ARTICLE IN PRESS

Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

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

Research
Energy Transition's Technical Pathways, Risks, and Equity—Mini Review

The Role of Deep Geothermal Resources in China's Energy Transition

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ARTICLE INFO

Article history:
Received 27 July 2025
Revised 4 December 2025
Accepted 16 December 2025
Available online xxxx

Keywords:
Deep geothermal energy
Geothermal utilization approach
Geothermal energy policy

ABSTRACT

Geothermal energy is a sustainable power source with considerable potential to facilitate net-zero emissions targets. China possesses extensive deep geothermal reserves, which could play a pivotal role in advancing its national energy transition. This paper reviews the principal approaches for exploiting deep geothermal resources, with emphasis on direct-use applications, power generation, and energy storage. Key technical and economic challenges are identified, including underground thermal imbalance, wellbore corrosion and scaling, mineralization reactions with CO_2, co-products extraction, brine reinjection blockage, and the advancement of drilling and stimulation technologies. Policy and regulatory constraints on geothermal development in China are critically examined and compared with established frameworks in leading geothermal-producing countries. Based on the insights, recommendations are proposed to advance deep geothermal development in China, including ① the establishment of a specific regulatory framework for geothermal exploration and development; ② enhanced investment in foundational research and the development of core technologies; ③ introduction of geothermal-specific fiscal policies; and ④ prioritization of the strategic implementation of geothermal projects across different regions.

1. Introduction

Transitioning the energy system toward cleaner and low-carbon sources is an inevitable trend to achieve the carbon peaking and carbon neutrality goals. Geothermal energy is recognized as one of the five major non-carbon-based energy resources, characterized by its low carbon emissions and high stability, and thus provides a viable pathway to support energy transition from traditional fossil fuels to a renewable energy mix [1]. Deep geothermal energy resources are generally classified into two categories: hydrothermal resources and hot dry rock (HDR) resources, where HDR constitutes the predominant form of deep geothermal energy enrichment [2]. China possesses widely distributed geothermal resources with considerable exploitation potential. Based on terrestrial heat flow and underground temperature distributions, the geothermal energy contained in HDR at depths of 3–5 km is estimated at approximately 150 trillion tonnes of standard coal equivalent (TCE), which is nearly 80 times the fossil energy reserves in China [3]. Assuming an exploitation rate of 0.02% and a carbon emission factor of 0.73 tons of carbon per ton of standard coal, the achievable carbon emission reduction would be approximately 2.2×10^{11} tons. It should be noted that the estimation of geothermal resources was derived using the volumetric method, wherein the reservoir thermal conductivity and the radiogenic heat production rate were assumed to be constant at 2.6 $W{\cdot}(m{\cdot}K)^{-1}$ and 1, respectively [4]. Deep geothermal energy utilization can generally be categorized into two pathways: direct utilization and power generation. Geothermal energy offers the significant advantage of providing stable baseload output, with capacity factors of 65%–90%, nearly double those of solar (20%–25%) or wind (30%–35%) systems [5]. Despite the current levelized cost of electricity (LCOE) for geothermal power generation (0.14–0.32 USD$\cdot$(kW$\cdot$h)$^{-1}$) remains higher than that of solar photovoltaic (PV; 0.04–0.11 USD$\cdot$(kW$\cdot$h)$^{-1}$) and wind (0.02–0.07 USD$\cdot$(kW$\cdot$h)$^{-1}$), geothermal energy still remains competitive when considering total system value, including capacity credit, storage avoidance, and grid stability [6]. In countries such as Iceland and Kenya, geothermal power already accounts for 30%–50% of national electricity generation, serving as a backbone for the national grid's stability [7]. China currently ranks first globally in the direct utilization of geothermal energy, which has been extensively applied in industrial processes, residential heating, agricultural greenhouses,

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https://doi.org/10.1016/j.eng.2025.12.012
2095-8099/

Please cite this article as: G. Li, Z. Xie, Z. Huang et al., The Role of Deep Geothermal Resources in China's Energy Transition, Engineering, https://doi.org/10.1016/j.eng.2025.12.012

and aquaculture. However, geothermal power generation remains in its early developmental stage, with a total installed capacity of less than 50 MW [8]. According to the geothermal energy report released by International Energy Agency (IEA) in 2024, with strong policy and financial support, the construction costs of geothermal power plants could decline by up to 80% by 2035, reaching a range of 3000–7000 USD·kW^{-1} [9]. Therefore, the exploitation of deep geothermal resources holds substantial potential for enhancing the reliability of the national grid system and reducing reliance on imported fossil fuels, making it strategically significant for China's energy transition.

