; Tong and Wu, 2013).

2.3.4. Time-dependent geometrical changes: System behaviour

Because of the deterioration of rock mass properties, on the one hand, and the weakening of the support system, on the other hand, the tunnel might face failures and instabilities (Figure 2.5).

The progressive weakening of the rock's micro- and/or macrostructure, the loss of strength and stiffness, enhancing creep (Singh, 1975; Kovari et al., 1983; Pellet et al., 2000) can lead to a reduction in fracture strength (Gnirk and Fossum, 1981; Eberhardt et al., 1998). Moreover, failure is enhanced by the presence of rock discontinuities (e.g. faults) and depends on their orientation and dip (Hammett and Hoek, 1981; Hoek, 1983; Junying et al., 2019; Zhou et al., 2019c; Zhang et al., 2021b), the distance to the cavity (Ma et al., 2020), the thickness (Zhang et al., 2016), the filling of the discontinuities (Zheng and Qi, 2016), and the support system condition (e.g. corrosion of the concrete, rock bolt and anchor bolt steels) (Craig, 2018; Zhou et al., 2019a). The initiative and growth of those cracks, particularly influenced by dynamic disturbances resulting from stress redistribution (see section 2.6.2), leads to the formation or extension of an excavation damage zone (EDZ) (Sato et al., 2000; Chen et al., 2015) if the rock mass strength is exceeded (Martino and Chandler, 2004). The EDZ is defined by the change of rock properties (i.e. deterioration of the rock mass) and extensive studies have been conducted to understand and predict the extent of excavation damage zone (Falls and Young, 1998; Bäckblom and Martin, 1999; Diederichs et al., 2004; Martino and Chandler, 2004; Read, 2004; Cai and Kaiser, 2005; Lei et al., 2017; Zhao et al., 2022). The development of an EDZ is a complex time-dependent process that involves several mechanisms such as stress redistribution, increased permeability, thermal effects, chemical effects, mechanical effects (Sato et al., 2000; Martino and Chandler, 2004; Kwon and Cho, 2008).

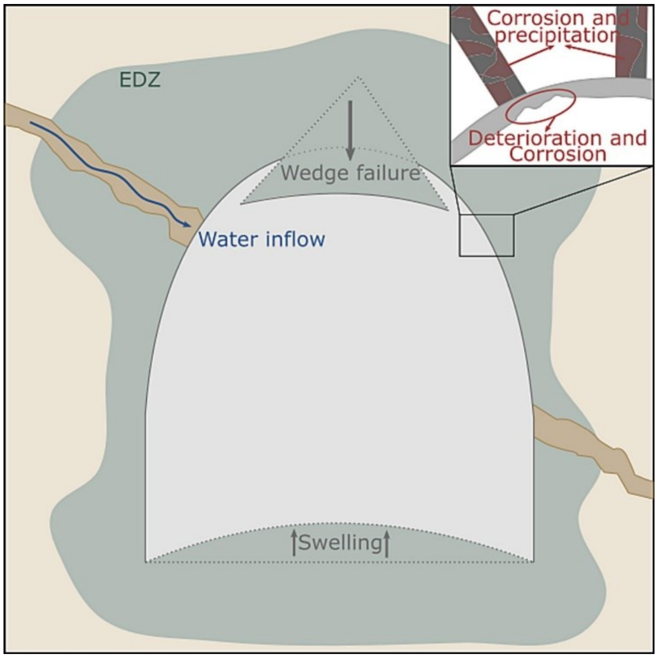


Figure 2.5. System behavior instabilities and support system deterioration.

Reinforcing, creating systems for failure detection or renewing the support system is crucial for maintaining tunnel stability, but challenges arise in predicting requirements based on hydro-mechanical properties, tunnel dimensions, ventilation management, and hydrogeological conditions. Proper support system management and monitoring are vital.

2.4. Mine gas

Harmful gases may potentially be present in a coal mine that can be combustible, explosive, asphyxiating and/or toxic (Doyle, 2001) such as methane, carbon dioxide, hydrogen sulfide or radon (MVEL, 2004). Methane and carbon dioxide being the predominant mine gas contents in coal mining (MVEL, 2004; Thakur, 2006).

2.4.1. Migration sources

These gases are adsorbed to the internal surface of the coal but also in the pore space of the coal and the surrounding rock (Thakur, 2006) (Figure 2.6). Gas release mainly occurs during the mining process due to the unloading of the rock mass, the opening of existing fractures and the formation of new gas migration flow paths (Ulery, 2006)(Figure 2.3). Gas sources may be site-specific and often associated with gas reservoirs in surrounding strata due to gas generation from organic matter or migration, organic-rich structures with originally low permeability (Kissell, 2006). The amount of released gas is highly dependent on the geological characteristics of the coal (e.g.permeability and inner structure) (Imgrund and Thomas, 2013), the permeability of the surrounding rock, the presence of geological features (e.g. sandstone paleochannels or clay veins) (Darton, 1915; Moss, 1927; Payman and Statham, 1930; Price and Headlee, 1943; McCulloch et al., 1975; Ulery and Molinda, 1984), the stress state (that has changed due to the mining activity), tectonic structures (Diamond, 1982; Thielemann et al., 2001) and fracturing processes during the mining process (Kissell, 2006; Imgrund and Thomas, 2013). This migration occurs through several transport mechanisms (e.g. pressure gradient, diffusion through concentration gradient and capillary suction and adsorption of liquids) enabled gas and liquid inflow. Moreover, an increase in permeability will occur over time due to the long-term degradation of host rock and concrete properties (Klausen et al., 2017).

Degassing of the remaining coal continues after the mining operation has ceased. Pumping operations usually decrease or cease completely, depending on the targeted final water level, resulting in a rise of the water table. The rising water can displace released mine gas from flooded sections towards higher levels of the mine, mainly through cavities, natural and anthropogenic (Rosner and Schetelig, 2011).

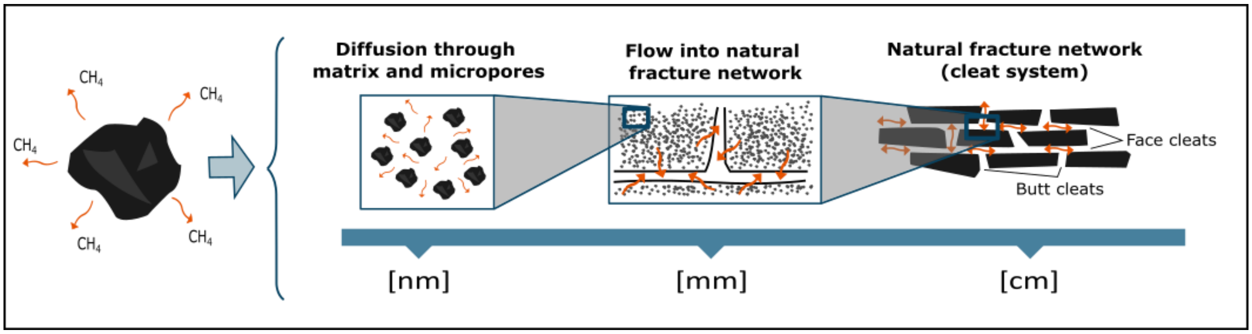


Figure 2.6. Presence and distribution of methane within a coal deposit: Desorption of methane from the coal surface and subsequent diffusion in the coal matrix and flow into natural fracture network (based on: (MVEL, 2004; Imgrund and Thomas, 2013).

2.4.2. Cases with ventilation and/or drainage

The construction of an entirely gas-tight lower reservoir is not possible. Therefore, drainage and ventilation systems are designed to mitigate gas accumulation in the mine. The ventilation system can release mine gas from shafts, nevertheless, due to the impact of methane on the climate, all mines try to avoid methane emissions and collect methane through drainage systems, to convert it into power production (Ministerium für Verkehr, Energie und Landesplanung des Landes

Nordrhein- Westfalen (MVEL), 2004). On one side, the drainage would mitigate the gas inflow in the UPSP and it is also often used after active mining as a safety measure to prevent gas leaks to the surface and through vent lines (Minke, 2016). On the other side, an operating drainage system, associated with operating monitoring allows an accurate knowledge of the gas condition in the mine and mitigates gas-related risks. However, the use of the mine as UPSP can create a conflict of interest. The inflow of air into the gas deposit would reduce the methane concentrations for production and cause fluctuating gas qualities, possibly below the methane concentration for which the energy recovery was designed or even within the explosive range of methane (Meiners et al., 2018).

2.4.3. Cases without gas risk prevention

In certain instances, the cessation of ventilation and mine gas extraction activities has resulted in an ongoing influx of gas into the mine, consequently leading to increased gas concentrations (Ministerium für Verkehr, Energie und Landesplanung des Landes Nordrhein- Westfalen (MVEL), 2004; Krämer, 2007). Furthermore, weathering processes and the propagation of fractures have facilitated the release of gas and the creation of pathways for gas migration. The absence of proper ventilation systems poses a risk of significant gas accumulation and subsequent gas migration, with uncertainties surrounding the mapping of potential accumulation areas due to limited monitoring outside of former mine openings (INERIS, 2016). Although a theoretical assessment of potential gas accumulations can be conducted to some extent based on mine plans that delineate former excavation areas and roadways (Krämer, 2007).

Moreover, in flooded mines, the water is likely to contain substantial quantities of carbon dioxide and hydrogen sulfide, both of which are highly soluble gases. Additionally, relatively lower amounts of radon and methane may also be present. According to Henry's law, the solubility of gases in water increases with higher pressure and lower temperature. During the ascent of water to the surface, the temperature may rise while the pressure experiences a significant decrease, particularly if the water originates from deep sources. This phenomenon can lead to the release of dissolved gases into the atmosphere (INERIS, 2016).

2.5. Hydraulic management

Hydrodynamic (i.e. the flow conditions of water) and aerodynamic (i.e. air under gravity or pressure flow conditions) processes are of major importance for the efficiency as well as safety of hydroelectric power plants in general, and UPSP in particular (Menéndez et al., 2019). Key parameters to describe flow conditions are the hydrodynamic pressure, the water height, the flow velocity, the shear stress and the evolution and propagation of waves.

The lower reservoir of a UPSP creates two specific boundary conditions regarding hydrodynamic aspects. Firstly, the reservoir's spatial extent is confined compared to conventional PSP. Secondly, the plant operation is based on a free surface flow in an enclosed environment, which poses the possibility of changes in the flow condition under specific operational conditions. These specific boundary conditions lead to several relevant hydrodynamic processes that need to be considered during the operation of a UPSP (Figure 2.7).

2.5.1. Position of turbomachinery and its connection to the lower reservoir

As with all other hydropower projects, the selection of the type of turbomachinery in a UPSP is critical for power production. plant efficiency, investment cost and operational flexibility of the plant (Morabito et al., 2020). Similar to conventional PSP, there is a choice between individual turbines and pumps or reversible pump-turbines (Akinyele and Rayudu, 2014). Morabito et al. (2020) give an overview of advantages and disadvantages of different types of turbomachinery for UPSP highlighting that impulse turbines such as Pelton turbines are unsuitable for a UPSP. Therefore, mostly Francis turbines or Francis pump-turbines are an eligible choice. Their operating concept allows for heads of several hundred meters and the machinery to be submerged while still remaining a good efficiency. Special care has to be taken for dampening flow oscillations at start and stop of operation and to avoid possible cavitation, which usually is done with a water lock in conventional pumped storage plants. This, however might be not possible in UPSP for reasons of accessibility or additional costs.

In practice, the draft tube of a UPSP is connected at one point to the network of channels,without the benefit of the kinetic energy conversion effects of a diffusor or an open surface reservoir in conventional PSP . This structural situation can lead to a high speed inflow being directed at a bend or a T-Junction (Brücker, 1997) into the channels, In general, flows in simplified 90°-bends and T-junctions show a high likelihood for oscillating flow features such as swirl-switching phenomena (Rütten † et al., 2001; Morabito et al., 2020) or vortex-induced instabilities. Pressure and force fluctuations are expected to be coupled with these oscillations. In Francis turbines, pressure fluctuations in the draft tube should be avoided since they affect the power stability and longevity of the turbine (Gao et al., 2018; Zhou et al., 2021). Hence, the placement of the draft tube outlet into the lower reservoir and the subsequent fluctuations need to be considered in the choice of an abandoned mine as an UPSP as well as the UPSP's structural and operational design and the selection of the type of turbomachinery.

