Sustainable Energy Technologies and Assessments 86 (2026) 104853

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Original article

Feasibility of Fifth-Generation district heating and cooling using mine water in Belgium: A Multi-Site Techno-Economic assessment

Sesil Koutra [a,*], Virginie Harcouët-Menou [b], Nicolas Dupont [c], Olivier Kaufmann [c], Vincent Becue [a], Shady Attia [d]

[a] Faculty of Architecture and Urban Planning, University of Mons, St. Havré 88, 7000 Mons, Belgium
[b] Flemish Institute for Technological Research (VITO), Boeretang 200, 2400 Mol, Belgium
[c] Faculty of Engineering, Fundamental and Applied Geology, University of Mons, St. Houdain 9, 7000 Mons, Belgium
[d] Sustainable Building Design Lab, Dept. UEE, Faculty of Applied Sciences, University of Liège, Liège, Belgium

ARTICLE INFO

Keywords:
District Heating/Cooling System
Decarbonization
Geomine concept
Energy transition
Fifth generation
Pilot project

ABSTRACT

Decarbonizing heating and cooling remains a major challenge for a building stock still reliant on fossil fuels. Fifth-generation district heating and cooling (5GDHC) offers simultaneous heating and cooling at low temperatures with higher efficiencies. This paper presents the first techno-economic feasibility assessment of 5GDHC using mine water in Belgium, applied to three Walloon coal basins (Liège, Charleroi, Mons) under the Walloon Recovery Plan. We integrate technical simulations, financial modelling, and cartographic analysis to screen and size potential pilot sites. Results show that mine-water reservoirs could supply ~ 1.69 TWh yr^{-1} of thermal energy region-wide, with site viability driven by demand density and match between demand and subsurface resource, renovation level, and governance model. Under balanced heating–cooling loads and adequate renovation, life cycle GHG emissions can be reduced by up to ~ 50% versus conventional systems; however, subsurface data gaps, tariff structures, and fragmented responsibilities introduce non-trivial uncertainty. We formalize these as design risks and provide sensitivity bands for demand, COP, electricity price, and well placement, outlining customized 5GDHC–Geomine design rules for Belgian contexts. The findings operationalize the Geomine concept—linking flooded mines with 5GDHC—as a replicable pathway for urban decarbonization.

Introduction

Urbanization remains a complex challenge encompassing social, economic, and environmental questions. By 2050, more than 60% of the world's population is expected to live in urban areas [1], with residential cooling demand projected to rise by more than 60% in 2100% ([2,3]), with more than half of the energy demand, predominantly supplied by fossil fuel technologies [4].

District heating and cooling networks (DHC) have long been recognized as a promising, yet challenging solution, playing a pivotal role in the fight against climate change with more than 6000 cases across Europe, supplying about 10% total heat demand and approximately 100 cooling systems [5]. They contribute by accelerating the adoption of renewable energy sources through the integration of green, sustainable, and high-energy technologies [6], leading to new synergies [7]. Throughout their lifetime, the DHC systems have evolved through four generations with well-defined operations corresponding to the dominating technology of the time, being steadily improved to increase efficiency by reducing losses during the distribution, leading to the highest performances [8] consisting of a rigorous strategy for decarbonization strategies and decentralized energy systems harmonized with the lines of the Clean Energy for all Europeans package and the targets for carbon neutrality [6].

Current research focuses on 4th and 5th generation DHC networks, considering the benefits of low temperatures with a growing rise (e.g. [3,4]) and the adoption of emerging technologies to minimize Greenhouse gas (GHG) emissions [9]. Fifth-generation district heating and cooling systems networks (5GDHC), represent a promising pathway beyond conventional measures for reducing primary energy consumption and emissions [10] with limited applications. The concept of 5GDHC has its roots in Ground Source Heat Pump systems, commonly used in single buildings' configurations, or Water Loop Heat Pumps, used in commercial centers [11]. A 5GDHC network is bi-directional, allowing simultaneous extraction or supply from the network for both heating and cooling requirements, enabling combined demand through

* Corresponding author.
E-mail address: sesil.koutra@umons.ac.be (S. Koutra).

https://doi.org/10.1016/j.seta.2026.104853
Received 5 July 2025; Received in revised form 3 December 2025; Accepted 23 January 2026
Available online 27 January 2026

Nomenclature

GHG	Greenhouse gas emissions
5GDHC	Fifth-generation district heating and cooling systems
DHC	District Heating and Cooling (networks)
DH	District Heating
USA	United States of America
T	Temperature
LTDH	Low-Temperature District Heating
4GDHC	Fourth-generation district heating and cooling systems
H2020	Horizon 2020
CHP	Combined Heat and Power
TRNSYS	TRaNsient SYStems simulation program
SE	Southeast
PSI	Population Stability Index
QGIS	Quantum Geographic Information System
RE	Renewable Energy
3D	3-Dimensions
CAPEX	Capital Expenditure investment
OPEX	Operational Expenses or Expenditure
SPW	Service Public Wallonie

small installations and shared pipes that recover waste heat [12]. Such networks, already implemented in several European countries (e.g. [13]), are noticeably developed in Eastern Europe and Scandinavia, but are at an infant stage in Belgium, with only a few initiatives under development in Flanders, but with no operational projects. Recently, in Western Europe, five pilot sites demonstrating and testing 5GDHC technology have been developed in the framework of the D2GRIDS EU-INTERREG project [14].

Despite the growing interest for the 5GHDC technology, its uptake at the European scale is slow and is hampered by multiple obstacles. Among others, evidence-based studies highlight significant techno-economic barriers and integration challenges in urban planning for 5GDHC [14]. In addition, previous work highlight the need for comprehensive assessment methods that jointly consider technical, economic, environmental, and social dimensions and the replicability for further operations.

This paper addresses that gap by (i) synthesising the originality of 5GDHC, (ii) reviewing leading European deployments and highlighting the ones with the largest potential for replicability in Belgium, and (iii) analysing the feasibility of two Belgian case studies combining the use of abandoned coal mines with 5GDHC as an example. The outcomes of the analysis distil limitations and provide recommendations for replicability.

The contextualization of the research developed in Section 1 outlines the motivation and rationale of 5GDHC networks while providing a detailed understanding of their operational concept and a description of the current challenges they face Section 2 presents a review of their applications in European case studies and assesses the replicability of the different cases in Belgium. Section 3 introduces the research design for assessing the feasibility in Belgian territories, specifically in the context of 5GDHC combined with flooded abandoned coal mines, and Section 4 analyzes the main findings of this. Section 5 concludes with a discussion of the main outcomes and future perspectives.

5GDHC networks: Motivation and current challenges

Historical evolution of DH(C) networks

Traditionally, DH(C) systems consist of a distribution network for producing and delivering heat to end-users. Considering the diversity of sources (e.g., gas, geothermal), the number and profiles of users, or combinations of them, the functional complexity can vary as well [15].

Thermal and cooling network technologies offer valuable insights into decarbonization strategies and premises for increased flexibility and resilience of the systems [16]. Nevertheless, the nomenclature used through the literature lens unveils misinterpretations and fragmented stream perspectives, particularly across technical, technological, and/or economic dimensions. Some studies, on the other hand, have emphasized social aspects (lack of acceptance and awareness, e.g. [17]) and policy frameworks in Europe (e.g. [18]). Werner [15], for instance, reviewed the DHC systems from their technical, environmental, and institutional contexts, while Mitterrutzner et al. [19] focused on their use at the building level, and others on business models (e.g. [20]), technological integration (e.g. heat pump, [21]) or prosumers' involvement (e.g. [22]).

Technically, district heating and cooling systems operate through a centralized process that generates and distributes hot water or steam [23], often resulting in significant leakages and operational costs [24]. To address these challenges, studies have explored innovative solutions, including the integration of renewable sources (e.g., geothermal energy and waste incineration) [25] to provide both heating and cooling services.