2. Major exploitation approaches for deep geothermal resources

2.1. Direct utilization of geothermal energy

2.1.1. Direct use applications

Direct utilization of geothermal energy represents the dominant approach to geothermal development in China. The country currently leads the world in the scale of direct geothermal energy use, accounting for nearly 57% of the global direct-use installed capacity in 2023 [10]. Since 2010, China's direct geothermal utilization has grown at an average annual rate exceeding 10%, significantly outpacing that of other countries (Fig. 1(a) [11]). The direct utilization of geothermal energy in commercial applications, including district heating, agricultural greenhouses, and hot spring development, offers substantial technical advantages (Fig. 1(b)) [11]. The Xiong'an energy mix represents a leading example of large-scale direct geothermal utilization in China. The geothermal field spans approximately 1256 km^2, integrating the simultaneous development of both medium–deep (600–4000 m) and shallow (0–200 m) hydrothermal geothermal resources. The geothermal reservoir is primarily composed of dolomite and sandstone formations, with fluid temperatures ranging from 60 to 130 °C and an average geothermal gradient of 32.4 °C·km^{-1} [12]. Notably, closed-loop heat extraction systems have been implemented to enable heat recovery without groundwater withdrawal, thereby enhancing environmental protection and long-term resource sustainability. In addition, advanced intelligent dispatching and temperature control systems are employed to optimize thermal efficiency and operational stability [13]. To date, the Xiong'an region has drilled roughly 60 medium–deep wells and 2360 shallow wells for geothermal heating, covering a cumulative heating area of about 12×10^6 m^2, which helps reduce CO_2 emissions by approximately 100 000 tons annually [14]. Despite these advantages, the performance of direct utilization of geothermal energy is limited to specific geographic regions, as it depends on hydrothermal resource distribution, reservoir permeability, thermal gradients, and heat demand. Additionally, the absorption chilling and district heating may also result in underground thermal imbalance or excessive cold accumulation, primarily due to improper well layout or low reinjection rates that cause a continuous decline in reservoir temperature. In regions with extensive deployment of ground-source heat pump systems, such as Beijing, long-term subsurface temperature decreases of up to 15 °C have been reported, significantly affecting the long-term operational efficiency of the systems [15]. To mitigate these challenges, cascade utilization strategies have been proposed to enhance overall thermal efficiency by enabling sequential use of thermal energy at different temperature levels [16]. Implementing cross-seasonal energy storage and peak load regulation, and achieving efficient cross-regional heat distribution will be critical works for the efficient direct utilization of geothermal energy. Moreover, integrating phase change materials into geothermal heating and cooling systems can stabilize ground temperature, improve heat-exchange efficiency, and reduce the required length of heat exchangers [17]. These technologies provide practical pathways for geothermal utilization in areas with limited hydrothermal resources or low geothermal gradients, supporting long-term system stability and sustainability.

2.1.2. Marine geothermal energy

Marine geothermal energy has emerged as a promising resource with significant potential, particularly as offshore oil and gas exploration advances into deeper waters. The offshore shallow hydrothermal geothermal resources in China are estimated to approximately 2.96×10^{11} TCE. Submarine geothermal systems are characterized by high pore pressure, elevated salinity, and cold overlying seawater. Their average heat flow is generally higher than that of continental regions, with heat sources primarily associated with mid-ocean ridges and back-arc spreading centers [18]. Marine geothermal energy offers valuable applications for offshore platforms, including direct heat supply and seawater desalination. Moreover, it enables the joint development of offshore heavy oil and natural gas hydrate resources by replacing conventional steam injection with geothermal heat, thereby improving hydrate production efficiency and reducing reliance on fossil fuels [18]. The development of marine geothermal energy could enhance resource utilization in nearshore areas, islands, reefs, and deep-sea regions,

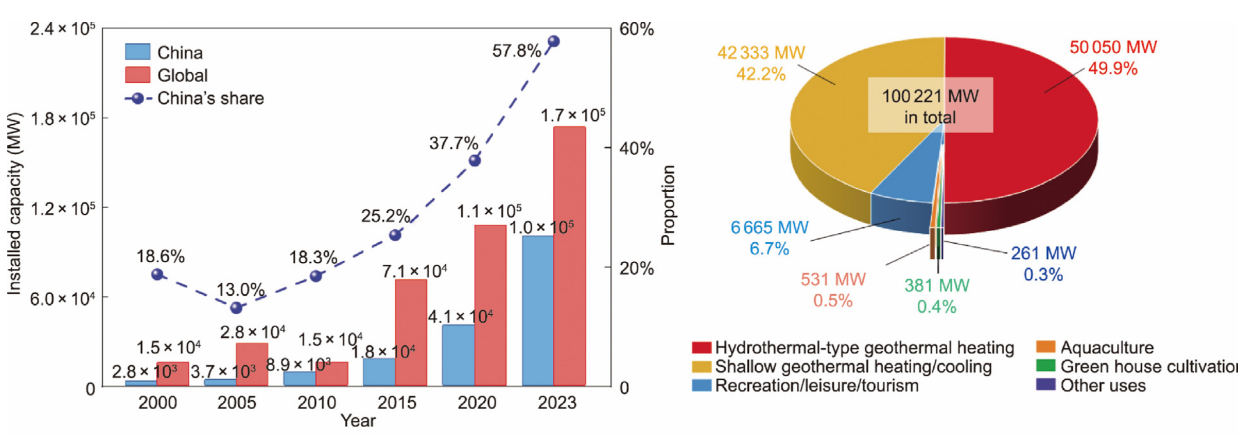

Fig. 1. Direct utilization of geothermal energy in China. (a) Variations of installed capacity for different years; (b) application ratios of geothermal direct utilization by the end of 2022 [11].

