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Original Article

Development status and prospect of underground thermal energy storage technology

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Abstract: Underground Thermal Energy Storage (UTES) store unstable and non-continuous energy underground, releasing stable heat energy on demand. This effectively improve energy utilization and optimize energy allocation. As UTES technology advances, accommodating greater depth, higher temperature and multi-energy complementarity, new research challenges emerge. This paper comprehensively provides a systematic summary of the current research status of UTES. It categorized different types of UTES systems, analyzes the applicability of key technologies of UTES, and evaluate their economic and environmental benefits. Moreover, this paper identifies existing issues with UTES, such as injection blockage, wellbore scaling and corrosion, seepage and heat transfer in cracks, etc. It suggests deepening the research on blockage formation mechanism and plugging prevention technology, improving the study of anticorrosive materials and water treatment technology, and enhancing the investigation of reservoir fracture network characterization technology and seepage heat transfer. These recommendations serve as valuable references for promoting the high-quality development of UTES.

Keywords: Aquifer thermal energy storage; Borehole thermal energy storage; Cavern thermal energy storage; Thermal energy storage technology; Benefit evaluation.

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Introduction

The global energy structure is gradually changing due to the energy crisis and environmental concerns, leading to an increasing use of renewable energy sources. A 2023 report from the International Energy Agency suggests that new installed renewable energy capacity is expected to grow by almost one-third year after year, with solar and wind power experiencing the highest increases. The projected global installed capacity for renewable energy in 2024 is estimated to reach 4.5 billion kW (IEA, 2022). China is a leader in renewable energy adoption, surpassing coal power capacity for the first time with over 1.2 billion kW of installed renewable energy by the end of 2022 (NEA, 2023). While the power generation sector focuses on increasing the share of renewables, the heating and cooling sector receives less attention in terms of decarbonization efforts (Fleuchaus et al. 2018). Approximately half of global energy consumption is used for heating and cooling, primarily relying on inefficient fossil fuel usage (REN21, 2018). Moreover, there is a substantial amount of energy waste associated with increasing energy consumption. Countries like China, the United States, and Turkey waste 20% to 50% of energy generated in industrial production through the release of waste heat into atmosphere (Chen, 2019;

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Ebrahimi et al. 2014; Lian et al. 2011). The efficient utilization of renewable energy and waste heat resources, such as solar energy and industrial waste heat, for clean heating, is the development trend with promising prospects in terms of energy efficiency.

The primary challenge in utilizing renewable energy for heating is managing the balance between energy supply and demand, which is particularly pronounced with solar energy due to its inherent variability across different periods of the day, regions, and seasons (Gluyas et al. 2020; Casasso et al. 2022). This variability often leads to a substantial mismatch between energy supply and demand, both temporally and spatially (Liu et al. 2023). To address these challenges, underground thermal energy storage (UTES) has gained increasing attention (Fleuchaus et al, 2018). UTES is a technology well-suited for long-term energy storage, offering substantial storage capacity, high efficiency, and minimal environmental impact (Zhang, 2023). Fig. 1 illustrates different types of UTES systems, including aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), and cavern thermal energy storage (CTES) (Matos et al. 2019; Chen, 2012). UTES involves storing a large quantities of industrial waste heat and solar radiant heat underground during the summer, and extracting it for heating purposes during the winter. This approach effectively alleviates the mismatch between the heat energy supply and demand, improving energy utilization, ensuring energy security, and providing important support for sustainable and high-quality development.

In recent years, UTES has experienced rapid development, with BTES being widely implemented in various construction projects. Although ATES demonstrates promising economic prospects, technical challenges have restricted its widespread adoption to only a few countries (Yao et al. 2023). On the other hand, CTES projects remain largely underutilized. Furthermore, the increasing depth of UTES for energy storage introduces new challenges for research and implementation. The complex geological conditions at greater depths impose stringent requirements on UTES projects. Additionally, understanding the mechanism of seepage and heat transfer in deep reservoir presents similar challenges to those encountered in geothermal mining, with limited knowledge and research on these processes. This paper comprehensively summarizes the research status of various UTES types, analyzes the applicability of key technologies, and the evaluation economic and environmental benefits. It also highlights existing issues in UTES, such as injection blockage, wellbore corrosion, scale formation, seepage, and heat transfer in cracks. The paper concludes with relevant suggestions to facilitate the high-quality development of underground energy storage.

1 Research status of underground thermal energy storage (UTES)

1.1 Aquifer thermal energy storage (ATES)

ATES systems are designed to store external heat or cold energy in confined aquifers by drilling wells, using groundwater as a heat transfer medium, and extracting heat or cold energy by pump-

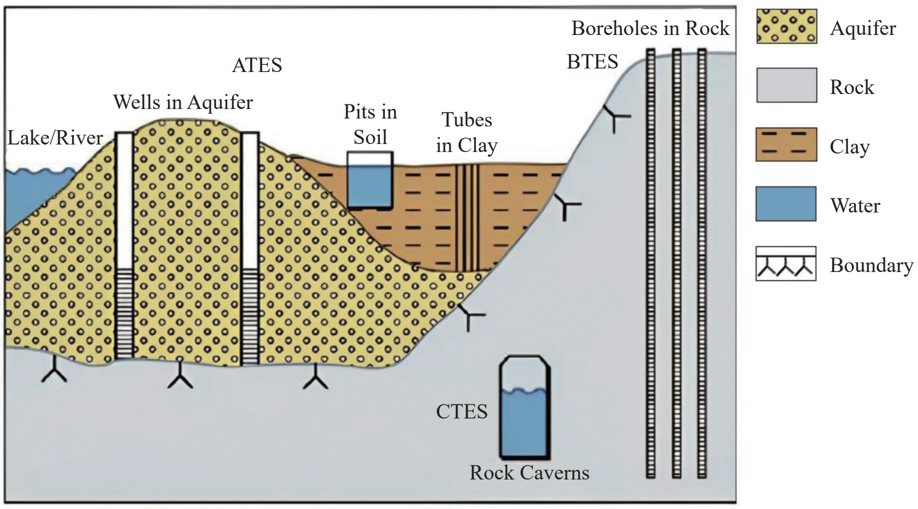

Fig. 1 Schematic representation of the most common UTES systems. Adapted from (Lee, 2013; Matos et al. 2019)

