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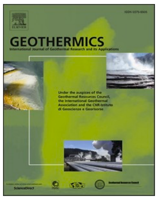

Aquifer thermal energy storage (ATES) for district heating and cooling systems: A review

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ABSTRACT

Seasonal thermal energy storage plays a pivotal role in transitioning district heating and cooling (DHC) systems toward the use of renewable energy. Among the available technologies, aquifer thermal energy storage (ATES) emerges as a promising form of sensible heat storage, utilizing the subsurface as the storage medium. This study reviews the integration of ATES systems with DHC networks, drawing insights from various case studies in the literature. It identifies and summarizes real-world ATES implementations at district scale and explores different modeling approaches for coupling ATES with DHC systems. Furthermore, we identify technological, policy, and deployment challenges that hinder the current widespread adoption of ATES with district energy networks such as ATES oversizing during design phase, market uptake during implementation and thermal imbalances during operational phase. By synthesizing findings from multiple case studies, this review highlights the current state of ATES technology and its significant potential to enhance the flexibility, efficiency, and sustainability of modern low-carbon DHC systems. Furthermore, we also identify that using a holistic system approach in analysis can support decision makers in implementing ATES at a district scale.

1. Introduction

Worldwide, operational demand in the building sector is responsible for a share of about 30% of the global final energy usage (Buildings - Energy System, 2024). In most countries, the energy required for heating is larger by far than the energy used for cooling. However, factors such as global warming, thermal insulation and rising standards in thermal comfort are creating new scenarios where cooling demand is expected to grow significantly in the next decades (Energy Technology Perspectives, 2025).

District heating and cooling (DHC) systems are a promising solution for reducing both primary energy consumption and CO_2 emissions from heating and cooling in buildings (Angelidis et al., 2023). District heating (DH) systems have been used for space heating and domestic hot water since the 1880s, and a variety of technological configurations exist. These can draw on a wide range of energy supply and conversion options, including natural gas, biomass, geothermal resources, solar thermal systems, industrial excess heat, large heat pumps, and combined heat and power plants (Malcher et al., 2025; Zuberi et al., 2021), allowing networks to integrate locally available resources and adapt to different regional conditions and decarbonization strategies.

The efficiency of DH systems has been continuously improved and five different generations can be distinguished (Lund et al., 2014). The first three generations of DH systems are characterized by centralized thermal stations, which feed high-temperature water or steam into pipes to distribute heat in urban areas (Lund et al., 2021). However, high-temperature DH systems suffer from significant heat losses and low potential for integration of sustainable energy sources. For these reasons, current research and development focuses on the 4th generation (4GDH) systems, which can reach high efficiencies by operating at low temperatures.

District cooling is a more recent development compared to district heating. District cooling systems are therefore neither as common nor as extensive as district heating systems. In recent years, research started to focus on new thermal networks that can deliver both heating and cooling services using the same pipes. Such networks are often defined as the 5th generation of district heating and cooling (5GDHC) (Buffa et al., 2019; Maccarini et al., 2023a).

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Seasonal heat storage is a key component in the 4th and 5th generations of DHC systems. Heat storage systems can temporarily store thermal energy for later use, helping to meet heating and cooling demands when renewable energy availability is low. By incorporating seasonal heat storage, DHC systems can, for instance, store surplus heat generated during the summer for use in the winter. Such strategies can reduce primary energy consumption and carbon emissions, while also providing cost savings for building owners and occupants (Wirtz et al., 2020).

One of the most effective and widely used seasonal heat storage methods is underground thermal energy storage (UTES), which uses the subsurface for storing thermal energy for both heating and cooling purposes (Fleuchaus et al., 2018). UTES systems are categorized based on their construction and include (1) Borehole thermal energy storage (BTES), (2) Pit thermal energy storage (PTES), (3) Tank thermal energy storage (TTES), (4) Cavern thermal energy storage (CTES), and (5) Aquifer thermal energy storage (ATES). Compared to other UTES technologies, ATES exhibits high storage capacities and low investment costs, making it well-suited for large-scale applications. However, they require comprehensive pre-investigation, the presence of aquifers and suitable hydrogeological conditions (Lyden et al., 2022).

Several review studies have investigated ATES systems across a range of dimensions, including operational performance, economic viability, environmental impact, and simulation methodologies, as summarized in Table 1. However, none of these reviews specifically focused on the integration of ATES within DHC systems and examined the characteristics of the associated energy supply and distribution infrastructure. This represents a notable gap in literature, as system-level coupling details are critical to understanding how ATES can be effectively deployed as a seasonal storage component within broader DHC systems.

The present study addresses this gap by providing a systematic analysis of ATES-DHC integration, drawing on both real-world operating case studies and hypothetical modeling and simulation studies. Through this analysis, the review also contributes to the broader field of geothermal energy utilization by demonstrating how shallow geothermal resources, exploited through ATES, can be effectively harnessed to deliver low-carbon heating and cooling at urban scale.

The review begins with a brief overview of ATES technology, covering its operating principles, historical development, and recent technical advances. This is followed by a description of the literature search methodology employed to identify and select the case studies examined in this review. The paper then presents two dedicated sections on ATES-DHC integration: the first examining real-world operating case studies (Section 4), and the second analyzing studies based on modeling and simulation (Section 5).

Table 1
Summary of different reviews on ATES systems.

Reference	Scope
Lee et al., 2010	Review on different modeling tools and methods for assessing the subsurface behavior of ATES
Pinel et al., 2011	A review focused on the seasonal storage of thermal energy and solar thermal energy for residential applications
Fleuchaus et al., 2018	Worldwide review of ATES sites and the opportunities, barriers and challenges in ATES implementation
Gao et al., 2017	Review focused on the thermal performance, economic and environmental impact of ATES systems
Shah et al., 2018	Review on application of STES systems with solar collectors and heat pumps with a focus on simulation methods and software tools related to STES systems.
Dahash et al., 2019	An overview of different STES systems with a comparison based on investment, operation costs and storage conditions
Lyden et al., 2022	Review of the different STES systems and the modelling methods of BTES and ATES for energy system analysis.
Mahon et al., 2022	Review of barriers and development of different STES systems for energy systems
Figueira et al., 2024	Review of shallow geothermal energy applications on district heating and cooling networks.
Marojević et al., 2025	Systematic review on ATES systems in Europe focusing on simulation methods, environmental impacts and economic feasibility.
Yazdani et al., 2026	Review of co-simulation approaches and coupling of subsurface models (ATES, BTES) with building energy simulation tools.

2. Operation, history and development of ATES

ATES systems typically consists of at least two wells, which are coupled via a heat exchanger that facilitates heat exchange with the connected building(s) (Bloemendal et al., 2015). The typical operation of an ATES system is shown in Fig. 1. In winter, warm groundwater is extracted from one well and circulated through the building systems via heat exchangers or heat pumps. The water, which is cooled during the process, is then injected into the other well. In summer the process is reversed. As all the water from one well is reinjected into the other, there is no net removal of groundwater from the system.

The concept of storing thermal energy in aquifers dates back to the mid-1960s in China (Yong-Fu, 1991; Shen, 1988; Zhou et al., 2015). In the attempt to mitigate land subsidence issues around Shanghai, it was discovered that injected surface water maintained its temperature for several months. This effect was exploited by textile companies, which began storing cold winter temperatures for use in summer (Tsang, 1978; Morofsky, 2007). The growing demand for industrial cooling led to a gradual increase in ATES applications in subsequent years. However, these early projects faced problems such as heat exchanger clogging that led to the shutdown of many systems (Molz et al., 1979, 1981; Jenne et al., 1992).

During the oil crisis in the 1970s, research and development of energy storage accelerated. This led to the exploration of thermal energy storage in aquifers in North America and Europe. Several ATES field tests were initiated during the 1970s, including experiments in Colombier, Switzerland (Saugy, 1992; Saugy et al., 1984), and Auburn, United States (Molz et al., 1979, 1981; Tsang and Hopkins, 1982; Molz et al., 1983). In the 80 s, large-scale international activities were launched (Molz et al., 1979; Andersson and Sellberg, 1992; Andersson, 1990), aiming at overcoming key technical challenges such as scaling, clogging, and unbalance between the stored heat and cold.

After demonstrating its engineering feasibility across multiple projects, ATES technology has been integrated into different European energy markets, primarily in Northwest Europe serving the dual purpose of providing heating and cooling for buildings. Presently, over 3000 ATES systems are in operation worldwide, with the majority, around 85%, located in the Netherlands, and 10% distributed across Sweden, Belgium, and Denmark (Fleuchaus et al., 2018; Drijver et al., 2019). These global ATES installations collectively yield an estimated annual output of heat and cold exceeding 2.5 TWh (Fleuchaus et al., 2018).

It is worth highlighting that most ATES systems operate at temperatures below 40 °C. These systems are referred to as low-temperature (LT) ATES (Mahon et al., 2022). There have been several tests and pilot projects involving high-temperature (HT) ATES systems, for example, the Auburn test project in the US (Tsang, 1978; Molz et al., 1979, 1981), Scarborough in Canada (Morofsky et al., 1992), Horsholm in Denmark (Jenne et al., 1992). However, these projects encountered technical challenges, which led to a loss of confidence in the technology (Sanner, 1999). Fleuchaus et al. (2020) performed a risk-analysis of HT-ATES highlighting the additional challenges in comparison to LT-ATES. Thus, currently only 2 HT-ATES systems, Rostock in Germany and Middenmeer in the Netherlands, are operating worldwide (Fleuchaus et al., 2020; Schout et al., 2014), and one recent HT-ATES within the PUSH-IT project is under development in Delft, the Netherlands (Geerts et al., 2026; PUSH-IT – Piloting Underground, 2026; Vardon et al., 2026).