while also contributing to energy storage and national energy security. However, the utilization of marine geothermal energy remains largely in the theoretical research phase, with limited field applications to date. This is primarily due to the high drilling and maintenance costs associated with the harsh deep marine environment, which pose significant challenges to system reliability and economic feasibility. Additionally, high hydrostatic pressures and low ambient seawater temperatures may lead to substantial heat losses along subsea pipelines, necessitating advanced thermal insulation materials and designs. Meanwhile, the high salinity and corrosive nature of seawater accelerate metal corrosion and scaling within wellbores and heat exchangers, necessitating the use of corrosion-resistant alloys or anti-scaling coatings. Future research should prioritize the exploration of geothermal resource-rich areas in the South China Sea and address the high upfront costs associated with drilling and completion geothermal wells in deep water environments.

2.1.3. Oilfield geothermal energy

Oilfield geothermal energy, which focuses on repurposing existing oil and gas wells, offers a practical and immediate opportunity for advancing the utilization of low-to-medium temperature geothermal resources. This approach involves extracting geothermal energy from both abandoned and active production wells. Current development strategies primarily involve the recovery of waste heat from oil production and the deployment of downhole heat exchange systems. The latter operates as a closed-loop configuration, in which a working fluid circulates within the wellbore through double U-tubes or coaxial pipes to extract heat directly from the surrounding strata [19]. Geothermal utilization in the Hailar oilfield has advanced through the application of coaxial heat exchange transformation of long-term shut-in and low-efficiency wells. With well depths of approximately 1800 m and bottom-hole temperature near 70 °C, the geothermal gradient ranges from 3.0 to 3.4 °C per 100 m. Under these conditions, a single well can achieve a heat extraction capacity of 155 kW. Deploying 20 such wells equipped with electric compression heat pumps (COP: 3.1) allows for a total heating capacity of 4.34 MW. This system enables an annual reduction of crude oil consumption by 1424 tons and CO_2 emissions by roughly 4399 tons, demonstrating notable economic and environmental benefits. Nevertheless, the high mineralization levels in the oil-bearing formations lead to severe corrosion and salt deposition, which impair heat transfer efficiency [20]. In contrast to conventional hydrothermal geothermal wells, where scaling is primarily dominated by carbonates or silica, scaling in geothermal oilfields applications is dominated by the precipitation of salts from highly mineralized formation water. This process is driven by temperature and pressure variations and the degassing of CO_2, which together lead to solution supersaturation and mineral precipitation [21]. Furthermore, converting oil wells into enhanced geothermal systems (EGS) application may pose risks, including unintended hydraulic connectivity between oil-bearing and water-bearing strata, which could lead to subsurface contamination and increased seismic hazards. To enhance the performance and safety of oilfield geothermal systems, it is essential to develop corrosion-resistant heat exchange tubing and optimize stimulation design protocols. Priority should be directed toward the development of advanced scale inhibitors capable of maintaining chemical stability under high-temperature, high-pressure, and high-salinity conditions, alongside the design of durable downhole anti-scaling coatings. At the same time, efforts should focus on establishing a dynamic scaling prediction model that couples pressure transients, CO_2 release, and crystallization kinetics, thereby forming an integrated framework for predicting and mitigating scaling processes in the complex geothermal fluid environments of oilfields.

2.1.4. CO_2 utilization and sequestration

CO_2 *in situ* mineralization and sequestration, where captured CO_2 is injected into geothermal reservoirs as the working fluid in place of water, has emerged as a highly promising negative-emission technology. Under high-temperature and high-pressure conditions, CO_2 reacts with reservoir minerals through dissolution and subsequent precipitation reactions, enabling secure long-term carbon storage while significantly reducing sequestration costs. The successful implementation of the CarbFix demonstration site in Iceland has proven the feasibility of CO_2 injection into high temperature geothermal reservoirs [22]. The field evidence indicated that CO_2-based EGS exhibit higher heat extraction efficiency than water-based EGS. This improvement arises from the lower viscosity and higher diffusivity of CO_2, which enable more efficient flow through complex fracture networks. Furthermore, the lower specific heat capacity of supercritical CO_2 facilitates faster heat exchange. Additionally, mineralization reactions within the reservoir can convert injected CO_2 into stable carbonate minerals over timescales of months to years [23]. As a result, geothermal reservoirs offer higher CO_2 storage efficiency and lower leakage risk compared to conventional oil and gas reservoirs. Nevertheless, controlling and optimizing mineralization reactions across diverse geological settings remains a significant technical challenge.

