

Review

A Review of Geological Energy Storage Technologies for Geothermal Energy Utilization

Guosheng Jia, Zhibin Zhang, Meng Zhang, Jiaqi Zhang, Zeyu Tao, Congfu Ma *, and Liwen Jin

School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an 710049, China

* Correspondence: macongfu521@xjtu.edu.cn

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Abstract: Geological thermal energy storage (TES) plays a vital role in the transition toward low-carbon and sustainable energy systems by mitigating the seasonal mismatch between renewable energy supply and heating/cooling demand. This paper systematically reviews recent advances in borehole (BTES), aquifer (ATES), mine/tunnel, and hybrid TES technologies, with a focus on their operational principles, system configurations, and integration into district energy networks. However, despite notable technical progress, the widespread deployment of geological TES remains constrained by site-specific geological heterogeneity, heat losses, clogging, and high upfront costs. Future research and development should prioritize the repurposing of existing underground infrastructure, the advancement of high-temperature and deep storage systems, the integration of digital and intelligent operation strategies, and the formulation of supportive policy and market frameworks. With continued innovation, geological TES holds substantial promise for enabling resilient, low-carbon, and cost-effective energy systems.

Keywords: geological thermal energy storage; geothermal energy utilization; decarbonized energy system

1. Research Background and Significance

Efforts toward carbon neutrality have accelerated the transition to low-carbon energy systems, with growing attention directed to the decarbonization of the heating and cooling sectors, which account for a substantial share of final energy consumption [1]. The widespread deployment of renewable energy has been a key driver of this structural transition; however, the thermal potential of sources such as solar and wind is more abundant in summer, while heating demand typically peaks in winter. This creates a pronounced temporal mismatch between renewable energy supply and building energy demand. Such seasonal discrepancy severely constrains the effective utilization of renewable energy and hinders progress toward deep decarbonization in the heating sector. Consequently, seasonal thermal energy storage has emerged as an indispensable solution to bridge this supply-demand gap and enhance the flexibility and reliability of future energy systems [2–4].

Geological thermal energy storage (TES) offers a promising solution to the seasonal supply-demand mismatch outlined above [5]. By leveraging the high thermal stability and large storage capacity of underground media—such as soil, rock, and aquifers—geological TES systems can store renewable energy or industrial surplus heat during summer for extraction during winter. Compared to conventional storage options such as tank thermal energy storage or battery storage, geological TES exhibits distinct advantages for long-cycle and large-scale applications, including reduced land occupation, lower long-term heat losses, and enhanced system stability. These inherent benefits have attracted growing research interest and positioned geological TES as a key enabling technology for integrating renewable energy into district heating and cooling networks, particularly in regions with limited surface space or suitable geological conditions [6].

Despite the growing body of research on geological TES, existing studies remain largely fragmented. First, most researches have focused on individual technologies in isolation—such as ATES or BTES—without offering a systematic cross-comparison of their applicable conditions, heat transfer mechanisms, and performance metrics [7]. Second, while numerous case studies have reported key performance indicators including storage efficiency, COP, and emission reduction potential, these data are often derived from disparate geological and climatic contexts with varying system designs, making direct cross-technology comparison difficult [8]. A systematic synthesis that normalizes and compares these dispersed data across technologies is still lacking. Third, there is a notable absence of integrated assessment frameworks that collectively consider technical, environmental, and economic



dimensions [9,10]. Most existing studies prioritize technical performance, with limited attention to environmental impacts such as land use efficiency, groundwater contamination risks, or ecosystem disturbances. Economic analyses, where available, are often contingent on specific subsidy policies or localized market conditions, limiting their generalizability. Consequently, a holistic understanding of the trade-offs and synergies among technical viability, environmental sustainability, and economic feasibility under different policy scenarios remains elusive. This review aims to bridge these gaps by providing a systematic cross-technology comparison and integrating insights from technical, environmental, and economic perspectives.