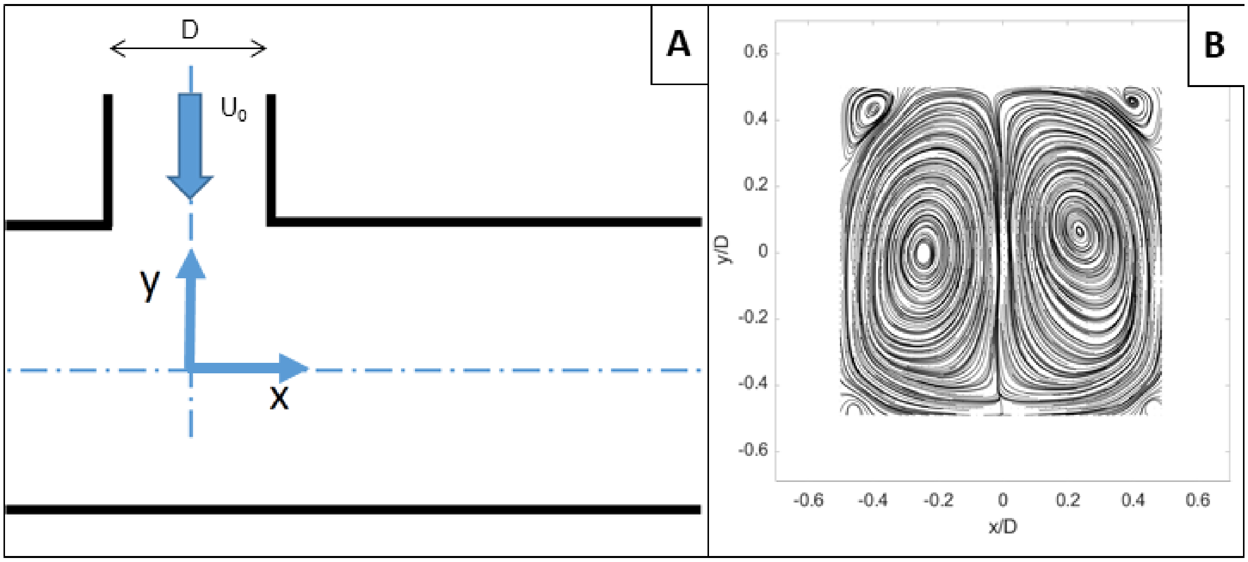


Figure 2.7: A. Experimental setup of a T-junction flow with an inflow velocity of U0 = 0.46 m/s in the junction and a diameter of the main channel of D = 0.05 m. B. Top view of the time-averaged streamlines captured with Particle Image Velocimetry in the cross-section at 1D downstream of the junction.

2.5.2. Hydraulic processes during operation

Hydrodynamic (i.e. the flow conditions of water) and aerodynamic (i.e. air under gravity or pressure flow conditions) processes are of major importance for the efficiency as well as safety of hydroelectric power plants in general, and UPSP in particular (Menéndez et al., 2019). Key parameters to describe flow conditions are the hydrodynamic pressure, the water height, the flow velocity, the shear stress and the evolution and propagation of waves.

The lower reservoir of a UPSP creates two specific boundary conditions regarding hydrodynamic aspects. Firstly, the reservoir's spatial extent is confined compared to conventional PSP. Secondly, the plant operation is based on a free surface flow in an enclosed environment, which poses the possibility of changes in the flow condition under specific operational conditions. These specific boundary conditions lead to several relevant hydrodynamic processes that need to be considered during the operation of a UPSP.

Firstly, during the filling or emptying of the lower reservoir of a UPSP, the water level rises or falls from an initial water level h0 to a final water level of hend. From a global point of view, the rate of water level change and its duration depend solely on the discharge, the chosen values for h0 and hend, the available volume of the reservoir and its cross-section (Pummer and Schüttrumpf, 2017). While these global processes are similar to those in conventional pumped storage plants, recent studies have shown that so-called local processes superimpose the global hydrodynamic processes in a UPSP (Pummer and Schüttrumpf, 2017). This can lead to changes in for example the water level of up to 50 % (Pummer and Schuettrumpf, 2018).

These local flow processes are characterized by the appearance of waves. When the reservoir is filled, a wave moves from the opening in the direction of flow along the channel and causes higher water levels and flow velocities to occur at the wave head. If the wave height exceeds the remaining freeboard in the channel, there may be a sudden increase in pressure within the channel. If the wave height reaches the reservoir ceiling and the flow changes from a free surface flow to a pressure flow, it can cause locally increased hydrostatic pressures. Pressure surges especially in the vicinity of the turbomachinery can affect their longevity and efficiency.

The wave height and wave speed that occur depend on the type of wave that arises in the specific situation. There can be undular bores, undular bores with secondary waves and breaking bores in a UPSP (Pummer and Schüttrumpf, 2017). Pummer and Schüttrumpf (2017) showed in experimental and CFD models that for the maximum water level the first waves that occur near the inlet of the reservoir are crucial (Figure 2.8).

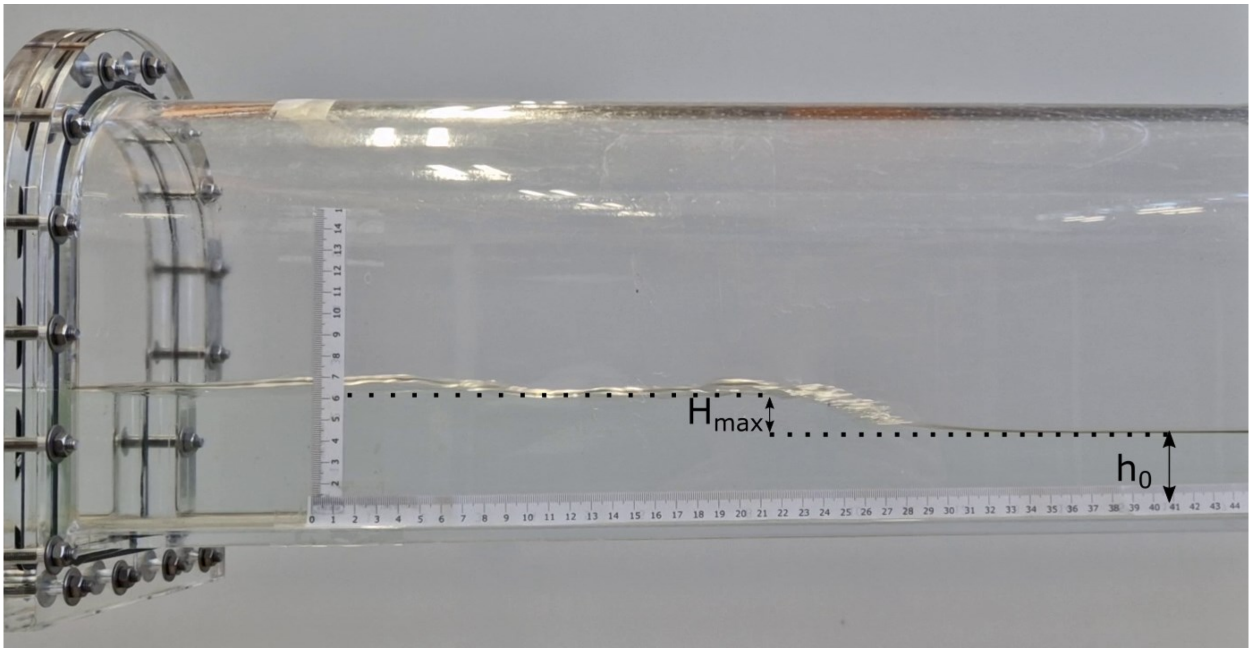


Figure 2.8. Wave at the inlet during the filling of an underground reservoir.

With time and through changes in the channel's cross-section or the impermeable reservoir boundaries the waves are reflected and change direction (Pummer and Schuettrumpf, 2018). Partial reflection, Mach reflection or total reflection of waves can occur and lead to changes in their hydraulic characteristics making the predictability of the hydraulic parameters more complex (Pummer and Schuettrumpf, 2018). When the discharge in the reservoir stops, the wave heights and wave velocities decrease over time. Since strong oscillations in the reservoir can affect UPSP operation negatively, the dampening process is relevant for UPSP operation.

The global and local flow processes are strongly affected by the operational parameters of a UPSP. Whereas global processes mainly depend on the discharge, the initial and final water level, the volume of the reservoir and its cross-section, local processes have further relevant influencing parameters (Table 2.1). The dependency especially on local flow processes from operational and structural parameters makes a detailed development of determination equations necessary (Pummer and Schüttrumpf, 2017). No comprehensive state of knowledge is known so far regarding the description of flow processes in UPSP that takes all relevant operational and structural parameters into consideration.

Table 2.1: Relevant hydraulic parameters in UPSP and known relevant operational and structural design parameters (Pummer and Schüttrumpf, 2017; Menendez et al., 2020b).

Relevant hydraulic parameters	Relevant operational parameters	Relevant structural parameters
Actual water level Wave height Flow velocity Oscillation period	Discharge Initial water level Final water level Total filling and emptying duration	Channel cross-section Channel length Channel geometry incl. number of channels and direction changes Wall roughness Bottom slope

In addition, similar to a conventional hydropower plant, in a UPSP, global and local flow processes in the lower reservoir are closely linked to the phenomenon of water surges or water hammer (Lupa et al., 2022). A water hammer occurs during changes in operating points or emergency shutdowns and can be triggered or enhanced by the operating time of wicket gates or valves, the geometry and general set-up of a hydropower plant’s components such as the penstock, or the reservoirs as well as the turbomachinery characteristics such as runner speed (Ramos and Almeida, 2001; Lupa et al., 2022). However, due to the special boundary conditions of a UPSP being underground, the relationships with influencing factors and the effects of the hydraulic phenomenon cannot be predicted with the same certainty as in a conventional hydro power plant.

They can affect all components of a hydropower plant negatively either by direct damage due to high-pressure surges or by fatigue of material due to the highly dynamic, cyclical loadings (Gagnon et al., 2016; Liu et al., 2016). Water locks can be considered to reduce the pressure surges in UPSP, as they are also used in conventional PSP. However, the positioning and construction of these components still needs to be investigated for a UPSP to ensure their effectiveness under special circumstances of an abandoned mine.

Finally, unlike conventional PSP, the air pressure in a UPSP is variable and differs from the atmospheric conditions (Menéndez et al., 2019). Without ventilation, air gets trapped in the lower reservoir during its filling and compresses, which results in higher air pressure and thus in less favourable flow conditions. As the air pressure increases, so does the hydrostatic pressure in the reservoir, which leads to a reduction in the net head between the upper and lower reservoir. This reduces the available stored energy in the UPSP.

Menéndez et al. (2019) have shown that for a specific UPSP scenario pressure-induced head loss could account for 12.5 % loss of available energy.

The excavation of ventilation shafts is necessary to allow the exhalation of the trapped air which is displaced during the turbine process (Kitsikoudis et al., 2020). Placement, geometric design and quantity of ventilation shafts need to be considered in the design of a UPSP to ensure good aerodynamic conditions while maintaining economic viability (Menéndez et al., 2020).

2.6. Stability under operation phase

2.6.1. Cyclic wetting and drying

It has been explained before (see section 2.3.2) that mechanical properties of various rock types vary greatly due to processes occurring under wet conditions (e.g. weathering, dissolution, hydration, leaching, swelling, slacking)(Figure 2.3). Regarding the long-term effect of cyclic dynamic water and water wave on host rock in UPSP systems, the mechanism of the water-rock interaction become more complicated.

In clay and mudstone formations, the alternation of wet and dry cycles induces a cyclic swelling-shrinkage phenomenon, resulting in the disintegration of the rock mass and deterioration of rock properties (Wild et al., 2017). Mudstone exhibits a progressive increase in maximum swelling strain with each cycle, eventually reaching a nearly constant value after multiple cycles (Doostmohammadi et al., 2009). This behavior can be attributed to mechanisms such as air breakage, crack opening, and stress relaxation at crack edges. The presence of swelling minerals in mudstone can cause cyclic stress accumulation and release, potentially leading to rock fatigue (Hale, 2003).

In the case of sandstones, cyclic wetting and drying treatments have been reported to decrease tensile strength, although there is some discrepancy among research studies (Hale, 2003; Zhao et al., 2017). It is plausible that an increased number of wetting and drying cycles could result in noticeable strength reduction (Hale, 2003). However, the mineralogical composition of sandstone plays a crucial role in the underlying weakening mechanism during cyclic wetting and drying, as it primarily involves chemical and corrosive deterioration processes such as dissolution, precipitation, dehydration, hydration, or swelling (Zhao et al., 2017). Consequently, the cyclic wetting and drying of sandstone can lead to enhanced softening and ductility, causing a shift in failure characteristics from brittle to ductile failure, particularly when subjected to a high number of cycles (Hua et al., 2015).

