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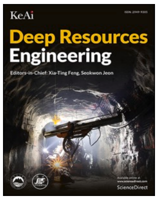

Review

Geothermal energy and tiered synergistic mining of geothermal energy and minerals: Advantages, issues, and paths

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ABSTRACT

Geothermal resources, especially hot dry rock (HDR), hold the unparalleled potential to decarbonize energy systems and bolster the global clean energy transition. Despite five decades of development, enhanced geothermal systems (EGS) remain constrained by limited power generation capacity, obstructing the commercial viability of deep geothermal energy. A comprehensive understanding of the limitations throughout the system operation is crucial for facilitating large-scale commercial utilization of HDR geothermal energy. Here, we compare the drilling-enhanced geothermal system (D-EGS) and the excavation-enhanced geothermal system (E-EGS) regarding reservoir construction and heat extraction, identifying a critical bottleneck: D-EGS suffers from non-reproducible fractured reservoir construction due to its dependence on site-specific geology, while E-EGS overcomes this by creating universally adaptable caved thermal reservoirs through mining technologies. We further propose a groundbreaking Tiered Synergistic Mining of Geothermal Energy and Minerals (TSMGM) framework, which integrates conventional mining techniques with EGS to extract HDR and mineral resources simultaneously. By stratifying resources into low- (<50°C), medium- (50–100°C), and high-temperature (>100°C) stages, TSMGM facilitates sequential extraction of both geothermal energy and minerals, significantly reducing operational costs and environmental risks. Although the TSMGM confronts substantial scientific and technical barriers, its modular design and tiered temperature-gradient exploitation strategy may advance HDR energy commercialization and enable integrated multi-energy development, positioning TSMGM as a potential catalyst for global carbon neutrality efforts.

1. Introduction

Human survival and development are heavily reliant on the access and utilization of energy [1,2]. Historically, fossil fuels have dominated global energy consumption due to their abundant availability, accounting for 83.14 % of the world's energy consumption in 2020 [2]. However, the extensive utilization of carbon-intensive fossil fuels has escalated carbon emissions, exacerbating global warming and associated ecological challenges. Consequently, promoting the decarbonization of the energy structure and fostering clean energy development is imperative to mitigate the environmental impacts of greenhouse gas emissions [1,3,4].

Coal has long been the dominant energy source in China, primarily due to resource distribution and reserve limitations. Its contribution to China's energy structure exceeds the global average [2,5]. Fortunately, implementing the 12th Five-Year Plan has led to significant advancements in transforming and upgrading the coal industry. These advancements include various advanced technologies such as green and precision mining [6,7], simultaneous extraction of coal and gas [8], and simultaneous extraction of coal and geothermal energy [9,10]. These theories and technologies actively investigate the integrated mining of coal and its associated resources by leveraging their energy-saving attributes to reduce energy consumption in coal production, gradually promoting the coal industry towards diversification and low-carbonization [1,6,11]. The coal proportion in energy consumption (Fig. 1a) steadily declined from 77.8 % in 2011 to 66.6 % in 2023, with an average annual decrease of approximately 0.93 % [12]. Despite this significant reduction, an additional decrease of 3.5 billion tons in coal

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consumption is necessary to achieve peak carbon dioxide emissions by 2030 [1]. Coal is expected to transition from a dominant to a primary energy source in the consumption structure, facilitating industrial upgrading and eliminating outdated production capacities. Since implementing the 12th Five-Year Plan (Fig. 1a), the share of clean energy in total energy consumption has significantly risen from 13.0 % in 2011 to 26.4 % in 2023, reflecting an average annual growth rate of approximately 1.12 %. This increase parallels the corresponding annual decline in coal consumption. By 2030, clean energy sources are projected to offset the decline in coal consumption due to commitments aimed at peaking carbon dioxide emissions. This transition offers significant development opportunities while posing substantial challenges for the clean energy sector [1].

The primary forms of clean energy include wind, hydroelectric, solar, and nuclear power. Wind, hydroelectric, and solar energies are non-concentrated sources heavily influenced by geographical and climatic factors, complicating efforts to maintain a stable and continuous energy supply[13]. Identifying areas suitable for large-scale exploitation of these renewable resources is particularly challenging, as most accessible locations have already been utilized. Despite its unmatched energy density and baseline potential, nuclear power struggles with geopolitical and security barriers to widespread adoption [14]. Considering the current state of energy exploration technologies, clean energy options face significant challenges in effectively bridging the energy gap resulting from the gradual phase-out of coal energy [15]. Therefore, it is imperative to investigate alternative clean energy sources with potential large-scale commercial development. Compared to other renewable energy sources, deep geothermal energy boasts widely distributed and vast reserves, offering a stable and continuous energy supply unaffected by seasonal variations, climate conditions, and day-night cycles [16–18]. These characteristics highlight its significant development potential, positioning geothermal energy as a promising candidate for the ultimate transformation [18,19]. In recent years, geothermal energy has achieved vigorous development. The number of countries and regions utilizing geothermal resources increased from 28 in 1995–88 in 2023 (Fig. 1b). The installed capacity and direct utilization of geothermal energy rose from 8664 $\mathrm{MW_t}$ in 1995–189,514 $\mathrm{MW_t}$ in 2023 [20]. However, conventional hydrothermal resources are geographically restricted to tectonically active zones, while Enhanced Geothermal Systems (EGS), though promising for deep heat extraction, face commercialization barriers due to inconsistent performance in heterogeneous formations, inadequate stimulation techniques, and high development costs. These challenges ultimately limit geothermal energy's ability to serve as a scalable replacement for coal in the global energy transition.

Therefore, studying the operational mechanisms and development limitations of deep geothermal resources and enhanced geothermal systems is meaningful to promoting the commercial utilization of deep geothermal energy and bridging the energy gap resulting from reduced coal consumption for peak carbon dioxide emissions mitigation.

2. Geothermal energy

Geothermal energy primarily originates from the heat produced by solar radiation and the natural decay of radioactive substances within the earth's crust [21–23]. This energy is stored in rocks, fluids, and magma [24], which can be categorized into shallow geothermal energy, hydrothermal geothermal energy, and petrothermal geothermal energy (HDR geothermal energy) (Fig. 2). The total amount of geothermal energy available within the first 10 km below the earth's surface is estimated at approximately 1.3×10^{27} J, equivalent to about 4.42×10^{16} t standard coal, sufficient to meet global energy demands for roughly 6 million years [25]. Geothermal resources are remarkably abundant in China, particularly the deep geothermal resource, with a prospective quantity of 8.56×10^{14} t standard coal. Based on a resource extraction rate of 2 %, the exploitable amount is equivalent to approximately 17.12×10^{17} t standard coal, which is 2993 times the total energy consumption of 5.72×10^{14} t in 2023 [12].