To address the research gaps identified above, this paper presents a systematic comparative review of geological TES technologies for seasonal heating applications. It focuses on: (1) the fundamental principles, heat transfer mechanisms, and storage medium characteristics of BTES, ATES, mine/tunnel TES, and composite/advanced systems; (2) a cross-technology comparison of operational performance and key performance indicators as documented in both research and engineering practice; (3) a critical assessment of the technical, economic, and environmental challenges currently hindering large-scale deployment; and (4) an outlook on future research directions and technology pathways. By integrating these multidimensional assessments, this review aims to synthesize fragmented knowledge across the field and offer practical guidance for technology selection, system optimization, and policy formulation—thereby supporting the transition toward low-carbon and environmentally sustainable energy systems.

2. Fundamental Principles and Classification

Geological TES utilizes underground spaces to inject thermal energy in the form of heated or cooled fluids into the underground geological body and recover it when needed. The feasibility and operational efficiency of the system are mainly influenced by the heat conduction, convection processes, and thermal physical properties of the soil and rock [11–13].

Depending on the type of storage medium and operation mode, geological thermal energy storage systems can be classified into the following categories:

- (1) Borehole thermal energy storage system (BTES): BTES relies on borehole heat exchanger arrays installed in soil or rock to store thermal energy. As a closed-loop system, it isolates the working fluid from the geological formation, with heat transfer dominated by conduction through the solid medium. Key performance determinants include the thermal conductivity and heat capacity of the surrounding material [14]. BTES is suitable for areas with weak groundwater flow and is often used for seasonal thermal energy storage in regional heating and cooling systems [11].
- (2) Aquifer thermal energy storage system (ATES): ATES stores thermal energy by injecting and extracting groundwater from permeable aquifers. As an open-loop system, it involves direct contact between the working fluid and the geological formation, with heat transfer occurring through both conduction in the solid matrix and convection via groundwater flow. System performance is highly dependent on aquifer permeability, hydraulic gradient, and water chemical properties [15]. ATES is well-suited for large-scale seasonal thermal storage but demands careful site selection to mitigate heat diffusion and prevent groundwater contamination [16–19].
- (3) Mine and tunnel thermal energy storage system: This system utilizes the space in abandoned mines and tunnels for TES, leveraging existing underground infrastructure. The operational performance is influenced by heat conduction in the surrounding rock mass and convective heat transfer via groundwater flow within the mine workings. The thermal conductivity of the surrounding rock, stratum structure, and groundwater flow characteristics are key determinants of system efficiency [20].
- (4) Composite and advanced TES: Emerging research has explored multi-component thermal energy storage systems—employing working fluids such as CO₂ and H₂—as well as integrated underground energy storage and carbon sequestration technologies. These innovations aim to improve energy storage density, heat transfer efficiency, and operational flexibility [21,22]. Compared to conventional water-based systems, these novel fluids exhibit superior thermophysical properties under high pressure and high temperature conditions, enabling deeper heat storage and broader operating ranges.

The selection and optimization of geothermal TES require comprehensive consideration of geological conditions, hydrogeological characteristics, and operational parameters (as shown in Figure 1). The key factors include the thermal properties of the strata, the characteristics of groundwater flow, the scale of heat storage, and the operation strategies, etc. With the development of computational methods, advanced numerical techniques such as dynamic grids and machine learning-assisted simulations have been gradually applied to geothermal heat storage research, used to handle complex heat transfer and mass transfer processes, reduce computational costs,

and improve prediction accuracy, thereby providing support for system assessment and optimization [23,24]. In summary, the diverse geothermal heat storage technologies and their numerical modeling methods provide a technical foundation for the integrated application of energy systems at different scales.

This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [25]. A systematic literature search was performed across multiple databases, including ScienceDirect (SD), MDPI and Google Scholar, using keywords relevant to geological thermal energy storage technologies. The study selection process adhered to the PRISMA four-phase flow diagram (Figure 2), comprising identification, screening, eligibility assessment, and final inclusion. This methodological framework ensures a rigorous synthesis of the fragmented body of literature and underpins the cross-technology comparison presented in this review.