The technologies associated with the 5GDHC derive from Ground Source Heat (and Water) Pumps, initially introduced for single buildings [26], which use local resources to meet specific demand by utilizing a distributed network. Despite their early conception and long track record in Nordic countries, the 5GDHC systems still present an appealing technological advancement for delivering efficiency and green solutions in recent years, acknowledging their key advantages for facilitating low-temperature integration. In this sense, Gjoka et al. [27] developed an advanced review of the steps involved in 5GDHC processes, including modeling approaches and design variables. Other comprehensive relative reviews include studies by Lizana et al. [22] on the integration of low-carbon technologies in Mediterranean cases, as well as similar studies in Denmark (e.g., [23]) or indicators for performance evidence in Italian systems, such as those by Noussan [28]. Similarly, Latosov et al. [29] evaluated the energy performance in Estonian cases [30].

Fundamentally, generations are characterized by breakthrough technologies in decreased temperatures [31]. Throughout their history, each generation has been characterized by a particular use of technologies. Dating back to the 1880 s in the USA and later expanding in Europe until the 1930 s [15], the first generation primarily used steam as the heat carrier [25] with temperatures ranging from 120°C to 200°C ([32,33]). Emerging in the 1930 s and until 1970 s, the second generation used pressurized hot water ($T_{supply} > 100°C$) as the heat carrier and altered from steam to superheated water [19] with temperatures to overcome the challenge of heat losses [24] aimed at savings through Combined Heat and Power (CHP) [34]. Second DH networks appeared in Soviet-based district heating systems with limited quality and capacities, replaced by the third one in the 1980 s and beyond (referred to as "Scandinavian district heating technology") and rapidly expanded in Central and Eastern Europe and outwards (e.g., China, Korea, USA). This evolution drastically increased efficiency by reducing the temperature supply to 70°C, making the introduction of plastic pipes into the system possible [23]. The evolution of this technology brought the 3rd generation (also known as "Scandinavian district heating technology") in response to the 70 s energy crises [35] with a more diverse mechanism at its protocol, based on chillers (with or without heat recovery) and cold storage, which was primarily established in the 1990 s, with interesting interactions with the electricity networks [23]. This generation utilized pre-insulated pipelines, contributing to the integration of renewable energies, such as biomass, to increase heating efficiency [32]; nonetheless, case applications are limited, for instance, in Turkey ([22,23]) or Germany (e.g., [28]). The progression to the next generation investigated the feasibility of RES integration to reach efficiency by maintaining the temperature at low standards (maximum 60-70°C) [36], usually defined as "Low-Temperature District Heating (LTDH)" networks (e.g., [28]), with the target of an improved match between supply and demand [37] and to promote the economic sustainability of the networks with the integration of alternative sources [38].

Among the challenges mentioned above, coordinating the application of 4th-generation DHC systems and achieving synergies to balance the requirements proved complicated in many countries. Considerable actions are being taken on the grid capacity for the buildings' connections and renovation processes to increase comfort, as well as addressing persistent heat losses (Fig. 1) [8].

Similarly to 4GDH systems, and initiated in China in 2008 named as "Energy Bus", and first used in 2015 in the FLEXYNETS ("Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS") 2020 project [37], the 5th generation has drawn attention over the past years with dozens of demonstration European cases launched [26]. Notably, the 5th generation networks minimize the heat losses using a similar design to the 4th generation with a range of renewable sources; however, it delivers supply temperatures to lower temperatures (<30°C) [39]. Another key feature of this generation is the capability to provide both heating and cooling, enabling renewable sharing ([26,27]), which distinguishes them from the 4GDH systems.

Criticizing the prior research, the overall trends still prioritize the techno-economic dimensions of the 5GDHC in a fragmented way. Notably, some studies broaden the environmental approaches in a limited operation, e.g., [36], with some exceptions, such as Murphy et al.'s [38] study, which expanded the impact analysis by using the LCA methodology. Other valuable contributions cover social perspectives, e.g., Lagoeiro et al. [37], who associated the 5GDHC systems with the assessment of potential social facets.

Characteristics and importance of 5GDHC systems

Currently, there are no standardized technical procedures for 5GDHC systems despite their rapid integration into smart systems. Overall, a 5GDHC system is non-linear, bi-directional, and decentralized, and utilizes a two-pipe (or single) system to directly utilize the rejected heat in district networks [40]. Common heat sources incorporated into the systems include decentralized technologies, such as combined heat and power (CHP) power plants for heat and electricity generation, geothermal energy, solar thermal, and heat pumps. The assessment of diverse sources is provided in studies, such as Wei et al. [41], which employ ranking techniques and consider multiple factors, including economic, environmental, and other aspects, as well as quantitative, qualitative, and objective aspects.

Scholars, e.g., Allegrini et al. [42], Ancona et al. [43], and Mohammadi et al. [44], have reviewed modelling tools for district heating and cooling systems to characterize their capabilities and accuracy, including simulations (e.g., EnergyPlus, TRNSYS, Modelica, etc.) [45].

Low temperatures and flexibility in 5GDHC systems enable efficiency through circular designs, minimizing time and costs, thereby achieving energy and economic efficiency. Simultaneously, scholars, e.g., Wirtz et al. [32], recognized the importance of 5GDHC systems for decarbonization strategies in Europe, using optimized mathematical models that demonstrate the production of over 50% fewer CO2 emissions compared to conventional methods. Nonetheless, only a limited number of demonstration projects are acknowledged [46].

The 5GDHC range in size and scale, from small schemes to larger areas, and includes any type of building and land use with standardized attributes in the generation processes of multiple heat sources, in centralized or decentralized configurations, to ensure flexibility and grid connections [47].

Dang et al. [41] contribute to the analysis of the 5GDHC to determine five main principles:

- **Closed-energy loops**: Approaching a fundamental principle to set up a closed energy grid that optimally returns flows at various time and spatial dimensions to analyze imbalances [42] by incorporating energy storage and reusing the hot air as a basic heating source.
- **Low-grade energy sources:** The transition towards decarbonization for the elimination of fossil fuels involves low-grade sources, e.g., industrial waste heat [43].
- **Demand-driven energy supply:** This principle describes the generation and distribution of energy that occurs when needed and the system's ability to respond effectively to meet consumers' requirements [44].
- **Decentralization:** The adoption of the approach of providing heating and cooling services at various temperature levels to effectively reduce losses and optimize infrastructure costs with the expansion of local clusters.
- **Integrated approaches:** The adoption of horizontal approaches aligned with diverse vectors, including the grid, plants, etc., to minimize peak loads and prioritize interactions and systems' balances.

Current challenges faced by 5GDHC systems

Reviews of scientific and grey literature revealed primary contributions covering various aspects of DHC, reflecting the growing interest in the topic, but also highlighted critical associated challenges.

5GDHC systems have already been widely adopted in several European countries and are emerging as a promising decarbonization solution ([6,24]). However, they continue to face numerous challenges regarding market adoption and techno-economic integration [18], as evidenced by ongoing scientific documentation of their nascent stage, such as the financial profitability ([48,49]). The lack of supportive [50] and administrative [51] guidelines, the operational complexities, the limited previous experiences [52], and the absence and trust [53]. Together, these factors highlight the urgent need for comprehensive research.

Prior approaches have often lacked robust frameworks for comprehensive uncertainty assessment, leading to multiple interpretations. For instance, Gong et al. [54] examined the evolution of 5GDHC systems for future research. Boussaid et al. [40], proposed a physics-based surrogate

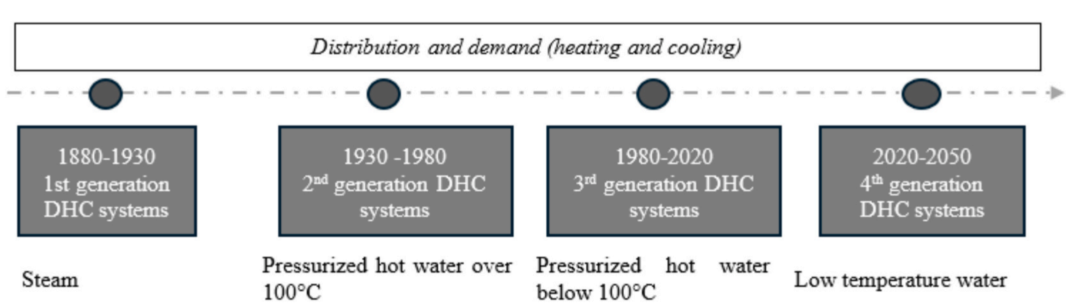

Fig. 1. Timeline of the four generations of district heating and cooling systems (. adapted from [8])

model for a 5GDHC system, capable of reducing simulation time by more than 90% compared to conventional ones. Other recent studies have focused on the building or demand side of 5GDHC systems, providing valuable insights into improving efficiency and forecasting demand. Maccarini et al. [55], for example, analyze the importance of technical criteria in calculating heat distribution in selected buildings in Denmark (Koge Nord).

