Unlocking the Geothermal Potential of Abandoned Flooded Mines: A Path to Renewable Energy and Regional Revitalization in Wallonia, Belgium – Methodology and Modeling Approaches

Virginie Harcouët-Menou[1], Nicolas Dupont[2], Olivier Kaufmann[2], Edgar Hernandez[1], Philippe Orban[3], Caroline De Paoli[3], Yanick N'Depo[2], Thierry Martin[2], Gert Moermans[1], Thomas Neven[1], Clémentine Schelings[4], Jacques Teller[4], Alain Dassargues[3], Thomas Waroux[5]

[1]*VITO, Boeretang 200, 2400 Mol, Belgium, virginie.harcouet-menou@vito.be, ORCID 0000-0001-7250-8581*

[2]*Geology & Applied Geology, Faculty of Engineering, University of Mons, Rue de Houdain 9, 7000 Mons, Belgium, nicolas.dupont@umons.ac.be, ORCID 0000-0003-4938-8686*

[3]*Hydrogeology & Environmental Geology, Urban & Environmental Engineering Unit, University of Liège, Quartier Polytech 1, Allée de la Découverte, 9, Bât. B52 – Sart Tilman 4000 Liège, Belgium, p.orban@uliege.be, ORCID 0000-0002-4338-0870*

[4]*LEMA, Urban & Environmental Engineering Unit, University of Liège, Quartier Polytech 1, Allée de la Découverte, 9, Bât. B52 – Sart Tilman 4000 Liège, Belgium, clementine.schelings@uliege.be, ORCID 0000-0001-7718-4539*

[5]*Town and Regional Planning, Faculty of Architecture and Urban Planning, University of Mons, Rue d'Havré 88, 7000 Mons, Belgium, thomas.waroux@umons.ac.be, ORCID 0009-0004-7043-6827*

Abstract

Geothermal energy from mine water can transform former mining regions into renewable energy hubs, supporting 5th generation heat networks. Wallonia, with its rich coal mining history, is well-suited for this approach. A 2019 study identified strong geothermal potential in the Couchant de Mons, Charleroi, and Liège basins, leading to three feasibility studies. These highlighted both opportunities and limitations of geothermal mine water projects, depending on demand and subsurface conditions. The most promising site in the Liège basin was selected for a pilot project to showcase how abandoned flooded mines can drive the energy transition, offering sustainable energy and storage while revitalizing post-mining areas in Wallonia.

Keywords: Mine water, geothermal, modelling, potential assessment

Introduction

The transition to sustainable energy as alternative to fossil fuel sources requires innovative solutions to meet growing energy demand while reducing environmental impacts. Geothermal energy from mine water represents a promising opportunity, repurposing abandoned flooded mines as geothermal energy sources and reservoir for seasonal thermal storage. Ideally this geothermal source is integrated into 5th generation energy networks to ensure high efficiency of this solution. These flexible networks allow buildings to exchange heat and cold with each other through a low-temperature grid, using smart controls to balance energy needs efficiently.

Belgium's Walloon region, with its coal mining history, has shown strong interest in this energy system. A key milestone was the 2019 regional study assessing the geothermal potential of mine water for energy production and storage (Dupont *et al*. 2021). This study laid the foundation for detailed feasibility studies of pilot projects in the coal districts of Liège, Couchant de Mons and Charleroi.

This paper presents a methodology for regional geothermal mine water potential assessment and site-specific feasibility studies. It explores models integrating subsurface characteristics and energy demand to optimize production and storage and discusses the modelling methods.

Estimation of the geothermal potential of mine water at the regional scale in Wallonia

The methodology used to estimate the potential of the Walloon coal mines developed by Dupont *et al.* (2021) is summarized in this section. In general, to estimate the geothermal potential of mine water a series of parameters must be defined, the methodology varies depending on the investigated scale and the energy use considered (heating, cooling or both).

At the project scale, geothermal potential can be estimated using key parameters like accessible water volume, temperature range, reservoir connectivity, and flow rates (Verhoeven *et al.* 2014). This requires detailed mining and hydrogeological data.

For mapping geothermal potential on the Walloon region scale, the large number of mine plans (tens of thousands) and limited hydrogeological data make this approach impractical. Thus, only mining void volumes and temperature ranges are considered key parameters as the accessible water volumes and their temperature are assumed to be derivable from these parameters.

The applied approach uses the number of exploited coal seams (n) per unit area as a proxy for mining void volumes, assuming homogeneous average thickness of a coal seam at basin's scale.