2.1.5. Synergistic production of associated resources

Fluids circulating within geothermal reservoirs typically dissolve a variety of valuable associated elements, including lithium, strontium, boron, and helium [24]. The simultaneous extraction of these valuable by-products during geothermal energy development has the potential to enhance the overall economic viability of geothermal projects. For example, measurements from a representative geothermal well in southern Xizang indicate a lithium concentration of approximately 23.5 $mg\cdot L^{-1}$ [25]. Economic assessments of solvent extraction-based lithium recovery suggest that such operations could become commercially viable under high lithium carbonate prices. However, compared to conventional salt lake brines and hard-rock lithium deposits, geothermal fluids generally exhibit lower lithium concentrations with complex chemical compositions, posing substantial technical and economic challenges. Moreover, the high concentrations of coexisting ions in geothermal brine severely limits the efficiency of selective lithium extraction. Studies have shown that Fe^{2+} can form iron oxide/hydroxide scaling layers on electrode surfaces, significantly impairing electrochemical capacity and lithium–sodium selectivity [26]. Currently, extraction technologies for lithium and other critical minerals from geothermal reservoirs remain at the research stage, which lacks regulatory frameworks for co-production. Future efforts should prioritize technological advancements in selective extraction and tailored reservoir management strategies to enable integrated geothermal and mineral resource development.

2.2. Power generation

2.2.1. Low-to-medium temperature geothermal resources

Low-to-medium temperature geothermal resources mainly refer to hydrothermal geothermal resources with temperatures ranging from 90 to 150 °C, which utilizes hot water or steam for power generation. Organic Rankine cycle (ORC) power plant are the commonly adopted technology for developing low-to-medium temperature geothermal resources, as they employ low-boiling-point working fluids that enable effective power generation while mitigating pipeline corrosion caused by geothermal fluids [27]. The selection of appropriate working fluids with suitable boiling points is essential for maximizing thermal extraction efficiency. Nonetheless, power conversion yields relatively low output due to limited temperature differentials. In addition, challenges such as geothermal brine reinjection blockage, scaling issue, borehole corrosion, H_2S emission restrict the development of low-to-medium temperature geothermal energy. For instance, geothermal fluids extracted from the Yangbajing geothermal field in Xizang Autonomous Region, China, contain various chemically active species, including H_2S (3–6 mg·L^{-1}), SiO_2 (100–250 mg·L^{-1}), CO_2 (5–10 mg·L^{-1}), and boric acid (77.6 mg·L^{-1}) [28]. Among these, acidic gases can corrode the negative-pressure systems of geothermal power plants when exposed to atmospheric oxygen, resulting in frequent replacement of pump impellers (every 3–6 months). Moreover, the operation of the 1000 kW unit at the Yangbajing Geothermal Power Station disturbed the temperature–pressure equilibrium of the underground geothermal system, leading to massive $CaCO_3$ precipitation [29]. This severe mineral scaling within geothermal wells and associated pipelines impedes hot-water flow and can ultimately lead to project shutdown. To enhance the thermal efficiency of energy systems, cascade utilization and integrating geothermal energy with other renewable sources of geothermal energy have been proposed, and offer a promising approach to improving the efficient usage of the low-to-medium temperature geothermal resources [30,31].

2.2.2. HDR geothermal resources

High-temperature and low-permeability geothermal resources typically refer to HDR, where reservoir temperatures generally exceed 180 °C. EGS is regarded as the primary approach for developing HDR reservoirs, in which hydraulic stimulation is used to create flow pathways between injection and production wells [32]. Geothermal heat is then extracted through artificially induced fracture networks using a circulating working fluid to generate power. However, field tests have revealed that challenges such as low rock drillability, fluid loss, low thermal exchange efficiency, and induced seismicity are commonly encountered. Additionally, the geometry of hydraulic fractures in HDR formations tends to be simple and planar, often resulting in poor hydraulic connectivity between injection and production wells [33]. Therefore, activating pre-existing natural fractures through hydraulic fracturing is critical for generating complex and interconnected fracture networks [34,35]. In 2024, United States-based company Fervo Energy successfully employed the multistage hydraulic fracturing technology to exploit high-temperature (approximately 191 °C) HDR reservoirs [36]. This advancement was achieved through the implementation of horizontal wells and multistage bridge plug-perforation stimulation methodologies (Fig. 2). The first heat generation test was conducted at the Cape Station project in southern Utah [37], where the initial water production rate and the temperature of the produced fluid reached 120 kg·s^{-1} and 187 °C, respectively. The estimated peak power output exceeded 10 MW, indicating potential for large scale production increases in future development of deep geothermal resources. Leveraging mature petroleum technologies, such as horizontal well with multi-stage hydraulic stimulation, offers a promising pathway to expand geothermal power capacity in the near term. Recent studies have shown that reservoir stimulation assisted by multi-lateral radial wells can guide fracture propagation and promote the formation of complex, interconnected fracture networks [33]. Meanwhile, a real-time monitoring system has been established to mitigate seismic risks induced by stimulation. This system employs signal-based color indicators, known as the traffic light system, to enable operators to adjust injection protocols based on real-time seismic data. The implementation of cyclic soft fracturing techniques has also been proven effective in mitigating seismic risk while improving the reactivation of natural fractures [38]. Nevertheless, the large-scale application of cyclic soft fracturing in China is still constrained by its relatively high stimulation cost. Continued research is essential to reduce the costs associated with drilling and stimulation technology in HDR reservoirs, which will be critical for the commercial viability of EGS development.