2.1. Shallow geothermal energy

Shallow geothermal energy, stored within the first 200 m below ground level and at temperatures not exceeding 25°C, has become the most extensively utilized form of thermal energy through ground source heat pumps. These pumps are employed in various applications, including seasonal heating, building cooling, and other related purposes. By 2020, the cumulative installed capacity of ground source heat pumps reached 77,547 MWt, with an annual utilization amount of 599,981 TJ [26]. These figures represent 71.60 % and 59.20 % of the total installed capacity and utilization amount of geothermal energy, respectively [26]. China leads the utilization of shallow geothermal energy, with an estimated annual recoverable capacity equivalent to approximately 700 Mt of standard coal [27]. In 2020, its installed capacity and utilization amounts were 26,450 $\mathrm{MW_t}$ and 246,212 TJ, accounting for 34.1 % and 41.0 % of the global total [26].

2.2. Hydrothermal energy

Hydrothermal geothermal energy typically refers to the energy stored within natural groundwater and steam at depths ranging from 0.2 to 3 km. It is the most extensively utilized form of geothermal energy, directly employed by 82 countries globally and utilized for electricity generation in 26 countries [28,29]. From 2010–2015, hydrothermal geothermal resources experienced rapid growth, with direct utilization capacity increasing from 49.40 $\mathrm{GW_t}$ to 69.13 $\mathrm{GW_t}$ and electricity generation capacity increasing from 10.7 $\mathrm{GW_t}$ to 13.5 $\mathrm{GW_t}$ [29]. The

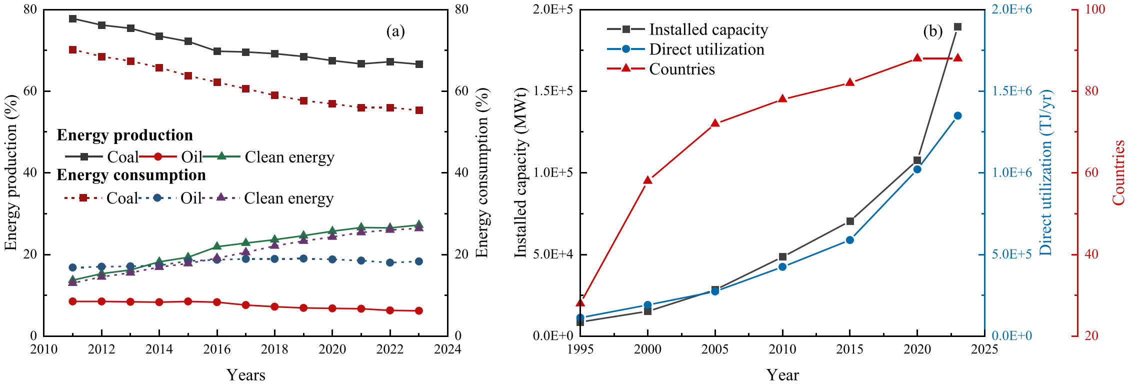

Fig. 1. Energy production and consumption in China and geothermal energy trends worldwide: (a) energy production and consumption in China since the 12th Five-Year plan, (b) the geothermal energy trends from 1995 to 2023.

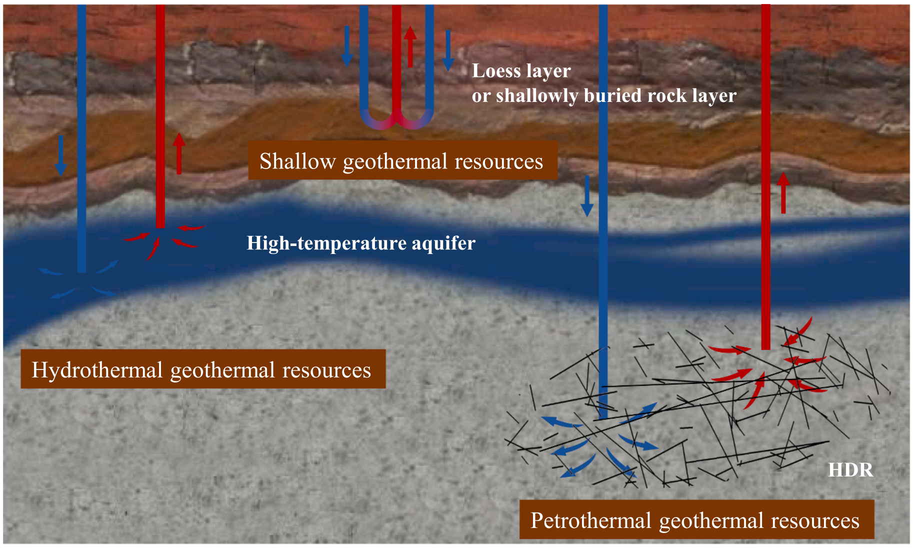

Fig. 2. Classification of geothermal resources.

hydrothermal geothermal resource in China is approximately 1.25 Tt of standard coal with an annual maximum recoverable amount of 1.865 Bt, considering reinjection requirements[27], resulting in a higher direct utilization than other countries. China is an early adopter of hydrothermal power generation, having initiated operations at Yangbajing in 1977. However, by 2020, its installed capacity had reached only 46.68 MW, which falls significantly short of the target set by the "13th Five-Year Plan" (500 MW) [27]. Moreover, hydrothermal geothermal resources present limitations in terms of geological reserves and regeneration rates, as well as comparatively low temperatures below 100℃, which results in limited opportunities for electricity generation [29]. Therefore, exploring innovative forms of geothermal resources is crucial to enhancing the power generation potential of geothermal energy. Among these alternatives, deep geothermal energy is considered an ideal option within the existing technological limitations.

2.3. *Petrothermal energy (deep geothermal energy)*

Petrothermal energy, called deep geothermal energy or HDR geothermal energy, is stored within solid rock formations at depths ranging from 3 to 10 km below the ground surface [30]. Its global distribution in regions of thermal anomalies presents exceptionally abundant reserves [30], surpassing hydrothermal resources by more than three orders of magnitude[24]. However, HDR geothermal reservoirs exhibit exceptionally high density and low permeability, posing significant energy extraction challenges [31]. The current viable approach for harnessing HDR energy involves implementing enhanced geothermal systems (EGS) to alter the thermal reservoir, aiming to achieve desirable permeability and fluid flow rates [32]. Despite its initiation in the 1980s and subsequent advancements over nearly five decades, the power generation capacity of HDR geothermal energy remains limited to a few megawatts. By the end of 2021, the cumulative installed HDR energy capacity worldwide was merely 37.41 MW [33]. This significant disparity between vast geothermal reserves and modest power generation highlights the substantial challenges in developing HDR geothermal resources [34,35].