In addition, rapid water fluctuations can accelerate deformation accumulation and the damage development and expansion of the radius of EDZ (Zhu and Bruhns, 2008).

2.6.2. Cyclic loading

During the operational period of UPSPs, the rock mass around the underground reservoir is continuously subjected to hourly/daily cyclic loads due to the fluctuation of internal water pressure (e.g. waves). The maximum amplitude of the pressure cycles is very small (i.e. a few kPa), compared to the gravitational and tectonic stresses in the surrounding rock mass (i.e. several MPa). However, under cyclic loading, many damage indicators develop imperceptibly or without fatigue failure, when the maximum cyclic stresses in the rock are below the crack initiation threshold σci (elastic range) (Brace and Bombolakis, 1963; Song et al., 2022). However, it is well known that if rock undergoes cyclic loading, it often fails at a lower stress than its monotonic strength if the stress is above the crack initiation threshold. Existing micro-cracks, fissures, defects and voids grow slowly in the rock and may cause fatigue failure (Le et al., 2014; Erarslan, 2016; Ghamgosar and Erarslan, 2016; Geranmayeh Vaneghi et al., 2018; Liu and Dai, 2021). This type of repetitive stress typically leads to loosening and decohesion of the rock grains (Martino and Chandler, 2004; Guo et al., 2012). Stress corrosion is thought to be the most relevant mechanism of fatigue that causes sub-critical crack growth.

Additionally, fatigue is usually accompanied by accumulated deformations in the rock based on a time-dependent mechanism primarily due to the growth of pre-existing microcracks (Atkinson, 1984; Cerfontaine and Collin, 2018). A typical deformation curve observed in cyclic loading tests consists of three stages as shown in Figure 2.9: I) the initial stage: axial strain increases rapidly in the first few cycles due to the development of new cracks and the strain increases at a deceleration rate (deceleration region); II) steady-state stage: the crack propagation and damage evolution occur with a constant rate leading to steady-state strain accumulation (stable propagation region); III) the accelerated stage: the rate of strain accumulation increases rapidly and leads to fatigue failure of the rock (acceleration region) (Attewell and Farmer, 1973; Khaledi et al., 2016; Cerfontaine et al., 2017; Cerfontaine et al., 2018). The fatigue behaviour of a rock material may depend on several factors, such as frequency, loading-unloading rate, waveform and amplitude of cycles as well as the applied confining pressure (Bagde and Petroš, 2005; Ma et al., 2013; Liu and Dai, 2021; Song et al., 2022). For instance, the influence stress frequency upon failure strain, low cycle fatigue testing (LCF) involves high stress amplitudes and low-frequency plastic strains, while High cyclic fatigue (HCF) is characterized by lower stress amplitudes and higher-frequency strains, resulting in distinct accumulated deformation behavior and rates of damage evolution (Attewell and Farmer, 1973).

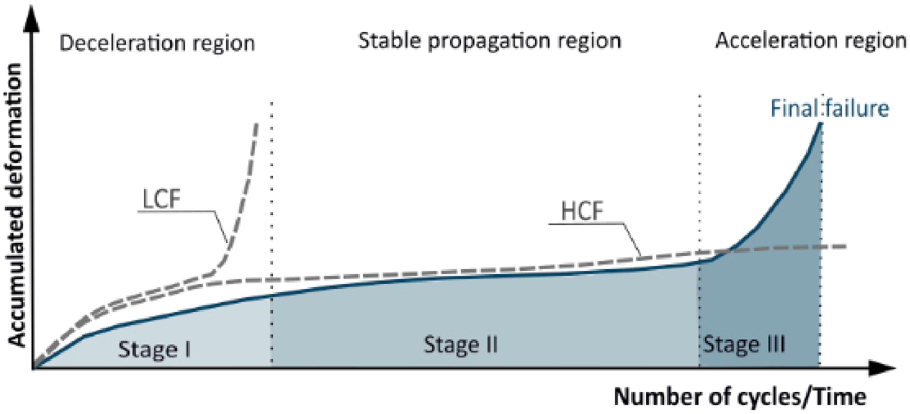


Figure 2.9: Typical deformation accumulation observed in cyclic loading tests (low cycle test: small number of cycles with high loads; high cycle test: large number of cycles with low loads) (Attewell and Farmer, 1973; Khaledi et al., 2016; Cerfontaine et al., 2017.

The delayed failure of a rock sample under constant applied stress is known as brittle creep (Cruden, 1974; Brantut et al., 2013), which is associated with the stability of many buildings and underground structures in mining and rock engineering, notably, creep and fatigue exhibit similarities in their characteristics. Both phenomena show time-dependent behavior and fail at an applied load lower than its monotonic strength (subcritical crack growth (Atkinson, 1984)), characterized by three stages of deformation rate: the primary (or transient) creep stage, the secondary (or steady) creep stage, and the tertiary (or accelerating) creep stage. The underlying mechanisms involved in these processes are intricate, complex, and influenced by various parameters, e.g. stress corrosion (Anderson and Grew, 1977; Atkinson, 1982, 1984; Brantut et al., 2013).

As mentioned above, the weakening effect of water on the strength/properties of the rock can have a stronger influence on the rock during cyclic loading and makes the deformation process complex (Zhong et al., 2022). For example, the hydro-mechanical properties of the rock, strength, Young's modulus, are increasingly degraded under cyclic loading and may even cause dynamic instability events in the tunnel (Roberts et al., 2015; Zou et al., 2016; Wang et al., 2017).

Another critical loading condition that can occur in an underground reservoir of a UPSP are the hydrodynamic forces during the switchover phase from pump to turbine operation, or vice versa (e.g. shock waves or high frequency impact loads). In such cases, the adjacent rock mass of the underground tunnel is subjected to rapid dynamic forces, which may cause instabilities (Menéndez et al., 2019).

Based on the comprehensive analysis of instability factors encountered during cyclic loading, it can be concluded that these factors have a significant influence on the hydro-mechanical condition of the tunnel circumference at a macroscopic level. Consequently, the integrity and overall condition of the tunnel are highly susceptible to adverse consequences. Dynamic disturbance can accelerate deformation accumulation and the intersection between cracks, also causing the rock mass around the tunnel to lose its integrity (Carter and Booker, 1990; Wang X N, 1998; Diederichs et al., 2004; Zhu et al., 2014). In addition, a coupled hydromechanical process and local heterogeneity can initiate and accelerate the damage development of rock mass, which may lead to expansion of the radius of EDZ (Zhu and Bruhns, 2008). In such circumstances, it presents a challenge to theoretically define the Excavation Damaged Zone (EDZ) and accurately quantify the radius of the fractured and irreversible deformation in UPSP. Several studies have explored the stability of underground spaces under cyclic loading using numerical stress analysis and have determined that dynamic loading significantly impacts the mechanical behavior and displacement of the surrounding rock mass (B. Damjanac, 2002; Johansson et al., 2013; Perazzelli et al., 2015; Khaledi et al., 2016).

2.6.3. Thermal-induced fracturing

The cyclic circulation of cold water in a UPSP system creates a so-called thermally affected zone (TAZ) around the lower reservoir. Depending on the depth of the lower reservoir and the water temperature, a temperature gradient of -5 to -40 °C can be expected within this zone (especially during the winter). From a geomechanical perspective, such a temperature drop can cause the surrounding rock to undergo transient thermal contraction, resulting in thermally induced tensile stresses. The magnitude and extent of the zone affected by the thermal stresses depend on several factors, such as the temperature gradient and the thermal properties of the rock, including its thermal expansion, heat capacity, and thermal conduction coefficients.

While the scientific literature on the potential consequences of thermal stresses in UPSPs is scarce and seldom explored, this topic has gained significant attention in other subsurface applications. For example, numerous studies on compressed air energy storage (CAES) in salt caverns have shown that rapid temperature drops can cause local mechanical instabilities in the form of spalling and tensile fractures on the cavern wall (Benoit Brouard et al., 2012; Djizanne et al., 2012). The formation of thermal cracks was also observed in a novel field experiment where the salt experienced a temperature drop of $\Delta T= -20C°$ (Blanco-Martín et al., 2018). Moreover, cyclic thermal stresses may even lead to the so-called thermal fatigue in the long term (Lu and Fleck, 1998), a process that has rarely been studied so far. This phenomenon has been observed in mine shafts due to seasonal temperature fluctuations (Wallner and Eickemeier, 2001; Heusermann and Eickemeier, 2008).

2.6.4. Water exchanges with the surrounding rock mass

In the case of an impermeable reservoir, pumping and discharge can lead to variations in the water level in the surrounding rock mass. In several pumping and discharge scenarios, simulations show this oscillation (Figure 2.3) with an exchange from the cavity to the aquifer during the discharge phases and an exchange from the aquifer to the cavity during the pumping phases (Bodeux et al., 2016; Poulain et al., 2021)(Figure 2.10). In most cases, infiltration is more important than exfiltration, which causes a reduction of the available volume in the lower reservoir and affect the efficiency of the UPSP (Pujades et al., 2019).

However, exfiltration may lead to environmental issues (e.g. contamination of the aquifer). Indeed, in coal mines, pyrite is a common sulfide mineral and its oxidation leads to a drop in pH. On the contrary, calcite present in carbonate rocks can lead to an increase in the pH (Pujades et al., 2019). Due to water exchange with the surrounding media, hydrochemical changes might lead to a change in the water chemistry in the surrounding aquifer (Pujades et al., 2019). However, Poulain et al. (2021) estimated in a chalk aquifer, a hydrochemical evolution in the aquifer only within a zone limited to the first 20 meters around the cavity.

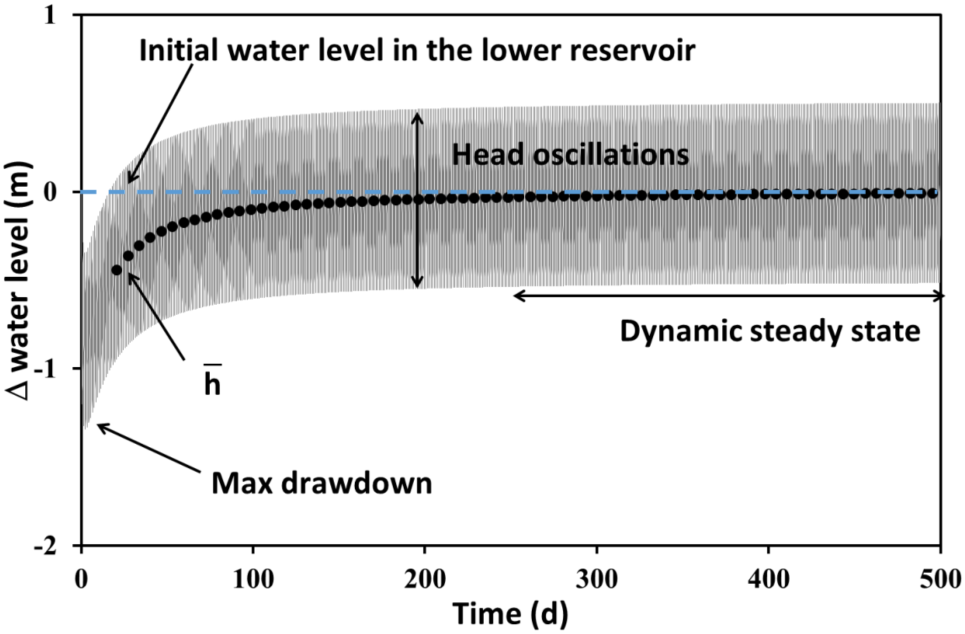


Figure 2.10: Computed variation of the piezometric head in the surrounding porous medium (synthetic scenario). It is considered that the water table is located at its natural depth before starting the activity of the UPSH plant. h^{-} is the mean water level during.

Finally, water inrush in the roofs and floors can deteriorate the stability of tunnel circumference due to upward development mechanism of water-conducting fractures which accelerate the damage process (Zhang et al., 2020).