Classification	Characteristics		Core Advantages	Primary Application Scenarios
	Heat transfer	Storage medium		
Borehole Thermal Energy Storage (BTES)	Conduction-dominated; heat exchange via BHE array in soil/rock	Solid medium; significant spatial variability in heat capacity and thermal conductivity	<ul style="list-style-type: none"> High siting flexibility Minimal environmental impact Modular and scalable 	Seasonal thermal energy storage for building clusters and community-scale systems
Aquifer Thermal Energy Storage (ATES)	Conduction/convection; heat transport via groundwater extraction and reinjection	Porous/fluid medium; high heat capacity, strongly influenced by porosity and flow velocity	<ul style="list-style-type: none"> Large-scale capacity and high efficiency Low operational costs 	Large-scale applications such as major public buildings and district heating/cooling networks
Minewater and Tunnel Thermal Energy Storage	Heat conduction in surrounding rock/ heat convection in mine water and ground water	Combined rocks and mine water; hybrid system utilizing existing underground space	<ul style="list-style-type: none"> Lower initial investment Exceptionally large storage volume 	Energy transition in mining areas and city large-scale energy storage
Hybrid and Advanced Systems	Multiple mechanisms (conduction/convection/ phase change)	Novel working fluids (CO ₂ , H ₂ , etc) offer superior thermophysical properties in deep geological conditions	<ul style="list-style-type: none"> Enhanced performance Multifunctionality 	Frontier research and demonstration projects; a key direction for future integrated energy services

Figure 1. Classification and characteristics of different geological thermal energy storage.

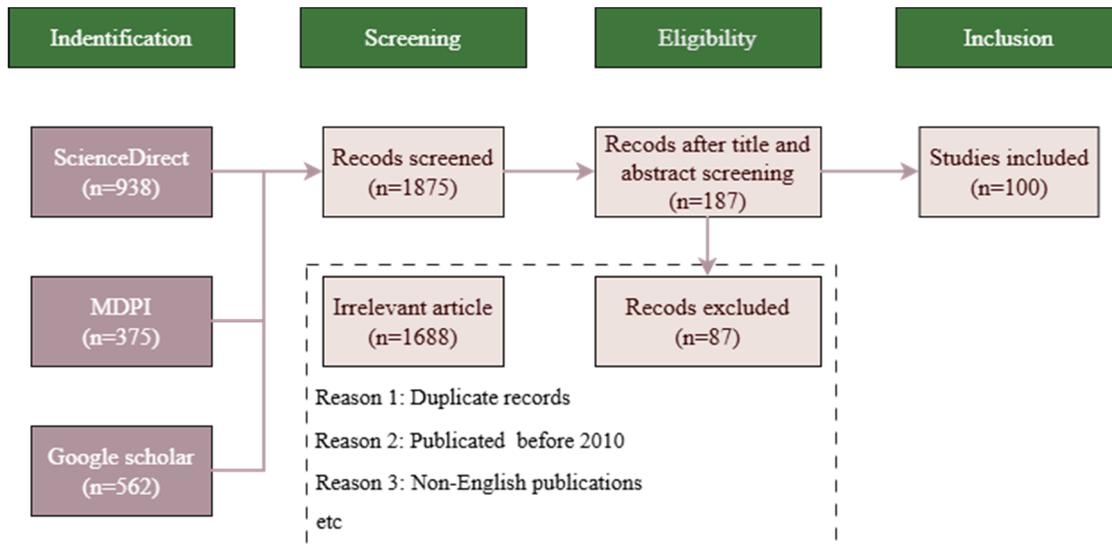


Figure 2. Prisma flow diagram.