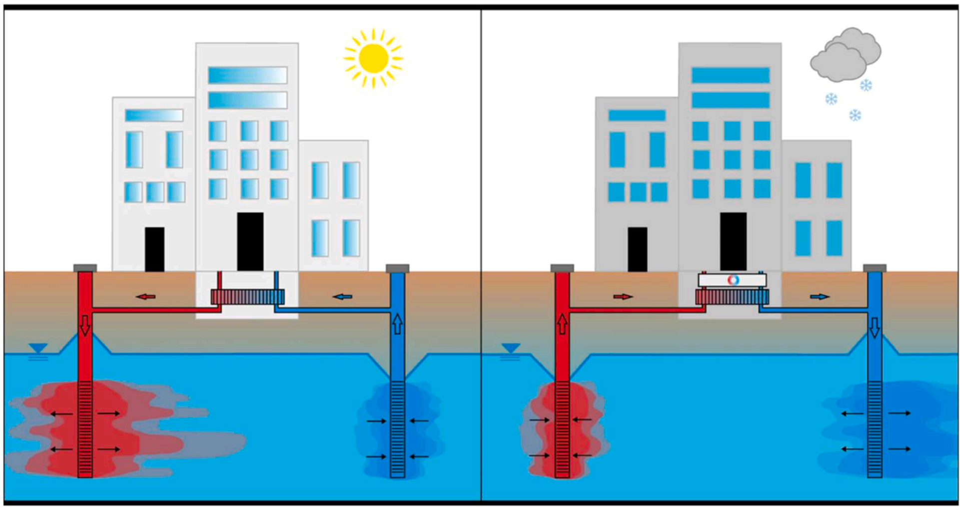

Fig. 1. Operation of ATES system in summer and winter (adapted from Fleuchaus et al. (2021), CC BY 4.0).

3. ATES in DHC applications: literature search methodology

To address the gap between ATES systems and their integration with district energy networks, we conducted a comprehensive literature review to identify relevant studies. Different scientific repositories and databases, including Scopus, Web of Science, and Google Scholar, were utilized to identify relevant articles. The review primarily focused on peer-reviewed journal articles; however, relevant conference papers were also included. Studies analyzing the operation of ATES in connection with a single building have been excluded from this work, as the focus here is on district-scale systems. A PRISMA based approach (Page et al., 2021) for carrying out the review was adopted to find the relevant articles about aquifer thermal energy storage integrated with district energy systems.

The following search strings with Boolean strings were used to find the articles:

- *Aquifer thermal energy* (TITLE-ABS-KEY: “ATES” OR “Aquifer thermal energy storage”) AND
- *District energy system* (TITLE-ABS-KEY: “buildings” OR “district energy” OR “district heating” OR “district cooling” OR “district energy network”) AND
- *Modeling studies* (TITLE-ABS-KEY: “Modeling” OR “Simulation” OR “case studies”)

Fig. 2 illustrates the updated PRISMA flowchart that outlines the selection process including the criteria for selection in the review. A total of 109 articles were retrieved using these search terms. Among them, articles with a broader focus on underground thermal energy storage, seasonal thermal energy storage, or borehole thermal energy storage were excluded from further analysis (n = 34). Duplicate search results were also removed (n = 13). After screening the abstracts and titles, the remaining 62 articles were assessed for eligibility, 11 of these articles were excluded because they included reviews on ATES systems with different scopes as highlighted in Table 1. The remaining 51 articles were then analyzed based on the inclusion criteria focusing on ATES systems integrated with district energy systems. Out of these 51 articles, 26 were excluded based on the criteria described in the flowchart.

The remaining 25 articles are classified into two groups. The first group consists of 10 articles covering 8 case studies on real-world operating ATES-DHC systems, which are discussed in detail in Section 4. The second group, comprising the remaining 15 articles, addresses modeling and simulation studies of hypothetical studies of ATES-DHC systems. These articles include feasibility assessment, performance evaluation, geothermal potential and techno-economic analysis through different modeling approaches and are reviewed in Section 5.

4. Real-world case studies

From the peer-reviewed literature, eight real-world case studies where ATES systems integrated with district energy networks are discussed in the following section. Table 2 provides detailed information on the different case studies, while Fig. 3 illustrates the geographical location of these case studies.

4.1. Overview and description of case studies

4.1.1. Shinshu University, Japan

The pilot ATES system at Shinshu University in Japan has been in operation since 2011 as shown in Fig. 4. Fujinawa et al. (Tomigashi and Fujinawa, 2011; Fujinawa and Tomigashi, 2012) evaluated the operation of the ATES by carrying out a numerical simulation along with using input data from field tests to evaluate the performance of the ATES system. An enhanced ATES system using nested well pairs for pumping and injection was proposed based on the simulation results, which supplies heating and cooling to an air conditioning system in the university. The enhanced ATES was compared with existing conventional ATES systems at the university in terms of thermal efficiency and recovery. Using a nested well system and adjusting the rate of pumping, the efficiency of the enhanced ATES was optimized. In terms of temperature in the cold plume and warm plume, the enhanced ATES performed better than the conventional ATES system. The thermal energy recovery from the enhanced ATES was superior to the conventional ATES system. Simulation results from the subsurface models based on gathered data from field tests showed the pumped water temperature from the enhanced ATES was higher by a factor of 1.5 °C during the heating season and 1 °C throughout the cooling season (Tomigashi and Fujinawa, 2011). The study highlighted the potential of ATES in providing cooling using air conditioning to the university.

4.1.2. German parliament, Germany

The operation of an ATES system in Berlin, Germany, which provides cooling to the parliament buildings with a total floor area of about 250,000 m^2 was assessed by Kranz and Frick (2013). The energy system consists of two ATES systems; one used as heat storage and the other ATES which serves as cold storage to support the building cooling demand. The performance assessment was based on measurement data, focusing on the coefficient of performance (COP) of the entire energy

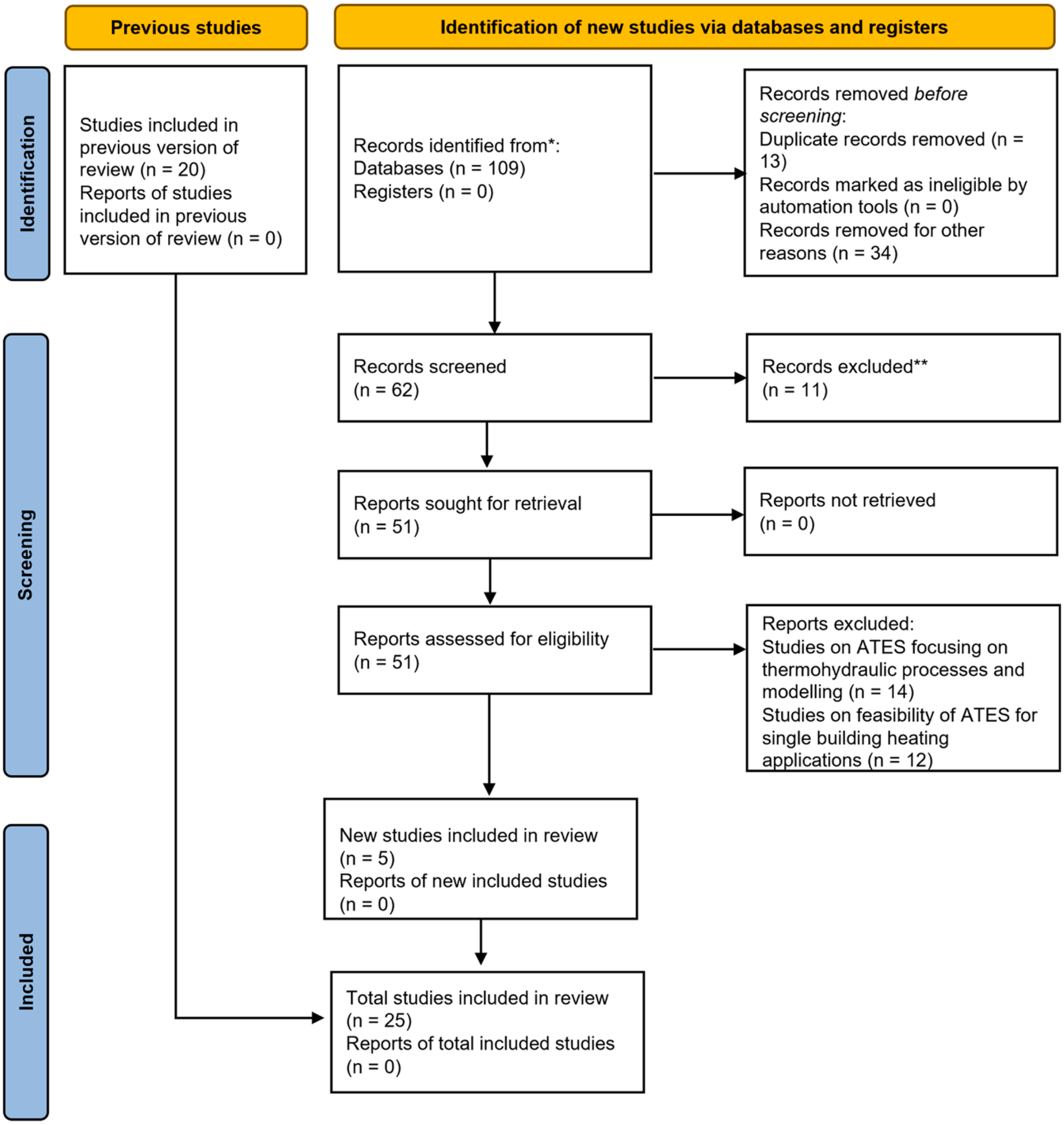

Fig. 2. Literature review methodology based on updated PRISMA guidelines (Page et al., 2021). *Records identified from Scopus. ** Review of ATES systems as highlighted in Table 1.

infrastructure, including both the subsurface ATES components and the building systems. A numerical model using TRNSYS/TRNATES was used to simulate the operation of the ATES. The influence of injection temperature on the regeneration time and discharged heat from the aquifer were used as key parameters in designing the ATES system. The performance of the ATES was evaluated in terms of supplied cooling energy and the efficiency in terms of COP. The COP was highest (7.8) during the year 2005–2006, which was closest to the design case. During subsequent years, more energy was extracted in winter than reinjected in the summer period. Although the ATES system operated successfully for several years and demonstrated the technical feasibility, the ATES system was abandoned mainly because of two reasons: (1) the waste heat was mainly used for an adsorption chiller and (2) deterioration of the well pumps (Fleuchaus et al., 2021; Stemmle et al., 2025).