2.7. Discussion

2.7.1. Reviewed of empirical, analytical, and numerical approaches

As explained previously, several unpredictable severe problems may endanger the stability and safety of the abandoned mine area (Luan et al., 2018). Therefore, identifying a suitable location for the underground reservoir in an abandoned mine and estimating the current condition of the mine can be challenging (Madlener and Specht, 2013; Tong and Wu, 2013; Menendez et al., 2020b; Menéndez et al., 2020). For this reason, it is essential to implement geological assessment and geotechnical design criteria to evaluate the long-term stability and serviceability of the underground reservoir prior to UPSP operation. However, to date, only a few case-studies have been carried out to identify the required geotechnical design factors in UPSPs (Uddin, 2012; Menendez et al., 2019b). A summary of the studies available in the literature on the geotechnical aspects of UPSPs is given in Table 2.2. In these studies, geotechnical stability analysis is performed by empirical, analytical, and numerical approaches.

As an example, the stability of a network of tunnels used as a lower water reservoir at 450 m depth was analyzed in a closed coal mining area at the Asturian Central Coal Basin (ACCB), Spain (Menendez et al., 2020b). For a preliminary design of the support systems and in order to determine the rock mass characteristics, empirical approaches based on rock mass classification systems were used. In addition, 3D numerical modeling was carried out to ensure the stability of the underground excavations. The deformation and extension of the critical zones were evaluated in the simulation with/without support systems (rock bolts) (Menendez et al., 2020b). Also, three-dimensional numerical models were built for water exchange of the Martelange slate abandoned underground mine in Belgium, which is a potential site to install a UPSP. These models helped to investigate the influence and evolution of the water exchanges between the underground reservoir and the surrounding medium and how they may affect the groundwater behavior around the tunnel and the hydraulic properties inside the underground reservoir (Pujades et al., 2020). Finally, in the Prosper-Haniel hard-coal mine in Germany, geological, economic, environmental, geotechnical feasibility and hydraulic aspects were analyzed during feasibility studies (Luick, 2013; Zillmann and Perau, 2015).

However, only a few studies have addressed all geotechnical aspects related to the stability of underground reservoir, especially under cyclic water-rock interactions. Characterization of strengths, hydro-mechanically coupled behavior, and deformation evolution (potential fatigue failure) both in the field and in experiments is of great importance to study the long-term stability of an underground water reservoir. A comprehensive understanding of these aspects requires further experimental and field investigations.

Table 2.2: Case study and stability consideration

Study area	***Literatures***	***Stability considerations for design an UPSP***
Asturian central coal basin (ACCB), Spain	(Menendez et al., 2019b)	● The stability of the powerhouse cavern ● The effect of air pressure on the tunnels and shafts
	(Menendez et al., 2020c)	● Stability of a network of tunnels ● The deformations and thickness of the excavation damage zones (EDZs) ● Support system
	(Menéndez and Loredo, 2020)	● The behavior of lower reservoir of UPSP during operation ● The existence of water and air interaction
	(Menendez et al., 2019a)	● The flow behavior in the tunnels. ● The behavior of the water-air mixture during the operation
Matelange, Belgium	(Pujades et al., 2020)	● Water exchange between the underground reservoir and the surrounding medium. ● Two scenarios: completely full or totally drained
	(Pujades et al., 2021)	● Hydrogeological features: hydrogeological properties and the groundwater characteristics and behavior ● The consequence of the hydraulic conductivity and elevation of the piezometric head
	(Pujades et al., 2018)	● Groundwater flow impact ● Water exchanges
Prosper-Haniel mine, Ruhr in Germany	(Montero et al., 2016)	● Hydraulic aspects for developing the project, considering construction, geotechnical, geological, and energy market restrictions.

2.7.2. Cost estimation and economical limits

The economic feasibility of Pumped Storage Hydroelectric (PSH) projects primarily depends on capitalizing on price differentials between high and low peaks of energy demand (Winde et al., 2017; Lyu et al., 2023). While PSH systems can have extended lifetimes, the initial investment required for an Upper Reservoir Pumped Storage (UPSP) remains substantial, posing challenges for governments and energy companies (Menéndez et al., 2019; Pikl et al., 2019b).

Menéndez et al. (2019) conducted a comprehensive examination assessing the economic efficiency of existing UPSP projects and identified their considerable construction costs. Excavating underground caverns and shafts, creating entirely new underground chambers, is the primary cost component, accounting for 30% to 60% of the total project expenditure (Pikl et al., 2019a). However, constructing new excavations allows for selecting high-quality rock formations and tailoring the dimensions of the underground reservoir, as demonstrated by the UPSP project in Bukit Timah granite, Singapore (Wong, 1996), and the O-PAC project in the Netherlands (Huynen, 2018; Kramer et al., 2020).

Utilizing existing caverns presents potential cost savings in excavation but requires additional investments in reinforcing the initial support system and implementing supplementary grouting measures to mitigate water seepage. For example, a limestone mine project in the USA requires approximately 200 million euros for grout curtain requirements (Uddin, 2003). Costs associated with implementing UPSP in abandoned mines can exceed those of conventional PHS projects, such as the Grund mine project in Germany with an investment cost of 180 million euros for a storage capacity of 400 MWh (Meyer, 2013).

However, certain projects demonstrate economic feasibility under favorable conditions, especially when rock mass properties are favorable (Wong, 1996; Kramer et al., 2020; Sousa et al., 2022). Wong (1996) study showed that utilizing a stable quarry as the upper reservoir requires minimal investments to address limited instability concerns, resulting in a project cost equivalent to that of an oil-fired plant.

Lyu et al. (2023) estimated that investments for UPSP projects in China should be comparable to conventional PHS projects, thanks to shorter construction periods, reduced rock excavation requirements, and avoidance of land acquisition costs. Additionally, implementing UPSP in mines can lead to cost savings associated with post-closure water management (Winde et al., 2017) and water treatment expenses (Zhang et al., 2021a). Some UPSP projects can even generate income from the excavated rocks, as seen in limestone mines (Uddin, 2003).

In summary, while the economic viability of UPSP projects can vary depending on factors such as construction costs, rock mass properties, and post-closure considerations, they present opportunities for cost savings and revenue generation in certain circumstances.

2.8. Conclusion

This research study focuses on the challenges of repurposing abandoned coal mines for UPSP projects, specifically examining the three main components influencing the decision-making process.

1.Stability: This component presents technical challenges throughout the project's lifespan. Understanding the mine's current condition, as well as the processes that degrade its stability before, during, and after construction and operation, is crucial. Time-dependent processes like humidity changes (e.g., weathering, dissolution, hydration, leaching, swelling, slacking, creeping, precipitation, corrosion), load changes (subsidence, fatigue, cyclic loading, support system renewal, stress distribution changes), and thermal stress variations can weaken the tunnel, leading to extension and failure issues along weak areas, particularly in the EDZ

2.Environmental and human safety: Safety is a crucial consideration subject to local regulations. Hazards associated with abandoned mines, such as mine gas accumulation and water contamination, require careful attention to protect the environment and human populations.

3.Productivity: is influenced by hydraulic processes, including discharge processes and local flow dynamics. Operational parameters, tunnel hydraulics, and geometry directly impact discharge efficiency. Time-dependent water height oscillations, pressure fluctuations, and variable hydrodynamic pressure (e.g., atmospheric pressure changes, hydrostatic pressure changes) significantly affect the system's discharge performance. Additionally, water surges and water hammer processes (e.g., high-pressure surges, material fatigue, dynamic and cyclic loading) pose risks that can compromise the operation of the UPSP, impacting all components of the hydropower plant.

Addressing these challenges is vital for the successful implementation of UPSP projects in abandoned coal mines. Further research is needed to weigh these parameters in decision-making and develop effective strategies and methodologies. Real study cases can provide opportunities to overcome these challenges and unlock the potential of abandoned coal mines as sustainable sources of pumped storage hydropower.

2.9. Additional Insights

Additional work has been conducted subsequent to the initial publication of this chapter. This section applies the challenges outlined in the paper to an analysis of the Prosper Haniel site (see section 1.3.1). Feasibility studies were undertaken to repurpose the Prosper Haniel coal mine into an Underground Pumped Storage Hydroelectric (UPSH) facility. Three options for the underground reservoir were evaluated, including the reuse of tunnels at levels 6 and 7, situated at depths ranging from 971 to 1008 meters. However, due to the progressive rise in water levels post-mine closure, the most viable option involved constructing a new ring-shaped tunnel between depths of 581 and 607 meters, leveraging existing shafts (Zillman and Perau, 2015)(Figure 3.3).

The operational requirements, such as sustained electricity production over 4-hour intervals, dictated a reservoir capacity of 575,000 cubic meters (Daou Pulido et al., 2013). Subsequent sections describe the application of various challenges to the Prosper Haniel site and their potential impact on decision-making regarding the mine's conversion to a UPSH facility.

2.9.1. Prevailing conditions in Prosper-Haniel

Since Prosper Haniel was active until 2018, the prevailing conditions in the actively managed tunnels were monitored intensively and, hence, are well known. These conditions include the existence and location of tunnels, the existence and condition of support structures and the tunnels' general geometry. This knowledge allows a potential UPSP planner to identify permanently stable and available components of the mine for UPSP use without additional explorations (Niemann et al, 2018). Hence, a first stability and productivity evaluation for this site is easily done without further costs for exploration.

On the other hand, no actual and accurate data on tunnel deformation since the closure is available. Since tunnel deformation can affect long-term tunnel stability, it needs to be monitored closely. Hence, an in-depth tunnel exploration is necessary during the design phase to determine the suitability of Prosper Haniel site as a UPSP. However, an in-depth exploration can be done using existing, well-proven survey methods such as photogrammetry and laser scanning. Furthermore, since short-term tunnel and support structure stability are well known, work safety is no concern during the exploration survey.

All in all, unknown mining cavity characteristics in Prosper Haniel pose only a mine concern regarding the use as a UPSP. The information about the mine's prevailing conditions until its closure are of great importance to evaluate the mine's general stability and productivity and ensure work safety during in-depth exploration necessary for determination of long-term stability.

2.9.2. Surface constraints and connectivity

The establishment of an energy storage facility necessitates several critical considerations. Among these, the connectivity to electrical grids plays a pivotal role. At the Prosper II (shaft 1) site, connectivity is facilitated by a 220 kV overhead transmission line linking to a transmission grid, with an additional 380 kV overhead line situated to the south. Adjacent to the site, a transformer station operates at 220 kV (Luick, 2013).

Furthermore, ensuring optimal accessibility to the power plant is imperative. The Prosper II site benefits from proximity to the Essen-Nord highways junction, enhancing access to the northern Ruhr area, northwest Dortmund, Solingen, Erle, and Essen city center. Rail access is provided through integration with the RBH Logistics GmbH network, a subsidiary of Deutsche Bahn (RBH, 2012), facilitating connections to the Rhine-Herne Canal approximately 2 km to the south and the port facilities at Bottrop's central port. These comprehensive transport links, including shipping and rail routes, enable efficient and cost-effective transportation of large and heavy machinery components to the site.

2.9.3. Presence of mine gas

As a former hardcoal mine the presence of mine gas has to be considered at the Prosper-Haniel site. During the operational life of the Prosper-Haniel mine safety measures and monitoring concerning mine gas were carried out according to applicable rules and regulations. Gas pre-drainage was conducted for the coal panels prior to extraction and degassing equipment and gas conversion installed at Prosper IV (shaft Prosper 9) (MVEL, 2004). Volume and contents of the drained gas varied with different coal seams and output over time (Luick, 2013). Gas drainage is ongoing at the Prosper-Haniel site after the end of active mining. The degassing concept of the RAG AG for the closing of the mine includes a vent line for shaft Franz-Haniel 2 and two vent lines for shaft Prosper 9, which are connected to several levels to ensure a controlled degassing, concerning the planned rising of the mine water level and end of ventilation (Imgrund and Orzol, 2020). Monitoring is conducted during the closing of the mine in accordance to the corresponding guideline, which includes regular measurements of gas contents and pressure differences at former shaft locations (as the primary migration pathways) (Imgrund and Orzol, 2020).

Mine gas presence has not been a disqualifying factor for Prosper-Haniel in previous studies (Luick, 2013; 2014; Niemann, 2018). A feasibility study for a potential UPSP included safety measures to mitigate gas risks, such as sealing off unused mine parts and explosion-proofing outlets (Niemann, 2018). Although gas presence is crucial for safety and monitoring, it is not a key decision-making factor. However, conflicts may arise between ongoing gas drainage and UPSP construction/operation.