ing the groundwater as needed (Huang et al. 2020). These systems require the chosen aquifer to maintain a constant temperature, resist external influences, be difficult to pollute, and offer moderate overall costs. They are categorized as single-well, double-well system, or multi-well system based on the number of well drilled (Zhang et al. 2021b; Long et al. 2005a). The major investment in ATES systems is attributed to drilling expenses. Single-well and double-well systems, also known as small aquifer thermal energy storage systems, have low investment costs and rapid payback periods. Conversely, multi-well system, a large-scale aquifer thermal energy storage system, entail higher investment, more pipelines, and stricter well spacing requirements.

The development of ATES can be divided into three stages. Initially, during the 1960s, China pioneered research on artificial groundwater recharge to mitigate ground subsidence caused by excessive urban groundwater extraction. This effort led to the development of the ATES system employing "winter injection for summer extraction" and "summer injection for winter extraction" strategies (Wu and Ma, 1999). Subsequently, these systems were widely adopted across the cities in China, with Shanghai alone providing cold energy capacity equivalent to over 50,000 kW of refrigeration by 1965, resulting in substantial electricity savings and reduced energy consumption (Ni et al. 2007). Subsequent years saw intensified ATES research and development in Europe and North America in response to the oil crisis. Various theoretical and experimental studies have been conducted. For example, a low-temperature energy storage test was carried out in an unconfined sand gravel aquifer, south of Neuchatel, Switzerland in 1974. In this test, a total volume of 493 m^3 water with a temperature of 51°C was injected into the aquifer. Subsequently, 16,370 m^3 of water was extracted, resulting in a heat recovery rate of 40% (Mathey, 1977). Similarly, Auburn University in the United States commenced a three-stage energy storage test for confined aquifers in 1976, with funding from the United States Department of Energy (Molz et al. 1983a; Molz et al. 1983b; Molz et al. 1979; Molz et al. 1978). Furthermore, a large-scale experimental study on the storage of heat and cold in the same layer of a low-temperature confined aquifer was conducted in Shanghai during 1984 and 1985. This study involved measuring the temperature of the aquifer through 34 observation holes and yielded a heat recovery rate of approximately 70% (Xue et al. 1990). Several other countries including France, Japan, Germany, and Canada also conducted various related trials. These tests demonstrated the technical feasibility oflow-temperature thermal energy storage in confined aquifers and its potential for considerable heat recovery. However, challenges such as groundwater chemical alterations and increased risk of well clogging due to high storage temperatures were identified (Ni et al. 2007).

The second stage involved technological development and the establishment of demonstration projects. By the early 1980s, the number of ATES systems applied in China reached its peak, with more than 400 wells in Shanghai alone used for both injection and extraction, storing 1,100 TJ of cooling energy annually (Morofsky, 1994). However, many ATES systems faced challenges such as aquifer fluid contamination, improper well configurations, and pipeline corrosion and blockage, which have caused several systems to cease operation (Zhang et al. 2021b). Despite these setbacks, early engineering projects provided valuable insights, and leading to increased experimentation and simulation research in China. Institutions like Nanjing University and Shanghai Jiao Tong University developed mathematical models and coupling models for simulating ATES behaviour and optimizing well layouts. Based on the Shanghai energy storage experiment, scientists from Nanjing University developed mathematical models. Their research findings indicated that, in most cases, natural convection cannot be disregarded when simulating groundwater heat transfer. Additionally, it was noted that temperature gradient has a negligible influence on groundwater flow when the water temperature is relatively stable (Zhang et al. 1997; Zhang et al. 1999a; Zhang et al. 1999b). Meanwhile, scholars from Shanghai Jiao Tong University developed a coupling model of flow and heat transfer for ATES, although the model did not consider natural convection. Their study focused on investigatingthe layout method of energy storage wells and suggested that actively controlling the spread range of energy storage water can lead to a more condensed arrangement of energy storage wells (Long et al. 2005b; Wang et al. 2005). In the same period of time, some European and American countries conducted successful engineering application and optimized shallow ATES system through the feasibility demonstration. In the 1990s, countries such as the Netherlands and Sweden implemented a series of ATES projects. In 1993 and 1994, the Sussex Hospital renovation project in Canada used a combined ATES and heat pump operation system, which could save $65,000 per year (Zhao et al. 2004).

The ATES system installed at the Reichstag in 2000 was able to meet 90% of the building's thermal needs and 60% of its cold needs (Kabus and Seibt, 2000). The Greenhouse ATES system at the Cukurova University-Adana in Turkey, in terms of energy efficiency, calculates that energy expenditure is reduced to 70%, crop yields are increased to 20-40% (Cetin et al. 2020).

The third stage marks the demonstration and commercialization phase of ATES technology. Due to favorable aquifer conditions and government support, the Netherlands has witnessed a steady rise in ATES projects. By 2005, the number of registered ATES projects had reached 537, with an annual increase ranging from 0 to 1,000 (Coenen et al. 2010; Lee, 2013). In 2017, there were more than 2,800 shallow ATES projects worldwide, 85% of which were in the Netherlands and 10% in Sweden, Belgium and Denmark (Fleuchaus et al. 2018), indicating the Netherlands' advancement towards large-scale commercialization.