Therefore, comparing the advantages and disadvantages of existing EGS and identifying the underlying factors that impede their large-scale exploitation is essential for exploring potential solutions and implementation strategies for HDR geothermal utilization.

3. Enhanced geothermal system

EGS are artificial geothermal systems that utilize engineering techniques to extract energy from HDR or low-permeability thermal reservoirs [36–38]. These systems include drilling-enhanced geothermal systems (D-EGS) (Fig. 3a) and excavation-enhanced geothermal systems (E-EGS) (Fig. 3b)[39].

3.1. *Classification of enhanced geothermal systems*

3.1.1. *Drilling-enhanced geothermal system (D-EGS)*

The D-EGS (Fig. 3a), the conventional enhanced geothermal system, primarily comprises injection wells, production wells, and thermal reservoirs created through fracturing technologies [40]. Its fundamental principle involves employing artificial enhancement techniques based on hydraulic measures, such as hydraulic stimulation, thermal stimulation, and chemical stimulation, to construct a high-temperature and low-permeability thermal reservoir[41]. Subsequently, a low-temperature working fluid is injected via the fractured network within the modified thermal reservoir for heat energy extraction and utilization [24,42].

The Los Alamos National Laboratory introduced the concept of employing D-EGS for mining HDR energy in 1970 and conducted a field application at Fenton Hill in 1973 [24]. This trial successfully

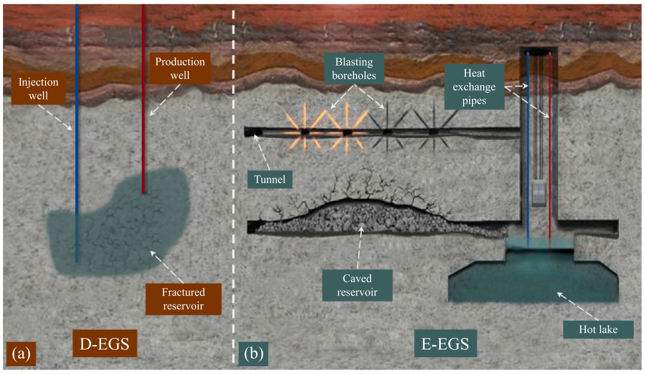

Fig. 3. Engineering models for different enhanced geothermal systems: (a) D-EGS and (b) E-EGS.

demonstrated the feasibility of D-EGS in extracting geothermal energy from HDR, significantly advancing related theoretical research and on-site engineering [34]. The development history of D-EGS can be divided into two stages: the research and development stage (1970–2000) and the demonstration stage (2000 to the present) (Fig. 4). Over the past 50 years, 44 engineering experiment projects have been implemented, yielding substantial research findings and valuable engineering experience [33,43–45]. Despite these advancements, commercial extraction of HDR geothermal energy has not yet been achieved, resulting in a cumulative installed power generation capacity of only 37.41 MW [33].

The complexity of reservoir geological conditions and the dependence of existing construction technologies on the in-situ geological environment presents significant challenges in developing a standardized model for replicating successful engineering experiences across different projects [34,46]. It is considered the primary constraint impeding HDR geothermal energy extraction commercialization based on D-EGS [22,33]. Variations in the geological conditions among different thermal reservoirs can result in a reconstructed reservoir quality lower than expected, leading to challenges such as limited reservoir capacity, insufficient heat exchange networks, significant working fluid losses, and notable risks of induced earthquakes [22,47]. Collectively, these disadvantages impede the development of D-EGS and can even lead to project suspension or termination in severe cases [34]. Fig. 5 illustrates the reasons behind the termination or suspension of 20 E-EGS projects. The primary cause for EGS termination is poor reservoir quality, which led to the closure of 7 E-EGS projects, accounting for 35.0 % of the total discontinued projects. The second most prevalent reason is seismic activity during reservoir construction, resulting in the suspension of 4 EGS projects, constituting 20.0 % of the overall projects. Drilling and fracturing accidents, inadequate funding policies, and other factors contribute to 15 % of the total project closures.

Moreover, there remains a significant limitation in the power generation scale of D-EGS. The average installed capacity for power generation per individual well in the operational Soultz project is approximately 500 kW [33,34]. Based on this benchmark, several thousand drilled wells would be necessary to fulfill the power demand of a prefectural-level city. In 2021, Beijing's total electricity consumption was 135.8 billion kW·h [12], corresponding to the need for approximately 31,003 geothermal wells if D-EGS were to supply all the electricity. It would require an estimated investment of 800 billion Chinese Yuan (CNY) (assuming a cost of 30 million yuan per well). Additionally, drilling a geothermal well every 0.5 square meters across Beijing (its area of 164,110 km^2) presents logistical and environmental challenges that make such extensive construction and elevated engineering costs unfeasible. Thus, it necessitates ongoing research and investment in D-EGS for thermal reservoir construction, seismic control, and power generation scalability to significantly advance the key technologies essential for the extensive extraction of HDR geothermal energy.

3.1.2. Excavation-enhanced geothermal system (E-EGS)

The E-EGS was introduced in 2016 to establish a scalable and replicable scheme for extracting HDR geothermal energy by leveraging the mining industry's extensive expertise and technical advantages [39,48]. After more than a hundred years of development, mining technology has developed construction techniques and equipment systems capable of operating in various complex geological environments. It can overcome geological limitations to construct mining systems that ensure the safe extraction of target minerals across most geological conditions. Consequently, E-EGS, utilizing mining technology, can reduce reliance on specific geological conditions and fracture characteristics, thus establishing a dependable and replicable approach for thermal reservoir construction.

The E-EGS comprises vertical wells, tunnels, pipelines, and thermal reservoirs formed through controlled blasting and caving processes (Fig. 3b). Its fundamental principle of thermal energy extraction involves constructing thermal reservoirs using mining-based techniques to enhance permeability and fluid flow rate, thereby facilitating heat exchange to extract HDR thermal energy. However, there are essential differences between E-EGS and D-EGS regarding reservoir construction and energy extraction. While D-EGS employs hydraulic fracturing measures to construct thermal reservoirs and extracts heat energy via fracture networks within the reservoir, E-EGS forms thermal reservoirs through mining-based techniques such as excavation, blasting, and caving, and harvests thermal energy using fracture networks, artificial heat lakes, and U-shaped heat exchange pipes. We will compare the benefits and drawbacks associated with D-EGS and E-EGS concerning thermal reservoir construction and heat energy extraction in Section 3.2.

3.2. Thermal reservoir construction

The construction quantity of the EGS thermal reservoir plays a pivotal role in determining the reservoir volume, effective heat exchange area, and system resistance, thereby dominating its heat extraction performance. The outlet temperature increases with the enlarged thermal reservoir and associated heat exchange area, and the fluid rate grows as the fracture resistance decreases during the EGS operation. Therefore, a commercially viable thermal reservoir must satisfy various indicators, such as adequate volume, a sufficient heat exchange area, and a stable fracture network with low fluid resistance, to achieve large-scale exploitation of HDR thermal energy [34,49,50].