3. Current Applications and Technological Progress

3.1. Borehole Thermal Energy Storage (BTES)

The BTES system is widely applied due to its low environmental impact, moderate initial investment and flexible site selection. It is particularly effective in seasonal energy storage in regional energy networks. Wang et al. [4] conducted an experimental and simulation study to review the application of BTES in building heating. The results indicated that the heat storage density of BTES is 15–30 kWh/m³, and the deep system can reach 2000–3000 m. After 4–5 years of operation, its efficiency can be increased to 40–54%, the long-term performance coefficient (COP) can reach 3.89, and at the same time, CO₂ emissions can be reduced by 64%. It is suitable for

regional heating and industrial waste heat recovery. Guo et al. [26] developed a large-scale living laboratory for BTES in China, through long-term field monitoring and modular system integration, and discovered that compared to directly discharging industrial waste heat, the BTES system recovered and stored 33,458.6 GJ of thermal energy in a single non-heating season, elevating the average temperature of the storage zone by 25.6 °C. Catolico et al. [13] numerically modeled a soil-borehole thermal energy storage system and found that BTES heat extraction efficiency increases as soil thermal conductivity decreases, but convective heat losses in high-permeability soils can reduce efficiency. Ahmadfard et al. [27] applied the finite line source model to simulate borehole thermal energy storage systems, demonstrating that over 10 years of operation, the cumulative energy storage error for a single borehole system is only 0.35% initially, decreasing to 0.02% long-term, with a maximum side heat loss deviation of just 3.1 W, indicating high thermal stability and computational accuracy of BTES in long-term operation. Welsch et al. [28] performed a comprehensive environmental and economic assessment of BTES in district heating, using life cycle analysis, and concluded that medium-deep BTES can reduce greenhouse gas emissions by over 40% and is economically viable even without subsidies.

BTES has excellent heat storage performance, long-term stability, significant emission reduction and economic advantages in regional heating systems. It is a mature and feasible solution for seasonal low-temperature heating and industrial waste heat utilization.

3.2. Aquifer Thermal Energy Storage (ATES)

ATES is applicable to large-scale applications such as public buildings, industrial facilities, and district heating and cooling systems. Compared with traditional systems, it can achieve significant energy savings and reduce CO₂ emissions. This technology is relatively mature, and more than 2800 systems have been put into operation worldwide, mostly in low-temperature conditions. Fleuchaus et al. [29] based on a review of global ATES system operation data indicated that this technology can achieve 40–70% energy savings, and the system investment payback period is usually 2–10 years. Marojević et al. [17] used the PRISMA method to conduct a systematic analysis of the simulation methods and environmental impacts of ATES, pointing out that under the conditions of policy support and mature underground engineering technology, the European region has a higher application advantage. Lu et al. [30] comprehensively evaluated the global potential of ATES based on social, economic, geological, hydrological and climatic factors, and the results showed that approximately 7% of the global regions are highly suitable for ATES, among which urban areas have the greatest application potential. Tas et al. [18] through global sensitivity analysis found that the permeability coefficient of the aquifer, the natural hydraulic gradient and the annual heat storage scale are the key parameters affecting the efficiency of the ATES system, which can be used to guide the feasibility assessment of engineering projects. Zhang et al. [31] through numerical simulation studied the ATES system constructed by hydraulic fracturing to build artificial diathermal belts (as shown in Figure 3), and the results showed that this method could reduce the heat loss rate by up to 8.38%, thereby improving the system’s heat storage efficiency.