2.9.4. Targetting an unsubmerged tunnel for the lower reservoir

Level 6 (at approximately 930 meters below sea level, mbsl) was initially considered in the feasibility study due to its substantial potential capacity, offering over 20 kilometers of tunnels. However, following the closure of the Prosper-Haniel mine, it is anticipated that the underground water level will rise from 1200 mbsl (below Level 6) to 580 mbsl. Utilizing a tunnel beneath this new groundwater level (i.e., a submerged level) would introduce significant challenges related to geotechnical stability (Alvarado Montero & Niemann, 2016). The additional costs required to reinforce the support system and ensure the tightness of the reservoir—through the use of grouted bolts and grout spray—would be prohibitively high, rendering the Underground Pumped Storage Plant (UPSP) economically unfeasible. Consequently, the selection of a submerged tunnel is critical, leading to the exclusion of Level 6. Instead, the new configuration proposed involves repurposing an existing shaft and excavating a completely new tunnel above the groundwater level (Alvarado Montero & Niemann, 2016).

2.9.5. Rock mass properties in Prosper Haniel

Prosper-Haniel is situated within a series of weak rock units near a fault zone, where stable and homogeneous rock units, such as thick sandstone beds, are only sporadically present (Zillmann and Perau, 2015). The host rock comprises a sequence of sandstone, siltstone, claystone, and coal beds, which possess properties that are not conducive to the construction of an Underground Pumped Storage Plant (UPSP) due to their low strength and sensitivity to water saturation. The poor quality of the host rock significantly constrains the potential size of the UPSP and necessitates extensive construction efforts, including the installation of additional support structures. Furthermore, the proximity to a fault zone restricts the possibility of extending the UPSP into faulted areas.

However, a notable advantage of the Prosper-Haniel site is its location in a non-folded area where rock strata are only slightly tilted (approximately 5°) (Niemann et al., 2018). This geological setting minimizes rapid changes in horizontal rock characteristics and reduces the likelihood of instabilities associated with rock deformation. The properties of the host rock are crucial for site selection, particularly for the construction of generator and transformer caverns. Therefore, these geological characteristics are key factors in choosing the target area.

Overall, while the geological characteristics of Prosper-Haniel are well understood, and the non-folded sedimentary strata present a significant advantage for the site, the weak rock units and proximity to a fault zone pose major disadvantages. These factors particularly affect the potential expansion of the lower reservoir and the construction of additional caverns, such as those required for turbomachinery.

2.9.6. Water effect on mechanical properties of the host rock

Ozarslan and Koken (2016) conducted Uniaxial Compressive Strength (UCS) tests on both dry and water-saturated rock samples from the hard coal mines in the Zonguldak coal district, Turkey. This geological unit belongs to the same Upper Carboniferous formation as the Prosper-Haniel coal mine. Given the geological similarities, the rock properties observed in the Zonguldak district can be extrapolated to infer the behavior of the Prosper-Haniel rock mass. The UCS tests revealed that the strength of the rock significantly decreases when saturated with water, particularly for siltstone (Table 2.3) (Junker et al., 2009). In addition to the softening of the rock mass, the leaching of joint fillings further reduces the stability of the openings.

Table 2.3: Average UCSi test results for dry, water-saturated rock sample and their ration (Ozarslan and Koken, 2016).

ROCK TYPE	DEPTH	UCSI DRY	(MPA)UCSI SAT	(MPA)UCSI SAT/UCSI DRY
FINE GRAINED SANDSTONE	-160m/-205m	117,8	71,76	0,61
FINE GRAINED SANDSTONE	-17m/-210m	144,5	111,89	0,77
FINE GRAINED SANDSTONE	-485m/-555m	105,69	74,36	0,70
SILTSTONE	-30m/-160m	48,20	17,40	0,36
SILTSTONE	-485m/-555m	49,90	21,07	0,42

The reduction of the great strength when the rock mass is saturated will significantly affect the tunnel stability. Moreover, the strength of rock sensitive to water will progressively decrease due to weathering and leaching of the wall. The reinforcement under these conditions might compromise the economic sustainability of the system. Therefore, the water sensitivity and the strength evolution when saturated of the rock mass is an important parameter and reinforce the importance of the geological target in the decision-making of the UPSP.

2.9.7. Prevention of concrete abrasion

The target rock unit in Prosper-Haniel is a thick sandstone bed unit favourable for mechanical properties and not too sensitive to wetting issues (i.e. slacking, swelling). However, hydraulic condictivity of sandstone can be not low enough to prevent water inflow or exfiltration in the reservoir. Therefore, hydraulic simulation were carried out by taking into account the reinforced concrete of the tunnel structure (Alvarado Montero & Niemann, 2016).

However, the number of pumping and discharge cycles might damage and leach the concrete layer. Therefore, the discharge simulations has been planned in order to limit the flow velocity to maximum value (2.5m/s) that prevents abrasion of concrete (Alvarado Montero et al., 2016). To conclude, although the prevention of the wall abrasion is a factor influencing the discharge management, this parameter will not influence the decision-making of the UPSP target.

2.9.8. Tunnel stability analysis

The roadway tunnel in Propser-Haniel are horseshoe shaped and suported by steel arch sets. Extra support can reinforce the tunnel with rockbolts and shotcrete. However, horseshoe shape is not favourable for water storage due to the high stress concentrations occuring when the tunnel is empty at the corners where the sidewalls meet the floor. Stress occurs as well of the crown of the horseshoe shape tunnel (Figure 2.11). These stress concentrations lead to displacements especially on the floor (upward displacement and floor heaving)(Özarslan et al 2013; Orzalan and Koken, 2015).

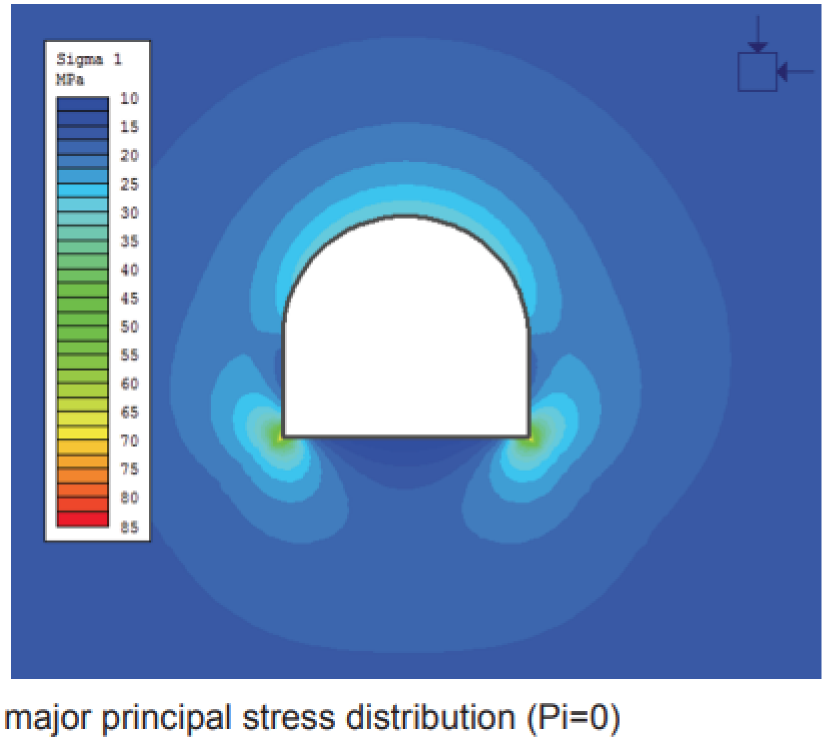


Figure 2.11: Major principal stress simulation for horseshoe shape tunnel at 600m depth (Orzalan and Koken, 2015).

To ensure the stability of the tunnel, only designed and reinforced lined coal mines main roadways can serve as an underground reservoir for a UPSP with a long-term cycling water storage. Therefore, the design of the tunnel and the potential additional cost due to the reinforcement of the tunnel is one of the main factor influencing the decision-making of the UPSP installation in a abandoned mine.

2.9.9. Conclusion

The feasibility study of repurposing the Prosper-Haniel coal mine for an Underground Pumped Storage Plant (UPSP) reveals several critical factors that significantly influence the potential conversion of the mine. These factors include geological conditions, water effects on rock stability, surface constraints and connectivity, the presence of mine gas, and the mechanical integrity of existing tunnels. Each of these criteria plays a role in the decision-making process for establishing a UPSP in an abandoned coal mine.

The conversion of the Prosper-Haniel coal mine into a UPSP is not only significant for the site itself but also holds broader implications for the reuse of abandoned coal mines globally. The findings from this study can serve as a foundation for developing a general framework for the reuse of coal mines as UPSPs. This framework can include:

1. Comprehensive Geological Assessment: Detailed analysis of rock properties, fault zones, and strata stability to identify suitable sites and ensure long-term stability.
2. Water Sensitivity analysis of the rock mass: Evaluation of the effects of water on rock strength and stability to inform reinforcement and design strategies.
3. Surface constraints and Connectivity Evaluation: Assessment of logistical considerations, including grid connectivity and transportation links, to ensure efficient operation.
4. Safety Measures for Mine Gas: Implementation of effective gas drainage and safety protocols to mitigate risks associated with mine gas.
5. Tunnel Design and Reinforcement: Development of optimized tunnel designs and reinforcement strategies to ensure structural integrity and economic feasibility.

By applying this framework, other abandoned coal mines can be systematically evaluated and repurposed for UPSPs, contributing to sustainable energy storage solutions worldwide. The Prosper-Haniel case study thus provides valuable insights and a practical approach for leveraging existing infrastructure to support the global transition to renewable energy.

2.10. References

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CHAPTER 3

GEOLOGICAL AND MINING FACTORS INFLUENCING FURTHER USE OF ABANDONED COAL MINES – A MULTI-DISCIPLINARY WORKFLOW TOWARDS SUSTAINABLE UNDERGROUND STORAGE

The contents of this chapter are under review at the Journal of Energy Storage (14/06/2024)

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3.1. Abstract

The repurposing of abandoned coal mines in Europe presents significant opportunities and challenges for sustainable underground spatial utilisation, 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. 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. The increasing need for renewable energy storage, driven by fluctuating supply and demand, has highlighted the potential of these underground spaces for applications such as underground pumped storage power plants (UPSP), heat storage, and compressed-air energy storage (CAES).

However, the initial conditions of these coal mines, characterised by heterogeneous rock mass conditions, low strength, and unfavourable permeability, pose significant challenges for ensuring long-term stability and water tightness. Using the Prosper-Haniel hard-coal mine in Germany as a case study, this research documents, highlights, and discusses the geological parameters and processes that influence the potential repurposing of abandoned coal mines. The study also examines various repurposing scenarios and their associated chances and challenges from a geological perspective.

A comprehensive 3D geological model has been developed to visualise the stratigraphy, tectonic structures, and mining data, aiding in the stability assessment of existing underground tunnels and serving as a base for further exploration. This model is essential for informed decision-making, providing a reference guide for regulatory authorities and stakeholders involved in similar projects. 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.

Keywords: Underground spatial utilization, Abandoned coal mines, Energy Storage Solutions, 3D Geological Modeling

3.2. Introduction

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) (Kapetaki, 2021). 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. In addition, many countries will be affected by a future progressive coal phase-out towards 2030 (e.g. Spain, UK, Northern Italy, Poland, and Ukraine (ESPON, 2018).

The potential reuse of closed mines for different purposes can directly address local economic challenges, for example, the cessation of fossil energy production 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 (Kivinen, 2017). Additionally, a notable secondary application involves utilizing underground mines and caverns (mainly granite, slate or salt) as oil or gas storage reservoirs (Midttømme et al., 2008; Hellström, 2012) or for hydrogen storage and heat storage in the future (Caglayan et al., 2020; Jüstel et al., 2024). Only three commercial CAES plants are currently operating in Germany, the USA and Canada and are also using salt caverns (Kim et al., 2023). Furthermore, numerous initiatives focus on leveraging warm mine water for various purposes or using the space as thermal energy storage reservoirs (Table 3.1). However, many coal mines saw limited use due to their rock mass properties. Coal-related formations often exhibit significant heterogeneity, low rock strength and unfavourable permeability, factors that contribute to underground mine instabilities and facilitate water circulation within the rock mass.