In recent year, China has reignited its focus on ATES technology. In 2013, the Chongming Agricultural Demonstration Base of Shanghai National Facility Agriculture Engineering Technology Research Center initiated China's first ATES technology localization project. This initiative comprised an integrated ATES system, groundwater heat transfer system, heat pump unit, terminal system, and energy storage system, which maintained a coefficient of performance (COP) of approximately 4.5 and achieved 100% groundwater reinjection. Subsequently, several ATES projects have been completed in Shanghai, Xiangyang, Xi'an, Zhuozhou, Nantong, and other cities (Yao et al. 2023). Table 1 provides details of some international cases of ATES projects.

1.2 Borehole thermal energy storage (BTES)

BTES is a method of storing heat energy in the soil using buried U-shaped tubes made of polyethylene plastic (PE tube) (Liang, 2022). The tubes, containing a flow medium such as water, air, CO_2, microencapsulated phase change material suspension, or nano fluid, are connected to the surrounding soil. Fig. 2 illustrates the BTES boreholes distribution, and the single borehole configuration. During the summer, heat storage takes place as heat energy exchanges between the soil and the fluid in the pipeline, transferring heat to the surrounding soil while simultaneously cooling the fluid. Conversely, this process reverses in the winter (Chen, 2012). To prevent freezing during winter, antifreeze is commonly added to the fluid. However, BTES systems experience heat loss due to heat conduction, necessitating the use of a heat pump to adjust the temperature when the heating or cooling capacity falls short of requirements.

The concept of vertically drilled heat exchangers underground was initially proposed by Kemler in 1946, followed by additional designs in 1947 (Kemler, 1946; Kemler, 1947). The concept soil heat storage was later introduced by Brun in 1965, but it was not until the oil crisis of the 1970s that large-scale underground heat storage systems, including porous BTES systems, emerged. The first such system, known as the 12-hole system, was constructed in the Jura mountains of France in 1976 for seasonal storage of solar energy. Subsequently, clay and soil BTES systems were established in Sweden, Switzerland, the Netherlands, and other countries. The late 1980s saw the development of BTES systems that combined heat extraction with heat pumps, as well as that

Table 1 International application cases of ATES

Year	Country	Purpose	Facility	Well depth (m)	Well number	Temperature (°C)	Capacity (MW)	Reference
2000	Germany	H+C	Building	320	12	19	/	Holstenkamp et al. 2017
2001	Sweden	H+C	Expo architecture	75	10	/	1.3	Andersson, 2007
2004	Germany	HT	District heating	1,250	2	55	3.3	Holstenkamp et al. 2017
2008	America	C	University	60	6	/	2	Paksoy, 2009
2013	China	H+C	Research Center	/	/	2.3	/	Yao et al. 2023
2013	Britain	H+C	Apartments	70	8	/	2.9	Fleuchaus et al. 2018
2015	Netherland	H+C	District heating	/	7	/	20	Fleuchaus et al. 2018
2015	Denmark	H+C	Airport	110	10	/	5	Larsen and Sonderberg, 2015
2016	China	H+C	factory	/	2	/	43	Zhang et al. 2021b

Note: H is Heat; C is Cool.

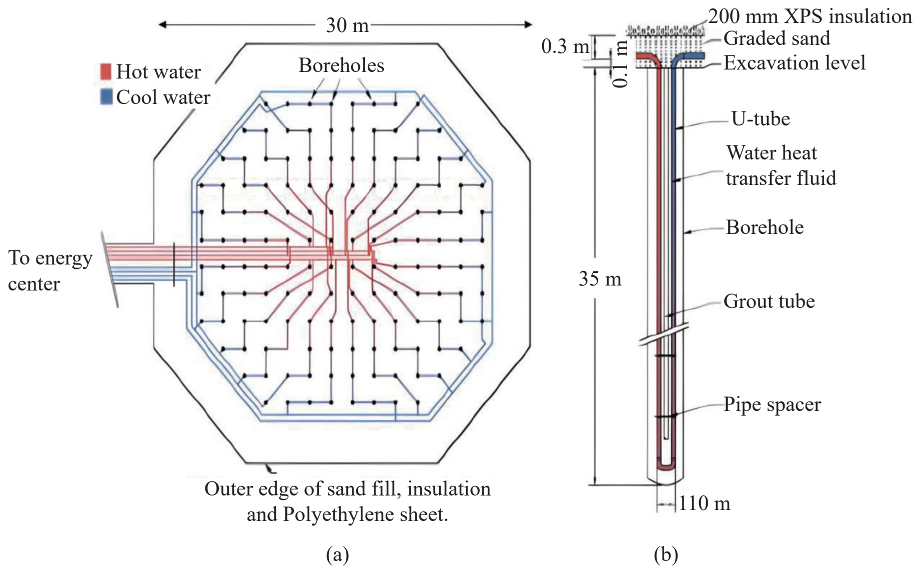

Fig. 2 Schematic diagram of BTES system: (a) boreholes distribution plan view; (b) single borehole configuration (Zhang et al. 2012)

extracted heat from boreholes via natural cooling without the need for heat pumps. By the 1990s, smaller-scale BTES programs gained popularity in Europe and North America (Gehlin, 2016).

In China, the BTES research commenced later but has rapidly progressed over the past two decades. Many scientific research institutions, such as Tianjin University, Harbin Institute of Technology, and Tsinghua University, have conducted extensive research on BTES coupled with ground source heat pump system using solar energy as the heat source. Tianjin University, for instance, designed a demonstration project integrating solar energy, buried pipe heat storage, and ground source heat pump, achieving optimal energy allocation and renewable energy utilization (Li et al. 2009; Guan, 2009), based on the TRNSYS simulation result that the renewable energy accounted for 86.5% of the total heat supply. Shandong Jianzhu University provided an optimal load ratio recommendation for a three-stage series buried tube heat exchanger (Diao et al. 2013). Furthermore, Chinese Academy of Sciences proposed a composite heat storage system that combined BTES with water tank heat storage, demonstrating improved energy transfer and heat control theory through experimental and numerical studies (Wang et al. 2020; Wang et al. 2021b).