4.1.3. Oslo Airport, Norway

An ATES system installed at Oslo Airport was evaluated by Birhanu et al. (Zerihun et al., 2015) (2015) with respect to different well placement configurations which is highlighted in Fig. 5. The ATES system consists of 18 wells, nine warm and nine cold wells with an average pumping rate of 28 m^3/h. A parametric evaluation of the underlying aquifer in Oslo was conducted to simulate the flow and thermal behavior of the ATES system. The model was simplified by considering it as a dipole system with one injection and extraction well, while the flow domain of the aquifer was reduced to improve computational efficiency. The study highlighted the importance of the tradeoff between computational efficiency and the size of the flow domain. Different pumping and injection well geometries were simulated to estimate the risk of thermal breakthrough in the aquifer. For the investigated six-month period, there was no risk of thermal breakthrough between the hot and cold wells of the aquifer. The model used in the study could be applied to other scenarios with modifications to well placement configurations. After one pumping/injection cycle, the aquifer's temperature increased by 1–2 °C, indicating significant energy recovery within the ATES system. The study underscores key limitations when simulating ATES systems, particularly the selection of the boundary conditions, in this case study no temperature flux was allowed at the boundaries. The energy recovery efficiency of the ATES system was also

Table 2
Overview of real-world case studies from literature (NA – not available, LT – low temperature, HT – High temperature, H – Heating season, C – Cooling season). For data where ranges were provided, the table shows the average value.

ATES site location	Well number	Pumping rate [m3/h]	Extraction/ Injection temperatures [°C]	HT/LT ATES	Aquifer depth/ thickness [m]	Aquifer geology	System capacity [MW]	Annual thermal load [MWh]	District network temperatures supply/return [°C]	Building types	Modelling tools of ATES	TRL	Year	Ref
Eindhoven (NL)	32	-	-	LT	-	-	H: 1.7, C: 8.8			University campus	-	7–8	2020	(Dvorak et al., 2020)
Brussels (BE)	16	-	-	LT	-	Sand & Clay	-			Not specified	FEFLOW	6–7	2021	(Bulté et al., 2021); (De Paoli et al., 2023)
Oslo (NO)	18	28	-	LT	-	Sand & Clay	-		-	Airport	COMSOL	8–9	2015	(Zerihun et al., 2015)
Stockholm (SE)	6	180	H: 10.4/6.3, C: 9.7/12.9	LT	-/11.5	Sand/Silt & Gravel	C: 1.5	-	-	Offices	-	7–8	2021	(Abuasbeh et al., 2021)
London (UK)	8	280	H: 17.6/9.8, C: 12.6/22.2	LT	-	Chalk	H: 1.8, C: 2.7	-	-	Residential	-	7–8	2024	(Jackson et al., 2024)
Paris (FR)	124 (70 operating)	H: 242, C: 300	-	HT	1460/10	Carbonate rocks	H:10	H: 11.4	-	Residential	MARTHE/ METIS	6–7	2015	(Réveillère et al., 2013)
Berlin (DE)	10	-	H: 22/5 C: 8/22.5	LT	45/-	-	-	C: 3950	C: 13/19	Offices	TRNSYS/ TRNSAT	7–8	2013	(Kranz and Frick, 2013)
Nagano (JP)	4	3	H: -/5, C: -/25	LT	41.5/-	Sand & Gravel/ Clay	-	-	-	University campus	SWATER	6–7	2012	(Tomigashi and Fujinawa, 2011), (Fujinawa and Tomigashi, 2012)

evaluated for two cycles of injection and extraction, which was around 75%–85%. This efficiency was however calculated using the ambient groundwater temperature and therefore results in a higher number compared to (Abuasbeh et al., 2021). Furthermore, the case study also showcased the use of a simplified dipole ATES model for simulating the thermal interactions within the aquifer during operation. The ATES showed no thermal interaction between the warm and cold reservoirs for a constant injection period of six months during the simulation period. The ATES system at Oslo airport was one such energy conservation measure adopted by the management to reduce the energy use for heating and cooling in the airport (Baxter, 2021).

4.1.4. High Tech campus Eindhoven, Netherlands

Focusing on the energy performance studies, an ATES system providing cooling to a university campus in Eindhoven, Netherlands was investigated by Dvorak et al. (2020) . Fig. 6 shows the location of the ATES system in Eindhoven (Ziel, 2017). The ATES system is the largest in the Netherlands, with a heating load of 12,378 MWh and a cooling load of 4494 MWh (Spruijt, 2020). The authors performed a modeling study to analyze the integration of additional heat from data centers into the existing district cooling (DC) network connected to the ATES system in the region. Various scenarios were explored to evaluate trends in ATES operation and DC management. The CO_2 reductions by the ATES system were compared between the current and future scenarios. The study concluded that integrating additional waste heat from data centers into the ATES system would save 1000 tons of CO_2 annually compared to 648 tons under current operation. The study was the first of its kind to analyze ATES operation with district cooling networks in Europe, as most studies focused on the impact of ATES on district heating networks. The ATES system in the case study was modelled using constant temperature sources for warm and cold wells during its operation. Like the ATES system in Oslo, the Eindhoven project faced the challenge of thermal breakthrough. However, while the Oslo system addressed this issue by optimizing well placement and controlling injection rates, the Eindhoven system relied on scenario modeling to predict long-term aquifer behavior to manage operational risks. The case study showcased a scenario to integrate waste heat into an existing ATES system thereby providing thermal balancing to the ATES wells which improves the thermal recovery from the ATES system (Dvorak et al., 2020).

4.1.5. Brussels, Belgium

Using a similar approach to analyze the impact of supplying heating and cooling to buildings from an aquifer, (Bulté et al., 2021) studied two separate ATES systems that utilized the same aquifer to provide heating and cooling to two buildings in Brussels, Belgium (Fig. 7). Each ATES system consists of eight wells, comprising four warm wells and four cold wells. The heat transport in the aquifer was simulated using the software FEFLOW. The temperature difference between the warm and cold wells for different scenarios was simulated for the heating and cooling season. The thermal imbalance between the warm and cold wells of the aquifer played a key role in determining thermal recovery and efficiency of the ATES. While the ATES system in Oslo demonstrates the effectiveness of a simplified dipole configuration, the system in Brussels showcased a more complex multi-well setup to support the building energy demand. The distinct locations highlight how regional energy demands, and aquifer properties, such as groundwater velocity, influence system design and operation. The ATES system in Brussels is an example for implementation of a suboptimal design where thermal imbalances occurred in the ATES system due to insufficient groundwater flow and thermal interaction between the ATES system and building energy side. As it is difficult to correct the thermal imbalances in the ATES once operation has started, the thermal impact on the subsurface also potentially increases with every year in operation. Due to the thermal imbalance, the coldest temperature in the warm wells increased from 12.5 °C to 18 °C. Thus, in order to reduce the thermal imbalance, the operational strategies of the ATES must be adjusted by the building

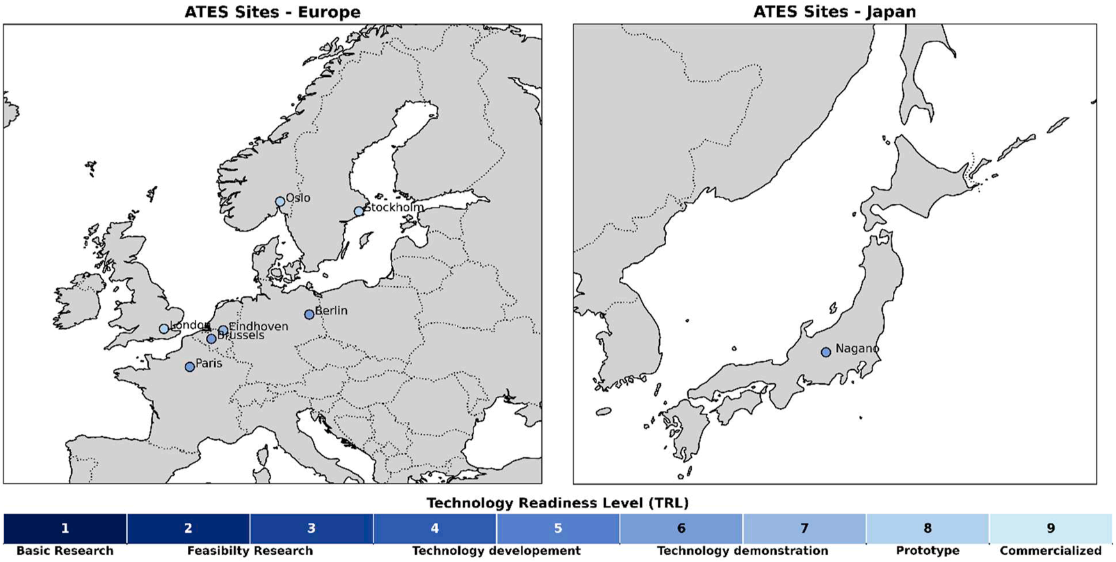

Fig. 3. Spatial distribution of real-world case studies for district heating and cooling networks with ATES, highlighting TRL for the ATES sites.

Fig. 4. ATES system at Shinshu University in Japan (modified and adapted from (Tomigashi and Fujinawa, 2011)).

management (Bulté et al., 2021). For example, by reducing the cooling and maximizing the use of heating from the ATES. Though operation in the upper aquifer was thermally unbalanced, a deeper aquifer was finally utilized to improve the efficiency and performance without affecting the heat storage in the other aquifers. (De Paoli et al., 2023).