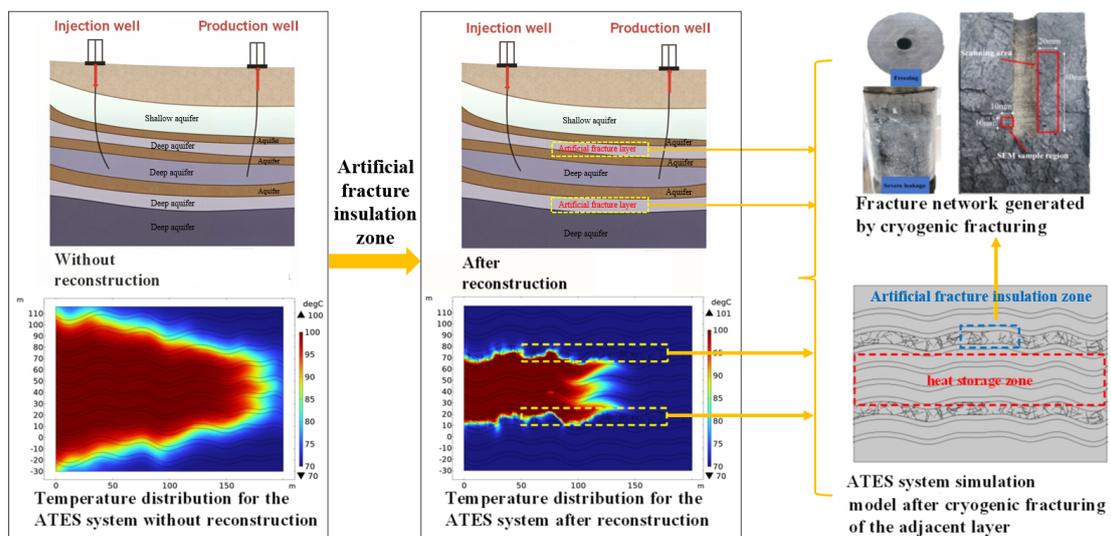


Figure 3. Comparison between conventional ATES and reconstructed ATES [31]. Adapted with permission from Ref. [31]. 2026, Zhang W, Wang M J, Yu H Y, et al.

ATES has been proven to have the feasibility for large-scale application, capable of achieving significant energy savings and CO₂ emission reduction effects. The related site selection and simulation methods are also constantly being improved. However, its application is still constrained by factors such as underground heterogeneity, the difficulty of design optimization under complex aquifer conditions, as well as regulatory and environmental uncertainties.

3.3. Minewater and Tunnel Thermal Energy Storage

Innovative approaches include the use of medium-deep and deep borehole systems, repurposing of abandoned oil/gas wells and mines, and the application of TES in tunnels and urban infrastructure. These methods expand the potential for TES deployment, especially in densely populated or infrastructure-rich regions. Li et al. [32] investigated thermal energy storage in underground backfilled mine stopes by embedding heat exchange tubes prior to backfill placement. Using a validated numerical model, they demonstrated that a typical coal mine stope can provide approximately 23 GWh of storage capacity with a 60% average recovery rate. Moreover, such systems can offer significant techno-economic advantages over conventional BTES due to lower installation costs and higher storage temperatures. Zhang et al. [33] experimentally investigated a phase change thermal energy storage system in backfilled mine goafs using a 1:15 scale similarity model. The cylindrical storage unit achieved thermal energy charging effectiveness of 0.98 and total charge-discharge effectiveness of 0.87 under optimized conditions. Scaled to engineering prototype, the system could store 422.88 GJ and extract 375.97 GJ of heat. Environmental assessment revealed carbon emission reductions of 83.0–88.1% per unit heating area compared to conventional heating systems. Knobloch et al. [34] designed and tested a high-temperature rock bed thermal energy storage system with a novel air flow configuration, and demonstrated a round-trip efficiency of up to 80.7% and stable operation over several years. Zhang et al. [35] numerically simulated geothermal-assisted compressed air energy storage (GA-CAES) using abandoned oil and gas wells, and found that geothermal pre-heating increases system efficiency and reduces project payback periods.

New technologies have expanded the types of energy storage media, enhanced system efficiency, and enabled large-scale energy storage and carbon management through the utilization of existing infrastructure. However, they still face challenges such as scalability, integrated optimization, and operational uncertainties.