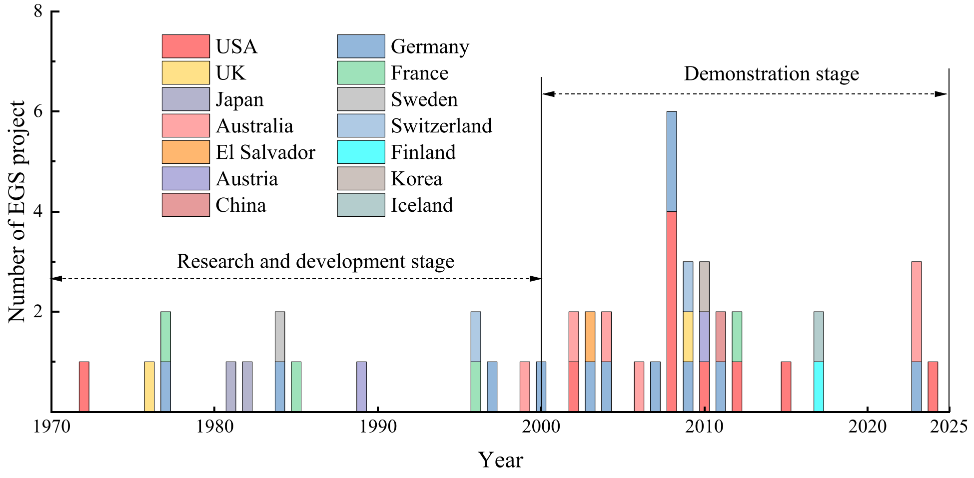

Fig. 4. Development history of D-EGS projects worldwide (after Kang et al.[33]).

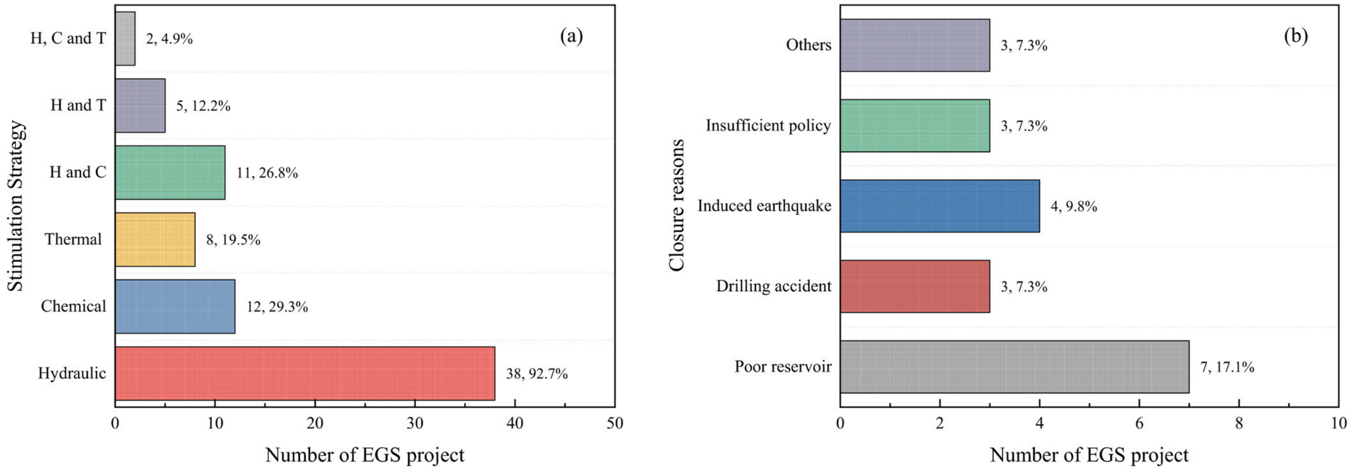

Fig. 5. Stimulation method and suspending reasons of EGS projects: (a) the stimulation method of EGS projects (H, T, and C denote the hydraulic, thermal, and chemical stimulations, respectively), (b) the closure reasons of EGS projects (after Kang et al.[33]).

3.2.1. Fractured thermal reservoir of D-EGS

The reservoir in D-EGS is constructed through hydrofracturing technology, resulting in a fractured thermal reservoir. The fracturing outcome is influenced by the interaction of multiple factors, including reservoir structure, natural fracture characteristics, and in-situ stress fields. Achieving the desired scale and distribution characteristics by controlling fracture initiation and propagation presents a significant challenge. The working fluid is introduced and circulated within the thermal reservoir under specific injection pressure to facilitate heat exchange[51]. Inadequate injection pressure may result in fracture closure due to crustal stress, thereby impeding fluid flow rates. Conversely, excessive injection pressure can lead to unwanted fracture expansion, which may increase fluid loss or even trigger seismic activity [41,52,53]. Consequently, while a limited number of D-EGS projects have achieved the desired power generation by leveraging high-quality fractured thermal reservoirs and implementing efficient fluid circulation systems through continuous reservoir fracturing, reproducing these successful engineering practices in other projects presents a significant challenge [19,34].

3.2.2. Caved thermal reservoir of E-EGS

The caved thermal reservoir in E-EGS is created by mining-based technology utilizing the block caving method [39,48]. Due to in-situ stresses, the rock mass undergoes continuous processes, including damage, cracking, breaking, and collapsing. Ultimately, the caved rock blocks fulfill the pre-excavated compensation space to achieve relative stress equilibrium, forming a unique thermal reservoir composed of broken rock blocks (Fig. 6)[54,55]. The cavability of the rock mass and the volume of the collapsed block primarily rely on the geological characteristics and caving engineering parameters. It is feasible to obtain the expected heat reservoir scale and rock block size by investigating the volume variation of the caved block under different geological conditions and engineering parameters in E-EGS [56–59]. The interweaving interstices between collapsed rock blocks form the heat exchange channels within the caved geothermal reservoir, which exhibit higher permeability and stability than fracture reservoirs.

The high-temperature environment during thermal extraction accelerates the damage and failure of the rock mass by hastening the caving process and expanding the reservoir boundary, resulting in a broader collapsed thermal reservoir space [60]. Furthermore, mining technology for caved reservoir construction offers greater safety measures than fractured reservoirs. It employs close-range geophysical exploration techniques in conjunction with tunnel engineering, effectively mitigating the impact of abnormal geological structures and minimizing the risk of induced seismic activity[39].