4.1.6. Stockholm, Sweden

Similar to the ATES system in Brussels, Abuasbeh et al. (2021) investigated an ATES system in Stockholm, which utilizes an aquifer within an esker formation to provide heating and cooling to office buildings (Fig. 8). The study evaluated the aquifer's performance based on five key performance indicators (KPIs) related to energy and hydraulics. These KPIs centered on temperature variations across the heat exchanger, aquifer wells as well as overall energy balances. The ATES system was assessed over an operational period of three and a half years based on monitoring and well logging data. The research emphasized the value of employing KPIs to monitor aquifer performance, ensuring balanced operation between the building and the storage system. Additionally, the authors argued that co-simulation of both the building and the energy storage system is crucial for developing an optimal operating strategy of the entire system. The ATES system in the Esker formation demonstrated significant differences compared to the ATES system in Brussels when utilizing energy storage in terms of well spacing and pumping volume. Moreover, the esker formation also proved to be an attractive option for the ATES system due to its high hydraulic conductivity and groundwater pumping rate. On the other hand, the experimental data from the ATES system showed that thermal breakthrough occurred in the cold wells of the aquifer, since the extraction temperature exceeded the ambient groundwater temperatures after 4 years of operation. The long-term monitoring of the ATES also provided insights into the performance of ATES by selecting KPI's which included the groundwater loop and building energy system to have a balanced and complete view of the energy system. The thermal recovery efficiency of the system for heating was between 28%–78% for three

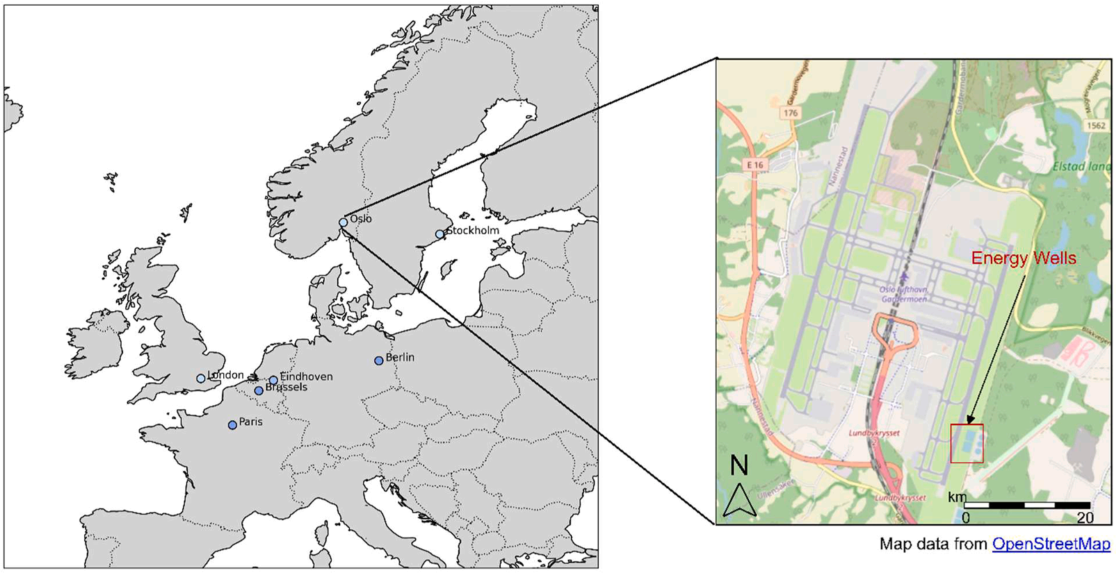

Fig. 5. Location of Gardermoen aquifer providing heating at Oslo airport. The location of the wells is highlighted with a red box. (Modified and adapted from Birhanu et al. (Zerihun et al., 2015)).

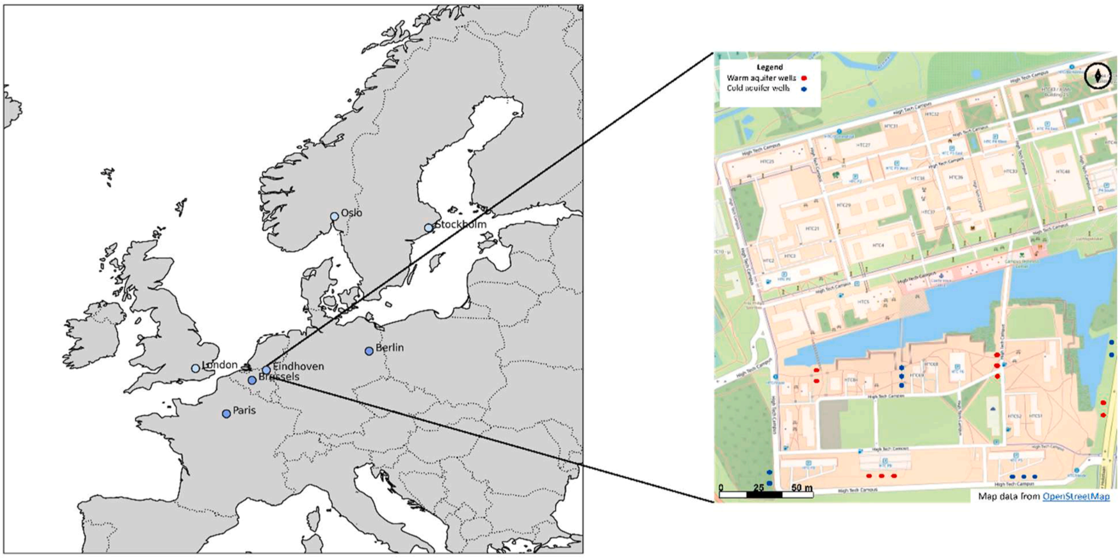

Fig. 6. ATES system at High Tech Campus Eindhoven, the location of the wells is highlighted by red and blue circles (Ziel, 2017) (modified and adapted from Ziel 2017).

storage cycles and for cooling the recovery was between 55%−61%. The thermal recovery was evaluated using the lowest possible temperature during the heating season and highest possible temperature during the cooling season. The thermal recovery efficiency remained stable during the observation period demonstrating the potential of ATES in providing heating and cooling energy to buildings.

4.1.7. Paris, France

While the previous studies focused on well placement configurations, there are studies which focus on the potential large-scale application of ATES with district energy systems. The Paris basin aquifer has been in use for 40 years and supplies geothermal heating to the nearby buildings (Lopez et al., 2010). Réveillère et al. (2013) used a model based on the characteristics of the aquifer to study the ATES system connected to approximately 7500 households in the district heating network of Paris. A mathematical model using the tool MARTHE was used to simulate the operation of the ATES for a period of 30 one-year cycles. After each cycle, the hydraulic balance and the thermal requirements of the ATES were observed. On average, for 30 years of operation, the ATES delivered 54 GWh/year of heat. The geothermal contribution from the ATES system corresponded to 70% of the energy supply mix in comparison to using the geothermal doublet without seasonal storage where the share of energy supply mix was only 50%. The work concluded that for a meaningful and proper energy analysis, the aquifer energy storage and district heating network should be evaluated as a single system. This study underscores the importance of system integration, a concept which is further explored in other studies (Zeghici et al., 2014; Tugores et al., 2015). Their findings stressed the importance of evaluating the ATES and district energy network as a unified system. The work highlighted the impact of ATES systems on the potential energy supply mix to the district energy network. Despite the long-term use of the dogger aquifer, effective management policies and preventative measures from

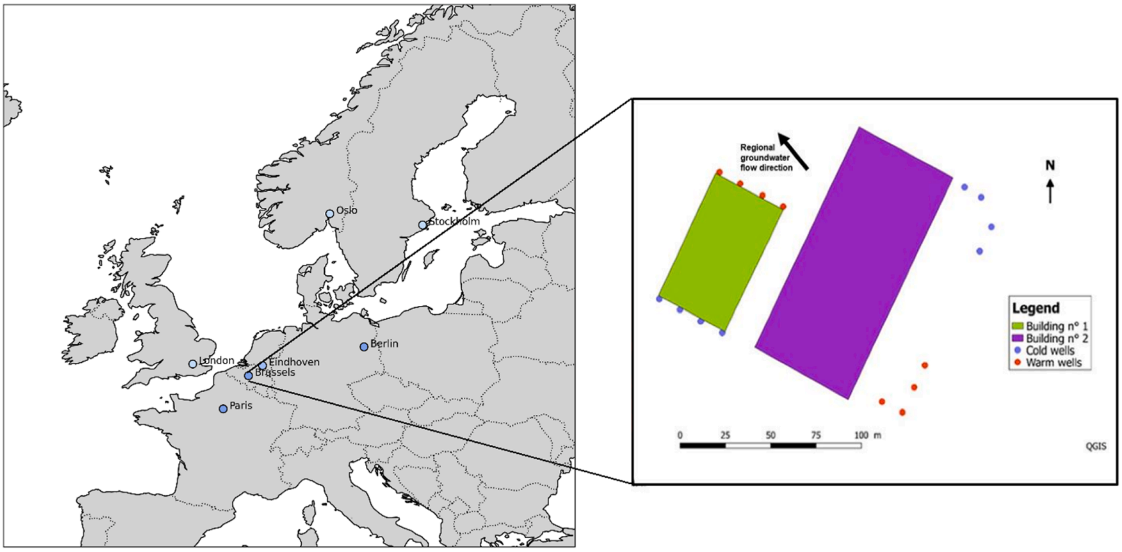

Fig. 7. Two ATES systems connected to buildings in Brussels studied by Bulte et al. (2021). The location of the wells is shown as red and blue dots. (adapted and reproduced from Bulte et al. (2021), *CC BY*).

Fig. 8. ATES in Stockholm supplying heating to office buildings studied by Abuasbeh et al. (2021). The system includes a spare well, which was utilized to analyze the operational performance of the ATES system. (adapted and reproduced from (Abuasbeh et al., 2021), *CC BY*).

the management have ensured the continual use of the aquifer as a source of geothermal energy (Lopez et al., 2010).

4.1.8. Wandsworth residential quarters, London

The potential of ATES implementation on district scale based on different ATES projects in the UK was assessed by Jackson et al. (2024). The ATES system, as shown in Fig. 9, at the Wandsworth riverside quarters in London was evaluated in terms of heating and cooling energy provided (Jackson et al., 2024). The ATES provides space heating and cooling with a maximum heating and cooling capacity of 1.8 MW_{th} and 2.75 MW_{th}, respectively with an annual energy of 508 MWh for cooling and 424 MWh for heating to the buildings. The maximum licensed extraction flow rate for the aquifer was 280 m^3/hr. The study utilized the operational data from the ATES that delivers low-carbon heating and cooling to the residential complex. The actual cooling energy supplied was lower than the licensed capacity of the ATES system, indicating that the ATES system is oversized compared to the building energy demands. The thermal recovery of the ATES was found to be lower for the cold wells ($T_r = 10$–25%) than the warm wells ($T_r = 10$–45%), this was due to more energy being extracted for cooling than heating. This overestimation in sizing leads to thermal energy imbalances of the ATES system and causes suboptimal performance during operation as seen from the thermal recovery factor. Nevertheless, the ATES system showed an example of successful implementation of the technology which can be utilized to provide heating and cooling to the connected residential buildings.