3.4. Hybrid and Advanced Systems

The integration of TES with regional energy networks is an important development trend. It can utilize various renewable energy sources, industrial waste heat, and even support grid regulation, enhancing the flexibility and resilience of the intelligent energy system. Sadeghi et al. [3] reviewed the application of BTES in regional heating and cooling systems through case studies and system modeling, finding that it can reduce system operating temperatures and improve efficiency, especially crucial for low-temperature DHC systems. Fry et al. [2] quantitatively demonstrated that integrating UTES into regional TEN can achieve an average seasonal performance coefficient of 3.1–13.7, peak COP exceeding 20, compared to traditional ASHP systems, reducing the normalized heating and cooling costs by approximately one-third, extending the lifespan of system components from 20 years to over 50 years, and enhancing system flexibility and supporting decarbonization. Lyden et al. [36] modeled the seasonal storage heat application at the regional level, showing that the integration of STES with regional energy networks can achieve a seasonal performance coefficient of 3.1–13.7, storage efficiency of 50–90%, heat recovery efficiency of 70–90%, and a unit storage cost approximately 100 times lower than electrochemical storage. Chicco and Mandrone [37] conducted numerical simulations of BTES operation in regional heating networks, finding that continuous heat storage extraction can meet base load and peak load demands, achieving significant energy and economic savings. Welsch et al. [28] based on life cycle assessment pointed out that integrating deep-borehole BTES with large solar collectors and small CHP systems can reduce greenhouse gas emissions by up to 54%, while maintaining economic competitiveness, with a normalized heating cost of 5.37 ct/kWh (as shown in Figure 4).

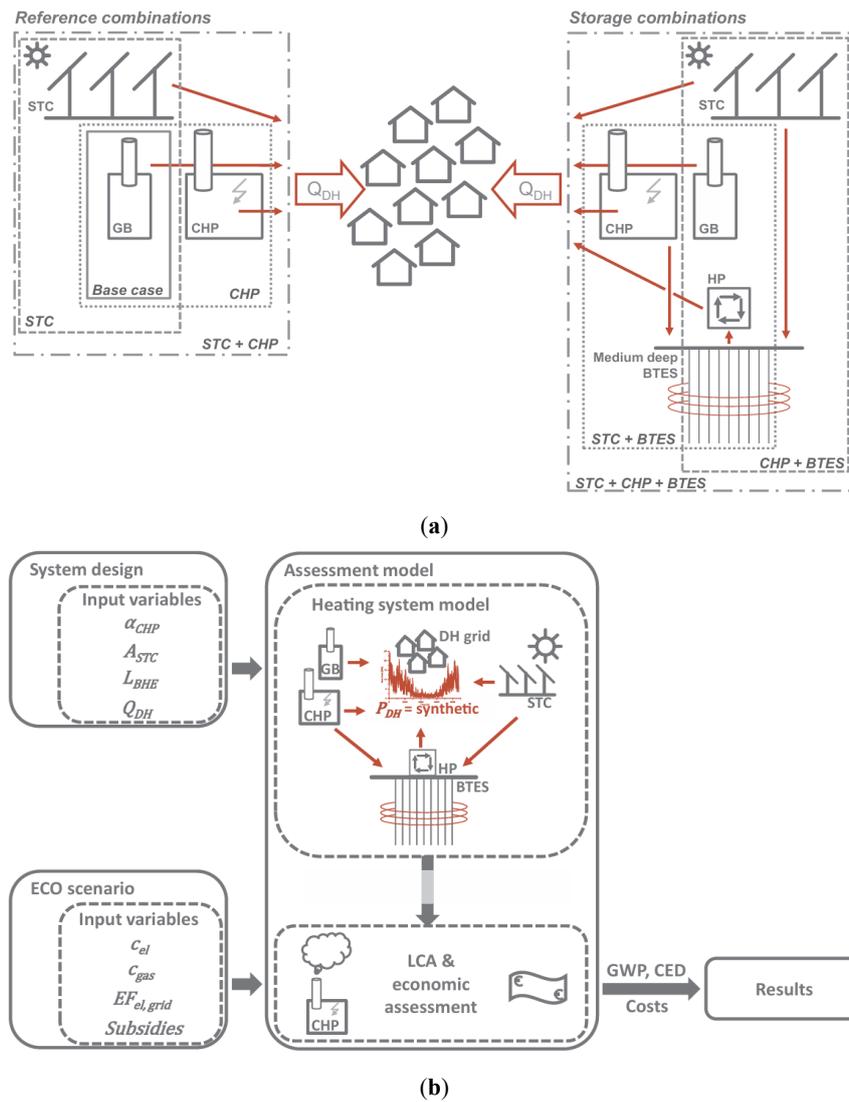


Figure 4. Borehole thermal energy storage in district heating systems. (a) Technical reference and storage scenarios; (b) Schematic illustration of the assessment model [28]. Adapted with permission from Ref. [28]. 2026, Welsch B, Göllner-Völker L, Schulte D, et al.