Table 2 highlights typical BTES projects worldwide, many of which have been established as research demonstration projects. For example, the Drake Landing Solar Community (DLSC) project in Canada, completed in 2006, featured 144 boreholes with a depth of 35m and achieved a solar guarantee rate of 97% (Sibbitt et al. 2012). In order to analyze the efficiency of the DLSC project, Catolico et al. (2016) conducted a three-dimensional numerical simulation using TOUGH2. Their findings indicated that the heat extraction rate of the BTES increases as soil thermal conductivity decreases. Moreover, the convective heat loss is greater and the heat extraction rate is lower in soils

Table 2 Application cases of BTES system technology worldwide

Year	Country	Purpose	Facility	Number of pipes	Depth (m)	Reference
2004	Canada	H+C	University	384	213	Dincer and Rosen, 2007
2007	Germany	H	school	80	55	Mangold, 2007
2011	China	H+C	Commercial center	3,789	120	Yin and Wu, 2018
2012	Denmark	H	District heating	48	45	Gehlin, 2016
2015	Romania	H+C	Research center	1,080	125	Gehlin, 2016
2016	China	H+C	District heating	468	80	Xu et al. 2018
2019	China	H+C	Airport	10,680	140/120	He et al. 2022
2020	China	H+C	Hospital	1,320	120	Wang et al. 2023

Note: H is Heat; C is Cool.

with higher permeability. Similarly, a noteworthy BTES project established in 2016 in Chifeng City, Inner Mongolia, integrated a solar industrial waste heat central heating system with cross-season BTES, enhancing the flexibility, stability, and energy efficiency of the energy system (Xu et al. 2018; Zhang, 2021). This project utilized a large-scale system with a heat storage volume of 500,000 m^3, 468 holes, and a total collector area of 1,002 m^2. The heat sources for this project were solar energy and industrial waste heat.

1.3 Cavern thermal energy storage (CTES)

CTES basically include flow mixed thermal energy storage and flow stratified thermal energy storage. In the former, water in the cave is fully mixed to maintain its temperature consistent, which heats the lower part of the cave, while extracts heat in the upper part. However, natural convection leads to thermal stratification and heat loss, which makes it more suitable for short-term heat storage. On the other hand, flow stratified energy storage relies on vertical water flow to establish the thermal stratification, heating in the upper part of the cave and extracting cold or pumping cold from the lower part (Chen, 2012). This method is well suited for seasonal heat or cold storage due to its high thermal efficiency.

Sweden is the country with the most CTES applications, mainly for short-term and seasonal energy storage. In fact, two of the world's first applications for thermal energy storage using caves were established in Sweden in the 1980s. The first one is Avesta reservoir with a capacity of 15,000 m^3, and the second is the Lyckebo reservoir located in the Uppsala district having a much larger capacity of 1,200,000 m^3. Subsequently, several other CTES projects were established in Sweden, Finland and elsewhere. One such project is the Oulu energy storage system in Finland, originally built to store oil, featuring two parallel caverns with a combined volume of 190,000 m^3. The system, filled with water in the cave and connected to Toppilas' thermoelectric plant, stores waste heat from the plant for district heating and generates approximately 10 MW of waste heat (Nordell, 2013). In spite of its advantage of large water circulation, the CTES application remains limited due to the terrain constraints and associated high operation cost.

Similar to the CTES working principle and successful commercial applications are the Hot Water Thermal Energy Storage (HWTES) and Gravel-Water Thermal Energy Storage (GWTES) systems. The HWTES system consists of a large insulated underground storage tank, which facilitates heat transmission through a water circulation network between the storage tank and the building heat exchanger (Socaciu, 2012). One of the pioneering HWTES projects is the Friedrichshafen project in Germany, where the water storage tank can reach the temperatures of 85–95°C (Xu et al. 2014), illustrated in Fig. 3. On the other hand, the GWTES system shares a similar structure but uses a mixture of water and gravel as the heat storage medium. The gravel aids in stress distribution, enabling a simple load-bearing device to stabilize the system. An example of successful application of GWTES is the system in Steinfurt, Germany, with a capacity of 1,500 m^3 and a maximum operating temperature of 90°C. This particular system utilizes solar energy to meet 34% of the annual heating demand, as illustrated in Fig. 4 (Pfeil and Koch, 2000).

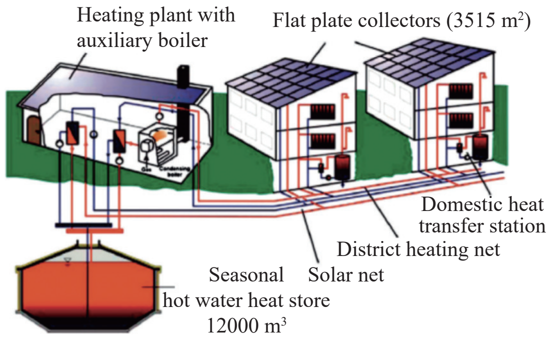

Fig. 3 HWTES system (Xu et al. 2014)

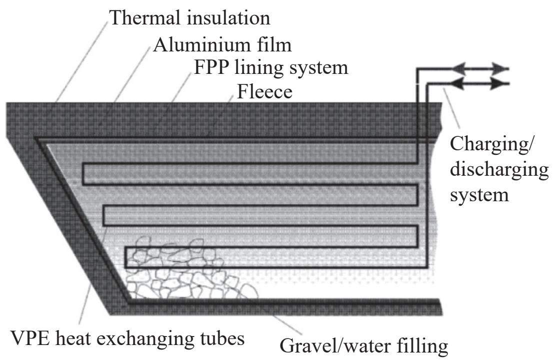

Fig. 4 GWTES system (Pfeil and Koch, 2000)