Advanced geothermal systems (AGS) have gained increasing attention in recent years, which operate by circulating working fluids through a closed-loop piping network to extract heat from HDR without direct fluid exchange with the surrounding rock matrix. This approach fundamentally eliminates key risks associated with EGS, including induced seismicity, reservoir scaling, and fluid loss [39]. The Eavor demonstration pilot in Canada has validated the technical feasibility of AGS, and the world's first commercial-scale AGS project—located in Geretsried, Germany, with an installed capacity of 8.2 megawatts of electrical power (MWe)—has been completed, and full commercial operation is planned to begin around mid-2026 [40]. If it works as intended, the closed-loop AGS geothermal concept could substantially expand geothermal deployment in regions where EGS or conventional hydrothermal systems are not viable.

2.2.3. Geothermal cascade utilization

One of the key advantages of geothermal energy is its capacity for cascaded utilization of thermal resources, leveraging the temperature gradient of geothermal fluids for sequential applications. By allocating each temperature range to the most suitable application, geothermal systems enable a temperature-grade utilization strategy that maximizes energy utilization efficiency and resource sustainability [41]. High-temperature geothermal fluids (>180 °C) can be first used for power generation. As the thermal fluid cools (60–90 °C), the residual heat remains sufficient for secondary applications (e.g., district heating), which could replace fossil-fuel-based heating systems that help with the reduction of CO_2 emissions. Further cooled fluids can then support tertiary uses (40–60 °C), including greenhouse planting and hot spring resorting, thereby improving its energy utilization efficiency and economic viability. Xian County, located in Beijing–Tianjin–Hebei Urban Agglomeration, has developed a demonstration project for the cascade utilization of geothermal energy, integrating power generation, district heating, and agricultural applications [42]. The demonstration base has achieved an installed power generation capacity of 280 kW, provides heating for 1.32×10^5 m^2, supports agricultural greenhouses spanning 3×10^3 m^2, and retains an additional heating potential of 1.5×10^5 m^2. This system has increased the comprehensive utilization rate of geothermal energy to 81.8%. Through this cascaded power-generation and heating system, the project reduces annual standard coal consumption by 4020 tons, cutting CO_2 emissions by 9600 tons and SO_2 emissions by 301 tons [42]. However, the current cascade utilization efficiency remains constrained by seasonal variations in heat demand. Furthermore, the high upfront capital investment and the optimization of infrastructure and temperature matching for each use stage remain major challenges. Thus, supportive fiscal policies and integrated multi-sector coordination are essential to facilitate the large-scale deployment of geothermal cascade systems. This includes establishing special subsidy funds for geothermal development and introducing tax incentives for cascade utilization projects to lower the initial investment barrier. Cross-departmental coordination mechanisms that integrate energy, housing, agriculture, and environmental sectors are essential to avoid the inefficiencies of fragmented development.

2.3. Geothermal energy storage

2.3.1. Underground thermal energy storage

Underground thermal energy storage (UTES) stores intermittent surface energy sources (e.g., wind, solar, and waste heat) in the form of stable thermal energy within underground spaces by circu-

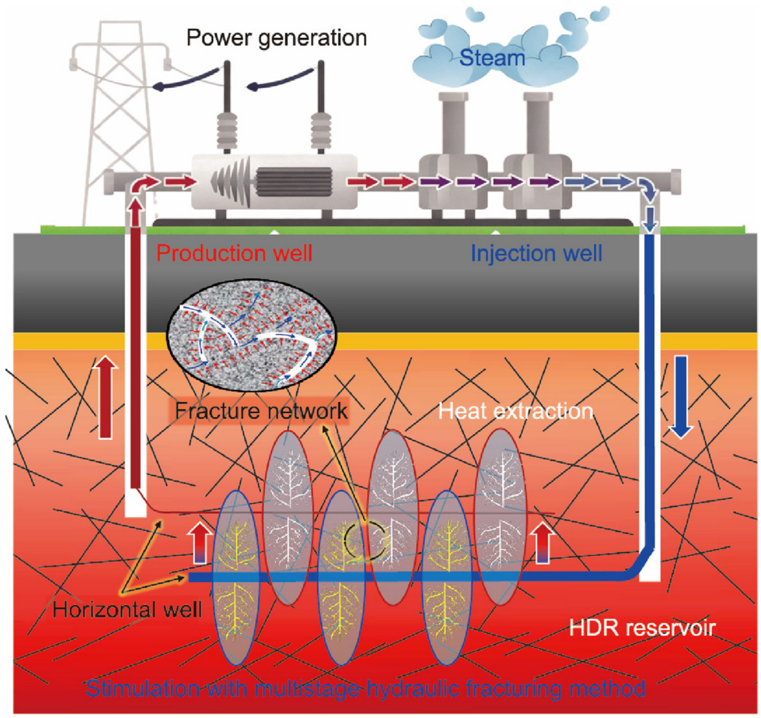

Fig. 2. Geothermal power generation achieved by multistage hydraulic fracturing.