3.3. Geothermal energy extraction

3.3.1. Principle of geothermal energy extraction

The extraction of thermal energy in EGS depends on heat exchange pathways, which consist of the fracture network in D-EGS and the interstice network in E-EGS. A low-temperature fluid is continuously circulated through these networks to facilitate efficient heat transfer with the high-temperature rock mass, thus harnessing the geothermal energy stored within [61]. Due to their higher permeability, The heat transfer fluid preferentially flows along fractures or interstices during thermal energy extraction. The process gradually connects fractures and matrix mass, forming preferential paths throughout the thermal reservoir. The low-temperature working fluid primarily exchanges heat with the surrounding rock mass near these preferential channels, resulting in increased fluid overpressure within the channels and cooling contraction of the surrounding rock. This phenomenon further enhances the aperture of the preferential channels and associated heat exchange efficiency[62,63], consequently promoting fluid flow and heat exchange in the channel areas while suppressing other areas[64,65]. As a result, the heat extraction capacity of EGS becomes reliant on the surrounding rock mass near preferential channels [66].

At the initial stages of operation, the preferential channel does not significantly affect heat extraction performance at the initial operation, resulting in comparable or even slightly improved extraction

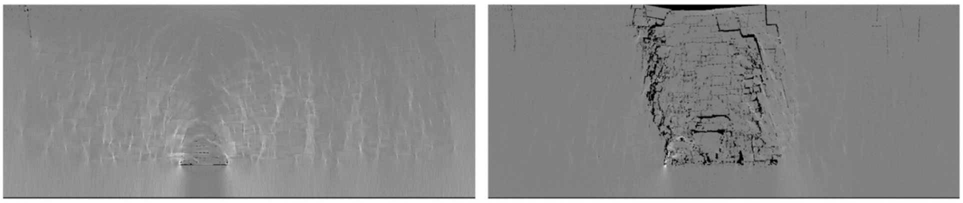

Fig. 6. The zoning model for coal mining-induced strata movement (after Li et al. [48]).

efficiency [67]. However, the rock temperature around preferential channels sharply decreases due to the limited heat exchange area, resulting in thermal breakdown and a sharp decline in outlet water temperature [34,68]. Such preferential channel effect is closely related to the heat exchange network of thermal reservoirs. A more complex network creates longer preferential paths, which weakens the preferential path effect, thereby postponing the thermal breakdown and enhancing long-term thermal energy extraction efficiency.

3.3.2. *Comparison of thermal energy extraction efficiency*

The heat extraction capacity of D-EGS is reliant on the fracture network formed by hydraulic stimulation. This stimulation typically initiates and propagates along weak areas within the rock mass with acceptable permeability, creating a primary fracture accompanied by numerous secondary fractures. The low-temperature working fluid rapidly flows through the thermal reservoir, following the primary and interconnected secondary fractures, forming preferential channels. While most D-EGS exhibit acceptable short-term heat extraction performance at the early stage, their long-term efficiency is often poor due to thermal breakdown induced by the preferential channel effect, which constitutes the primary reason for the closure of D-EGS systems [34]. The thermal reservoir of E-EGS is constructed from collapsed rock blocks, resulting in a heat exchanger area composed primarily of interstices between caved rock blocks. Adjusting engineering parameters such as blasting and drilling techniques makes it feasible to control the distribution of collapsed blocks and achieve uniformly dispersed void spaces. The working fluid flows along these evenly distributed interstices, creating multiple preferential channels. It significantly increases the effective heat exchange area and postpones thermal breakdown, ultimately providing a more stable long-term thermal energy extraction efficiency than D-EGS.

Fig. 7 presents a comparative analysis of the long-term heat extraction efficiency among three distinctly modified thermal reservoirs: a caved reservoir, a fractured reservoir, and a fractured reservoir augmented with connected fractures. The numerical model shown in Fig. 7a~c is a rectangle with a length of 1000 m, a width of 400 m, and thus a reservoir area (S) of 4.0×10^5 m^2. The fluid is injected from the left boundary (AB) at a constant mass flow rate (M_f=0.01 kg/s) and discharges from the right boundary (CD) after flowing through the reservoir with the impermeable upper (BC) and lower boundaries (AD). The upper (BC) and lower boundaries (AD) are constant temperature constraints at 200℃, whereas the left (AB) and right boundaries (CD) are thermal-insulated. Fig. 7b illustrates that the caved thermal reservoir consistently demonstrates the highest extraction efficiency, surpassing 4000 GJ/a over 30 years. Notably, during the initial six years of operation, the efficiency of the standard fractured reservoir aligns closely with that of the caved reservoir and even briefly exceeds it. However, its performance experiences a significant decline after this period, yet it continues to outperform the fractured reservoir with interconnected fractures throughout the observed timeframe. Initially, this latter configuration exhibits a marked increase in extraction efficiency compared to the caved and simple fractured reservoirs. Nonetheless, its efficiency undergoes a rapid, negative exponential decrease, falling below that of the other reservoir models within just three years of operation. These findings underscore the distinct benefits of the caved reservoir design in sustaining enhanced long-term heat extraction performance in geothermal energy systems[69].

3.4. *Bottleneck and breakthrough of EGS*

The D-EGS is primarily hindered by the lack of replicable geothermal reservoir construction technologies and the sub-megawatt-level power generation capacity per well. These issues necessitate attention in future scientific research and engineering applications. Current mitigation strategies in engineering practice focus on reducing permeability contrasts and increasing high-permeability channels to maximize effective heat-exchange surface area. While existing stimulation methods and power cycles (e.g., CO_2 [70], supercritical CO_2 [71–73], and nanofluids [74,75]) can temporarily improve heat transfer efficiency in dominant channels[76], they demonstrate limited long-term enhancement of thermal extraction efficiency. Fortunately, the ORGE program (Frontier Observatory for Research in Geothermal Energy), led by the US Department of Energy, aims to establish a replicable and classical technology for enhanced geothermal systems [77]. The program focuses on cutting-edge technologies for characterizing, constructing, and monitoring geothermal reservoirs [78,79]. Cutting-edge investigations at the Utah FORGE project have yielded critical advancements in machine learning-optimized well geometries[80], fracture monitoring via distributed acoustic sensing [81], and seismic risk mitigation strategies [82]. These developments contribute critical insights to improve EGS efficiency and operational safety.