Table 3.1. Example 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 Mine layout was accessed through directional drilling technology (Hahn et al., 2018) ● Zeche Zollverein in Essen, Germany 28°C warm mine water originating from the mine drainage (Hahn et al., 2018) ● Robert Müser colliery in Bochum, Germany 20°C warm mine water originates from the mine drainage (depth of -570 m NHN) (Hahn et al., 2018) ● 7 operational mine water utilization plants in Saxony (e.g. e West Saxon University of Zwickau), Germany Shallow geothermal reservoirs (Hahn et al., 2018)
THERMAL ENERGY STORAGE	● St- Maximim, France Shallow mine (10m depth) (Philippe et al., 2019) ● Mustikkamaa caverns, Finland Former oil caverns (Blomqvist et al., 2020) ● Avesta, Sweeden Rock cavern (Bergstroem and Ekengren, 1993) ● MineWater 2.0, Netherlands Coal mine (Verhoeven et al., 2014) ● Sèvres, France Limestone mine (Arnould et al., 1983) ● Mons, Belgium Chalk mine (Montjoie, 1981)

3.3. Methodology

This study involves a comprehensive geological exploration, examination of the different potential reuse and documentation of geological and mine-related challenges pertinent to the repurposing of former coal mines for various energy production and storage technologies (e.g. UPSH, CAES, heat storage, and geothermal). Through the compilation of literature and empirical evidence concerning these challenges, a framework is established to delineate criteria influencing the selection of appropriate reuse possibilities.

Due to the large quantity of mining data, the establishment of repurposing criteria will facilitate decision criteria into the datasets essential for assessing the technical feasibility of repurposing coal mines into energy storage reservoirs. This facilitates the estimation and quantification of the extent to which a mine meets the requirements for accommodating specific energy storage technologies.

To test the potential conversion to the real conditions of a coal mine, we use the hard coal mine “Prosper Haniel” (Germany) as a study case offering a large dataset due to its long mining history (Drozdzewski, 1993; Luick, 2013, Schmidt and Barth, 2015).

3.4. Model and data

3.4.1. Geological and mining characteristics of Prosper Haniel mine

The Prosper-Haniel coal mine is located in the Ruhr area in North-West Germany (Figure 3.1). The mine covers an area of approx. 165 km² and can be accessed by a total of five sinking shafts and one inclined shaft (Table 3.2), and through 7 levels of roadways (Table 3.3). The coal mine stopped production in 2018 with the closure of level 6 (RAG AG, 2022).

Table 3.2. List of the shafts in the Prosper-Haniel coal mine (Luick, 2013).

SHAFT	**DEPTH (MBSL)**	**LENGTH (M)**	**WIDTH (M)**	**CONNECTED TUNNELS**	**APPROX. VOLUME (M3)**
HANIEL 1	530,7	600,1	6	3	16967
HANIEL 2	1007,8	1077,3	6,5	3,5,6	35748
PROSPER 9	960,5	1013,4	7,25	6	41836
PROSPER 10	1246,5	1316	8	4,5,7	66174
HÜNXE	1364	-	8	4,5	-
FÖRDERBERG	705,3	-	21,7	5	-

Since the closure in 2018, the minewater 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 (Fischer, 2015). This coal mine has previously been subject to feasibility assessments concerning its further utilization either as the underground reservoir for a UPSP (Montero et al., 2013; Niemann et al., 2018) or as a repository for heat storage (Geo-MTES, 2018). However, since its closure in 2018, no further research has been carried out to investigate a further reuse.

Table 3.3. List of the roadways in the Prosper-Haniel coal mine (data from (Luick, 2013).

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

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 (Drozdzewski, 1993). 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 (Piecha, Ribbert, and Wrede, 2008). The Horst Formation above contains more sandstones, while the Dorsten Formation at the top comprises claystones, siltstones, and thick fluvial sandstone layers (Geologischer Dienst NRW (GD), 2020).

Upper Cretaceous sedimentary strata unconformably overlay the Carboniferous units (with a slight northward tilt and increasing thickness (Littke et al., 1994; Wüstefeld et al., 2017). In Prosper 1 the Cretaceous/Upper Carboniferous boundary lies around 135m below sea level (-135 m), dropping to -304.5 m near shaft 10 (Figure 3.3).

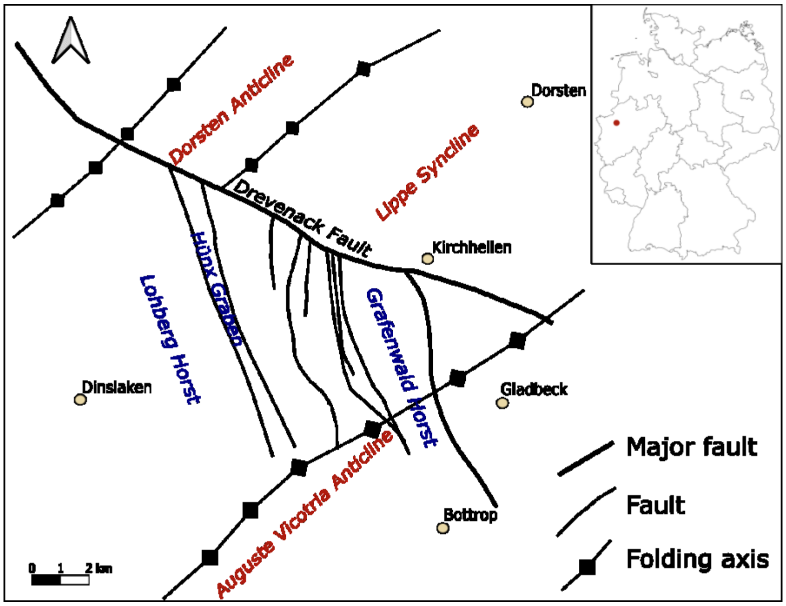
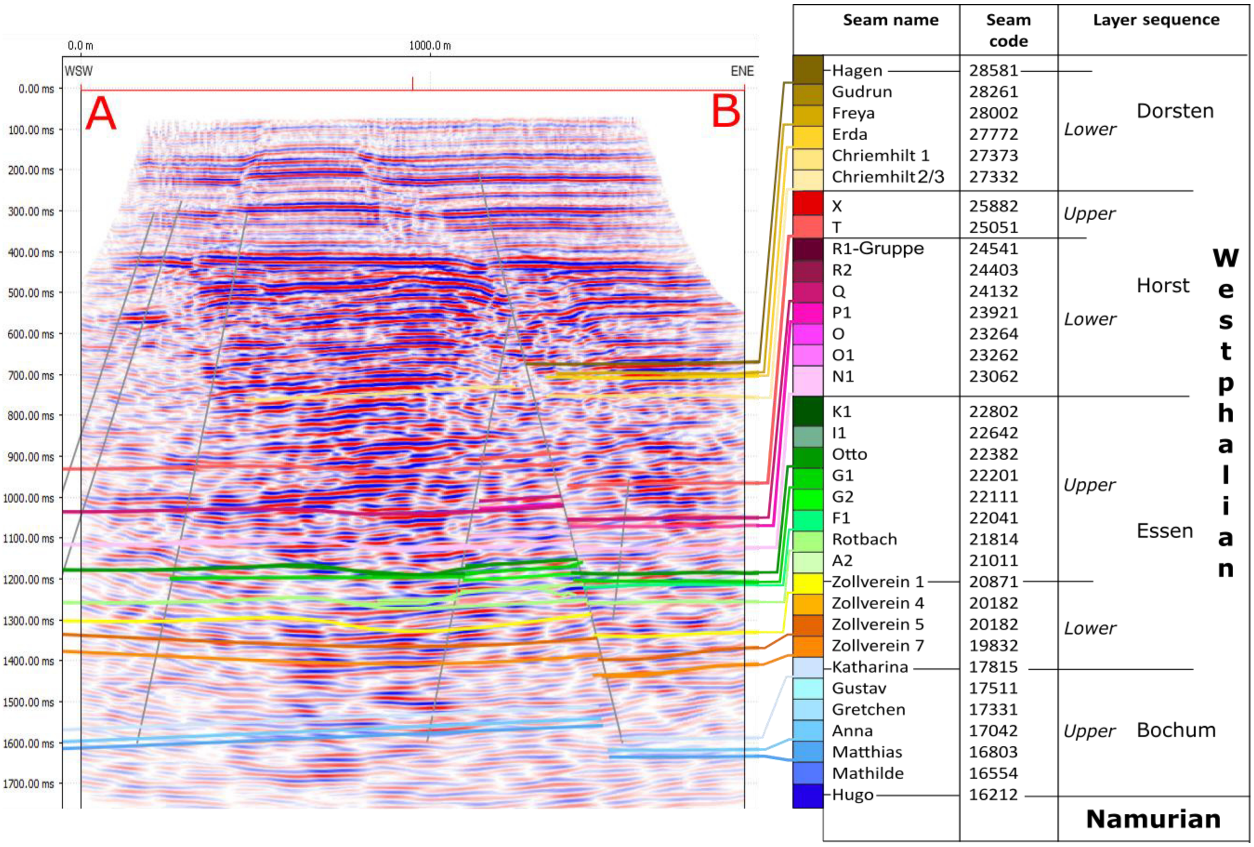


Figure 3.1. Simplified structural map of the Prosper-Haniel coal mine area.

Tectonic compression during the late Carboniferous deformed the pre-existing rock units, resulting in the formation of synclines, anticlines, and thrust faults primarily oriented southwest-northeast (Table 3.4) (Drozdzewski, 1993). Post-Carboniferous faults intersect these structures, creating horst and graben structures predominantly oriented northwest-southeast.

3.4.2. Data and boundaries

A geological model was built with Petex 3D MOVE with the purpose of visualising, analyses and enhancing the available data. The stratigraphy of the 3D geological framework model integrates data from 34 coal seams between the base of the upper Bochum Formation (Westphalian A2) to the top of the lower Dorsten sequence (Westphalian C1)(Figure 3.2). The 3D fault set included in the model comprises 230 fault planes, from which 38 main faults were defined and used for model construction. In addition, exploration boreholes including petrological data sorted by three main groups (e.g. sandstone, claystone, coal) and one 2D seismic reflection line (Figure 3.2) were included in the model. XYZ point data of levels 2, 3, 4, and 6 and parts of levels 5 and 7 were implemented in order to provide an overview of the underground mining space (Figure 3.3).



Seam name	Seam code	Layer sequence	
Hagen	28581	Lower	Dorsten
Gudrun	28261		
Freya	28002		
Erda	27772		
Chriemhilt 1	27373		
Chriemhilt 2/3	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	

Figure 3.2. 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.

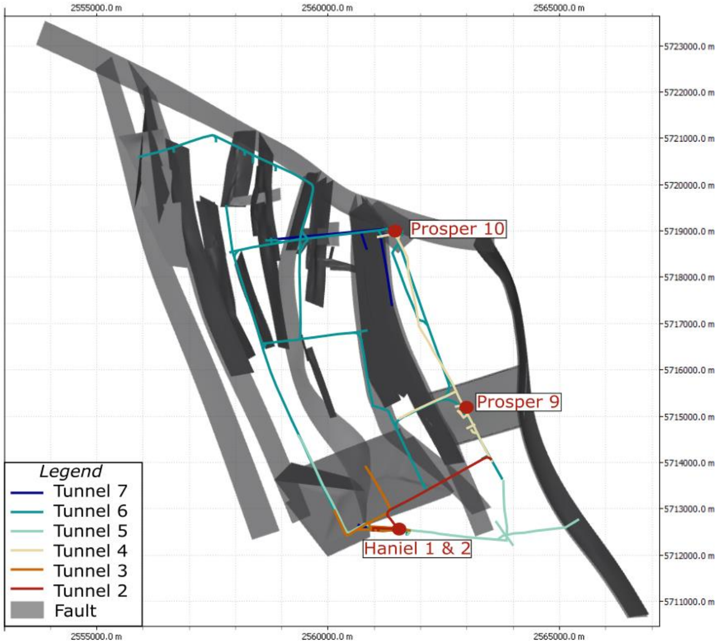


Figure 3.3. 3D-view from top onto faults and the tunnel system of the Prosper-Haniel coal mine.

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 South-West by the edge of the Auguste-Victoria Anticline (Figure 3.1). Location data for individual coal seams are available from depths between -350m to -1600 m.

3.4.3. 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 meters in the central part of the syncline to 610 meters 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 meters for the Essen formation (Figure 3.2 & Figure 3.3).

The top horizon of the Essen layer deepens from 445 meters at the syncline's edge to 1100 meters in its central region and a maximum depth of 1415 meters in the Hünxe graben. The base horizon of the upper Horst layer varies from 480 meters to 975 meters in the syncline, reaches a depth of 1210 meters in the Hünx graben and dips from 510 meters to 810 meters in the Grafenwald horst. Lastly, the top horizon of the Horst layer is situated at depths ranging from 410 meters at the Lippe Syncline edge to 760 meters in its central region (Figure 3.4).