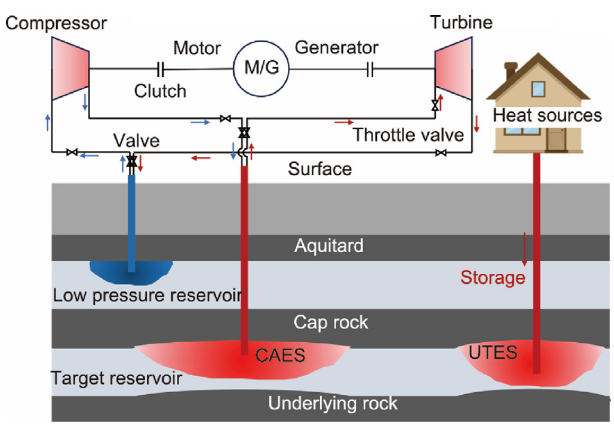

Fig. 3. Schematic diagram of geothermal energy storage principles. CAES: compressed air energy storage; MG: motor/generator.

lating water or supercritical CO_2 as the medium (Fig. 3). UTES offers significant advantages, including large storage capacity, low capital cost, and seasonal energy retention. It enables the integrated utilization of diverse energy sources, addressing imbalances in energy supply and demand across time and space. This reduces reliance on fossil fuels and contributes to energy conservation and emission reduction [43]. Vantaan Energia in Finland is currently planning to construct the world's largest seasonal thermal energy storage system, known as the Varanto project. The project consists of three caverns located 140 m below the surface, each measuring 40 m × 20 m × 300 m, with a total volume exceeding 1 million cubic meters. It will be capable of storing 90 GW·h of heat, sufficient to meet the annual district heating demand of a medium-sized city in Finland. A distinctive feature of the project is its ability to store hot water at temperatures up to 140 °C, making it a representative example of shallow high-temperature thermal energy storage. After preliminary construction work in November 2025, the project is scheduled for completion in 2030 [44]. The Varanto project represents the current state-of-the-art in the field of shallow high-temperature thermal energy storage. However, the operational experience from shallow UTES cannot be directly extrapolated to deeper geothermal reservoirs, where geological conditions are significantly more complex. Deep-to-intermediate geothermal reservoirs differ significantly from shallow ones in lithology, permeability, and temperature distribution. Despite the growing interest in UTES deployment at greater depths, systematic approaches for evaluating thermal storage feasibility and associated reservoir risks remain underdeveloped. The favorable geological conditions for deep geothermal energy storage are illustrated in Table 1.

Moreover, corrosion and scaling in wellbore facilities caused by water–rock interactions severely undermine the longevity and safety of thermal storage systems. It is worth mentioning that the high-temperature aquifer thermal energy storage (HT-ATES) project in Neubrandenburg, Germany, experienced distinct corrosion phenomena compared to conventional hydrothermal geothermal systems [45]. The temperature cycling subjected the wellbore to repeated heating–cooling cycles, where thermal fatigue effects caused the rupture and detachment of metal corrosion-resistant films, resulting in significant corrosion. Additionally, periodic temperature variations induced selective mineral deposition according to temperature gradients, potentially triggering repeated dissolution-reprecipitation processes. This mechanism leads to more complex scale layer structures than those observed in hydrothermal systems. Therefore, further research is needed to elucidate the complex multi-field coupling mechanisms among thermo–hydro–mechanical–chemical (THMC) processes under temperature cycling during thermal energy storage. There is an urgent need to optimize thermal energy storage operation strategies to establish the matching relationship between charge–discharge strategies and heating/cooling demand, thereby achieving higher storage efficiency.

Table 1
Favorable geological conditions for various geothermal applications.