For minimum and maximum temperatures, the proxies used are the minimum and maximum mining depths for each unit area, respectively (*depth_min and depth_max*). This approach assumes a uniform geothermal gradient of 30°C/km across the Walloon coal basins, which is generally valid for this region.

The source data used to determine the geothermal potential of mine waters are the cross-sections of the "Mining Administration", drawn every 100 meters from east to west at a scale of 1:5000. In practice, all cross-sections were examined and sampling was carried out using a 100 m grid. This resolution allows for a local to highly localized assessment of geothermal potential.

After data acquisition and validation, the information was imported into a Geographic Information System (GIS) for spatial analysis. Fig. 1 illustrates the maximum extraction depths obtained for eastern Wallonia and the number of exploited coal seams in the same area.

With the aim of utilizing mine water for both heating and cooling potential, the following proxy was selected to estimate the

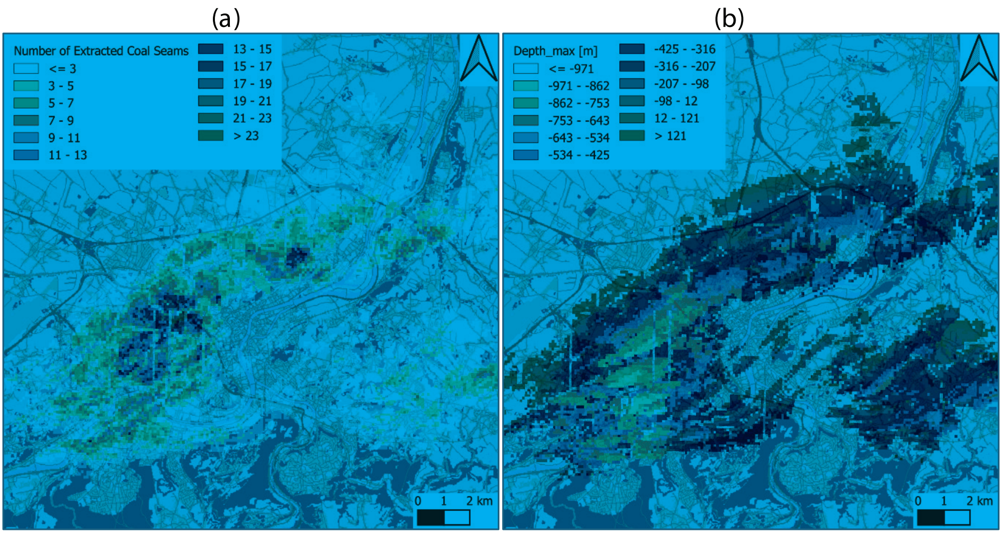

Figure 1 (a): Distribution of maximum extraction depths in the Liège district. (b): Distribution of the number of extracted coal seams in the Liège district. Source: Dupont et al. *2021.*

geothermal potential: (*depth_max –depth_min*) * n. Simplified, this proxy represents the total recoverable energy within a 100 m grid cell. The distribution of the geothermal potential proxy for mine water in eastern Wallonia is illustrated in Fig. 2a (left part).

By definition, the proposed proxy for representing the geothermal potential of mine water is a local measure, reflecting conditions at each sampled point. To scale up potential estimates for hypothetical geothermal mine water projects, a decision-support tool was developed for site selection. The approach assumes a simplified 5th-generation network, including a deep well (hot) and a shallow well (cold) connected to a backbone (primary network) within a defined radius.

Given the adopted simplifications, for a hypothetical site connected to such a system, the maximum geothermal potential of mine water is estimated by determining the minimum and maximum extraction depths within the radius and integrating the number of exploited coal seams:

$$\textit{proxy of "Site" geothermal potential of mine water} = \frac{(depth\_max - depth\_min).\sum n}{\int search\ area}$$

In Fig. 2a (right part), the “site” potential estimated for a radius of 800 m is illustrated. This methodology enables us to highlight the most favorable areas for implementing geothermal projects using mine water connected to 5th-generation networks. The exercise was conducted for the main coal districts in the region. The study's key finding is that, under conservative assumptions, Wallonia has the technical subsurface potential to develop several geothermal projects like the pioneering geothermal project using mine water in Heerlen.

Feasibility studies in the Walloon coal basins: Liège case study

Based on this positive geothermal potential regional evaluation, in 2021, the Walloon Administration launched three feasibility studies for pilot geothermal projects using mine water in the three most significant mining districts, namely Couchant de Mons, Charleroi, and Liège basins.