Novelty and Contribution

To the best of the authors' knowledge, no comprehensive techno-economic feasibility study of 5GDHC networks has yet been conducted in the Walloon region (Belgium).

The current research aims to bridge that gap conducting an exploratory assessment of the 5GDHC network design in three selected cases. A particular focus is placed on applications of 5GDHC architecture that leverage abandoned coal mines as geothermal sources and thermal storage facilities ("Geomine"). The study further seeks to provide perspectives on scientific methodologies developed for the three selected Walloon cases, motivated by the Wallonia Recovery Plan 2022 – PRW79 [56].

This work contributes: (i) the first Belgian feasibility of 5GDHC–minewater (Geomine) integration at multi-site scale; (ii) a triangulated method combining technical simulation, financial modelling, and GIS screening; (iii) quantified regional potential (~1.69 TWh yr^{-1}) and site-level viability drivers (demand density, renovation, governance); and (iv) a formal uncertainty frame (subsurface, tariff, COP, demand) that yields design-ready sensitivity bands and policy guidance.

European review of 5GDHC networks

International case studies and comparative insights in Belgium

The Netherlands' Mijnwater project in Heerlen stands out for its successful reuse of flooded coal mines to supply thermal energy through a bidirectional, low-temperature grid. This network enabled prosumers to exchange heat using building-specific heat pumps coordinated by a central system operator. The project's success can be attributed to its strong municipal leadership, early regulatory support, and the availability of accessible mine water reservoirs [42]. Belgium also has a coal mining history and flooded abandoned coal mines are present both in Wallonia and in Flanders. The geothermal and thermal storage potential of the mines has been assessed for the Flemish colleries. Although the results were positive, highlighting the subsurface geothermal and storage technical potential that could be combined with 5GDHC networks, no full feasibility studies integrating surface demand, subsurface potential and full techno-economic analysis have demonstrated viable business cases.

There is also a lack of a cohesive national policy or institutional alignment to replicate this model effectively. In Switzerland, cities like Zurich and Geneva have developed "anergy" networks that operate at ambient temperatures, primarily using lake water and geothermal energy as sources. Their integration into dense urban planning schemes and renovation policies, backed by rigorous energy efficiency standards and financial incentives, has made them exceptionally effective [57]. Applying this to Belgium, however, poses challenges of decentralized structures, usually hamper policy enforcement and coherence between building codes and energy planning.

Germany offers insights through the JenErgieReal and Wärme-Atlas projects, where diverse heat sources—including wastewater and geothermal—are integrated using thermal storage and digital control systems. According to a national survey of 53 5GDHC networks, the most successful cases integrate thermal storage and data-driven operations under clear regulatory environments [58]; Belgium, by contrast, has limited legal pathways for shared thermal storage or designated zones for experimental implementation.

Denmark presents a mature example, with decentralized 5GDHC pilots in Copenhagen and Aarhus. Here, success is underpinned by high public trust, transparent energy tariffs, and widespread acceptance of district energy systems. According to Connolly [59], Denmark also boasts one of the highest heat demand coverage rates via district heating in the EU. Belgium, however, still suffers from inconsistent tariff schemes and limited public engagement.

Estonia's Tallinn Smart City initiative reflects the forefront of digitalization in thermal systems. By incorporating artificial intelligence, seasonal storage, and predictive analytics, Tallinn has optimized thermal load balancing and responsiveness. Estonia's success relies heavily on centralized planning and digital infrastructure—areas where Belgium currently lags [60].

A recent survey highlights that the primary life cycle greenhouse gas emissions of 5GDHC networks can be reduced by up to 52% compared to traditional systems, particularly in contexts with efficient integration of local energy sources [61]; Yet, these reductions depend on optimal use of heat pumps and balanced heating/cooling loads, which may not be fully feasible in Belgium's older urban fabric.

Although Flanders is engaged in European initiatives, such as D2Grids, and is involved in feasibility studies, such as those at the Beerse-Zuid industrial park, no full-scale 5GDHC implementation has yet achieved the level of success necessary to stand alongside the leading European cases [60].

These case studies offer a diverse spectrum of enabling conditions and systemic limitations. To distill their comparative relevance to Belgium, the following table summarizes the main enabling and limiting factors by country (Table 1).

Lessons from success and Failure

Across Europe, successful 5GDHC systems share several key enablers. These include the presence of high-density and mixed-use urban environments, strong legal frameworks, reliable access to low-grade heat sources, and early engagement between utilities, planners, and building owners. Crucially, public trust and stakeholder coordination play a pivotal role in ensuring the long-term viability of the system. Conversely, projects often fail or underperform when they lack regulatory clarity, are hindered by fragmented governance, or face resistance due to poor communication and inadequate technical readiness of the building stock ([26,58]).

Recent thermoeconomic analyses confirm that 5GDHC systems,

Table 1
Analysis of key case studies of 5GDHC applications in Europe.

Country	Key Success Factors	Key Limitations Relative to Belgium	Transferability to Belgium
Netherlands	Minewater reuse: strong municipal leadership; original EU-funding	Belgium lacks a unified mine water policy	High if institutional alignment is achieved
Switzerland	Dense urban planning, strict building codes	Belgium has fragmented governance, weaker code enforcement	Medium with regulatory reform
Germany	Research ecosystem; legal zones for innovation	Absence of legal testbeds and thermal storage framework	Medium if legal instruments are developed
Denmark	Public trust, tariff transparency, heat network legacy	Tariff opacity, low user trust	Low unless transparency improves
Estonia	Digital tools of controlling, centralized planning	Underdeveloped digital energy infrastructure	Low without major digital investment

while effective in energy sharing and environmental impact, may not always outperform fourth-generation networks economically unless heating and cooling demands are simultaneous [62]. This trade-off is particularly critical for Belgium, where the residential sector typically experiences heating-dominant demand patterns.

Moreover, lifecycle assessments conducted on 5GDHC systems reveal significant environmental advantages—GHG reductions of up to 52%—especially when embedded carbon and system flexibility are factored in [61]. This supports the viability of such systems in dense urban clusters found in Belgian territories, provided the building stock is adequately renovated.

When we apply these insights to Belgium, multiple structural barriers emerge. Belgium's institutional fragmentation across federal, regional, and municipal levels creates policy misalignment. Energy and urban planning responsibilities are not integrated, hindering the deployment of coherent infrastructure. Furthermore, Belgium's older building stock often lacks insulation and has high thermal inertia, limiting the effectiveness of low-temperature distribution systems. Additionally, public perception of district heating remains mixed, partly due to historical inefficiencies and mistrust in utility governance [55].

That said, Belgium holds several latent advantages. The country's history of coal mining offers a technical foundation for minewater-based heating and cooling networks. If a proper match can be established between heating and cooling demand and the subsurface potential near abandoned flooded mines, this approach could offer a promising alternative for thermal energy production and storage. Its dense urban centers and prevalence of users are conducive to networked systems. When buildings are designed or retrofitted to align with the optimal operating conditions of such networks, namely, high-temperature cooling and low-temperature heating, 5GDHC systems can deliver highly efficient and sustainable energy solutions. Furthermore, the Walloon Region's ongoing exploratory studies (e.g., the case of Liège) align well with international approaches, suggesting a readiness for pilot deployment [60].

To move from feasibility to implementation, Belgium must address these gaps holistically. A national framework that harmonizes building renovation standards, provides legal clarity for decentralized energy systems, and incentivizes digital infrastructure is essential. Public communication campaigns and participatory governance structures are also needed to rebuild trust and engage communities in the energy transition.

Feasibility of 5GDHC networks in Belgium

According to the Energy Poverty Barometer [63], approximately 4% of Walloon households struggle to cover their basic energy needs, with increasing vulnerabilities in particular population groups, such as single-parent families and isolated individuals. In comparison, the energy use of houses in Belgium is 70% higher than the European average [64].