1.4 Comparison of different types of energy storage systems

ATES is an open-loop energy storage system, recognized as the most energy-efficient shallow geothermal technology, suitable for seasonal storage, but heavily dependent on specific aquifer properties and conditions. During cold storage, energy storage efficiency ranges from 70%–100%, while under heat storage conditions, it varies between 50% and 80% (Lee, 2013). BTES operates on the same principle as ATES but functions as a closed-loop system, offering versatility but not limited to specific reservoir locations such as aquifers. It is particularly well-suited for both cold and hot storage and the recovery needs of end-users. However, the efficiency of a BTES system in a given location may be affected by natural groundwater flow (Lee, 2013), with an efficiency potential of up to 40% (Gao et al. 2015). The suitability of each UTES technique depends on local site conditions, including geological and hydrogeological conditions. In large-scale applications, ATES is the most advantageous technology, while BTES is the most versatile system, applicable across all scales. CTES are best-suited for scenarios involving strong load/unload fluctuations or exceptionally high-power demands (Matos et al. 2019). Each type of thermal energy storage system carries its distinct advantages and disadvantages, outlined in in Table 3.

2 Key technologies and methods of UTES

2.1 Groundwater reinjection technology

Groundwater reinjection serves as the fundamental requirement of ATES, and is a crucial method to mitigate environmental problems caused by energy storage. The recycling of pumped and reinjected groundwater is the main characteristic of ATES (Liu et al. 2016). However, groundwater circulation is closely related to the subsurface water processes involving water, energy and matter (Yuan et al. 2022). Failure to meet required standards in reinjected groundwater can lead to a range of ecological and environmental challenges. Pressure reinjection and vacuum reinjection are the two main methods of groundwater reinjection (Wu, 2004). Pressure reinjection entails pressurizing the surface water source to establish significant head pressure, thereby creating a substantial head difference between the static water level and the hydraulic slope surrounding the well. This enables the reinjection water to overcome resistance and penetrate into the aquifer. Pressure reinjection is unaffected by groundwater depth or aquifer permeability, making it suitable for injecting water into appropriate aquifers. However, it exerts a greater force on the filter pipe mesh and aquifer, rendering it more suited for deep wells equipped with strong filter mesh. On the other hand, vacuum reinjection operates under vacuum conditions, leveraging the vacuum siphon effect to causes rapid water entry into the pump pipe. This disrupts the original pressure balance, creating a water head difference that enables the reinjection water to overcome resistance and permeate into the aquifer. Vacuum reinjection is effective in reducing chemical precipitation and is suitable for aquifers with deep water levels (where the buried depth of the static water level exceeds 10 m) and good permeability (Zhu et al. 2005).

2.2 Multi-energy coupling underground thermal energy storage technology

In recent years, the emergence of the "geothermal +" model, characterized by "multi-energy complementarity and intelligent coupling", has gained prominence. This model utilizes the coupling and complementary capabilities of various energy supply systems to achieve cascade utilization and cross-peak complementarity of different energy grades (Pramanik and Ravikrishna, 2017). Through the multi-energy complementarity scheme involving geothermal (ATES + BTES + medium and

Table 3 Comparison of thermal energy storage systems (Rad and Fung, 2016; Schmidt et al. 2003)

	ATES	BTES	GWTES	HWTES
Storage medium	Ground material/water	Ground material	Gravel-water	Water
Heat capacity (kW h/m^3)	30–40	15–30	30–50	60–80
Storage volume for (1 m^3 of water equivalent)	2–3	3–5	1.3–2	1
Geological requirement	· Natural aquifer layer with high hydraulic conductivity; · Confining layers on top and below; · No or low natural groundwater flow; · Suitable water chemistry at high temperatures; · Aquifer thickness 20–50 m	· Drillable ground; · Groundwater favorable; · High heat capacity; · High thermal conductivity; · Low hydraulic conductivity; · Natural groundwater flow <1 m/s; · 30–100 m deep	· Stable ground conditions; · Preferably no groundwater; · 5–15 m deep	

deep geothermal), 100% clean energy can be achieved for cooling, heating, and power supply. The successful application of this energy scheme has been demonstrated in various engineering projects. For example, the Beijing Daxing International Airport project, inaugurated in September 2019, maximizes the use of renewable energy sources such as geothermal, coupled with flue gas waste heat and sewage waste heat. The system includes 10,680 underground pipes covering an area of 267,000 m^2, providing a heating capacity of 54.2 MW in winter, a cooling capacity of 48.8 MW in summer, and serving a total energy supply area of 2.57 million m^2. This aligns with the goal of achieving a renewable energy utilization rate of not less than 10% (He et al. 2022; Wang et al. 2021a). Another prominent project is the Hefei Binhu Science City Regional Energy Project, which is the first "geothermal+" multi-energy complementary regional energy project in China. This project incorporates various complementary energy supply forms, such as ground source heat pump, sewage source heat pump, water storage, ice storage, and natural gas triple supply. With a maximum cooling capacity of 186.8 MW and a maximum heating capacity of 129.4 MW (Yin, 2022), this project's successful operation optimizes energy allocation and maximizes the utilization of renewable or clean energy sources.