4.2. Comparative analysis of real-world case studies

From the different case studies analyzed, it is observed that most ATES systems are LT-ATES operating with storage temperatures < 25 °C, except the one in Paris which was a HT-ATES system. Typical injection temperatures range between 8- 12 °C in the cold wells and 15–20 °C in warm wells, reflecting the thermal separation requirements for efficient

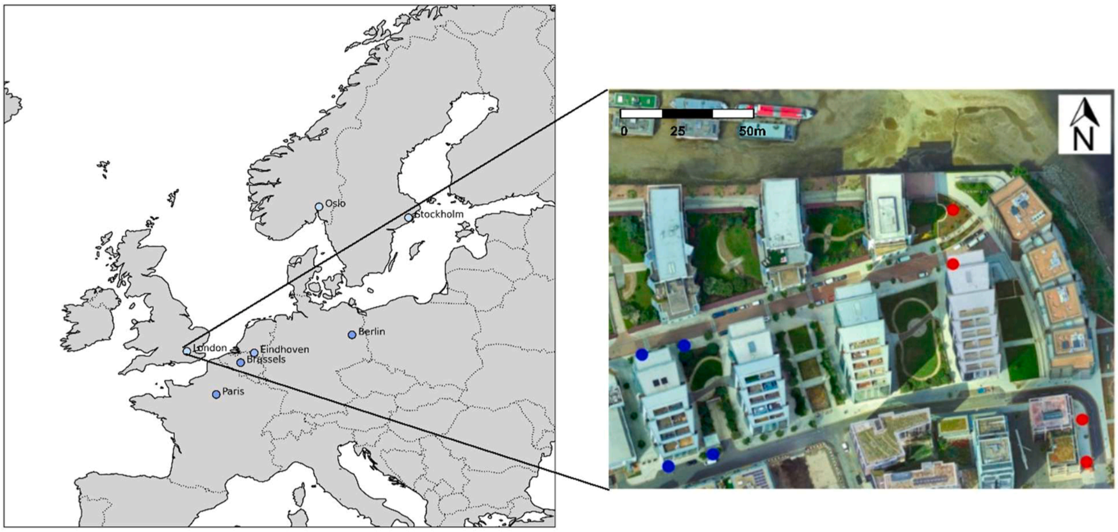

Fig. 9. ATES system supplying heating and cooling to a residential complex in London. The figure on the right shows the locations of the warm and cold wells indicated by red and blue dots. (adapted and reproduced from Jackson et al., 2024, *CC BY*).

storage. These temperature thresholds are critical in maintaining the thermal efficiency of the aquifer and enabling long-term use of the ATES. Higher injection temperatures are not allowed in many countries in the EU due to regulations set by local governments and environmental authorities to prevent negative impacts on groundwater quality and to prolong the operational life of the ATES system (Blum et al., 2021; Hähnlein et al., 2013).

In terms of capacity, it is observed that medium sized ATES (1.5 - 5.0 MW) systems are the most common, as they strike a balance between investment costs, system complexity, demand and scalability. Large-scale ATES, such as the 12.4 MW system in Eindhoven, are less common but demonstrate the scalability of the technology for district energy applications. The number of wells is proportional to the heating and cooling capacity of the ATES system.

Of the eight case studies, the majority supply thermal energy to commercial and institutional buildings, such as offices, university campuses and airports. Only one case study is dedicated to residential buildings, while two studies do not specify the building type.

Long term performance and reliability of the aquifer was addressed in the study by Abuasbeh et al. (2021). The case study site highlighted the need for modeling to identify and achieve optimum operation strategies for the efficient use of the ATES system. Unlike the ATES system in Belgium, which had issues with thermal balancing due to improper well placement (Bulté et al., 2021), the ATES system in Oslo demonstrated a normal operation without thermal breakthrough showcasing the importance of proper well placement and operating strategies when deploying the ATES on large scale (Zerihun et al., 2015). ATES systems, such as the one at Riverside Quarter in London (Jackson et al., 2024), have utilized operational data from the wells to evaluate the thermal recovery and annual energy produced from the ATES. Since the chalk aquifer at Wandsworth riverside quarter was less heterogenous than sand and sandstone aquifers in other sites, the thermal recovery from the ATES degraded over time (Jackson et al., 2024). This highlights the role of aquifer heterogeneity to ensure long-term performance of the system.

Among the different case studies, the research has predominantly focused on potential CO_2 emission reductions (Dvorak et al., 2020; Zerihun et al., 2015; Jackson et al., 2024; Beernink et al., 2022), thermal recovery (Zerihun et al., 2015; Abuasbeh et al., 2021; Jackson et al., 2024), system optimization (Abuasbeh et al., 2021; Jackson et al., 2024; Réveillère et al., 2013; Tomigashi and Fujinawa, 2011), and energy use of ATES systems compared to conventional heating and cooling sources, such as boilers and chillers (Kranz and Frick, 2013). In studies where monitoring and injection tests of ATES were conducted, operational data was utilized to monitor and evaluate the performance of the ATES systems. From the case study sites, we observe that ATES systems and their integration with DHC networks is most common in countries from Northern Europe like Netherlands and Belgium where there is a presence of a high number of aquifers and policies encouraging geothermal energy use (Bloemendal et al., 2015; Hähnlein et al., 2013). District heating and cooling data, such as supply and return temperatures from the different ATES sites, were not available for most of the studies reviewed. Similarly, economic performance indicators were generally not reported for the case studies investigated. However, ATES integration to DHC is more viable economically for larger systems (>2 MW) as highlighted by Herrmann et al. (2026). Out of different STES technologies, ATES systems have the lowest capital costs per storage volume (10€/m^3).

5. Model-based case studies

This section discusses studies where ATES integration with DHC systems is explored through modeling. Table 3 presents the ten modeling studies of ATES systems identified from literature, categorized based on the modeling approaches utilized. The studies include hypothetical scenarios on ATES integration with district energy networks. From the studies identified in the literature, modeling, and simulation approaches for ATES systems with district energy networks can be categorized into three distinct approaches:

- Use of detailed Multiphysics and numerical tools for ATES models with operational building and district energy data as external inputs, e.g., time series data.
- Co-simulation between Multiphysics tools for ATES and building performance simulation (BPS) tools for the district energy system.
- Use of a single simulation platform for both ATES and district energy network for system level models.

Fig. 10 illustrates the three different modeling approaches. The first approach is typically used in studies that focus on the subsurface, with an emphasis on analyzing the performance of the ATES (Todorov et al., 2020a,2020b; Tas et al., 2023). The second approach, co-simulation, is used when analyzing the interaction between the ATES and the district energy system is of particular interest. While this method provides detailed insights, it typically involves high computational effort, requiring significant processing power and can be time-consuming. The third approach involves using a single simulation environment to model

Table 3

Modeling studies on ATES connected with district heating and cooling networks (modeling approaches are abbreviated, DM - detailed modelling, CS - Co-simulation, SE - Single environment. *Modeling tools are not specified), (Annual thermal load: S – small building, M- medium building, L- large building). *For data where ranges were provided, the table shows the average value.*

ATES site location	Well number	Pumping rate [m3/h]	HT/LT ATES	Aquifer depth/ thickness [m]	Annual thermal loads [MWh]	Building types	Modelling tools of ATES	Modeling tool for building/district system	Modeling approach	Year	Ref
Utrecht (NL)	-	-	LT	-	-	-	MODFLOW/ SEAWAT	NetLogo/ MATLAB	CS	2019	(Rostampour et al., 2019)
Bucharest (RO)	-	-	HT	1600/-	-	-	SEAWAT	TRNSYS	CS	2014	(Zeghici et al., 2014)
Turku (FI)	23	104	LT	-/10	H: 67,971, C: 12,382	-	MODFLOW	Input file	DM	2020	(Todorov et al., 2020)
Pukkila (FI)	10	54	LT	-	H: 4407	Offices	MODFLOW/ MT3DMS	Input file	DM	2020	(Todorov et al., 2020)
Utrecht (NL)	78	-	LT	45/30	-	Mixed-use	MODFLOW/ MT3DMS	BCI	CS	2022	(Beernink et al., 2022); (Rostampour et al., 2016)
Ghent (BE)	13	5	LT	-/18.5	-	-	MODFLOW	-	DM	2023	(Tas et al., 2023)
Berlin-Charlottenburg (DE)	2	-	HT	-/10	-	University campus	Modelica	Modelica	SE	2015	(Tugores et al., 2015)
Fictional	-	-	-	-	-	-	Modelica	Modelica	SE	2023	(Maccarini et al., 2023)
Berlin, Hamburg and Munich (DE)	5 (Berlin), 12 (Hamburg), 3 (Munich)	-	LT	-	-	Data centers	TRNATES	TRNSYS	SE	2015	(Drenkelfort et al., 2015)
Delft (NL)	2		HT		Sinusoidal heat load	University Campus	DARTS	TESPy	CS	2026	(Vardon et al., 2026); (Kukrer et al. 2025)
Hilversum (NL)	-	-	LT	-	S: 54.45 M: 72.28 L: 285.83	Mixed-use	Python	Python	SE	2025	(Beijneveld et al., 2025)
BeerseZuid (Belgium)	1	-	LT	10–50	-	Mixed-use	Theoretical model	GIS based DH model	SE*	2026	(Chicherin, 2026)
Rome (Italy)	2	-	LT	-	-	Mixed-use	GeoSIAM	TRNSYS 18	CS	2025	(Pallotta et al., 2025)