In practice, the Walloon Region's energy policy aims to promote and develop renewable and sustainable energy sources, to drastically reduce the use of fossil fuels and associated greenhouse gas (GHG) emissions, in line with the Paris Agreement and its implementation. Local strategies are also fostering long-term commitments to align with the region's decarbonization trajectory. In this context, diverse initiatives are emerging to advance research and develop technical mechanisms that support the energy transition. Among others, Belgium's Walloon region, with its coal mining history, has shown strong interest in the combined use of 5GDHC and abandoned flooded coal mines for thermal energy production and storage.

A key milestone was the 2019 regional study, which assessed the geothermal potential of mine water for energy production and storage ([65,66]). This study laid the foundation for detailed feasibility studies of pilot projects in the coal districts of Liège, Hainaut, and Charleroi, which were launched in 2022.

Walloon coal basin and Specificities for geothermal mine water systems

Coal is the only conventional fuel that can be extracted in Belgium. It was produced essentially from underground mines and has been used intensively since the Industrial Revolution. Its use declined around 1960 in response to the decline in the extraction of these resources. In Wallonia, the last underground mine closed in 1984, while in Flanders, mining continued until 1992. From West to East, the Walloon coal basin has been divided into several districts, the most important being Couchant de Mons, Centre, Charleroi, and Liège (Fig. 2).

Mining operations have frequently reached depths of around 800 to 1,000 m, while the most superficial levels are often located just a few dozen meters from the surface. The number of coal layers exploited on a single vertical axis frequently ranges from 10 to 15 and can even exceed 30 in some sectors (especially in the Couchant de Mons district).

The Walloon coal basin has specific characteristics that distinguish it from other coal basins considered for mine water geothermal valorization (e.g., Heerlen, SE Netherlands). First, the Walloon coal basin is geologically located along the Variscan front. Thus, the coal seams extracted in the mines were slightly too strongly deformed (presence of folds and faults), depending on their proximity to the front. This results in the possible compartmentalization of the mine due to the presence of one (or several) faults and, therefore, of the mine water system that would use this mine. Secondly, coal mining in Wallonia is an ancient practice, dating back at least eight centuries.

The simultaneous presence of this mining works at shallow depths (generally < 150 m), above more recent extraction operations during the 19th and 20th centuries, increases the difficulty on several levels. The oldest parts of the mines have had few, if any, documents, leading to significant uncertainties regarding the presence and geometric/hydrogeologic properties of the most superficial mining levels. In the 20th century, the mining method progressively changed from short-wall to longwall due to the mechanization of the walls. Previously, the method used was similar to room-and-pillar mining. These techniques led to two types of coal mine workings. Modern coal mining generally results in the creation of quite stable, deconsolidated zones within the bedrock (goaf/gob), caused by the collapse of the roof. In contrast, ancient mining works consist of cavities whose long-term stability is not ensured. The geometry of residual volumes, their characteristics (particularly hydrological parameters), and the behaviour of flows when using a minewater system are expected to be significantly different.

The point of attention is related to the current state of former coal mines in Wallonia. Most of the shafts have been backfilled due to regulations, so they no longer provide direct access to the mine for a mine water system. Furthermore, there is no way of measuring the water level in the former mines, which is a problem given that the mine water systems can only operate in flooded mines. Despite direct measurements, Walloon coal mines are, by default, considered to be completely flooded, except those converted for the underground storage of natural gas. This assumption is partly supported by the volume of mine dewatering at the time of closure and by PSI data; however, it requires further confirmation.

Research design and Scope

The three feasibility studies followed the same methodology, as described in Harcouët-Menou et al. (2025) [67]. The assessment began at the basin scale and progressively narrowed down to identify the most promising sites for potential pilot projects within each basin, for which the feasibility studies were subsequently conducted. This step considered both the geothermal potential of the mines and the surface heat demand. At each selected site, a detailed analysis of the subsurface was conducted, including a series of models designed to assess the behavior of the mining reservoir and identify the optimal well situation for integrated mining planning. The relevant simulations enabled the identification of risk management and system design, while the technical and

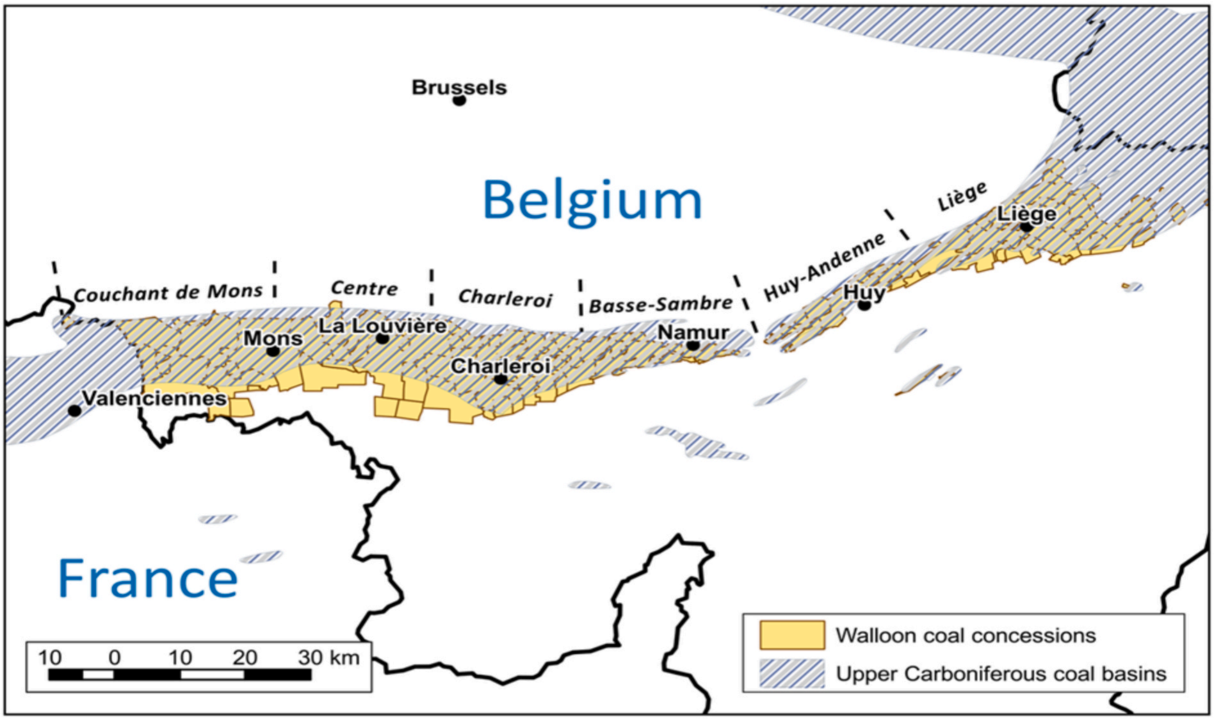

Fig. 2. Walloon coal basin and districts (UMons, . adapted from [68])

financial feasibility was launched in two demonstration projects in Charleroi and Couchant de Mons, unveiling the necessity for an explorative strategy. Bridging the gap between methodological design and evidence-based applications on 5GDHC architecture, the study seeks to connect these with the disused, abandoned coal mines that serve as geothermal sources and thermal storage facilities ("Geomine").