2.3 Numerical simulation

Numerical simulation can establish geometric models based on actual conditions and conducts simulation calculations and analyses, providing reliable and accurate prediction schemes for practical applications. It allows for the pre-optimization of complex practical problems that are difficult to address through experiments, and provides feasible technical and theoretical suggestions for subsequent design and operation (Chen, 2019). commonly employed numerical methods in UTES research include finite element, finite difference, and finite volume techniques (Regnier et al. 2022; Stemmle et al. 2024; Yang et al. 2023). With the development of computer technology, various commercial modelling and simulation software, such as COMSOL, FLUENT, and FEFLOW, have been continuously developed, making it more convenient to approximate solutions for complex problems. As a result, these software programs have become increasingly applicable in this field. This paper summarizes the common numerical modelling software methods and characteristics of UTES, as shown in Table 4. For example, Kim et al. (2010) used COMSOL to establish a well system model of ATES and investigated the effects of drilling distance, water conductivity coefficient, and pumping rate on thermal interference. Similarly, Zhang et al. (2016) coupled the aquifer part with the heat pump system based on FLUENT/Simulink and determined the influence of the original underground flow on the performance of the two pumping and two rejection ATES systems under heating conditions by analyzing changes in the underground temperature field and COP of the unit. Furthermore, numerical models are often employed for sensitivity analysis of various influencing factors of the system due to their calculation accuracy. Han and Yu (2016), for instance, developed a numerical heat transfer model of BTES that considered the fluid heat transfer process in 3D soil and 1D pipes. They conducted a comprehensive sensitivity analysis of multiple factors affecting system performance, including material properties, design parameters, and operating conditions.

3 Economic and environmental benefit evaluation

3.1 Economic benefit evaluation

Ensuring healthy economic benefits is fundamen-

Table 4 Common numerical simulation software for UTES and its characteristics (Gao et al. 2017)

Code	Numerical scheme	Characteristic and application conditions
VS2DH	Finite difference	2-D； constant density fluid; variably saturated porous media; single phase fluid flow
FEHM	Control volume finite element	3-D； for multiphase flow of heat and mass with air, water, and CO_2
MT3DMS	Finite difference	3-D； always coupled with MODFLOW; simulating heat transport due to the analogy between heat and mass transfer processes
FEFLOW	Finite element	3-D; able to incorporate spatially variable aquifer properties, geologic layering, and screening of pumping/injection wells over multiple intervals
TOUGH2	Integral finite differences	3-D； variably saturated porous and fractured media; coupled transport of water, vapor, noncondensable gas, and heat
FLUENT	Finite volume	3-D； useful in fluid flow, heat transfer, chemical reaction etc.
COMSOL	Finite element	3-D； multiphysics; different module

tal for the widespread adoption and utilization of UTES, promoting numerous scholars to conduct extensive case studies and analyses on its economic feasibility and market potential. Ciampi et al. (2018) evaluated the advantages of a solar heating system using TRNSYS, focusing on different solar collector areas, short-term heat storage tank volumes, and BTES volumes. Their assessment encompassed economic, energy-saving, and environmental protection aspects. Li et al. (2021b) studied a campus district heating system in Norway, analyzing the utilization of waste heat through the introduction of a water tank for heat storage and BTES. They compared the economics of different schemes and found that the BTES scheme achieved a 96% utilization rate of waste heat, resulting in a 6% annual energy cost savings, albeit with a lengthy 17-year investment payback period. In a review of technical and economic literature, Yang et al. (2021) emphasized the evaluation of economic feasibility in underground energy storage using the Levelized Cost of Energy (LCOE), which can be expressed by the following formula:

$$\mathrm{LCOE}=\frac{\mathrm{I}+\sum_{t=1}^{n}\frac{\mathrm{O}+\mathrm{M}}{(1+r)^{t}}}{\sum_{t=1}^{n}\frac{\mathrm{E}_{t}}{(1+r)^{t}}} \quad (1)$$

Where: I is the initial investment, r is the real discount rate, n is the system lifetime, O+M is the annual cost of operation and maintenance, and Et is the annual heat production.

By comparing the LCOE of UTES systems and traditional heating systems, an economic feasibility assessment of different types of underground energy storage is then conducted to determine their market development potential. Wesselink et al. (2018) predicted the market potential of deep ATES systems based on the Groningen district heating project in the Netherlands. Their results suggested that, under European energy policies, ATES systems exhibited lower LCOE compared to natural gas, indicating superior economic benefits. The LCOE of ATES systems ranged from 2.76 euros/GJ to 3.54 euros/GJ, whereas the LCOE of natural gas was 6.51 euros/GJ to 16.51 euros/GJ. Renaldi and Friedrich (2019) modeled the applicability of the Canadian DLSC project in the United Kingdom using TRNSYS software. Their results showed that while the BTES system was technically feasible, it had lower performance and higher LCOE compared to existing local energy supply system, requiring local policy support for economic viability. According to Yang et al. (2021), among various underground energy storage systems, ATES and BTES demonstrate better economic benefits. However, compared to natural gas and decentralized solar heating solutions, ATES is more economically competitive in the heating market, while BTES has higher costs and a longer payback period.

3.2 Environmental benefit evaluation

UTES serves as a pivotal link between building energy consumption and the utilization of renewable energy sources, acting as a natural buffer that bridges energy source with building demand. Unlike conventional fossil fuel-dependent systems, UTES integrates various intermittent clean energy sources, such as solar heat, power plant waste heat, and industrial waste heat to building energy storage and utilization (Huang et al. 2020). This approach substantially reduces the consumption of fossil fuels, leading to significant environmental benefits including reduced carbon dioxide, sulfur dioxide, and other emissions. For instance, Kılkış et al. (2017) demonstrated that newly designed large-scale ATES systems coupled with solar collectors and photovoltaic thermal arrays resulted in substantial energy savings and CO_2 emission reductions compared to existing energy supply systems.

Environmental evaluations, as detailed by Zhou et al. (2022) who compared the performance of UTES operation with conventional air conditioning and heating systems, focus on energy conservation and emission reduction. The study estimated annual cumulative heating and cooling loads of different building types to calculate energy savings and emission reductions. The specific calculation formulas are presented in Table 5. Notably, the underground energy storage system in Shanghai showcases immense potential, with an annual energy saving of 10.187 million tons of standard coal, as well as substantial reductions in CO_2, SO_2 and dust emissions of 251.62, 2.04, and 1.02 million tons, respectively. These results highlight the significant energy conservation and emission reduction effects of the systems.