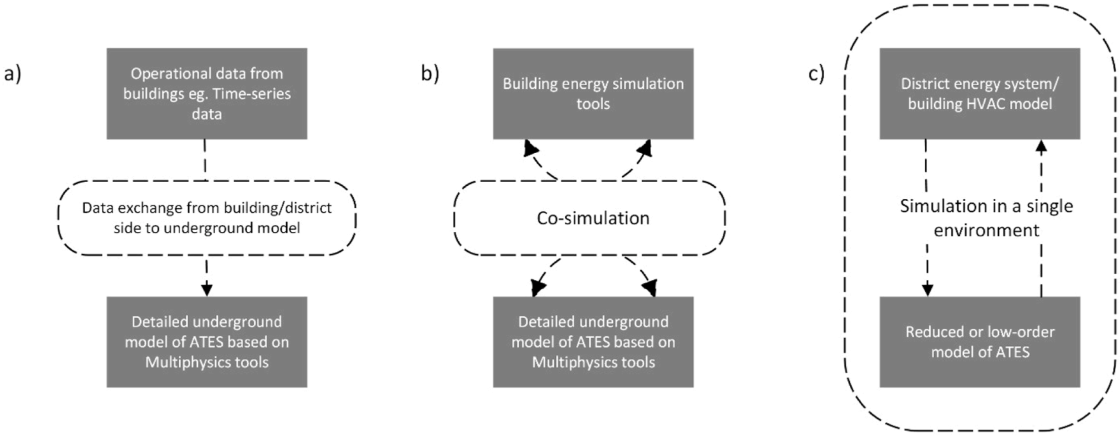

Fig. 10. Modelling approaches for ATES connected with district energy systems (arrows indicate information exchange between the different interfaces).

both the ATES and the district thermal system together. While studies only focusing on district energy network and ATES have been prioritized in this section, a study by Bozkaya et al. (2018) focusing on building energy model with ATES is highlighted in the co-simulation subsection.

5.1. Numerical and detailed multiphysics model of ATES with operational district energy data

Multiphysics and numerical tools for subsurface modeling, such as COMSOL, FEFLOW, and MODFLOW, are commonly used for detailed groundwater simulations of ATES operation. These tools are developed using the finite element, finite volume, or finite difference methods to analyze the thermo-hydraulic and mechanical processes occurring within the subsurface. They simulate mass and heat transport based on the fundamental equations governing mass and energy balance in the aquifer, providing detailed insights into subsurface behavior. MODFLOW is a free and open-source tool which makes it easier for code transferability and use of the software. Other groundwater simulation tools such as TOUGH, SHEMAT, TOUGH2 and UTCHEM have been developed specifically for modeling multiphase flow and heat transfer in hydro-geothermal reservoirs (Lee, 2010; Gao et al., 2017). The different subsurface models reviewed have analyzed the characteristics of the ATES system such as thermal plume evolution, temperature distribution, fluid flow properties, and hydraulic head distribution in the subsurface.

Different well configurations for ATES systems were evaluated using modeling tools in the study conducted by (Beernink et al., 2022; Bloemendal et al., 2014). The potential of a hypothetical ATES for an aquifer with a low transmissivity was estimated by Tas et al. (2023) in a campus setting in Belgium. MODFLOW was used to simulate the fluid transport in the aquifer. The well placements were optimized based on the data gathered from previous pumping and injection tests conducted around the case study site. The thermal recovery and hydraulic head distribution for warm and cold wells in checkered and lane arrangements were compared over a period of 20 years. The study also analyzed the possibility of thermal breakthrough between the wells and the pumping rate required to prevent clogging in the wells and the flooding of the aquifer. Checkered well arrangement was also found to maintain the hydraulic balance in the aquifer and utilize the available space effectively to meet the building heating and cooling demands.

A similar approach was explored by the GreenSCIES project (Revesz et al., 2022) in Islington, London where the study assessed the potential for thermal balancing of an ATES system for a low-temperature district energy network (Revesz et al., 2022a, 2022b). A pre-feasibility study of the ATES was carried out to study the effect of groundwater abstraction on the underlying aquifer. Preliminary results from the groundwater flow and heat transport modeling of the ATES system revealed that thermal interference of the ATES system was acceptable. The results from the study also indicated that the revenue from the ATES project would increase by approximately £94,000 annually. EnergyPro was used for the techno-economic analysis of the ATES system.

Further evidence of integration of ATES with district energy networks comes from studies conducted in Finland by Todorov et al. (2020a, 2020b) where MODFLOW/MT3DMS was used to simulate the operation of the ATES, and a simplified steady state excel model was used to validate the simulated results from one case. Finland was chosen due to its high geothermal penetration level and limited large-scale applications of ATES systems in the country. Todorov et al. (2020) aimed to develop a novel method to analyze the performance of the ATES system in district heating and cooling applications. The work used district heating and cooling hourly data as input to the ATES system model. The study was performed using limited and uncertain data but demonstrated that it is possible to holistically integrate groundwater ATES models with energy demands from the DH network.

In another study on a Finnish suburb, an ATES system was coupled with a ground source heat pump (GSHP) to evaluate the techno-economic benefit of the coupled GSHP and ATES connected to the district heating and cooling (DHC) network (Todorov et al., 2020). The purpose of GSHP is to recover excess heat from the district cooling side and improve the COP of the GSHP. The district heating network was integrated with the groundwater model using hourly operational data from the DHC network as input. This research employed a combined groundwater and techno-economic modeling approach to study the energy system holistically. The study indicated that during an 8-year operation, the abstraction temperature and heat recovery factor (HRF) of the aquifer storage stabilized after a period of 3–4 years. The techno-economic analysis revealed that the total investment cost was about 1.1 million € of which 22% was for heat pumps and heat exchangers, and 75% was for the piping and well cost.

The Pukkila study also assessed the long-term impact of the ATES system on groundwater. It was observed that in a period of 20 years, the thermal plume area around the warm well remains the same with a thermal radius of 75 m whereas near the cold wells the thermal plume spreads over a few hundred meters (Todorov et al., 2020). Hence, a recommendation that the location of the cold wells should be downstream and separated from the warm wells to reduce thermal interference between the wells of the ATES. Techno-economic analysis of the ATES-GSHP model showed that the energy production cost was thirty €/MWh which was lower than the Finnish DH price in 2017.

These studies demonstrate that it is possible to assess the performance of ATES systems coupled with district energy networks by using operational building data as input for the ATES model. This approach is useful for evaluating system performance under various conditions, such as well placement, thermal balancing, and energy recovery. However, if the focus is on analyzing the dynamic interactions between the subsurface and the district system, alternative modeling approaches are required to capture those complexities

5.2. Modeling of subsurface and use of building energy modeling tools (co-simulation)

Co-simulation involves data exchange and coupling between the subsurface models with the above surface models to obtain a complete understanding of the integrated system. There are different ways to couple modeling tools, this involves data exchange using files, network communication and the use of functional mock-up units (FMU's) (Yazdani et al., 2026). In this approach, the temporal synchronization for data exchange between the two models is done using different synchronization schemes. One such method is the Gauss-Seidel synchronization method which is a sequential, non-iterative method for information exchange between the models (Formhals et al., 2022).

Researchers exploring the interaction between subsurface ATES systems and district thermal networks have recently applied co-simulation approaches to enhance the depth of their analyses (Zeghici et al., 2014; Rostampour et al., 2019; Bozkaya et al., 2018). For instance, subsurface processes in ATES can be simulated using multiphysics tools such as FEFLOW or MODFLOW, as mentioned in the previous section, while district heating systems are modeled with BPS tools like TRNSYS or EnergyPlus. Thus, co-simulation provides a detailed analysis of the interactions between subsurface thermal processes and above surface district energy systems, capturing complex heat transfer dynamics and energy recovery mechanisms. By leveraging the strengths of each domain-specific tool, co-simulation enables a detailed analysis of the entire energy system (Lyden et al., 2022). However, despite these advantages, co-simulation approaches often result in high computational effort, which can significantly increase simulation time and require substantial computational resources. Thus, it is important to carry out co-simulation when system analysis cannot be simulated by simpler approaches such as (Tugores et al., 2015; Maccarini et al., 2023).

Expanding the co-simulation approach, Beernink et al. (2022) analyzed an ATES system connected to a district energy network serving 26 multi-dwelling buildings in Utrecht, Netherlands. The study sought the optimal well placement for the ATES system based on simulation results compared to the overall GHG emissions from different well configurations. MODFLOW was used to simulate the ATES operation, and a Building Climate Installation (BCI) model was developed to calculate the energy demands of each building and determine the energy use of the components. The findings indicated that denser well placements such as mono wells, not only fostered a higher adoption rate of ATES technology due to flexible placements of wells but also resulted in reduced GHG emissions by favoring utilization of heat pumps over electric and gas boilers. The well placement and overall thermal recovery from the ATES depended on the building size and associated storage volume. The reduction in GHG emissions from ATES adoption was almost 50% in the year 2030 relative to emissions in 2019. This approach of integrating ATES with district energy networks is further explored in subsequent studies.

Building on this framework, the performance of a district heating network in Romania was assessed by Zeghici et al. (2014). The district heating network supplying heating to 13 multi-story buildings was evaluated by comparing the existing district heating energy supply with a new proposed energy system consisting of renewable energy storage (HT-ATES), natural gas and electricity from the grid. The integrated HT-ATES-CHP system was designed using TRNSYS based on previous projects in the Netherlands and Germany. Like the Beernink et al. (2022) study, this research highlights the critical role of co-simulation for holistic system evaluation. The results from the simulations demonstrated that the new system consisting of the HT-ATES, heat pumps and CHP turbines can save 82% of CO_2 emissions and reduce energy consumption by 43%.

The combined modeling of subsurface and district energy networks draws clear parallels with Beernink et al. (2022) findings of lower CO_2 emissions from adoption of ATES technology and improved energy performance of the overall energy system, and also highlighting the importance of co-simulation in large-scale district energy networks. The HT-ATES system was modeled in SEAWAT code, and the resulting values such as thermal recovery, energy efficiency in cold and warm storage, water flow rate and temperature were integrated with the TRNSYS model of the district heating network. The study also emphasized the role of seasonal energy storage in offering flexibility between the energy supply system and the connected buildings, by storing the excess heat produced for future use.