Based on the exchange of thermal energy between buildings, the network carries a low temperature required for heating and cooling. Geomine interacts with 5GDHC to develop connections to abandoned coal mines via substations equipped with bidirectional heat pumps,

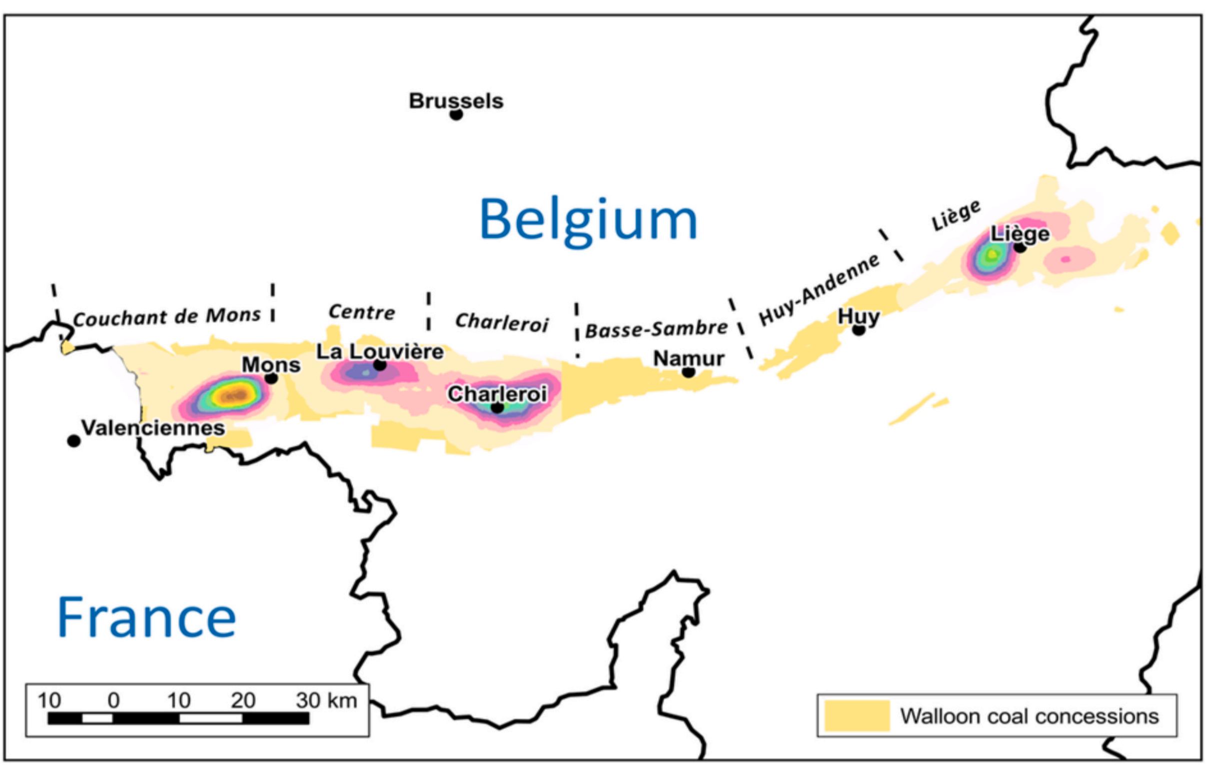

Fig. 3. Mine water system potential for the 4 most important coal districts, considering its connection to a 2.5 km diameter 5GDHC (UMons, . adapted from [68])

minimizing electricity demand and improving performance. Another notable advantage is the high-capacity thermal storage solution for large-scale seasonal storage.

Methodological approach

In 2019, the Walloon Region's Energy Administration launched a study to assess the geothermal potential of former abandoned coal mines at the regional scale and promote renewable transition. The study identified strong geothermal potential in the Couchant de Mons, Charleroi, and Liège basins (Fig. 3), estimated at at least 1690 GWh/year based on conservative assumptions [64]. Towards this roadmap, considerations of the geothermal potential are critical to overcome the hindrances of limited assessment in the mining basins (Mons, Charleroi, Liège) to secure energy supplies.

Following up on the positive results of the regional scale study, local studies aiming at the identification of potential Walloon pilots were launched in the three basins. The methodological design of the studies for each basin was developed in two steps: 1) the selection and the site definition, and 2) the feasibility study (Fig. 4).

The first step of the studies focused on characterizing and defining the **perimeter** of the demonstration projects. This preparatory phase involved the proposal and pre-selection of pilot sites, as well as the collection of data on technical and practical aspects (e.g., surfaces, density, land-use, and other constraints). It also involved engaging local stakeholders and estimating future energy requirements.

Data collection, inventory, and sites' pre-selection

The first step of the methodological approach was to identify the local actors associated with the buildings and sites that have the highest heating and/or cooling requirements. To facilitate and standardize the data inventory, a survey was developed and distributed to collect and analyze data (e.g., heating/cooling requirements, electricity consumption, renewable sources, equipment, building age, and efficiency) on a city scale, visualized with the aid of Geographical Information Systems.

In this preliminary step, the local actors provided information (surveys and questionnaires) on the energy consumption and needs of buildings located on the (pre-)identified sites, considering as well the future developments. Priority was given to buildings with the highest heating and/or cooling demand and the identification of the actors with the major energy demand; for this step, an exhaustive cartographical analysis was developed (ex., Fig. 5).

For the surface demand, public operators can use gas and electricity meters to provide heating and electricity. By contrast, cooling requirements are generally embedded in electricity consumption data, which UMONS processed in QGIS. The various consumption data is recorded in the attribute tables of each entity, along with information on its name, function, and associated operator, user, and/or owner/manager.

Another pivotal lever for the site pre-selection has been economic development, as well as technical opportunities, given the connections to buildings currently equipped with heat pumps, which are potentially connectable to 5GDHC networks.

In complement to the surface on-site diagnostics, geological and hydrological data were collected and synthesized to create dynamic (3D) representations. These models served as a basis for defining the potential location of the Géomine system and for evaluating thermal resources associated with the abandoned mines. As part of this step, a series of maps was developed to support the site assessment.

Surface estimation and heating/cooling requirements

When actual consumption data for existing buildings was lacking, an estimation of the usable surfaces was realized with the use of the construction code and the calculation of the compatible land uses (commerce, offices, hospitals, or sports halls) to estimate the heating and cooling demand as follows:

- Heating consumption = Fuel consumption [kWh/m^2] x Useful floor area [m^2]: (1)
- Cooling consumption = Electricity consumption for cooling [kWh/m^2] x Useful floor area [m^2]: (2)

Sites' analysis and classification

The subsequent step involved identifying the perimeter and analyzing data collected from the predefined sites (Fig. 6). The selection of potential sites is determined by a spatial analysis (geographical situation of major consumers, e.g., educational, health, and sports poles) and strategic decision-making by city actors, investors, and developers.

For each basin, based on the collected data, the sites identified as potentially attractive were ranked according to suitability criteria for hosting a pilot project. Priority was given to the reuse of energy and the exploitation of local energy sources, including both thermal and electrical sources. The selection of the pilot site was also motivated by the potential to extend the network around this central core in the short, medium, and long term, ensuring the project's viability and adaptability in the future. Key criteria included heating and cooling requirements, subsurface potential in the vicinity of the site, building types and land uses (including new constructions and renovations), number of users, presence of major energy consumers, and private and public actors.

Feasibility study

The detailed feasibility studies were conducted as the subsequent step of the basin-scale preliminary study, including diverse and hybrid methods (Fig. 12). One of the first steps in the feasibility study was to identify buildings that could be connected to a future 5GDHC thermal energy network based on qualitative and quantitative criteria. In parallel, the available heating and cooling capacity from the mines and the 5GDHC system was estimated.

Data on surface energy demand were collected, focusing on the central perimeter of the pilot site. A preliminary techno-economic analysis followed this initial phase of detailed information gathering. This analysis aimed to assess the match between the thermal requirements identified and the "Géomine" concept to validate the relevance and feasibility of the projects.

In this phase of the approach, the prior data collection is refined and focused on the perimeter of the selected site(s) for the analysis of multiple options and combined scenarios, including the potential storage, renovation opportunities, and strategies of renewable energy (RE) contributors in proximity to the site. The analysis of relevant data identifies the network typologies for installations in pilot cases. This

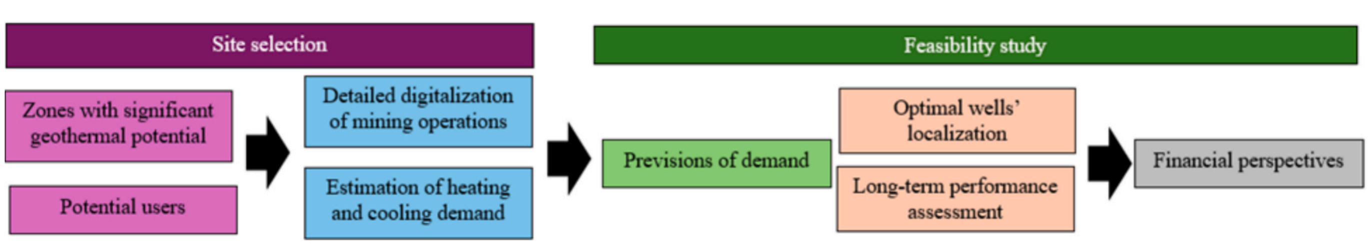

Fig. 4. Structure of the individual local-scale studies.