Key geologic factor	Lithology	Geothermal gradient (°C·km^{-1})	Porosity/permeability	Depth (m)
Geothermal direct utilization	Dolomite/sandstone/limestone	> 20	Porosity > 10%; permeability > 10 mD	1000–2000
Marine geothermal	Basalt/carbonate rock	> 50	Porosity > 10%; Permeability > 1 mD	1000–4000
Oilfield geothermal	Sandstone/carbonate rock	> 30	Permeability > 1 mD	2000–3000
CCUS in geothermal	Sandstone/carbonate rock	> 20	Porosity > 15%; permeability >0.1 mD	800–3500
Geothermal associated resources	Fractured volcanic rock/sandstone/ carbonate rock	> 30	Porosity > 5%; permeability > 1 mD	1500–3500
Geothermal power generation	Granite/basalt	> 50	Porosity > 5%; permeability > 0.1mD	3000–5000
Geothermal energy storage	Sandstone/carbonate rock	> 25	15% < porosity < 30%; 1 mD < permeability < 500 mD	100–2000

CCUS: carbon capture, utilization, and storage; 1 mD = 10^{-4} μm^2.

2.3.2. Compressed air energy storage

Compressed air energy storage (CAES) in geothermal reservoirs is an innovative hybrid energy storage system that utilizes porous geothermal formations as storage sites for high-pressure compressed air (Fig. 3). By leveraging geothermal heat during expansion, this approach enhances thermodynamic efficiency and offers a cost-effective, environmentally sustainable energy storage solution [46]. CAES is primarily used for grid balancing, where the stored air can be released to generate electricity during peak demand periods, and often integrates intermittent renewable energy sources to optimize energy utilization. Despite its promise as a high-potential, low-carbon solution for large-scale energy storage, CAES in geothermal reservoirs faces significant technical challenges, particularly the risk of air leakage in sealed reservoirs and the need for sufficient mechanical integrity of the reservoir to endure pressure cycles. The high-pressure environment for gas storage and the repeated injection–extraction cycles impose considerable stress on the energy storage system. Particularly in geothermal reservoirs characterized by extensive pre-existing natural fracture sets, the progressive propagation of the fractures may compromise caprock integrity or connect with large scale faults, thereby increasing the risk of gas leakage [47]. In extreme cases, uncontrolled gas leakage can culminate in a large-scale surface blowout, which poses severe safety hazards to onsite personnel and surface gas storage facilities. The 2015 California blowout at a gas storage facility exemplifies the catastrophic consequences of such failures, underscoring the importance of ensuring the geomechanical safety of subsurface energy storage operations [48]. Therefore, it is necessary to understand fracture network behavior under cyclic pressure and temperature variations. Additionally, exploring alternative working fluids with higher densities (e.g., CO_2) may enhance storage efficiency and support the carbon peaking and carbon neutrality goals [49].

3. Policy and regulatory challenges

Deep geothermal energy offers a stable, low-carbon power source with strong potential for base-load generation. However, despite technological advancements, its large-scale development remains constrained by multiple policy and regulatory barriers.

(1) Unclear subsurface ownership and licensing frameworks. Legal definitions of subsurface ownership and usage rights are often ambiguous, particularly for deep geothermal reservoirs that overlap with other underground resources, such as minerals, groundwater, and renewable energy. These resource domains fall under the jurisdiction of multiple departments, including the Ministry of Natural Resources, Ministry of Ecology and Environment, and Ministry of Water Resources of China. As a result, overlapping management responsibilities and inconsistencies among regional regulations governed by the Mineral Resources Law, Water Law, and Renewable Energy Law have led to insufficient legislative clarity and a coherent regulatory system to support geothermal exploration and development. In contrast, several European countries have initiated amendments to their legal frameworks to accelerate geothermal applications. For instance, the Netherlands introduced a dedicated legal procedure for geothermal projects in 2022, decoupling them from the default framework historically applied to oil and gas exploration. Similarly, France has proposed measures to shorten permitting times by half through the parallel evaluation of project applications [9].

(2) Insufficient investment in fundamental research and key technologies. Deep geothermal reservoirs are typically characterized by extreme conditions, including high temperature, high rock strength, high *in situ* stress, and low permeability, posing significant challenges in exploration, drilling, stimulation, heat extraction, and power generation. Since the 1970s, demonstration projects have been initiated in western countries to assess the technical and economic feasibility of deep geothermal exploitation. By contrast, China's engagement in deep geothermal energy development began much later. Since 2012, with support from national initiatives such as the 863 Program and the National Key Research and Development Program, initial breakthroughs have been achieved in the exploitation of HDR resources. Nonetheless, limited research funding and the absence of large-scale pilot demonstrations continue to impede further advancements. Additionally, the inadequate quality of subsurface data and the restricted availability of standardized public data-sharing platforms persist as major challenges for geothermal developers in accurately assessing project risks. In comparison, the United States and France are taking the lead by establishing public-access geothermal data repositories, which substantially advance fundamental research in geothermal development [50,51].