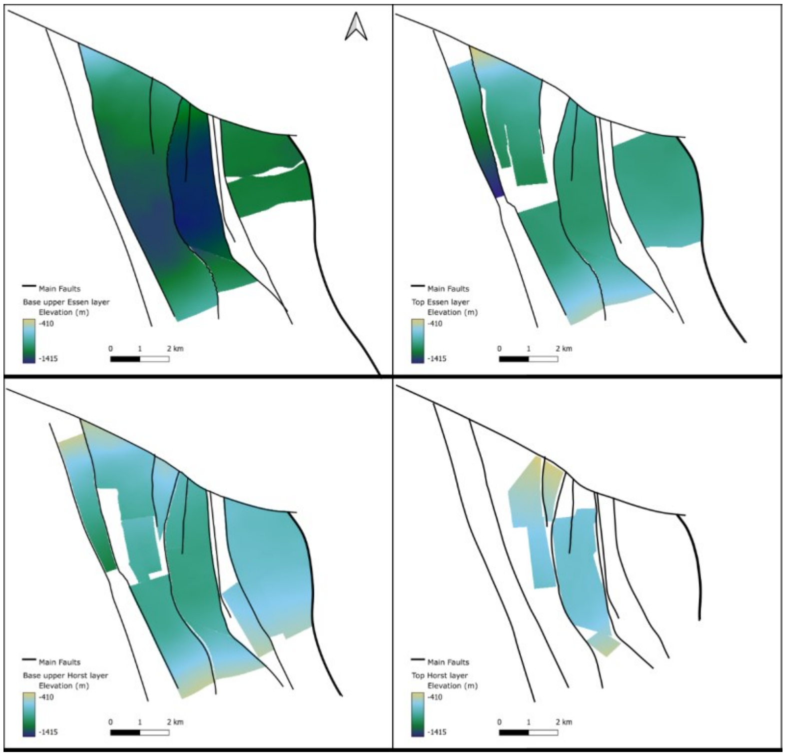


Figure 3.4. Depth map of the base of the Upper Essen layer, the top of the Essen layer, the base of the Upper Horst layer and the top of the Horst layer.

The development of a 3D geological model significantly enhances the visualization of stratigraphic, 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.

3.5. 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 3.4), CAES (Table 3.5), Heat storage (Table 3.6) and geothermal application (Table 3.7).

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 (Figure 3.5). 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 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.

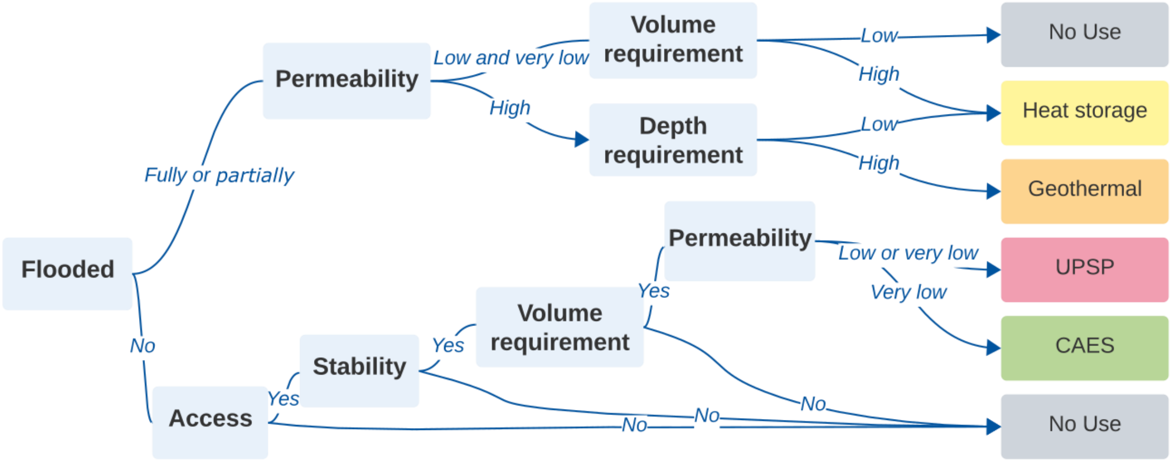


Figure 3.5. Simplified decision tree for the main requirements for heat storage, geothermal, UPSP and CAES technologies.

3.6. Reuses and their requirements

3.6.1. UPSP

The successful installation of Underground Pumped Storage Power (UPSP) 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 3.4). These include the requirement for a competent and homogeneous rock with a good understanding of the 3D distribution of the rock mass properties, fault system and potential weathered zones (Coates, 1983). The rock mass susceptibility to variations in humidity also needs a comprehensive understanding (water sensitivity, slacking, or swelling) (Özarslan et al., 2013; Luick, 2013; Colas et al., 2023).

Table 3.4. Key parameters for UPSP installation in abandoned mines from the literature.

CRITERIA	LITERATURE	UPSP CRITERIA
FLOODED	(Menendez et al., 2019a)	- Should be installed in mines that are not completely flooded
ACCESS	(Kratzsch, 1983)	- Accessibility guarantees access to the information on the mine geometry and stability
STABILITY	(Colas et al., 2023)	- Cyclical processes (wetting and drying, fatigue of the rock mass and thermal-induced stresses) can influence the reservoir's stability.
	(Menendez et al., 2019a; Zhang et al., 2021)	- The support system's deterioration might pose a major challenge to tunnel stability, especially with water presence.
	(Cerfontaine et al., 2018)	- Fatigue is critical due to fluctuating water levels and increasing overburden.
	(Sasaoka et al., 2016)	- Stability issues might happen because of the slaking phenomenon, increasing the presence of discontinuities
PERMEABILITY	(Bodeux et al., 2016; Bodeux et al., 2017)	- Groundwater interactions can influence UPSP operation
DEPTH & VOLUME	(Luick, 2013; Pikl et al., 2019b)	- Critical considerations involve assessing the underground reservoir's volume and depth, with tunnel selection heavily influenced by slope orientation toward shafts.

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 (Coates, 1983; Cerfontaine et al., 2018; Colas et al., 2023).

Moreover, productivity is the economic factor influencing decision-making in UPSP 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 (Luick, 2013; Pikl et al., 2019a).

Finally, other aspects need to be considered for the long-term success of the installation such as the ventilation system of the underground reservoir (Xue et al., 2020), the groundwater chemistry and hydrochemical effects (Schnepper et al., 2024) or mine gas-related issues (Colas et al., 2023).

3.6.2. Compressed air energy storage

The primary prerequisites for the successful implementation of a CAES system require having an airtight, dry and stable underground reservoir (Table 3.5). 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 strength 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 (Chen and Wang, 2022; Kim et al., 2023; Schmidt et al., 2024). 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 (Zhou et al., 2017; Schmidt et al., 2024). 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 (Lutyński, 2017).

Table 3.5. Key parameters for CAES in abandoned mines from the literature.

CRITERIA	LITERATURE	CAES CRITERIA
FLOODED	(Lutyński, 2017)	- Problems of water inflow and reduction of volume by reusing flooded mines
ACCESS		
STABILITY	(Perazzelli et al., 2014)	- Very large deformations can happen in weak rocks via (numerical analysis).
	(Kim et al., 2013; Kim and Changani, 2016)	- Focus on fractured zones, from mining, as they increase permeability and air leakage risk.
	(Chen and Wang, 2022; Schmidt et al., 2024)	- 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	(Di Wu et al., 2020)	- The rock permeability might need to be reduced essentially to reduce air leakage during the operation.
	(Menendez et al., 2019a).	- It is recommended to target a homogeneous, impermeable rock mass.

The tunnel or shaft's shape and condition can significantly affect the needed concrete lining volume, concrete bulkheads or steel lining potentially offering cost advantages during construction (Schmidt et al., 2024). 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 (Lutyński and Kołodziej, 2024).

3.6.3. Heat storage

The successful reuse of coal mines as heat storage reservoirs requires firstly 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 (Perez Silva et al., 2022; Silva and McDermott, 2023)(Table 3.6). 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 (Geo-MTES, 2018).

Table 3.6. Key parameters for heat storage in abandoned mines from literature.

CRITERIA	LITERATURE	HEAT STORAGE CRITERIA
FLOODED & ACCESS	(Rodríguez and Díaz, 2009)	- The coal mine must be flooded
	(Philippe et al., 2019)	- Efficiency of thermal storage in a partially flooded underground cavity
STABILITY	(Ferket et al; Rodríguez and Díaz, 2009; Bücken et al., 2022)	- Temperature difference between the reservoir and injected water may induce thermal stress in the reservoir and fault reactivation
PERMEABILITY	(Hamm and Bazargan Sabet, 2010; Burnside et al., 2016)	- The mine must exhibit favourable, alongside control of water circulation within the rock mass.
	(Smith et al; López and Smith, 1995; Hahn et al., 2019)	- An understanding of stratigraphy and fault systems is necessary to map potential hydraulic paths or barriers for estimating regional water circulation.
	(Menéndez et al., 2019)	- Shaft stability and permeability to prevent heat loss during injection or pumping.
DEPTH & VOLUME	(Menendez et al., 2019b)	- The tunnel geometry must be known to assess the potential volume of the reservoir

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 (Bonte et al., 2011), changes in water viscosity (Zeghici et al., 2015) and in water chemistry.

3.6.4. Geothermal

Similar to heat storage, the hydrogeological characteristics of the reservoir constitute the primary criteria (e.g. flooded mine with good permeability and stable fault system)(Table 3.7).

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 (Jardón et al., 2013; Rudakov and Inkin, 2022).

Table 3.7. Key parameters for geothermal re-use of abandoned mines from literature.

CRITERIA	LITERATURE	GEOTHERMAL CRITERIA
FLOODED & ACCESS	(Menendez et al., 2019a)	- Require flooded mines, which generally have closed more than 5 years ago
STABILITY	(Andrews et al., 2020).	- 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	(Jardón et al., 2013; Rudakov and Inkin, 2022).	- 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

3.7. Identification of the key dataset

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 or regional geological surveys. By compiling and weighing these datasets, we ascertain the essential datasets required for constructing a robust geological model (Table 3.8). This process facilitates the identification of critical parameters crucial for assessing the coal mine's geological profile.

Table 3.8. Importance of dataset for each application.

	Data	**UPSP**	**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	++	++	+	-

3.7.1. Key data for UPSP

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 (Niemann et al., 2018; Gonzalez de Lucio, Gabriela de los Angeles et al., 2020). In the Prosper-Haniel case, the stratigraphy is built with available mining data (coal seams bed) (Figure 3.4), geological exploration borehole data (lithology)(Figure 3.3) and reconnaissance seismic-reflection data (Figure 3.2). The available data are combined in a 3D model that can contain as property e.g. the rock strength, the porosity, permeability, or the elasticity (Özarslan et al., 2013). For example, the sandstones from the Upper Carboniferous in the Prosper-Haniel coal mine are generally fine-grained (Kasielke, 2015, Lippert, 2017) with a mean porosity of 6% (Koch et al., 2011; Wüstefeld et al., 2017) and a mean permeability of $<10^{-18}m^2$ (Kruszewski et al., 2021). Any spatial change of rock type (e.g. from claystone to sandstone and coal) increases the extrapolation uncertainty and reduces the general rock mass strength. Stress measurements have been conducted, and research has developed static 3D geomechanical models to predict the spatially continuous distribution of undisturbed in situ stress states and evaluate the reactivation risk of major fault zones, with findings indicating that the major horizontal stress aligns NW-SE. (Heidbach et al., 2018; Kruszewski et al., 2021; NRW G, 2024). In addition, rock slope stability in coal-measure rocks is influenced by coal-coated discontinuities, with friction angles ranging from 10° to 40° depending on joint cleanliness (Alber and Fritschen, 2011; Alber and Schwarz, 2015). Incorporating in-situ stress field data, the friction angle of the discontinuities, the coefficient of lateral pressure (Zillmann and Perau, 2015) and seismic event catalogues would provide insights into the stress field and faults stability. 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 (Ewert, 2019).

An important task is to include man-made features in the geological 3D model to calculate the available volume in line with the geological requirements (avoiding unstable areas). The determination of the geometry (size and shape of the tunnels), their connection to shafts and the slope orientation can be readily done in the model (Montero et al., 2013; Montero et al., 2016). Specifically for Prosper-Haniel, the level 6 of the mine would present a promising UPSP volume in horse-shoe shape (approx. 680,000 m^3) at a depth between -902 and -960 m connected to 3 shafts (Haniel 2, Prosper 9 and 10) and with a favourable slope (1 to 2°) dipping towards the shafts (Luick, 2013) (Figure 3.3).