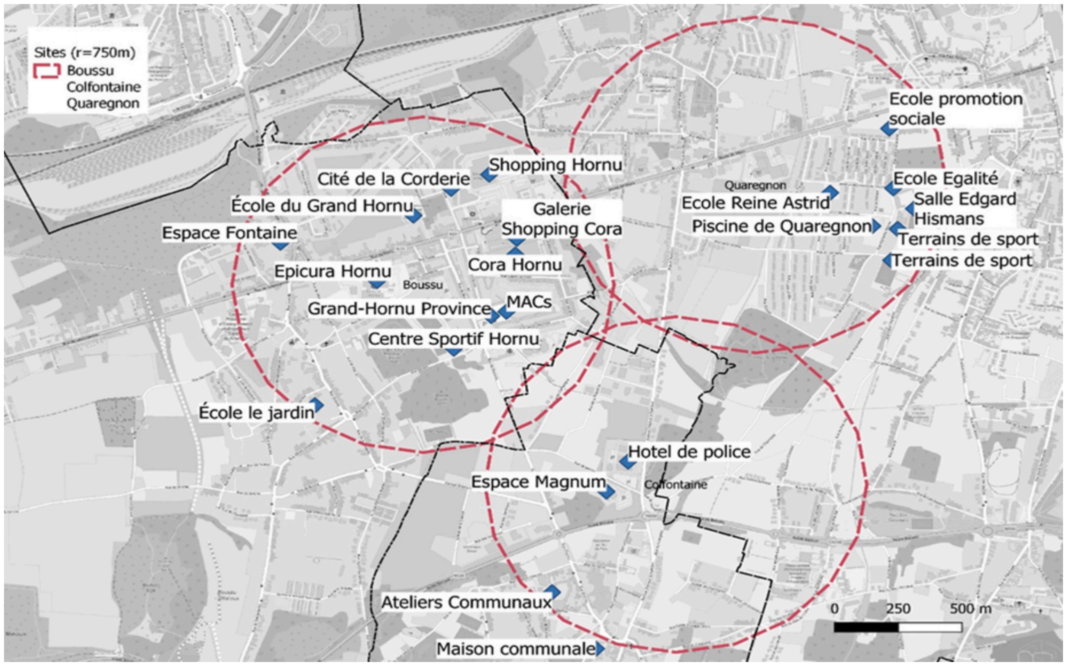

Fig. 5. Example of actors with the major energy demand in the site of Boussu-Colfontaine-Quaregnon (Waroux, 2023, ©UMons).

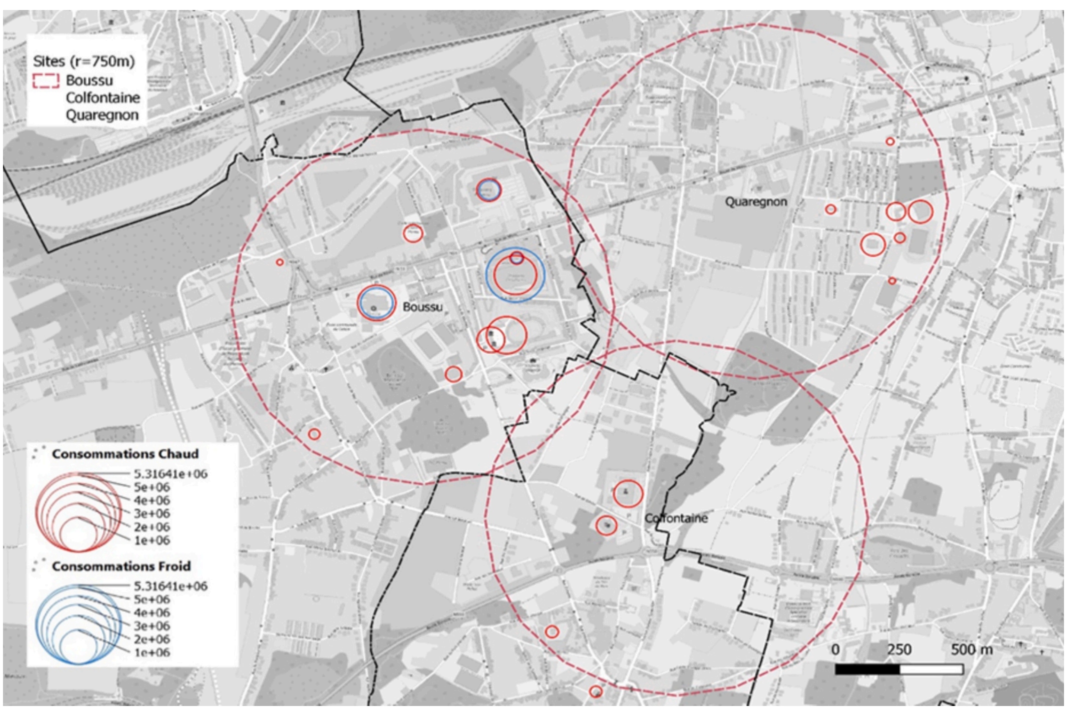

Fig. 6. Example of major heating/cooling consumers in site 1 (Boussu, Colfontaine, Quaregnon) in the case of Couchant de Mons study (Waroux, 2023, ©UMons).

phase is completed by investigating the buildings' typologies, consumption profiles (loads), and conducting a preliminary techno-economic study of different behaviors, thermal requirements, and response capacities of the existing mines to estimate the forthcoming necessary investments based on energy and other data. Complementary to this step, the risk assessment processes with the 3D modeling of mining works and mapping their structures (e.g., shafts and galleries), including as well geothermal simulations of two categories: (1) a 1D pipe model corresponding to the network of the shafts and galleries of the considered mine (2) a multi-domain model, in which each element of the mine (shafts, galleries, goaf, gob) has been discretized and assigned its hydrogeologic properties. The 1D pipe model served as a basis for defining potential well locations for two-well systems. The thermal resources associated with the abandoned mines for different scenarios, using both geothermal models, including well location and heating and cooling demand characteristics of prosumers connected to the grid, are evaluated as the next step. The impact of uncertainties in the various parameters of the underground reservoir models (e.g., mine geometry, flooding level, etc.) on their capacity for storage and/or use as a source was analyzed through sensitivity studies conducted using the subsurface models. Potential environmental risks are diagnosed as geological/hydrogeological, technical, environmental, operational, financial, societal, and legislative.

Discussion

Implications for Belgium. Feasibility is not primarily a technology gap; it is a systems-integration and governance gap. Three levers dominate: (1) building readiness, by mandating low-temperature-ready renovation in target clusters to ensure 5GDHC performance; (2) legal and tariff clarity, through designated thermal-storage zones, transparent cost-reflective tariff models, and pre-defined ownership of mine-water assets; and (3) digital operations, with funded data-driven control (predictive load balancing and storage scheduling) as a condition for public support. These measures align with the Geomine pathway and enable staged, bankable deployments.

International experience with 5GDHC demonstrated its viability where enabling conditions exist. Regulatory gaps, governance fragmentation, and technical limitations in the building stock constrain direct application in Belgium. However, if addressed through national coordination, planning integration, and digital investment, Belgium can leverage its geothermal and urban assets to deploy 5G Digital Health Care at scale. A tailored approach—not direct replication—is required for success, given the models' complexity and the use of robust methods that incorporate stochastic approaches, anticipating uncertainties and risks to achieve optimal designs.

By adapting the lessons of Europe's frontrunners, Belgium can lead in customized, scalable, and resilient thermal networks; nevertheless, the alignment with renovation policies based on renewables, the development of particular regulations on energy sharing, and the encouragement of vigorous infrastructure and public engagement to increase acceptance and replicability of successful stories in the forward-looking strategies. Further local developments related to policy formulation and technical assessments (e.g., reliability, operational complexities, etc.) or affordability, safety, or noise reduction should be prioritized.