The integration of BTES or ATES with regional energy systems can enhance system efficiency, flexibility and decarbonization potential, but further optimization of control strategies is still necessary.

To facilitate direct comparison of these technologies, Table 1 summarizes key performance indicators reported in the literature, including Typical storage temperature, storage efficiency, system COP, and typical payback periods. It should be noted that the values presented reflect commonly reported ranges in the literature rather than strictly defined technical limits.

Table 1. Key challenges and future directions in geological TES and UHS.

Parameter	BTES	ATES	Mine/Tunnel TES	Composite/Advanced TES
Typical storage temperature	Different temperature ranges (25–90 °C) [26,38–40]	Low (<25 °C) [29]	Low to medium (15–60 °C) [32,33]	Medium to high (up to >100 °C) [21,41]
Storage efficiency	>70% [4,42,43]	40–70% [18,44–46]	60–90% [32,33]	Up to 90% [36]
System COP	3–6 [4,47]	2.4–5 [48,49]	—	Up to 20 [2]
Payback period	10–20 years [4,50]	2–10 years [29]	—	<10 years [35,51,52]
Main limitations	Geometry-driven losses, limited recovery, soil stability, slow charge-up [3,11,53]	Aquifer availability, groundwater flow/heterogeneity, water quality, regulatory limits, interference [16,17,54]	Contaminants, poorly known geometries, structural integrity, non-optimal shapes [9,55]	Complex integration/control, material durability, large-scale construction and insulation [56–58]

3.5. Economic and Environmental Impact of Geological TES System

The TES technology can achieve significant emission reduction and economic benefits by integrating TES with renewable energy and small backup devices. Baeuerle et al. [59] compared underground TES, hydrogen storage, and renewable metal energy carriers in industrial net-zero thermal buildings for seasonal energy storage. The results showed that the annual storage cost of underground TES was 1–26 times lower than that of ground tanks, but it was limited by space and economic conditions. Welsch et al. [28] conducted a life cycle assessment of BTES in regional heating and found that it could reduce greenhouse gas emissions by more than 40% and was economically viable without subsidies. Dahash et al. [60] reviewed large-scale hot water tanks and pit TES systems, stating that although the construction cost is high, their charging and discharging capacity is stronger, and they have less dependence on hydrogeological conditions than ATES and BTES. Hoekstra et al. [61] analyzed the economic and environmental benefits of European ATES pilot projects, indicating that reasonable site investigation and monitoring can overcome obstacles and achieve sustainable integration of renewable energy. Matos et al. [62] emphasized that the location of underground heat storage reservoirs should be determined based on specific conditions to ensure economic and environmental feasibility. Overall, the economic and environmental assessment verified the cost-effectiveness and emission reduction potential of underground storage, and improvements in site selection and monitoring also enhanced the sustainability of the project.

In addition to its energy and economic benefits, geological TES offers distinct environmental advantages related to land use. Unlike above-ground thermal storage facilities—such as hot water tanks or compressed air energy storage systems—which require substantial surface area, underground TES systems are largely invisible once installed, with only minor surface footprints for access points and heat exchange stations [63]. This characteristic renders geological TES particularly attractive in densely populated urban areas where land is scarce and expensive [64]. The compatibility of these systems with urban environments is evidenced by their growing adoption in cities worldwide [2]. Geological TES can also generate additional environmental co-benefits through the repurposing of otherwise idle or hazardous underground infrastructure. The conversion of abandoned mines, tunnels, and oil or gas wells into thermal storage reservoirs not only avoids the environmental costs associated with new construction but also helps mitigate legacy issues such as mine water contamination or subsidence risks [65,66].

However, there are still issues such as high initial investment, limited annual cycling times for some technologies, and the need for improved economic models and policy support [67,68].

4. Major Challenges

Solving the problem of geothermal heat storage is of vital importance for realizing its potential in the global energy transition.