Another co-simulation work focusing on a HT-ATES in Delft, Netherlands was evaluated by Kukrer et al. (2025). The co-simulation framework adopted TESPy for above surface energy model and a DARTS-based subsurface model to evaluate the long-term stability of the HT-ATES in district heating networks (Vardon et al., 2026). For a 10-year simulation period, the HT-ATES proved to be a viable source of heat. The thermal recovery for the ATES increased from 23% in the first year to 42% in year 10. The dependance on auxiliary sources of heat such as gas-fired boilers reduced significantly in the later years of simulation showcasing the viability of the system. The co-simulation framework adopted proved beneficial in coordinating the surface and subsurface models in real-time by utilizing a dynamic cutoff control strategy.

The use of predictive control strategies with co-simulation was explored by Rostampour et al. (2016). Using a model predictive control (MPC) approach, building energy installations with varying spatial placement policies using NetLogo and coupled interaction of ATES with MODFLOW were investigated. The developed ATES model was simulated for varying building thermal loads and well placement strategies. The study highlighted the importance of constraints such as charging time, storage duration and discharging of stored energy in the integration of ATES with thermal grids.

In a similar study, Rostampour et al. (2019) used the MPC strategy for spatial planning of ATES wells using NetLogo and MATLAB to model the building loads and control for the case study city of Utrecht, Netherlands. MODFLOW/SEAWAT was used to simulate the hydrological properties of the ATES. This control-driven co-simulation approach added a dynamic, real-time element to the system evaluation that was not present in the earlier studies by Beernink et al. (2022) and Zeghici et al. (2015). Based on the different scenarios simulated, the study analyzed the thermal efficiency of the ATES system, the average COP of ATES and average economic efficiency of ATES systems as indicators under varying well placements strategies and the potential reduction in greenhouse gas emissions from the well placements. MPC strategy proved an effective approach in evaluating the system performance of the ATES in terms of GHG savings, GHG abatement costs and average subsurface usage efficiency connected to the building energy system. With the rapid implementation of ATES systems, the MPC approach is useful for planning and operation of the ATES system.

The environmental impact of ATES systems coupled with heat pumps was studied in a co-simulation approach where the building energy system was simulated under different climate conditions in TRNSYS and the ATES system was simulated using GeoSIAM (Pallotta et al., 2025). The Total Equivalent Warming Impact (TEWI) of the ATES based system, and an air-water source heat pump was analyzed. The systems were compared over a 15-year period and the ATES-based system showed substantially lower climate impact, about 22% compared to the traditional air-water source heat pump. This study highlighted the importance of using time dependent assessment to evaluating ATES system against other technologies.

While the co-simulation approach has been useful to study the interaction of ATES with district energy systems, it is also time intensive due to high processing power and computational effort required (Formhals et al., 2022). The computational challenges arising from information exchange between the different tools and the order of data flow between the different platforms during runtime must be also carefully implemented.

5.3. Modeling in a single simulation environment

Recent studies have explored the use of single simulation environments to model coupled subsurface, district, and building energy systems, enabling a more integrated analysis of thermal interactions and dynamic behavior across scales. Two main modelling workflows are currently established in literature. The first is based on TRNSYS, a modular transient simulation tool widely used for building and district energy system analysis (Beckman et al., 1994; Klein, 1988). Within this workflow, the TRNATES model is employed to simulate the subsurface thermal processes, allowing for the coupling of ATES with building and network components (Schmidt, 2004). The second workflow relies on Modelica, an open, equation-based modelling language designed for multi-domain physical systems. Modelica supports the development of highly detailed and dynamic models using open-source libraries such as the Buildings Library (Wetter et al., 2014) and the IBPSA Library (Wetter et al., 2019), which provide standardized components for HVAC systems, energy networks, and different control strategies.

Drenkelfort et al. (2015) employed TRNATES, an open-source ATES model designed for integration with TRNSYS, to simulate the performance of ATES systems. Their study focused on analyzing the operation of ATES in supplying cooling energy to different DC systems in Germany. From the different simulation runs carried out, the study concluded that the operational hours of ATES depend on the ambient and subsurface temperature. Overall, they found that ATES implementation can assist a medium sized district cooling system to reduce the energy demand of the cooling system.

A simplified one pipe 1D model of a DHC network with an ATES was developed by Tugores et al. (2015) using the Modelica language. The model assumes transient convective and conductive radial heat flow in porous media. The ATES model was integrated into a district heating network model, which was developed as a single aggregated building using a pipe model developed from earlier work. Additionally, a low-order building model was employed to estimate heating and cooling demands by considering heat gains and losses through conduction and solar radiation. The study demonstrated that Modelica is highly suitable for simulating complex energy systems.

Along a similar approach, Maccarini et al. (2023) developed a low-order model of an ATES for the IBPSA Modelica library (Wetter et al., 2019) based on convective and conductive heat transfer through porous media. The low-order ATES model was compared against other multiphysics ATES modeling tools such as COMSOL, SEAWAT, Tough2 and MOOSE to test the capability and accuracy of the developed model. The results demonstrated that the developed model predicted the aquifer temperatures during typical operation considering injection, drawdown and build-up phase with a normal mean bias error (NMBE) of 1.6×10^{-2} and 9.0×10^{-5} for probe distances of 1 m and 10 m, respectively. The work highlighted the use of the developed low-order model to carry out building energy simulations.

Evaluation of ATES integration with low-temperature DHC networks was discussed in (Beijneveld et al., 2025; Chicherin, 2026). The modeling tools utilized for the study were developed in Python. In the work by Chicherin (2026), the subsurface model was developed using theoretical equations governing mass and heat transfer in the subsurface. The study highlighted the importance of focusing on system-level performance when integrating ATES with district heating networks, while also showing that the sizing and placement of wells significantly affect ATES efficiency. The author found that a 10% increase in ATES heat capacity led to a 6% reduction in the thermal radius, indicating that materials with higher heat capacity absorb more heat and limit the spread of the thermal plume within the aquifer.

A multi-carrier energy system including PV, HP and ATES integration with a DH network in the Netherlands with the primary goal to reduced CO_2 emissions was analyzed (Beijneveld et al., 2025). Both the DH network and the ATES system were modeled in Python. Different configurations of the ATES were explored to identify the optimal configuration to prevent heat and distribution losses. Distributed ATES configuration showed an increase in heat losses of up to 140% in the ATES and 39% in the distribution network compared to a centralized configuration.

Simulating both subsurface and above-surface ATES systems using a unified simulation platform is an efficient and streamlined approach. By integrating these components into a single simulation environment, the complexities of cross-platform data transfer and compatibility issues are eliminated, enabling seamless interaction between subsurface thermal storage dynamics and above-surface heating and cooling infrastructure. Furthermore, using a single simulation tool simplifies the workflow for researchers and engineers, facilitating better optimization and decision-making in designing and managing ATES systems. However, in such cases the sub-surface model is typically developed using reduced order modeling approaches or grey box techniques, which offer lower accuracy compared to detailed multi-physics tools.

5.4. Summary of model-based case studies

Among the studies reviewed in Section 5, detailed modeling (DM) represents the most common typology. Three studies (Todorov et al., 2020a, 2020b; Tas et al., 2023) focus on numerical or multiphysics-based simulations (e.g., MODFLOW, MT3DMS, or SEAWAT) that use building energy data as input to evaluate ATES operation and performance. These models provide a detailed understanding of the subsurface thermo-hydraulic, mechanical and chemical processes. However, this modeling approach does not enable a real-time representation or analysis of the above-ground energy system, as building energy data is used only as an input. In comparison with co-simulation approaches, it is less computationally demanding.

The co-simulation (CS) approach, represented by five studies (Zeghici et al., 2014; Beernink et al., 2022; Rostampour et al., 2016; Kukrer et al.; Pallotta et al., 2025), involves coupling groundwater models (e.g., MODFLOW, SEAWAT) with building or district energy models (e.g., TRNSYS, MATLAB, NetLogo). Coupling through co-simulation can be implemented using text files, network connections, or embedded functions. Each coupling method has its own advantages and drawbacks (Yazdani et al., 2026). Data exchange via text files is more prone to errors; this approach was adopted in the study by Bozkaya et al. (2018). Co-simulation enables a comprehensive real-time analysis of the interaction between the subsurface and the energy system. However, it also introduces challenges, such as increased computational time, greater data exchange complexity, and higher processing requirements. Despite these limitations, co-simulation is a valuable approach for studies that require a holistic understanding of the coupled system's performance in real time.

Finally, single simulation environment (SE) modeling accounts for five studies (Tugores et al., 2015; Maccarini et al., 2023; Drenkelfort et al., 2015; Beijneveld et al., 2025; Chicherin, 2026), which employed tools such as Modelica, TRNSYS and Python to simulate the dynamic behavior of ATES integrated with buildings or district energy systems. One study did not specify the modeling tool used to carry out the analysis (Chicherin, 2026) as highlighted in Table 3. These low-order models facilitate faster computation and are particularly valuable for assessing system-level performance and testing different control strategies. Using a single software environment reduces the computational time and effort required for system analysis, although this trade-off often results in simplified subsurface models. At the same time, it allows users to study the interaction between subsurface and above-ground energy systems without the complexity of co-simulation.

From the different modeling approaches reviewed, simulations within a single environment are particularly suitable for feasibility assessments or ATES potential studies, where an overall understanding of the integrated system is required. Co-simulation, on the other hand, is mainly used when a detailed long-term analysis of both the surface and above-ground systems is needed.

Overall, the reviewed works show a balanced distribution of modeling typologies, three DM, five CS, and five SE studies. Table 4 compares the three modeling approaches in terms of their level of detail for subsurface and building/district network representation, as well as their associated modeling and computational effort.