The study triggered the barriers to 5GDHC replicability, emphasizing a wide range of technical and non-technical indicators. Performances and uncertainties are under exploration related to the operation strategies and efficiency, and require a well-established library and intensified research of robust scenarios and diverse contexts. To address these unanswered queries, more studies in real cases with various influencing factors coupled with advanced modeling, sensitivity and risk analysis, optimization methods, and other forecasting approaches should be incorporated to validate 5GDHC reliability to turn them into deterministic, and accurate designs.

Conclusions

Despite the significant progress in the technical difficulties of the design, operation, and application of the 5GDHC networks, the study unravels gaps, but also outlines potential directions and perspectives for future research in Belgium (and Europe overall). The energy atlas and climate pressures addressed the potential benefits of 5GDHC networks and overlooked their difficulties.

In conclusion, the pilot projects covered by the feasibility studies offer interesting potential for the development of mining geothermal resources, but also entail risks that will need to be carefully assessed before implementation and, in some cases, managed throughout the project's life cycle. The first part focuses on the collection and analysis of existing data in the pre-selected areas and the analysis and ranking of these sites. The second part of the study focused on the feasibility of the selected site, including the collection and synthesis of surface demand and subsurface data collected within the perimeter of the site under investigation. A preliminary techno-economic analysis was conducted to assess the feasibility of the proposed concept in meeting the identified surface demand. In light of these findings, a subsoil analysis in the study area aimed at assessing the overall reservoir capacity, including the creation of a series of models of the behavior of the mining reservoir under defined stresses. A detailed design of the 3D model of the reservoir, combined with dynamic simulations, completes the study.

In response to these findings, a subsurface analysis of the study area was conducted to assess the overall capacity of the reservoir, including a series of models that simulated the mining reservoir's behavior under defined demand scenarios. The methodologies used to model the mining reservoir are described in Harcouët-Menou et al. (2025) [67], and the results of the simulations were analyzed. Simulations are particularly valuable for determining the optimal position of wells when installing a Geomine system on-site, enabling us to anticipate the integration of potential new prosumers in the study area. The results obtained provide estimates of the reservoir's maximum capacities, particularly in terms of production rates, and enable us to assess the risks associated with a thermal breakthrough as a function of the flow rates exploited. This analysis forms an essential basis for planning and managing the risks associated with the operation. Additionally, the CAPEX and OPEX of these pilot projects were estimated based on the various components of the systems and operational parameters defined.

Surely, the promising development of 5GDHC networks is a multi-challenging problem, and not purely technical. Developing solutions and balancing stakeholders' interests, supported by political and societal engagement, seems primordial. Apart from political and funding support, comprehensive frameworks and relative guidelines for the network operation, trading, and business model have a pivotal role as well for supporting and encouraging a well-designed and structured ecosystem, which will actively bring on board prosumers.

Through the conduct of an innovative methodological framework on the exploratory feasibility of 5GDHC networks within the Geomine concept, the research provides prospects to settle potential practical developments, which will accelerate the decarbonization processes and the establishment of decentralized systems in Belgium and beyond, and track future developments of these systems. In future work, the dynamic behaviors of simulations of 5GDHC networks in candidate sites, with the quantification of relevant benefits, are envisioned to unveil the significant potential and validate future developments by integrating multiple analytical dimensions of their applications into holistic and supporting decision-making processes, thereby facilitating their integration into energy planning strategies with standards and policies for their practical deployment in the concerned areas beyond the technical dimensions.

CRediT authorship contribution statement

Sesil Koutra: Writing – review & editing, Writing – original draft, Methodology. **Virginie Harcouët-Menou:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Nicolas Dupont:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Olivier Kaufmann:** Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Vincent Becue:** Validation, Supervision, Conceptualization. **Shady Attia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Conceptualization.

Declaration of competing interest

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

Acknowledgements

This work was supported by the SPW (Service Public de Wallonie) Department of Energy (SPWTLPE). The authors wish to express gratitude to Dr. Thomas WAROUX, Architect, Faculty of Architecture and

Urban Planning, University of Mons, for his contribution to cartographical analysis.

Data availability

Data will be made available on request.