Additionally, the DEEPEGS project, a collaborative effort among multiple countries in the European Union, seeks to exploit deeper and hotter geothermal resources while enhancing the power generation capacity of single wells. Currently underway, the Reykjanes project in Iceland is expected to achieve a power generation capacity of 30 MW per well [83,84]. The E-EGS project also faces multiple challenges, including

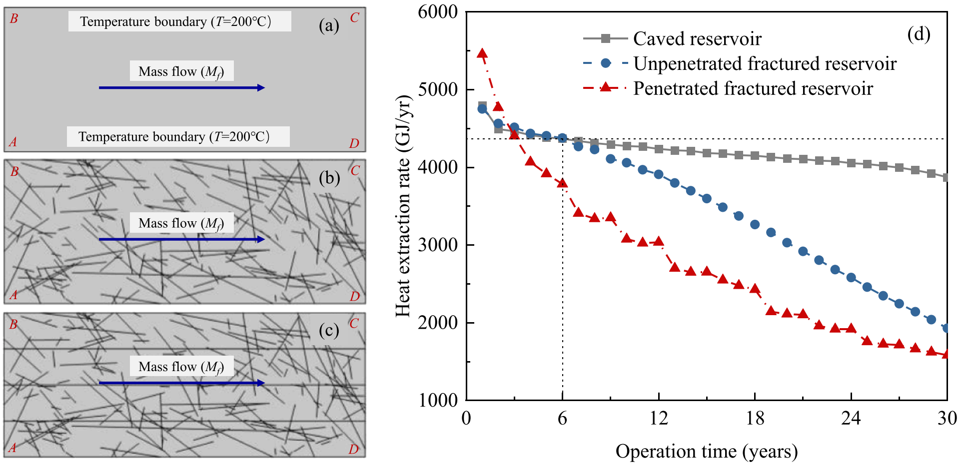

Fig. 7. Different reconstructed thermal reservoirs and their heat energy extraction efficiency: (a) caved reservoir with a rock permeability of 1E-14 m^2, (b) unpenetrated fractured reservoir with a rock permeability of 1E-18 m^2 and fracture aperture of 1E-4 m, (c) penetrated fractured reservoir with a rock permeability of 1E-18 m^2 and fracture aperture of 1E-4 m, and (d) heat energy extraction efficiency of different reservoirs (after Li et al.[69]).

prolonged construction timelines requiring continuous financial and personnel investments and unprecedented scientific and engineering difficulties due to high-temperature and high-pressure environments. The need to construct large-diameter vertical shafts and extensive tunnel projects significantly extends the construction period, necessitating consistent funding and personnel allocation. The exceptionally high-temperature and high-pressure conditions within the E-EGS also present unique scientific and engineering challenges that demand substantial financial, human, and time resources.

Therefore, it is impractical for E-EGS to replace D-EGS in the short term or achieve commercial extraction of HDR geothermal energy. Instead, long-term financial investments and sustained research efforts are necessary. One potential strategy for advancing E-EGS involves collaborating with the mining industry, leveraging existing engineering technologies, expertise, and talent from shallow mining areas to research high-temperature and high-pressure environments [9,10]. The tiered synergistic mining of geothermal energy and minerals (TSMGM) presents a feasible solution for developing E-EGS under this strategy [7, 8].

4. Geothermal and mineral resources gradient mining system

4.1. Geothermal and mineral resources gradient mining system

The TSMGM is a co-mining approach proposed to address the challenges faced in deep mineral mining due to high-temperature and high-pressure conditions, intending to reduce associated costs [85]. Building on the E-EGS framework, TSMGM classifies geothermal and mineral resources into low-temperature, medium-temperature, and high-temperature categories based on rock mass temperature. It proposes targeted thermal mineral collaborative mining plans, namely mineral mining, heat and mineral co-mining, and heat mining models (Fig. 8).

4.1.1. Mineral mining in the first temperature stage

In the first temperature stage, rock temperatures remain below 50°C. Mineral resources are primarily located in shallow to middle geological depths, where most operating and abandoned mines are situated. Conventional mine cooling technologies, such as ventilation and refrigeration, are employed to maintain environmental temperatures within safe limits, ensuring the secure extraction of mineral resources during this stage. The benefits brought by the rock temperature are insufficient to support the extraction of geothermal resources. Consequently, a low-temperature mineral mining model is adopted in this stage, combining traditional thermal hazard prevention technologies with mineral mining methods to prevent hazards and effectively extract mineral resources. It is essential to emphasize that experimental engineering to extract thermal energy from rock masses should be carried out in mines with high rock temperatures, typically exceeding 40°C. These efforts can expedite the development of thermal energy extraction systems and reduce the research and development time needed for higher-temperature applications.

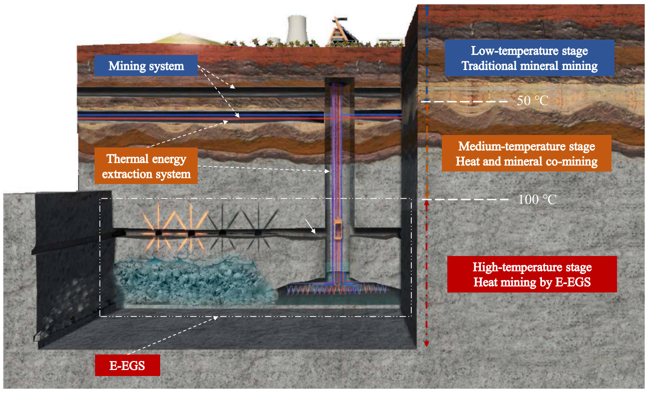

Fig. 8. The tiered synergistic mining of geothermal energy and minerals.

4.1.2. Heat and mineral co-mining in the second temperature stage

The upper limit temperature for the rock mass in the second stage is set at the water vaporization temperature at atmospheric pressure, which is 100°C. This threshold surpasses that required for geothermal resources, enabling the direct utilization of thermal energy across various fields via extraction systems. However, increasing rock temperature substantially raises cooling costs and difficulties through conventional technologies, potentially exceeding reasonable expenses for thermal hazard prevention in mineral mining. Therefore, we propose the thermal and mineral co-mining approach in this stage. This method initially extracts the geothermal energy within the mineral resource, followed by conventional mining techniques once the temperature has decreased to a manageable level. The co-mining approach enhances thermal energy extraction at medium temperatures while simultaneously reducing the temperature of mineral resources to levels suitable for conventional mining. This dual benefit improves overall mining efficiency by effectively lowering cooling costs and increasing the accessible reserves of mineral resources.

4.1.3. Heat mining in the third temperature stage

At the third temperature stage, rock temperatures exceed 100°C as mining depth increases. The elevated temperature diminishes the grade of most mineral resources and complicates maintaining a safe working environment, making long-term mineral extraction impractical. However, this temperature reaches the threshold suitable for power generation through large-scale geothermal energy extraction. Therefore, the heat mining method utilizing the E-EGS, which focuses solely on extracting deep geothermal energy, is appropriate for thermal resource mining at this temperature stage. By leveraging existing infrastructure from shallow and medium-stage mining operations, the E-EGS thermal reservoir and associated engineering can be built at an acceptable cost, enabling commercial-scale extraction of high-temperature geothermal energy.