The main difference between the regional-scale potential study and local feasibility studies lies in considering surface demand, local reservoir detailed mapping and modelling. A similar methodology has been followed for the three studies (Fig. 3).

First, basin-scale assessments were conducted, progressively narrowing down to identify the most promising locations for potential pilot projects in each basin. This process involved aligning the mine’s geothermal potential with surface demand.

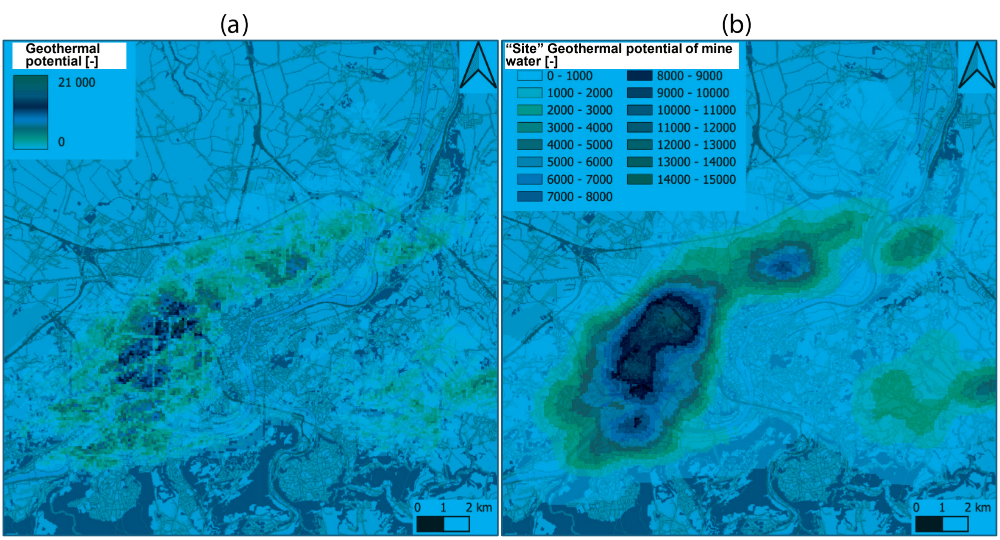

Figure 2 *(a): Distribution of the geothermal potential of abandoned flooded mines in the Liège District. (b): Distribution of the "Site" geothermal potential of mine water in the Liège district for a radius of 800 m. Source: Dupont* et al. *2021.*

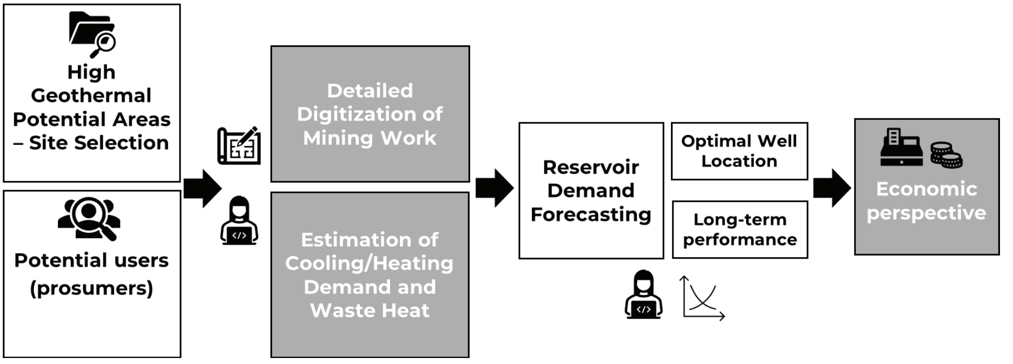

Figure 3 *Methodology for conducting the feasibility studies.*

For each basin, three potential pilot locations were evaluated with the most viable one chosen for a detailed feasibility study. Fig. 4 presents the conceptual design developed for the mine water project as part of the feasibility studies.

Second, surface and subsurface data related to the site's perimeter was collected and synthetized. The heat and cold prosumers to be connected were identified as well as their demand profiles. The model of the mine reservoir was elaborated by digitizing and conceptualizing the geometry of the interconnected galleries, shafts, and extracted coal panels of the flooded mine in the fractured Westphalian formations. This step is time-consuming but essential to describe the mine reservoir as realistically as possible to ensure the reliability and robustness of the results and its behavior under defined exploitation scenarios.