References

[1] K. Mutka et P. Papillon, « 2020-2030-2050, common vision for the renewable heating and cooling sector in Europe - European technology platform on renewable heating and cooling », Joint Research Centre: European Technology Platform on Renewable Heating and Cooling, Institute for Environment and Sustainability.
[2] Department of Economic and Social Affairs, « World Urbanization Prospects. The 2014 revision », United Nations, 2015.
[3] Santamouris M. Cooling the buildings - past, present and future. Energy & Buildings 2016:617–38.
[4] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016:1634–53.
[5] Fedrizzi R. « Flexynets second webinar "Low temperature district heating and cooling networks". Consulté le: 5 avril 2025. [En ligne]. Disponible sur: » 2015. http://www.flexynets.eu/en/Media.
[6] European Union, « Communication from the Commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the regions. An EU strategy on heating and cooling », European Union, 2016. Consulté le: 27 mai 2025. [En ligne]. Disponible sur: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52016DC0051.
[7] European Commission, *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulaiton 2023/955 (recast)*, Directive, 2023.
[8] Lake A, Rezaie B, Beyerlein S. Review of district heating and cooling systems for a sustainable future. Renew Sustain Energy Rev 2017:417–25.
[9] R. Simon, M. Kane, et S. Wyler, « Alternative solutions for the optimal integration of decentralized heat-pumps in district heating/cooling networks », in *Proceedings of ECOS 2020-The 33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, Osaka, Japan, 2020.
[10] Pozzi M, Spirito G, Fattori F, Dénarié A, Famiglietti J, Motta M. Synergies between buildings retrofit and district heating. the role of DH in a decarbonized scenario for the city of Milano. Energy Rep 2021:449–57.
[11] European Parliament, *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*, 2010.
[12] Volkova A, Pakere I, Murauskaite L, Huang P, Lepiksaar K, Zhang X. 5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems. Energy Rep 2022.
[13] B. Rezaie et M. A. Rosen, « District heating and cooling: review of technology and potential enhancements », *Applied Energy*, p. 2-10, 2012.
[14] « D2Grids, rolling out 5th generation district heating and cooling. Interreg North-West Europe. D2Grids », https://vb.nweurope.eu/projects/project-search/d2grids-increasing-the-share-of-renewable-energy-by-accelerating-the-roll-out-of-demand-driven-smart-grids-delivering-low-temperature-heating-and-cooling-to-nwe-cities/#tab-1.
[15] Werner S. International review of district heating and cooling. Energy 2017:617–31.
[16] H. Knutsson, M. Holmén, et E. Perez Vico, « From islands to platforms: Innovation pathways for district heating firms across Europe », *Energy Research & Social Science*, 2025.
[17] Moller Sneum D, Billerbeck A, Kachirayil F, McKenna R. Barriers to district heating deployment: Insights from literature and experts. Energy Policy 2025.
[18] Billerbeck A, et al. Policy framework for district heating: a comprehensive overview and analysis of regulations and support measures across Europe. Energy Policy 2023.
[19] Mitterrutzner B, Callegher CZ, Fraboni R, Wilczynski E, Pezzutto S. Review of heating and cooling technologies for buildings: a techno-economic case study of eleven European countries. Energy 2023.
[20] A. Sandoff et J. Williamsson, « Business models for district heating », *Advanced District Heating and Cooling (DHC) Systems*, p. 293-317, 2016.
[21] Lygnerud K, Ottosson J, Kensby J, Johansson L. Business models combining heat pumps and district heating in buildings generate cost and emission savings. Energy 2021.
[22] K. Lygnerud, T. Popovic, S. Schultze, et H. Kortegaard Stochkel, « District heating in the future-thoughts on the business model », *Energy*, 2023.
[23] Mazhar AR, Liu S, Shukla A. A state of art review on the district heating systems. Renew Sustain Energy Rev 2018:420–39.
[24] Chicherin S, Mašatin V, Siirde A, Volkova A. Method for assessing heat loss in a district heating network with a focus on the state of insulation and actual demand for useful energy. Energies 2020.
[25] Sorknaes P, et al. The benefits of 4th generation district heating in a 100% renewable energy system. Energy 2020.
[26] Buffa S, Cozzini M, D'Antoni M, Baratieri M, Fedrizzi R. 5th generation district heating and cooling systems: a review of existing cases in Europe. Renew Sustain Energy Rev 2019:504–22.
[27] Gjoka K, Rismanchi B, Crawford RH. Fifth-generation district heating and cooling systems: a review of recent advancements and implementation barriers. Renew Sustain Energy Rev 2023.
[28] Noussan M. Performance indicators of district heating systems in Italy - Insights from a data analysis. Appl Therm Eng 2018:194–202.
[29] Latõšov E, Umbleja S, Volkova A. Promoting efficient district heating in Estonia. Util Policy 2022.
[30] Gjoka K, Rismanchi B, Crawford RH. Towards sustainable urban energy solutions: a multi-dimensional assessment framework for fifth-generation district heating and cooling systems. Energy & Buildings 2025.
[31] H. Lund *et al.*, « The status of 4th generation district heating: research and results », *Energy*, p. 147-159, 2018.
[32] Revesz A, et al. Developing novel 5th generation district energy networks. Energy 2020.
[33] Zeh R, Ohlsen B, Philipp D, Bertermann D, Kotz T, Stockinger V. Large-scale geothermal collector systems for 5th generation district heating and cooling networks. Sustainability 2021.
[34] H. Lund *et al.*, « 4th generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems », *Energy*, p. 1-11, 2014.
[35] Ostergaard D, Smith K, Tunzi M, Svendsen S. Low-temperature operation of heating systems to enable 4th generation district heating: a review. Energy 2022.
[36] Lund H, et al. Perspectives on fourth and fifth generation district heating. Energy 2021.
[37] EURAC, « FLEXYNETS European Project ». 2018. Consulté le: 18 juin 2025. [En ligne]. Disponible sur: https://cordis.europa.eu/project/id/649820.
[38] Yao S, Wu J, Qadrdan M. A state-of-the-art analysis and perspectives on the 4th/5th generation district heating and cooling systems. Renew Sustain Energy Rev 2024.
[39] Gudmundsson O, Schmidt RR, Dyrelund A, Thorsen JE. Economic comparison of 4GDH and 5GDH systems-using a case study. Energy 2022.
[40] Lagoeiro H, Maidment G, Ziemele J. Potential of treated wastewater as an energy source for district heating: Incorporating social elements into a multi-factorial comparative assessment for cities. Energy 2024.
[41] L. Dang Minh, L. Quang Nguyen, J. Nam, T. N. Nguyen, et S. Lee, « Fifth generation district heating and cooling: A comprehensive survey ».
[42] S. Boesten, W. Ivens, S. C. Dekker, et H. Eijdems, « 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply », *Advances in Geosciences*, p. 129-136, 2019.
[43] Von Rhein J, Henze GP, Long N, Fu Y. Development of a topology analysis tool for fifth-generation district heating and cooling networks. Energ Conver Manage 2019:705–16.
[44] Wei B, Wang SL, Li L. Fuzzy comprehensive evaluation of district heating systems. Energy Policy 2010.
[45] A. Prasanna, V. Dorer, et N. Vetterli, « Optimisation of a district energy system with a low temperature network », *Energy*, p. 632-648, 2017.
[46] Averfalk H, Ingvarsson P, Persson U, Gong M, Werner S. Large heat pumps in swedish district heating systems. Renew Sustain Energy Rev 2017:1275–84.
[47] W. H. Song, Y. Wang, A. Gillich, A. Ford, et M. Hewitt, « Modelling development and analysis on the Balanced Energy Networks in London », *Applied Energy*, p. 114-125, 2019.
[48] Fuss S, Szolgayova J, Obersteiner M, Gusti M. Investment under market and climate policy uncertainty. Appl Energy 2008:708–21.
[49] Zhang M, Wang Q, Zhou D, Ding H. Evaluating uncertain investment decisions in low-carbon transition toward renewable energy. Appl Energy 2019:1049–60.
[50] Angelidis O, Ioannou A, Friedrich D, Thomson A, Falcone G. District heating and cooling networks with decentralised energy substations: opportunities and barriers for holistic energy system decarbonisation. Energy 2023.
[51] Selvakkumaran S, Axelsson L, Svensson IL. Drivers and barriers for prosumer integration in the swedish district heating sector. Energy Rep 2021:193–202.
[52] Huang P, et al. A review of data centers as prosumers in district energy systems: Renewable energy integration and waste heat reuse for district heating. Appl Energy 2020.
[53] A. Volkova, I. Krupenski, H. Pieper, A. Ledvanov, E. Latosov, et A. Siirde, « Small low-temperature district heating network development prospects », *Energy*, p. 714-722, 2019.
[54] Gong Y, Ma G, Jiang Y, Wang L. Research progress on the fifth-generation district heating system based on heat pump technology. Journal of Building Engineering 2023.
[55] Maccarini A, Sotnikov A, Wetter M, Sulzer M, Afshari A. Influence of building heat distribution temperatures on the energy performance and sizing of 5th generation district heating and cooling networks. Energy 2023.
[56] SPW, « Le Plan de Relance de la Wallonie. Qu'est-ce que c'est, concrètement? Aperçu des décisions prises par le Gouvernement depuis l'adoption du Plan ». 2019. Consulté le: 18 juin 2025. [En ligne]. Disponible sur: https://www.wallonie.be/sites/default/files/PRW%20-%20Factsheet_avril%202023.pdf.
[57] Edtmayer H, Nageler P, Heimrath R, Hochenauer C. Investigation on sector coupling potentials of a 5th generation district heating and cooling network. Energy 2021.
[58] Wirtz M, Schreiber T, Muller D. Survey of 53 fifth-generation district heating and cooling (5GDHC) networks in Germany. Energ Technol 2022.
[59] D. Connolly, « Heat roadmap Europe: Quantitative comparison between the electricity, heating and cooling sectors for different European countries », *Energy*, p. 580-593, 2017.
[60] Volkova A, Pakere I, Murauskaite L, Huang P, Lepiksaar K, Zhang X. 5th generation district heating and cooling implementation potential in urban areas with existing district heating systems. Energy Rep 2022.

[61] Gjoka K, Crawford RH, Rismanchi B. A comparative life cycle assessment of fifth-generation district heating and cooling systems. Energy & Buildings 2024.
[62] Calise F, Cappiello FL, Cimmino L, Dentice d'Accadia M, Vicidomini M. A comparative thermoeconomic analysis of fourth and fifth generation district heating and cooling networks. Energy 2023.
[63] B. Delbeke et S. Meyer, « The Energy Poverty Barometer (2009-2016) », King Baudouin Foundation, 2018. Consulté le: 2 juin 2025. [En ligne]. Disponible sur: https://media.kbs-frb.be/en/media/7604/20180315NT.pdf.
[64] S. Mohammadi, C. Bojesen, et M. Vinge Muff, « A modeling approach for district heating systems with focus on transient heat transfer in pipe networks - A case study in Studstrup, Denmark », in *Proceedings of ECOS 2015 - The 28th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems*, France, juill. 2015.
[65] N. Dupont, O. Kaufmann, V. Harcouêt-Menou, et J. Mattijs, « La géothermie des eaux de smines et son potentiel en Wallonie (sud de la Belgique », *Géologues*, p. 82-89, 2021.
[66] Harcouët-Menou V, et al. Détermination du potentiel géothermiques des anciennes mines désaffectées en Wallonie. SPW-Energie 2020.
[67] Leontidis V, Hernandez E, Pogacnik J, Wangen M, Harcouët-Menou V. Controlling injection condistrions of a deep coaxial closed well heat exchanger to meet irregular heat demands: a field case study in Belgium (Mol). Geotherm Energy 2025.
[68] N. Dupont, O. Kaufmann, V. Harcouët-Menou, et J. Matthijs, « La géothermie des eaux des mines et son potentiel en Wallonie (sud de la Belgique) », *Géologues*, p. 82-89, 2021.