In summary, the TSMGM, integrating traditional mining techniques with enhanced geothermal systems, presents substantial advantages by mitigating thermal hazards in low to medium-temperature zones. It ensures the safe extraction of mineral resources while facilitating harnessing geothermal energy in medium to high-temperature regions[85]. The escalating costs associated with elevated temperatures encountered during mineral resource exploitation are counterbalanced by tapping into medium and high-temperature geothermal sources. Concurrently, the substantial investments required for deep geothermal development are alleviated by exploiting mineral deposits in cooler temperature domains concurrently. The TSMGM offers a viable solution for collaboratively mining geothermal and mineral resources, thereby facilitating the advancement and transformation of mining industries. Among various mining sectors, the coal industry in China demonstrates the highest potential for transitioning to co-mining thermal resources.

4.2. Transformation advantage of the coal mining industry

By the end of 2022, there were 16 mines globally with a mining depth exceeding 3000 m, reaching a maximum depth of 4350 m and a peak rock temperature surpassing 80°C [86]. As mining depth increases, thermal hazards become a critical challenge constraining safe extraction operations. This issue is compounded by the need for increasingly complex and costly prevention measures [9]. In China, the depth of mines has been increasing steadily at an annual rate of 8–20 m/a [86], resulting in 22 mines with depths over 1200 m and the highest rock temperatures exceeding 50°C [9]. These rock temperatures are suitable for investigating thermal energy extraction during low to medium-temperature stages using TSMGM technology. The mining industry provides essential mining technologies, engineering sites, and human resources to support the rapid development of TSMGM [85]. Given its extensive history and pressing transformation needs in response to low-carbon emission requirements, the coal industry is uniquely positioned to significantly aid this transition from conventional coal mining to co-mining coal and heat via TSMGM.

4.2.1. Advantages in technologies and engineering

The depth range of 0–2000 m for coal resources corresponds to the initial two stages of TSMGM (Fig. 9). Most coal mines are located within the first temperature stage, providing ample opportunities for research and experimental sites for developing low-temperature geothermal extraction systems. These systems are subsequently refined and validated through applications in medium-temperature coal mines, ultimately contributing to the establishment of theoretical frameworks and construction technologies necessary for efficiently utilizing both low and medium-temperature geothermal resources [87].

4.2.2. Advantages in underground space

Numerous coal mines are expected to cease operations or permanently close in response to carbon reduction and safety governance requirements, leading to approximately 15,000 abandoned mines and 138 million cubic meters of underground space by 2030 in China [88,89]. These vacant underground spaces will gradually be inundated with surface water, pressurized water, and other sources, creating substantial underground reservoirs with stable temperatures suitable for thermal energy utilization in seasonal heating and cooling applications. The deserted mining areas can also function as deep in-situ experimental sites equipped with operational systems for ventilation, transportation, and other essential infrastructure. This arrangement facilitates comprehensive experimental research on in-situ rock and fluid mechanics, thereby advancing technical and theoretical frameworks for TSMGM [1,90].

4.2.3. Advantage in talent reserve

As of the end of 2020, China’s coal industry had a talent reserve of 3.47 million people, supporting stable and safe operations within coal mines and associated industries [91]. However, the push for reduced coal production capacity driven by low-carbon requirements inevitably leads to job cuts in coal enterprises, presenting challenges to the coal industry and social stability. One potential solution is to form a dedicated team for the geothermal energy industry by repurposing some of the existing expertise from the coal sector. This approach could enhance the personnel reserves in geothermal extraction and capitalize on their technical and construction experience to develop geothermal extraction projects.

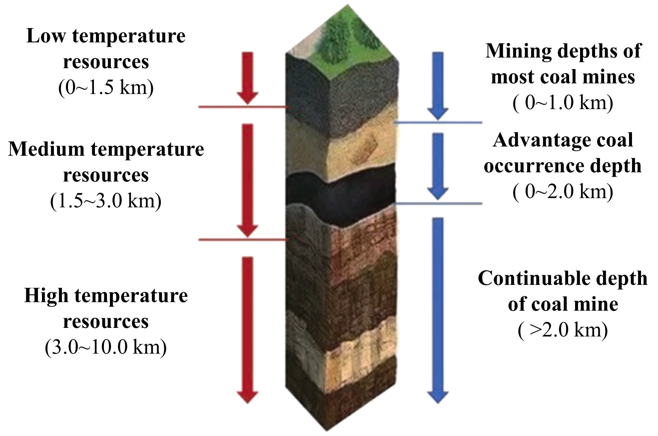

Fig. 9. The occurrence status of coal and geothermal resources (after Guo et al# [87]).

In summary, the coal industry’s transformation creates a pivotal opportunity to harness deep geothermal energy at scale. This transition provides essential technological and professional talent support crucial for advancing key technological challenges, foundational engineering infrastructure, and the skilled workforce, thereby effectively accelerating the rapid progression of TSMGM. Moreover, this model demonstrates global replicability beyond China, particularly in the US, where abundant abandoned mines, mature geothermal supply chains, and a skilled workforce synergistically support combined geothermal-mineral extraction [92]. Such alignment positions TSMGM as a scalable solution for worldwide post-coal energy transitions.

5. Critical scientific issues in for extracting deep geothermal resources

As mining activities extend to greater depths, the challenges posed by high stress and permeability pressure in deep rock formations intensify, which complicates the extraction of deep-seated mineral resources, the construction of support shafts and tunnels, and the mitigation of dynamic hazards [8,90,93–95]. The high-temperature conditions encountered during deep geothermal mining further exacerbate operational complexities and disaster prevention efforts [96,97].

The current theoretical framework for traditional mineral resource mining is becoming obsolete and may even be overturned. Developing new theories, methods, and technologies suitable for extracting deep resources in high-temperature and high-pressure environments is imperative. Thus, refining the fundamental scientific issues and conducting focused scientific investigations and engineering experiments are critical prerequisites for addressing key engineering and technical challenges in achieving large-scale exploitation of HDR geothermal energy (Fig. 10).

5.1. Mechanical properties and damage mechanism of rock mass under high-temperature and high-pressure environment

Rock masses’ mechanical properties and damage mechanisms in high-temperature and high-pressure environments are closely intertwined with numerous aspects of deep underground engineering. These include the excavation and support of shafts and tunnels, the construction of thermal reservoirs, the blasting and caving of rock masses, and the prevention of dynamic disasters during mining activities. Consequently, understanding these phenomena is a fundamental scientific issue for extracting deep geothermal energy resources. Recent advances in the field demonstrate that rock masses subjected to high-temperature and high-pressure environments exhibit significantly altered mechanical behaviors characterized by structural modifications such as thermal-induced microcracking and progressive strength deterioration[98,99]. Comprehensive energy-dissipation analyses have further elucidated the mechanisms behind fracture network development under coupled thermo-mechanical loading conditions[100]. However, significant scientific challenges remain unsolved, particularly regarding (1) the anisotropic damage evolution resulting from mineralogical heterogeneity[101], (2) the development of robust constitutive models that can accurately simulate long-term thermo-mechanical-creep interactions [102], and (3) the prediction of dynamic permeability evolution that critically affects reservoir integrity[98]. These fundamental research findings provide essential theoretical foundations for optimizing hydraulic fracturing strategies and ensuring long-term wellbore stability in enhanced geothermal systems[103,104], while also highlighting critical knowledge gaps that require further investigation.