(3) Limited subsidies or feed-in tariffs. The deep geothermal sector is confronted with inherent challenges, including high upfront capital investment and extended payback periods. In comparison to wind and solar energy, deep geothermal energy projects receive limited financial incentives in China. In 2025, China's Ministry of Finance allocated approximately 63 billion RMB in subsidies to support wind and solar power projects for electricity generated from renewable energies [52]. However, no equivalent fiscal incentives have yet been introduced for geothermal power generation. Although China's National Energy Administration advocates for the establishment of a favorable policy environment and implementation of supportive fiscal measures, inconsistencies in execution at the local level persist. These challenges include non-uniform regulatory standards and wide disparities in resource tax rates, which vary widely from 1 to 30 RMB per ton across different regions due to resource distribution disparities. Moreover, in cases where geothermal heat is extracted without water usage, resource taxes are still imposed based on the volume of water, which undermines the enthusiasm of enterprises for engaging in

geothermal investment. As a result, the scale of deep geothermal exploitation has fallen short of national targets, highlighting the urgent need for more coherent and targeted policy frameworks. It should be noted that while a few major countries, such as Japan and Turkey, continue to employ national fixed feed-in tariffs for geothermal energy as of 2025, the global trend has shifted toward market-oriented mechanisms, such as auctions or competitive tenders, contracts for difference (CFDs), feed-in premiums, and tax credits in countries including Germany, Iceland, and the United States [11].

4. Conclusions and recommendations

As a clean and reliable source of baseload energy, deep geothermal energy holds substantial potential for accelerating the transition to low-carbon energy consumption. To promote the development of deep geothermal energy in China, the following recommendations are proposed.

Establish a dedicated regulatory framework for geothermal exploration and development. A comprehensive regulatory framework should be established to promote the sustainable and efficient utilization of geothermal energy. It is recommended that a national coordination mechanism, led by the National Energy Administration, be formed to clearly delineate the responsibilities and jurisdictions of the local provincial governmental departments involved in geothermal resource development. Administrative procedures related to land use, mining rights, and the approval processes for thermal and electrical projects should be streamlined to reduce bureaucratic barriers. Geothermal energy should also be integrated into national energy-saving and carbon reduction assessment systems, thereby reinforcing its role in advancing low-carbon urban development. The European Union has formulated a geothermal-specific Implementation Plan, incorporating geothermal energy as a strategic technology within the Net-Zero Industry Act, from which valuable policy implications can be drawn for China. Furthermore, nationwide geothermal data acquisition efforts should be strengthened through the establishment of a unified and comprehensive database encompassing the entire geothermal exploration and development stages. To ensure standardized and scientifically informed deployment, dedicated geothermal legislation should be introduced, along with geothermal-specific technical standards that guide every stage of development.

Enhance investment in foundational research and the development of core technologies. National science and technology initiatives should be specifically dedicated to the exploration and development of deep geothermal resources, which would foster theoretical innovation and promote the independent research and development of key technologies. National research platforms (e.g., state key laboratories and fundamental research centers) should be established to build strategic scientific and technological capabilities in deep geothermal fields. Additionally, more geothermal pilot demonstrations should be deployed in representative geothermal fields to validate theoretical advancements, technological feasibility, and accelerate the translation of research outcomes into engineering applications.

Introduce geothermal-specific fiscal policies. To promote the development of deep geothermal heating and power generation, performance-based subsidy schemes should be established, providing financial support based on the quantity of heat or electricity produced. Preferential electricity pricing policies for residential users can further attract private sector investment. Additionally, tax incentives for geothermal energy are suggested to be aligned with those established for other renewable energy sources, such as solar PV and wind, which have benefited from direct subsidies and a 50% reduction in value-added tax. Resource taxes should be waived for geothermal projects that achieve full reinjection of geothermal fluids, promoting environmentally sustainable utilization of geothermal resources.

Optimize regional deployment strategies for geothermal applications. In the near term, geothermal power generation should be prioritized in geothermal resource-rich regions (e.g., southeastern and southwestern China), where megawatt-scale projects can be realized by leveraging existing petroleum development technologies such as horizontal well completion with large-scale multi-stage stimulation. Conversely, in northern and central China, where mid-deep geothermal reservoirs exhibit relatively lower geothermal gradients, development should focus on cascade utilization and the synergistic integration of geothermal energy with other renewable sources to maximize overall thermal efficiency. In the longer term, as the cost of geothermal well drilling and completion continues to decline, large-scale EGS projects at the gigawatt level are expected to be developed at major deep geothermal resource-rich regions, targeting deeper geothermal reservoirs at depths of 5000–8000 m. Additionally, the selection of suitable locations for deep geothermal energy storage is essential for balancing peak load demand, and should account for the efficiency of electricity transmission from remote geothermal regions to densely populated metropolitan areas.

CRediT authorship contribution statement

Gensheng Li: Funding acquisition, Conceptualization. **Zixiao Xie:** Writing – original draft, Investigation. **Zhongwei Huang:** Supervision, Funding acquisition. **Xianzhi Song:** Project administration, Funding acquisition. **Xiaoguang Wu:** Validation, Methodology.

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.

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for this journal and was not involved in the editorial review or the decision to publish this article.

Acknowledgments

The authors would like to acknowledge the financial support by the National Natural Science Foundation of China (52421002, U24B2032, and 52192621) and Science Foundation of China University of Petroleum (Beijing) (2462025XKBH018).

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