4 Problems and suggestions

4.1 Problems

4.1.1 Injection blockage

Injection blockage is a critical determinant of energy storage efficiency, which has led to the cessation of many projects. For example, the

Table 5 Energy conservation and emission reduction indicators (Zhou et al. 2022)

	Parameters	Formula	Unit
Energy conservation	Cumulative cooling load per unit air conditioning area	$Q_c = a_c q_c t_c$	Kwh/m^2
	Cumulative heat load per unit air conditioning area	$Q_h = a_h q_h t_h$	Kwh/m^2
	The modified cumulative cooling load of the building	$Q_r = \frac{(1-1/\varepsilon_h)}{(1+1/\varepsilon_c)} Q_h$	Kwh/m^2
	Energy savings during the cooling season	$\Delta E_c = DQ_r\left(\frac{1}{\varepsilon_t} - \frac{1}{\varepsilon_c}\right)$	kgce/m^2
	Energy savings during the heating season	$\Delta E_h = \frac{3,600Q_h}{q_{bm}\eta_t} - \frac{DQ_h}{\epsilon_h}$	kgce/m^2
	Annual energy savings	$\Delta E = \Delta E_c + \Delta E_h$	kgce/m^2
	Annual electricity savings	$\Delta P = \frac{\Delta E}{D}$	Kwh/m^2
Emission reduction	CO_2 emission reduction	$Q_{CO_2} = Q_s \times V_{CO_2}$	t/a
	SO_2 emission reduction	$Q_{SO_2} = Q_s \times V_{SO_2}$	t/a
	Dust emission reduction	$Q_{fc} = Q_s \times V_{fc}$	t/a

Note : a_c and a_h are the adjustment coefficients of cooling load and heating load respectively, and they are both 0.52; q_c and q_h are the cooling load in summer and heating load in winter respectively, W/m; t_c and t_h are the operating time of cooling in summer and heating in winter respectively, h; ϵ_c and ϵ_h are the energy efficiency ratio of refrigeration and heating of underground energy storage system; ϵ_t is the energy efficiency ratio of conventional air conditioning refrigeration; η_t is the operating efficiency of coal-fired boilers; q_{bm} is the calorific value of standard coal, taking 29,307 kJ /kg; D is equivalent to the consumption of standard coal per kwh, 0.327 kgce/kwh; Q_s is conventional energy replacement quantity, tce/a; V_{CO_2}, V_{SO_2} and V_{fc} are the emission intensity of CO_2, SO_2 and dust respectively, which are 2.47 t/tce, 0.02 t/tce and 0.01 t/tce, respectively. 2; The buried tube heat exchanger is designed for heating conditions in winter, and auxiliary cold source is used for peak regulation in summer, so that the heat extraction to the underground in winter and the heat storage to the underground in summer are basically balanced. Therefore, when calculating energy saving, the summer load is modified based on the winter load to ensure the balance of heat absorption and emission in winter and summer.

Plaisir Thiverval-Grignon system in France was designed to store waste heat from waste incineration plants but faced shutdown due to well plugging issues (Kallesøe et al. 2020). The causes of blockage vary and include physical, chemical, and biological factors (Du et al. 2009; Feng et al. 2022; Xia et al. 2023). Physical blockage primarily occurs when suspended particles accumulate at the injection wellhead, reducing injection capacity and causing blockage. Gas blockage and compaction blockage are the factors. Currently, significant research have examined large particle blockage, focusing on the impact of suspended matter concentration, particle size, and injection flow rate (Siriwardene et al. 2007; Zheng et al. 2013; Mays and Hunt, 2007). However, understanding of small and medium particle blockage, particularly colloidal particles, remains limited.

Chemical blockage is mainly caused by the disruption of water-rock interaction, leading to mineral dissolution and precipitation, and subsequently reducing the permeability of the aquifer. Despite extensive studies, the complex nature of chemical blockage requires further exploration. Most studies suggest that the possibility of plugging and water quality changes is relatively low when the chemical composition and soluble salt concentration of injected water are similar to that of the original groundwater (Du et al. 2009). Consequently, numerous scholars have conducted extensive compatibility and water-rock reaction experiments to analyze the mechanism and properties of chemical blockage. However, the mechanism of chemical blockage is complex, and there are numerous influencing factors. Indoor experiments can only provide a simple analysis of a specific chemical reaction process, and the hydrogeochemical theories and methods involved are still immature.

Biological blockage, caused by microbial communities such as algae and bacteria, forms biofilms on particles, reducing aquifer permeability. Composite blockage often combines various blockage conditions, posing challenges to understanding and mitigation efforts. Bacterial growth is an important cause of blockage, for instance iron bacteria, sulfate-reducing bacteria and saprophytic bacteria are the most studied biological blockage bacteria (Li et al. 2021a).

4.1.2 Wellbore corrosion and scaling

Wellbore corrosion and scaling pose significant challenges in the operation of UTES systems. CO_2, H_2S, and O_2 dissolved in water are primary contributors to corrosion, as they are prone to forming acidic solutions upon in contact with the steel in the wellbore (Deng et al. 2021). Furthermore, the presence of microorganisms such as sulfate-reducing bacteria and iron bacteria can also exacerbate corrosion. Numerous studies have demonstrated that proper utilization of anti-corrosion technology can recover 30%–40% of corrosion losses (Huang, 2012). However, existing research on anti-corrosion technology focuses more on anti-corrosion materials for ground equipment rather than underground wellbore casings. Moreover, most UTES technologies still adhere to the petroleum industry standards (Deng et al. 2021). Chemical corrosion inhibitors effectively prevent corrosion but may contaminate water quality and subsequently impact the reinjection process.