Two modeling approaches were then used to predict the reservoir's behavior (Fig. 5). One assumes that flow occurs mainly through mine galleries, considering only the interconnected gallery network. In this case, wells must target these galleries and are linked exclusively through this network. A second approach is a numerical model that includes both galleries and mined panels as well as the host rock, treating the system as a multi-domain discretized porous media similar to the discrete fractured network approach (Karimi-Fard *et al.* 2004). Here, wells can target either galleries, mined panels, or both. These two approaches are complementary. The first enables rapid screening and well placement optimization, allowing numerous simulations in a short time but simplifying fluid-rock interactions. In contrast, the second approach better represents complex thermal and hydrological exchanges within the reservoir, considering

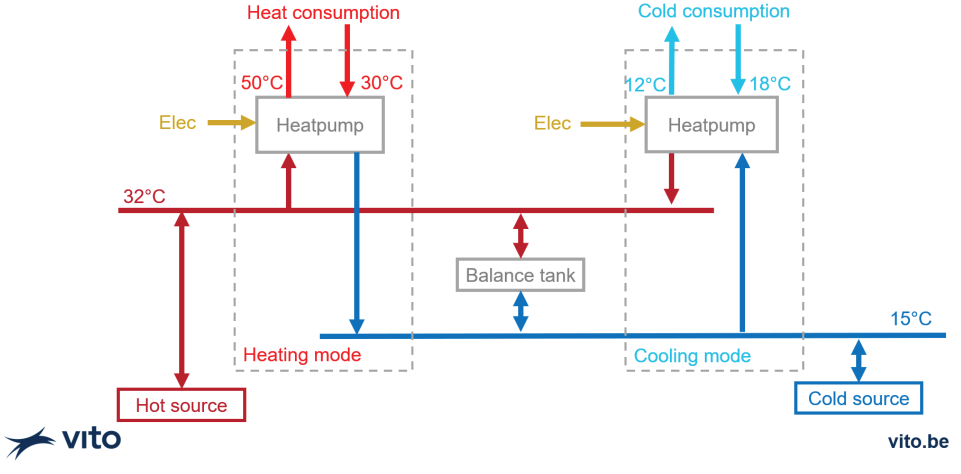

Figure 4 *Conceptual design of the investigated mine water geothermal system, called GEOMINE system.*

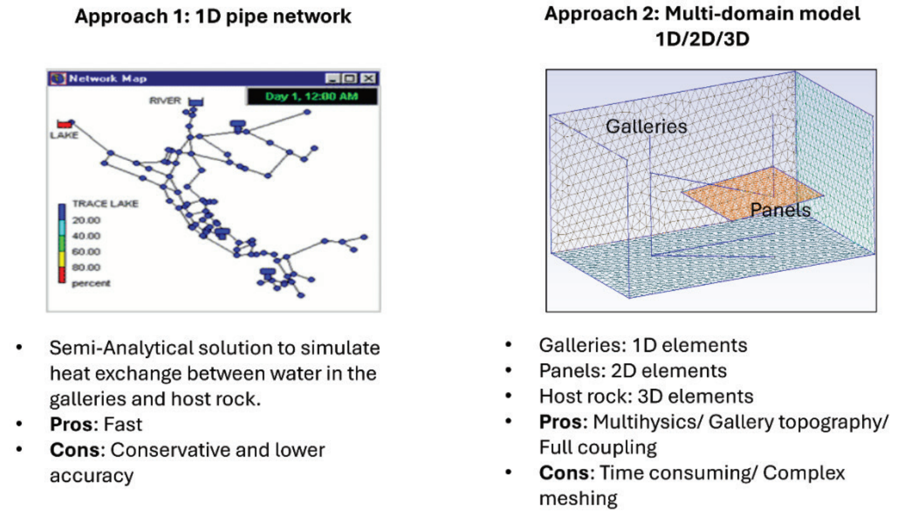

***Figure 5** Modelling approaches followed in the feasibility studies.*

the geological properties governing heat transfer and fluid flow.

The first simulations, coupled to Python optimization scripts, enabled us to identify and optimize the positioning of the wells of the geothermal system. A modified in-house version of the open-source code EPANET is used to run the simulations. It requires the network of galleries, shafts, blind shafts, and other connecting mine structures as input to accurately define the reservoir geometry. This model can be used as well to evaluate, in a conservative way, the project's sustainability by assessing the thermal breakthrough risks for defined production scenarios. Results provide essential insights for planning, risk management and system design.