3.7.2. Key data for CAES

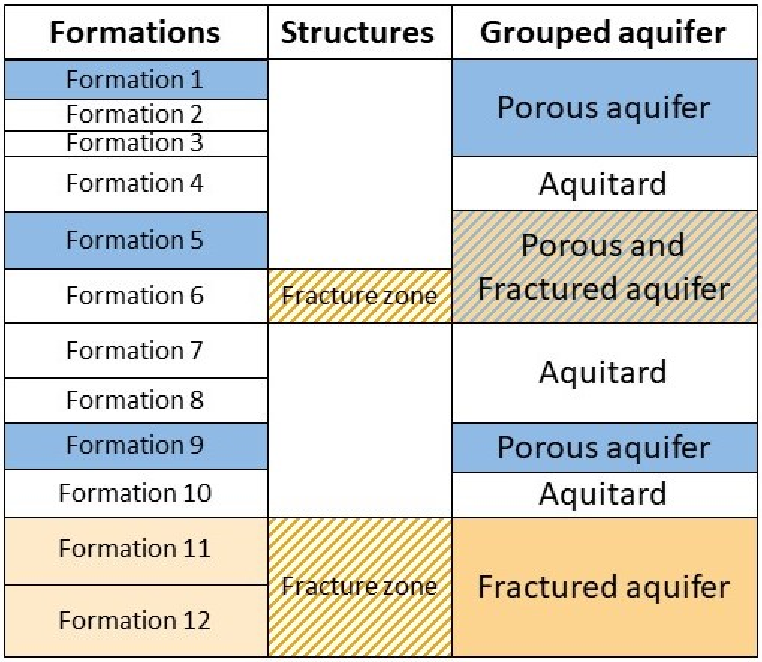
Incorporated in the 3D geological model of PH, the tunnel geometry can be used to measure the potential volume available above the current or planned water table (580 mbsl by 2035). In addition, the exploration boreholes, the stratigraphy and the fault system (Figure 3.3) offer a 3D spatial distribution 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 the EDZ.

Additionally, similar to UPSP 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 (Figure 3.4) 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.

3.7.3. Key data for heat storage & geothermal exploitation

The feasibility of the reuse of Prosper-Haniel for heat storage has been studied with a strong focus on groundwater modelling with a 3D numerical groundwater flow and heat transport (Bracke and Bussmann, 2015; Geo-MTES, 2018). The aim is to ensure a lifetime of 40 to 50 years of seasonal heat storage (Bracke et al., 2019). The construction of a 3D geological model as a framework for numerical modelling includes data on the stratigraphy, faults system and tunnel geometry (Figures 3.1, 3.2 and 3.4). In order to build the groundwater model, groundwater contour maps (Rüber, 1995) and hydro-stratigraphic units (Figure 3.6) were implemented. In addition, the fault system and deformation zones were studied (Aydin and Johnson, 1978, 1983; Faulkner et al., 2010; Geo-MTES, 2018) to characterise the nature of the filling (e.g. clay content) (Coldewey and Wesche, 2017), the geometry of the faults (e.g. strike, dip, length, with), and their connection to permeable formation. Water discharge measurements from fault zones documented over time example rates of approx. 1.2 m^3 min -1 and 0.1 m^3 min-1, were also taken into account in the model.

A similar model is necessary for geothermal applications. However, because the area triggers interest in several geothermal projects and because the water recharge needs to be understood, the model needs to analyse 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. (2021) 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.



Formations	Structures	Grouped aquifer
Formation 1		Porous aquifer
Formation 2		
Formation 3		
Formation 4		Aquitard
Formation 5		Porous and Fractured aquifer
Formation 6	Fracture zone	
Formation 7		Aquitard
Formation 8		
Formation 9		Porous aquifer
Formation 10		Aquitard
Formation 11	Fracture zone	Fractured aquifer
Formation 12		

Figure 3.6. Schematic representation of formations/rock units, structure and hydrostratigraphic units important for heat storage and geothermal exploitation (modified after Geo-MTES, 2018).

A study in 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 (Bücken et al., 2022). The Prosper-Haniel mine reaches a depth of 1,013.1 m (Shaft 9) and 1,316.5 m (-1,246.5 m NN)(shaft 10) in the Upper and Lower Essen strata. At that depth a temperature of 45C° is expected (Hahn and Bussmann, 2015) while the loading temperature ranges between 90C° to 135C°.

Therefore, thermal stress is expected and must be studied. Utilising 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 (Kruszewski et al., 2021) must be conducted to assess potential fault reactivation, which may induce seismic events.

3.8. Conclusions

We have explored multifaceted considerations surrounding the repurposing of abandoned mines for energy storage, with a focus on Underground Pumped Storage Power (UPSP), Compressed Air Energy Storage (CAES), heat storage, and geothermal applications. Through a comprehensive literature review, we have identified key parameters for the successful implementation of such technologies, including flooding conditions, accessibility, volume, depth, permeability, and the stability of underground infrastructure.

We use the case study of the Prosper Haniel coal mine providing insights into the characteristics of underground coal mines and the associated dataset. The construction of a 3D geological model further aids in visualizing the compilation of the stratigraphy and tectonic structures and mining data.

Emphasizing the significance of compiling and repurposing relevant datasets underscores the necessity of informed decision-making in utilizing abandoned coal mines as energy storage reservoirs. Research on uncertainty estimation (for example, using information entropy and Bayesian inference) helps quantify and reduce uncertainties in these datasets. This ensures more accurate, reliable decisions for repurposing these sites, enhancing their feasibility and safety (Wendebourg et al., 2020). However, to fully harness their potential, further research is imperative. This includes refining parameters, enhancing decision-making models, and leveraging advanced data analytics to maximize efficiency and sustainability.

Furthermore, to advance our understanding and utilization of underground coal mines as energy storage solutions, efforts are needed in several key areas. Firstly, interdisciplinary research initiatives should be encouraged to investigate the interplay between surface constraints and underground conditions. This necessitates conducting comprehensive studies that integrate geotechnical, geological, and economic analyses to provide an understanding of the feasibility and potential challenges associated with repurposing abandoned mines.

Moreover, enhancing 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 take into account factors such as site accessibility, geologic complexity, and infrastructure requirements. By accurately assessing the financial implications of repurposing underground coal mines, decision-makers can identify opportunities to optimize project budgets and secure funding.

In summary, achieving a comprehensive understanding of the reuse of underground coal mines for energy storage requires a multifaceted approach that encompasses technical expertise, interdisciplinary collaboration, and advanced decision support systems. By addressing these challenges and leveraging emerging technologies, we can unlock the full potential of abandoned mines as valuable assets in the transition towards a more sustainable and resilient energy infrastructure.

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CHAPTER 4
GENERAL CONCLUSIONS AND OUTLOOK

4.1. General Conclusions

The research presented in this thesis focused on the geological and structural factors that influence the feasibility of repurposing the Prosper-Haniel mine and similar abandoned coal mines for sustainable energy storage solutions. The study addressed the following key points:

1. **Understanding Cyclical Geological Processes**

Cyclical processes in abandoned coal mines were investigated with respect to their influence on the stability of underground pumped storage plants (UPSP). These processes include time-dependent processes caused by changes in humidity and cyclic wetting and drying (e.g. weathering, dissolution, hydration, leaching, swelling, slacking, creeping, precipitation, corrosion). Cyclic wetting and drying cause significant deterioration in rock types like clay, mudstone, and sandstone, leading to disintegration and reduced tensile strength. These processes also include cyclic loading and stress re-distribution (subsidence, fatigue, cyclic loading, support system degradation, thermal stresses). Cyclic loading from fluctuating water pressures can lead to sub-critical crack growth and fatigue failure over time. Thermal-induced fracturing from cold water circulation creates tensile stresses, causing spalling, fractures, and thermal fatigue. Finally, water exchanges due to pumping and discharge cycles affect reservoir volume, efficiency, and hydrochemical conditions in the surrounding aquifer. These processes critically influence the hydro-mechanical conditions and long-term stability of UPSPs, requiring advanced engineering solutions for durability and efficiency.

2. **Geological modelling**

A comprehensive 3D geological model of the Prosper Haniel mine was developed to analyze the geological parameters influencing the feasibility of mine repurposing. The construction of 3D model gives a good understanding of the geological and mining conditions of the mine. This model provided critical insights into the stratigraphy, tectonic structures, and mining impacts, demonstrating the importance of understanding cyclical geological processes. In addition, it offers a good overview of the availability and applicability of the existing data for potential feasibility study on different application (e.g. UPSH, CAES, heat storage, geothermal heat production).

3. **Geological and Mining Challenges**

The analysis of the Prosper-Haniel mine as case study, complemented by literature analysis of other European coal mines, highlighted significant geological challenges, including heterogeneous rock mass conditions, low rock strength, and unfavorable permeability for coal-mine re-use. These factors pose risks to the long-term stability and water tightness required for the repurposing of mines into energy storage facilities. The Prosper-Haniel mine, in particular, exhibited complex structural geology, which necessitated a detailed understanding of its subsurface characteristics to ensure safe and effective repurposing.

The Prosper-Haniel mine implemented rigorous safety measures and gas monitoring protocols. This included gas pre-drainage for coal panels and the installation of degassing equipment. Post-mining, gas drainage continues with a comprehensive plan for controlled degassing, ensuring the safe closure of the mine. The implementation of these measures has been crucial in maintaining safety and environmental compliance, setting a precedent for future mine repurposing projects.

4. Potential Applications and Criteria for Success

The Prosper-Haniel mine serves as a case study for developing a general framework for the reuse of abandoned coal mines. Utilizing a 3D model and feasibility studies on the Prosper-Haniel mine, which explore the potential for converting abandoned coal mines into underground pumped storage plants (UPSP) (Luick, 2013; 2014; Niemann, 2019) and heat storage reservoirs (Geo-MTES, 2018), we have identified key criteria essential for successful repurposing. These criteria include ensuring structural integrity, maintaining effective productivity, and ensuring environmental protection. Building on the literature and our understanding of the Prosper-Haniel mine, we expanded the potential applications by establishing criteria for compressed air energy storage (CAES) and geothermal applications. This framework can be applied to other sites, providing guidelines for the assessment and implementation of energy storage solutions.

The repurposing of abandoned coal mines offers a sustainable solution to energy storage challenges. By converting these sites into UPSP, CAES, heat storage, and geothermal energy facilities, we can leverage existing infrastructure to meet growing energy demands while minimizing environmental impact. This approach aligns with global efforts to transition towards renewable energy sources and reduce greenhouse gas emissions.

4.2. Outlook

Overall, this study has demonstrated the potential for assessing and repurposing abandoned coal mines for sustainable energy storage applications. However, further research is recommended to enhance the understanding and implementation of these solutions:

1. Detailed Geological and mining analysis

Continued analysis of geological and structural conditions in other potential repurposing sites to develop more generalized criteria for mine repurposing. This will enhance our understanding of how underground characteristics influence construction costs is paramount for ensuring the economic viability of energy storage projects in abandoned coal mines. Quantitative assessments of critical geological and mining processes, such as concrete and support system fatigue, cyclical thermal stress induced by small temperature fluctuations and wave propagation are essential to evaluate their implications on system stability and productivity.

2. Advanced Monitoring Techniques

Implementation of advanced monitoring techniques to ensure ongoing safety and environmental compliance during and after repurposing. Integrating these environmental monitoring methods and geospatial data allows for the accurate assessment of site stability, resource availability, and potential hazards. This evaluation is essential to ensure the feasibility, safety, and efficiency of repurposing efforts, transforming former mining sites into sustainable energy storage solutions while mitigating environmental risks.

3. Integration of New Technologies

Exploration of innovative technologies and methodologies to improve the efficiency and feasibility of energy storage solutions in repurposed mines. Further research on uncertainty estimation, such as the application of information entropy, plays a crucial role in quantifying and mitigating uncertainties within these datasets. to fully realize the potential of these methodologies, further research is imperative. It focus on refining parameters, improving decision-making models, and utilizing advanced data analytics to optimize efficiency and sustainability.

4. Interdisciplinary research initiatives

The investigate of the interplay between surface constraints and underground conditions necessitates conducting comprehensive studies that integrate geotechnical, geological, and economic analyses to provide a complete understanding of the feasibility and potential challenges associated with repurposing abandoned mines. By combining the expertise from various fields, these initiatives can identify critical factors that impact the stability, safety, and economic viability of repurposing projects. Such collaborative efforts are essential for developing innovative solutions that address complex issues, ensuring that repurposing strategies are both practical and sustainable.

5. Policy and Regulatory Framework

Development of a robust policy and regulatory framework to support the safe and effective repurposing of abandoned mines for sustainable energy applications.