5.2. Flow and heat transfer mechanism of multiphase media under high-temperature and high-pressure environment

Flow and heat transfer characteristics in thermal reservoirs are pivotal to geothermal systems’ performance and operational longevity.

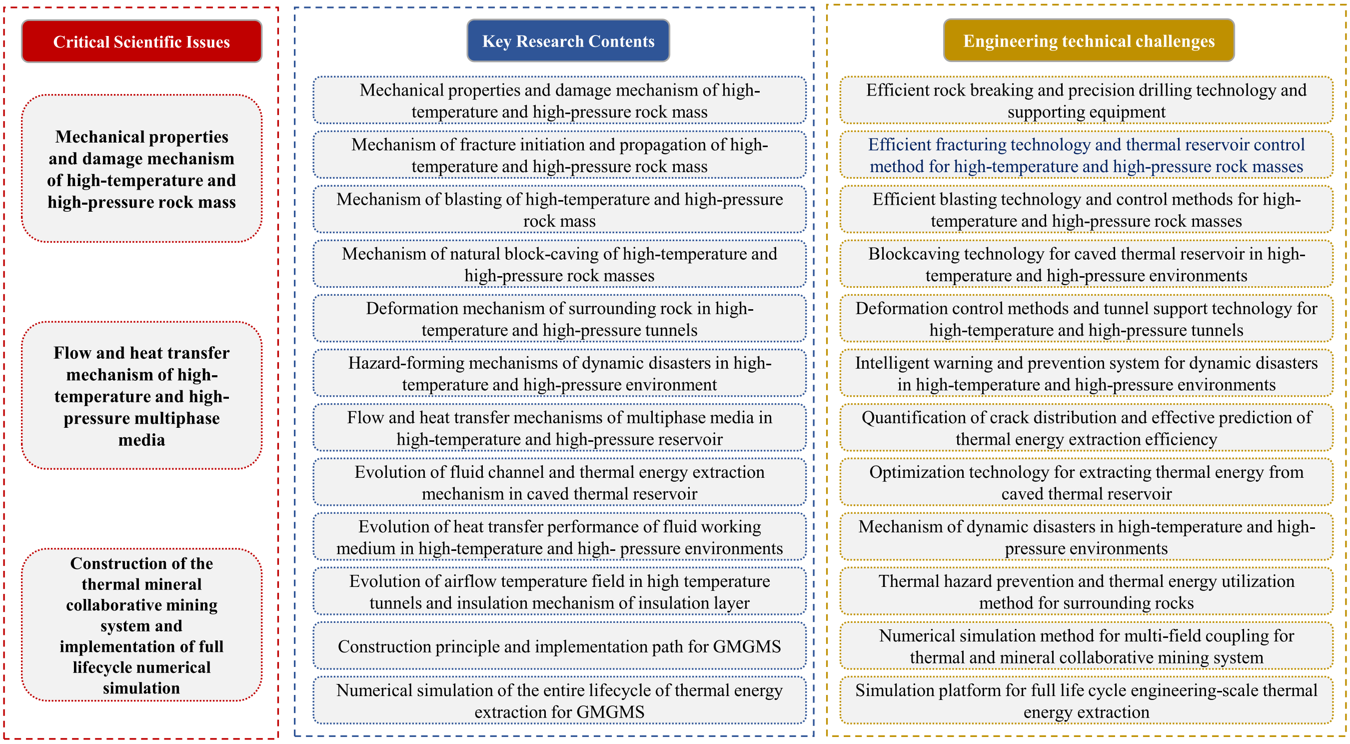

Fig. 10. Key scientific issues and engineering technical challenges during deep geothermal energy extraction.

Therefore, comprehending the mechanisms underlying flow and heat transfer in multiphase media under high-temperature and high-pressure conditions is a fundamental scientific issue in deep geothermal exploitation. Contemporary research on multiphase flow and heat transfer in high-temperature and high-pressure environments has progressed significantly, particularly in understanding thermo-hydro-mechanical-chemical (THMC) coupling processes governing fluid-rock interactions, including the enhanced numerical frameworks for THMC simulations[105] and experimental investigations of phase behavior and interfacial dynamics in supercritical hydrothermal systems[106]. However, persistent challenges remain in (1) fully characterizing multiphase flow instabilities under extreme conditions [107], (2) predicting long-term material degradation[108], and (3) scaling laboratory findings to field applications. These insights are crucial for optimizing fracture-controlled heat extraction in enhanced geothermal systems (EGS), paving the way for sustainable deep geothermal energy exploitation.

5.3. *Construction and implementation of full lifecycle simulation for co-mining system*

The third pivotal scientific issue in deep geothermal mining involves the development of a comprehensive lifecycle model for collaborative mining systems [92]. It includes investigating the coordination mechanisms between thermal and mineral co-mining engineering and assessing their impact on the performance of thermal energy extraction. Current literature reveals a notable scarcity of studies addressing this subject, highlighting its potential as a critical research frontier in subsequent investigations.

6. Discussion and conclusions

As decarbonization accelerates the adoption of clean energy, deep geothermal resources emerge as a strategic frontier. E-EGS addresses the geological and scalability limitations of traditional D-EGS, enabling standardized, large-scale deployment.

The TSMGM provides an integrated solution for combined mineral and geothermal resource development by implementing temperature-adaptive mining strategies. Its innovative coupling of shallow mining with deep geothermal extraction presents an efficient pathway for E-EGS implementation while boosting overall energy yield.

The substantial compatibility between coal mining and geothermal extraction in resource distribution and operational continuity enables the TSMGM to effectively utilize the coal industry's existing assets and skilled personnel during its energy transition.

Deep geothermal energy extraction faces unresolved scientific and technical hurdles, requiring sustained research and innovation. Addressing these challenges through foundational and cutting-edge studies is vital to unlocking commercial-scale deployment of deep geothermal resources worldwide.

CRediT authorship contribution statement

Fangchao Kang: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Chun'an Tang:** Writing – review & editing, Resources, Project administration, Methodology, Conceptualization. **Yingchun Li:** Writing – review & editing, Resources, Methodology, Formal analysis, Conceptualization. **Tianjiao Li:** Methodology, Investigation, Formal analysis, Data curation. **Wendi Zhang:** Methodology, Investigation, Formal analysis, Data curation. **Chongchong Cai:** Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

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

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