The extraction process of UTES involves the upward water migration through the aquifer into the wellbore, leading to scaling due to temperature and pressure change (Zhang et al. 2022). Carbonate, sulfate, and silicate are the common substances contribute to scale formation. Current research on the scaling mechanism of wellbores primarily focuses on the effects of temperature, pH value, and ion type on scaling. Despite significant progress made in related research, its practical application in engineering remains challenging. Among these, water treatment is a commonly used method (Zhang et al. 2021a), though the long-term effectiveness of inhibitors is uncertain.

Corrosion and scaling are closely related in the UTES systems, with scaling promoting corrosion. When scaling occurs in the pipe equipment of the wellbore, oxygen diffusion is hindered, leading to an uneven oxygen concentration. This differential concentration of oxygen promotes corrosion. Moreover, scaling also facilitates the growth of microorganisms, particularly sulfate reducing bacteria, which further contributes to microbial corrosion by reacting with hydrogen (Holstenkamp et al. 2017). As the UTES operation life extends, corrosion and scaling become more severe, resulting in problems such as water quality deterioration and reinjection difficulties, threatening system longevity.

4.1.3 Seepage and heat transfer in fracture

Understanding seepage heat transfer is crucial for optimizing UTES operation efficiency. However, theoretical research often lags behind practical applications, leading to engineering challenges such as groundwater thermal imbalance and hydrothermal pollution. Fractures, acting as both storage space and flow channel for groundwater, significantly impact seepage heat transfer and have been extensively studied (Yuan et al. 2022). The basic unit of fracture network is a single fracture, which can intersect to form cross fractures, ultimately forming discrete fracture network (Zhang, 2022). While existing experimental studies mainly focus on single fractures simulated in laboratories, there is a lack of research on multiple crack groups and fracture networks. Numerical simulations are often used to study complex fracture networks, but they face challenges in accurately characterizing fracture morphology and spatial distribution. Current numerical models, while useful, are simpler than actual reservoir states, resulting in low accuracy and difficulties in controlling seepage and heat transfer. Consequently, existing numerical simulations cannot provide accurate guidance for practical projects.

4.2 Suggestions for future research

Based on the current state and challenges of UTES, the following suggestions are proposed:

4.2.1 Further study on the mechanism of blockage formation and anti-blockage technology

Firstly, research should delve deeper into understanding the mechanism behind individual type of blockages. By comprehensively studying specific blockage type, it becomes possible for researchers to investigate the interaction processes and mechanisms of different types of blockages. Furthermore, mathematical models should be developed to simulate and quantitatively predict various blockage processes. Secondly, to address the limitations of existing blockage treatment methods such as back lifting and well washing, emphasis should be placed on the development of anti-blockage technology. While complete avoidance of blockages may not be feasible, it is imperative to develop new technologies, methods, and equipment that offer continuous control and treatment of blockages.

4.2.2 Enhancing anti-corrosion materials and water treatment technology research

In terms of anti-corrosion technology, emphasis should be placed on advancing the development of anti-corrosion materials, such as stainless steel, titanium alloy, nickel alloy and other corrosion-resistant substances. Furthermore, attention should be directed towards the development of metal coatings, organic coatings and other materials to combate corrosion and scaling phenomenon effectively. The prevention of wellbore corrosion and scaling is heavily dependent on maintaining water quality. However, the addition of chemical agents and fungicides can cause pollution to the environment. Therefore, there is a current research focus on green corrosion inhibitors derived from natural plants. These inhibitors not only mitigate pollution caused by the use of chemical corrosion inhibitors, but also reduce economic costs and promote a sustainable operation of the system.

4.2.3 Enhancing characterization technology of reservoir fracture network and the study of seepage heat transfer

As UTES depth increases, probing the seepage and heat transfer process within reservoir fractures becomes increasingly challenging. To address this, it is essential to elevate the visualization level of the reservoir and the characterization capability of the fractures. The size, occurrence, density and spatial distribution of fractures surrounding the wellbore are described and analyzed by means of surface outcrop and imaging logging, etc., to reveal the characteristics and connectivity of the fracture network within the reservoir. Moreover, establishing a suitable seepage heat transfer model coupled with the fracture network and the wellbore is crucial. This model will improve the prediction accuracy and provide valuable guidance for practical engineering applications.

5 Conclusions

(1) The current status of various UTES forms is summarized as follows: Shallow ATES has achieved relative maturity and widespread commercial applications in several countries, but the theoretical technology and engineering applications of middle and deep ATES are less developed. Because of the rapid development of ground source heat pump, BTES is more widely used in practical projects. Due to the constraints of geological conditions and high cost, CTES has limited engineering applications globally, while HWTES and GWTES, akin to of CTES principles, have successfully realized commercial deployments worldwide.

(2) Groundwater pumping and injection recycling form the foundation of UTES but also brings challenges such as injection blockage and wellbore corrosion and scaling. These problems reduce the heat recovery efficiency and shorten the service life of UTES system. In addition, numerical simulation methods have important applications in the design and operation of UTES systems. However, challenges persist due to insufficient research on theoretical issues related to seepage and heat transfer, low visualization level of deep reservoirs, and overly simplified numerical models.

(3) Among UTES systems, ATES and BTES show favorable economic benefits. ATES is particularly competitive in the heating market compared to the current heating systems, while BTES requires governmental policy support due to its higher cost and longer investment payback period. In terms of energy conservation and emission reduction, UTES effectively utilizes solar energy, power plant waste heat, industrial waste heat and other energy sources to supply building energy, substantially reducing fossil energy consumption and emissions of carbon dioxide, sulfur dioxide and other pollutants, thus delivering significant environmental benefits.

(4) The integration of multi-energy coupling with UTES is the future development direction of underground energy storage. This approach gives full play to the coupling and complementary capabilities of diverse energy supply systems, facilitating the cascade utilization and cross-peak complementarity of energy grades. Such integration plays an important role in improving the utilization rate of energy and optimizing energy allocation strategies.

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