6. Trends and challenges

The integration of ATES systems with district energy systems offers a promising solution for fulfilling the heating and cooling demands of buildings and reducing dependence on fossil-based sources (Perera et al., 2023). Compared to other seasonal storage technologies such as pit, borehole and tank storages, ATES systems have lower operating and maintenance costs (Lyden et al., 2022). However, the high initial investment which comes with drilling and installation of equipment with the uncertainty about financial benefits hinders widespread adoption. Environmental and economic studies (Lyden et al., 2022; Bloemendal et al., 2014; Stemmle et al., 2021; Schüppler et al., 2019; Daniilidis et al., 2022) indicate that ATES systems generally result in lower greenhouse gas emissions and shorter payback periods compared to conventional sources such as natural gas boilers and electric heaters. Nevertheless, the potential for negative impact on groundwater quality and bacterial growth within the wells which leads to well clogging poses technical and environmental risks (Blum et al., 2021; Schüppler et al., 2019). Hence, proper well placement and site-specific investigations are critical before deploying ATES systems. A thorough techno-economic analysis is also essential to fully realize their potential.

To effectively support district heating networks, ATES systems must possess adequate capacity for both charging and discharging of aquifer wells, particularly during periods of peak demand. Maintaining thermal balance is crucial for long-term operational efficiency of the ATES. Widespread use of ATES systems may lead to long-term thermal interactions between systems if these systems are not properly sized and operated as the case in Belgium (Bulté et al., 2021). Potential conflicts of ATES with other groundwater uses can occur in areas with water scarcity. However, in common practice groundwater extraction for drinking water or agricultural purposes is located outside urban areas where ATES systems are in operation (Pellegrini et al., 2019).

The barriers in maturity and growth phases have been discussed in detail by Pellegrini et al. (2019) and Fleuchaus et al. (2018), European legislation differs in terms of ATES development and implementation as already pointed out by Fleuchaus et al. (2018). Optimal use of the subsurface is necessary to improve the performance and recovery of energy from the subsurface (Bloemendal et al., 2014). Through modeling and simulation studies, the impact of ATES can be estimated and the investment costs, payback time, and avoided CO_2 emissions are parameters which are vital for implementation of future ATES systems. Integration of ATES with energy grids is a feasible alternative which increases the energy yield and efficiency of the network (Sadeghi et al., 2024).

Table 4
Comparison of different modeling approaches based on level of detail and computational effort. (●●●: High, ●●: Moderate, ●: Low).

	Detailed multiphysics modeling (DM)	*Co-simulation (CS)*	*Single simulation environment (SE)*
Level of detail for subsurface	●●●	●●●	●
Level of detail for building/district network	●	●●●	●●●
Modeling and computational effort	●	●●●	●●

The limitations and potential for the deployment and installation of ATES systems with district heating networks were discussed by Wesselink et al. (2018). A conceptual framework highlighting the different conditions such as technical, theoretical, economic and market potential to identify the feasibility of ATES systems is useful for the implementation of ATES systems into existing and future district energy networks. The different focus levels in ATES implementation were identified, and the framework was developed. Using two different scenarios, a sensitivity analysis was conducted to find the influence of different policies such as energy investment rebate, percentage of investment, full load hours and energy tax on the implementation of HT-ATES. In the alternative scenario, the energy tax showed a considerable influence on the LCOE with almost two times lower price than the business-as-usual (BAU) scenario. It was also observed that the LCOE of HT-ATES is influenced by their lifetime (Wesselink et al., 2018).

The market opportunities of integrating ATES with district energy networks were explored by Hoekstra et al. (2020) within the E-USE(aq) project (Bloemendal et al., 2016). Different ATES sites in Denmark, Italy, Netherlands, and Spain were considered based on district heating and cooling demand and their respective economic figures. The work explored the benefit of utilizing ATES systems to enhance the large-scale adoption of the ATES technology. The overall CO_2 emission reduction per year from the adoption of ATES was evaluated, as well as the opportunity to use bioremediation with ATES systems in case of soil contamination. The integration of ATES with district energy networks proved to be important in reducing CO_2 emissions arising from meeting the heating and cooling demands of buildings.

The thermal energy from the ATES can also be balanced cost effectively by considering different sectors such as office buildings, residential buildings and industrial buildings. The factors influencing the integration of ATES with district heating networks from a systematic perspective were discussed by Scholliers et al. (2024). Both the life-cycle costs (LCC) and life-cycle assessment (LCA) were utilized to identify the factors affecting the integration of HT-ATES into district heating networks. These include potential environment, economic and technical key factors.

The work identified environmental factors such as well material, drilling of subsurface and disposal of construction waste during subsurface construction (Stemmle et al., 2021). In the operation phase, the lifetime of heat pumps and heat exchangers was noted as important for ensuring functional equipment performance. Technical factors during operation such as the operating hours, COP and flow rate play a vital role. Potential economic factors such as piping costs, valves and borehole length during construction stage are important for consideration. During the operation stage, the electricity for running the pumps and COP of the heat pump were identified as critical factors in ATES operation. Among the four-life cycle phases: (1) development, (2) construction, (3) operation and (4) end-of-life, construction and operation were identified as the two most significant phases. The impact of these factors on the construction and operation of HT-ATES was assessed using a PESTLE analysis (Scholliers et al., 2024). This methodology can also be applied to the integration of LT-ATES and other seasonal energy storage technologies.

Integration of ATES with distributed energy systems was discussed in earlier works by Perera et al. (2023), where the main aim was to improve the flexibility of existing district energy systems with the integration of aquifer thermal energy storage (ATES) as seasonal thermal energy storage (STES). The overall assessment of the ATES system was done using techno-economic parameters, optimization of the distributed energy system based on the ATES for grid integration to minimize the CO_2 emissions from fossil fuels.

Regulatory frameworks for ATES systems vary across the EU. For example, in the Netherlands, legislation allows permit holders to place wells based on requested storage volumes, with unused permits being reallocated to new investors, fostering ATES deployment. Despite progress in some countries, others lack comprehensive national strategies for exploiting the ATES technology. At the same time, country-specific policies regarding ATES are lacking. A survey conducted by Stemmle et al. (2024) examined the prevalent ATES policies across 82 countries through different experts and organizations. The findings revealed that policies vary widely among the countries in terms of ATES existence and design. Comparison of different countries revealed that Netherlands, Denmark and Germany have varying degrees of maturity of ATES with mature, developing and growing markets, respectively (Fleuchaus et al., 2018).

7. Conclusions and outlook

This review presents a state-of-the-art overview of current research on aquifer thermal energy storage (ATES) systems integrated with district heating and cooling (DHC) networks. The work examines the integration of ATES systems with DHC networks by analyzing insights and findings from different case studies. It highlights and summarizes real-world ATES implementations at a district scale, investigates different modeling approaches for coupling ATES with DHC systems, and explores the technological, policy, and deployment challenges that limit their widespread adoption. Based on the different studies reviewed, the following conclusions can be drawn.

ATES implementation on district and city scale is limited due to financial, legislative and technical barriers (Bulté et al., 2021; Jackson et al., 2024; Zeghici et al., 2014). From the different case study sites presented in this paper, ATES systems are used to provide thermal energy to buildings in countries with cold climates, i.e., Northwest Europe. Countries like Netherlands and Belgium have a large number of ATES systems installed and in operation (Fleuchaus et al., 2018). The scalability of the ATES technology is demonstrated at Eindhoven Campus in the Netherlands, which is one of the largest ATES systems in Europe (Spruijt, 2020; Ziel, 2017). This demonstrates the potential and scalability of ATES systems in effectively providing thermal energy to district energy systems. To achieve decarbonization of district energy systems, seasonal thermal energy storage technologies such as ATES play a key role in utilizing geothermal energy to meet the increasing thermal energy demand. Thermal recovery efficiency, an important parameter for evaluating the performance of ATES systems, was reported for only three real-world case study sites. Future works should therefore focus on analysing this indicator across a broader range of ATES applications.

In terms of modeling and simulation studies, three main approaches have been identified from literature. The current research has primarily focused on analyzing the subsurface characteristics and performance of ATES systems through modeling and simulation using numerical and physics-based models of the subsurface, and co-simulation methods as discussed in this work (Bulté et al., 2021; Todorov et al., 2020; Drenkelfort et al., 2015; Zeghici et al., 2015; Tas et al., 2025) with a few of studies focusing on modeling in a single environment (Tugores et al., 2015; Maccarini et al., 2023; Beijneveld et al., 2025; Chicherin, 2026). Overall, there a several models of ATES developed and implemented subsurface analysis, however the analysis of system level impact on ATES integrated district energy systems is lacking (Lee, 2010). In some cases, operational data from the district energy network was used to analyze the behavior of the connected ATES system such as in Finland by Todorov et al. (2020a,2020b). Long term ATES monitoring using experimental data to develop KPI's is used to assess the performance of ATES systems (Abuasbeh et al., 2021). Modeling approaches can be utilized to predict the long term operation and develop efficient operating strategies for ATES integrated energy systems (Lyden et al., 2022).

There is a notable research gap in the modeling of ATES systems connected with district energy networks, with district energy data often treated as predetermined inputs as seen in the case of Finland and Paris (Réveillère et al., 2013; Todorov et al., 2020). Future research should therefore adopt an integrated approach using building energy simulation tools like Modelica or TRNSYS and integrating groundwater models in e.g. FEFLOW, MODFLOW or COMSOL to conduct a comprehensive analysis of the energy system, to better understand the interaction between the ATES and district energy network.

The complexity of developed models should align with the study's goals. Sophisticated modeling techniques are necessary for detailed analysis and long-term predictions, while simpler models would suffice for preliminary assessments (Lyden et al., 2022). Simplified low-order models which can be utilized to analyze the system performance of the storage system with district energy networks are an alternative to using a computationally challenging co-simulation approach (Maccarini et al., 2023; Scalco et al., 2022).

A comprehensive framework for ATES implementation encompassing both technical and legislative actors is essential to further develop the growth and implementation of ATES integration with district energy networks. By applying different modeling and simulation approaches, research on ATES systems has enhanced our understanding of the interactions between thermal energy storage and district energy networks. The platform-based design (PBD) approach for the design of energy systems which was discussed by Sulzer et al. (2023), offers an opportunity to bridge the different domains and disciplines which can help engineers, policymakers and stakeholders in carrying out smarter design choices for implementing renewable based energy systems.

CRediT authorship contribution statement

Mohammed B. Rabani: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Alessandro Maccarini:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Kathrin Menberg:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Philipp Blum:** Writing – review & editing, Resources, Investigation, Funding acquisition. **Alireza Afshari:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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