The second approach simulates coupled groundwater flow and heat transfer. In this case, the 3D highly heterogeneous rock domain is complemented with discrete 1D and 2D elements representing mine galleries

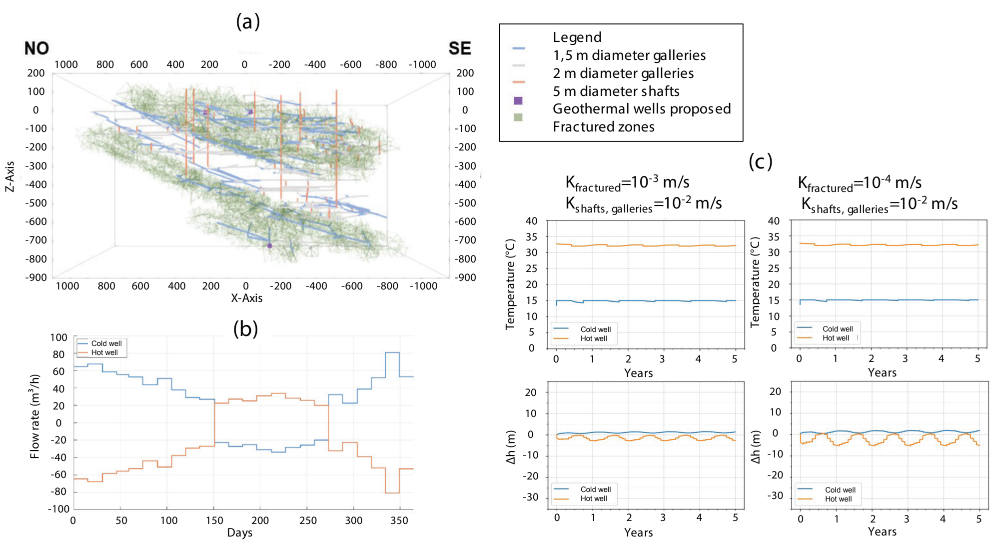

***Figure 6** (a): Representation of the mine reservoir. (b): Example of demand flow profiles. (c): Resulting simulated production temperature and head variations at the two wells of the system over a 5-year period for defined hydraulic properties of existing shafts and galleries of the mine reservoir and of fractured zones resulting from coal exploitation.*

and panels respectively. Feflow© is used to allow temperature-dependent density and viscosity, in a complex 3D heterogeneous domain. This second approach allows to test additional options for the wells, such as wells targeting panels, galleries or both. Its main drawback lies in the time-consuming nature of the simulations and the complexity of the required meshing procedure.

For wells targeting galleries, the results in terms of production temperature and head variations of the two approaches are relatively similar in case the host rock is considered as very low permeability. The main difference is the head response at the wells of the system, which is generally lower when considering the host rock, due to diffuse flow in the rock that is not considered in the first model.

The response in temperature and in head for a realistic demand scenario in the Liège's case is illustrated in Fig. 6. The system concept foresees using a reversible heat pump and a geothermal doublet. Hot water is pumped from the deepest parts of the open network, and cold water is re-injected at 15 °C in the shallower parts comprising galleries or fractured rocks. A seasonal inversion is planned to cool the buildings during summer, considering reinjection of hot water at 32 °C. Overall, production temperatures remain relatively stable, and the expected pressure variations are acceptable for the modeled scenarios. The surface demand can be fulfilled by the GEOMINE system.

One of the lessons learned is that the main challenge to design the whole geothermal project and to assess its future efficiency is the uncertainties inherent to such a highly heterogeneous underground reservoir, such as: the permeability in backfilled mine wells, extension and location of fractured zones and permeability of panels. They can impact the simulation results of short-, mid-, and long-term temperature evolution in pumping and injection zones. This case study highlights the importance of relying on modeling approaches using detailed mine data to provide reliable predictions. Uncertainties in temperature, pressure, and flow rates affecting GEOMINE design and operation should be addressed in the follow-up exploratory phase.

Conclusion

This paper outlines the Walloon region's approach to demonstrating how abandoned mines can drive the energy transition, provide sustainable energy and storage solutions, and revitalize post-mining areas. The region adopted a step-by-step strategy, beginning with a regional potential assessment, followed by multiple feasibility studies. The presented work has major implications for renewable energy in former mining regions. In Liège, the implementation of the proposed project is expected to cut CO_2 emissions by 55–72% and reduce primary energy consumption by 31–44%. The findings have led to a call to implement a pilot geothermal project at the location of the Liège selected site, which intends to serve as a model for similar initiatives across Wallonia or Europe. This research highlights the potential for abandoned mines to play a central role in the energy transition, providing both a sustainable energy source and storage solution while addressing environmental and economic challenges in post-mining areas.

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