4.1. Technical Challenges

The performance and safety of underground TES are highly dependent on local geological conditions, such as heterogeneity, permeability, and the integrity of the roof rock. Different types of reservoirs (depleted oil and gas fields, salt caverns, aquifers) vary significantly in terms of heat storage suitability, leakage risk, stability, and reserves [69–72]. High thermal conductivity rocks and underground water flow can lead to significant heat loss in the TES system, reducing energy storage efficiency. Therefore, it is necessary to optimize well spacing, system design, and operating parameters [73]. Sediment and mineral precipitation-induced blockages, as well as wellbore and equipment corrosion, can affect long-term operation and increase maintenance costs. Advanced anti-blockage, anti-corrosion materials, and water treatment technologies are urgently needed [74]. Moreover, coupling TES with other renewable energy sources, regional heating, or multi-energy networks will increase system complexity. Multi-physics field modeling and real-time monitoring are required to optimize design and operation [75].

4.2. Economic and Environmental Challenges

Although underground thermal energy storage offers significant cost advantages for large-scale, long-cycle applications compared to alternatives such as battery storage or above-ground tanks [59,76], the economic landscape is more nuanced when examined at the technology level. First, the initial investment varies substantially across technologies: BTES costs are dominated by drilling and heat exchanger installation, with investment costs accounting for a substantial portion of the levelized cost of heat [10]; ATES requires considerable expenditure on exploration wells and hydrogeological assessment, though its payback period can be attractive under favorable conditions [17]; while mine-based systems benefit from existing underground access but incur uncertain retrofitting expenses [65]. Second, despite higher absolute upfront costs, geological TES exhibits significantly

lower levelized cost of energy storage (LCOES) compared to lithium-ion batteries and tank thermal storage [77]. This cost advantage stems from the long operational lifespan and minimal maintenance requirements of well-designed underground systems [78]. Third, economic feasibility remains highly sensitive to policy frameworks. The successful deployment of ATEs systems in Europe has been underpinned by investment subsidies, carbon pricing, and renewable heat incentives [79]. In contrast, under purely market-driven conditions without subsidies, payback periods for geological TES can extend to a range that may deter private investment despite positive lifetime returns [80].

These economic considerations, together with the environmental and safety risks outlined above, underscore the need for integrated assessment frameworks. The main challenges and future development directions are summarized in Table 2.

Table 2. Key challenges and future directions in geological TES and UHS.

Challenge/Direction	Description	Key Advantages	Citations
Geological complexity	Site-specific risks, heterogeneity	Storage safety, efficiency	[69–72]
Thermal/hydraulic losses	Heat loss to surroundings	Energy recovery, system design	[3,73]
Clogging/corrosion	Wellbore scaling, material degradation	Long-term operation, maintenance	[55,74]
Geochemical/microbial effects	Byproduct formation, corrosion	Storage integrity, safety	[69,70,72]
Economic/environmental risks	High cost, leakage, contamination	Feasibility, public acceptance	[3,21,73]
Digitalization/integration	Smart modeling, multi-energy coupling	Efficiency, flexibility	[17,70]

5. Future Directions

Based on the previous review of geothermal energy storage technology, several key development directions can be proposed.

- (1) Utilizing abandoned oil and gas wells, mines, and other underground spaces for TES or UHS can reduce costs and environmental impacts, while increasing the storage capacity.
- (2) Advancing high-temperature and deep storage technologies to enhance energy density and system flexibility, supporting wider applications.
- (3) Introducing machine learning, advanced simulation, and real-time monitoring technologies to optimize system design, predictive maintenance, and operational efficiency.
- (4) Targeted policy, market, and standardization frameworks. Concrete measures are needed to accelerate geological TES deployment, including: (i) fiscal instruments—investment tax credits, renewable heat tariffs, and exploration subsidies; (ii) market mechanisms—enabling seasonal storage participation in energy trading and ancillary services, and public-private partnerships for infrastructure repurposing; and (iii) technical standards—including unified site selection criteria, design protocols, environmental monitoring requirements, and performance metrics—to ensure cross-project comparability and serve as replicable references for future deployments.

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