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Research Article

Integrated Theoretical and Numerical Perspectives on Geothermal Energy Extraction, Heat Transfer, and Deep Mining Systems: Advances, Mechanisms, and Multidisciplinary Implications

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Abstract

The progressive deepening of mining activities and the global pursuit of low-carbon energy systems have converged to position mines not only as sites of resource extraction but also as complex subsurface energy systems. In recent decades, increasing attention has been directed toward understanding geothermal energy extraction from mines, the coupled thermal–hydraulic–mechanical behavior of fractured rock masses, and the integration of heat management with mine safety and sustainability. This study develops a comprehensive, publication-ready synthesis and original analytical framework grounded strictly in recent and foundational literature on mine geothermal systems, underground heat transfer, backfill-based thermal storage, enhanced geothermal systems, fracture evolution, and in situ subsurface investigation technologies. Drawing on numerical modeling studies, case-based analyses, and theoretical advancements reported across mining science, geothermal engineering, and deep Earth exploration research, the article systematically elaborates on life-cycle thermal responses of mine geothermal systems, the role of groundwater flow, fracture evolution, non-Darcy flow effects, and the synergetic design of geothermal wells and backfill heat exchangers. Special emphasis is placed on how geological controls, mining-induced structural evolution, and engineered interventions such as phase-change heat storage backfill and multi-branch geothermal wells collectively influence energy extraction efficiency and thermal hazard mitigation. The methodological approach integrates conceptual modeling, numerical simulation paradigms, and interpretative analysis of reported case studies, avoiding mathematical formalism while offering deep theoretical interpretation. Results are discussed in terms of emergent patterns across different geological and operational contexts, highlighting how heat transfer pathways evolve dynamically with mining progression and backfill deployment. The discussion critically evaluates limitations in current modeling assumptions, scale effects, and uncertainties related to fracture characterization, while also connecting mine geothermal research with broader developments in deep Earth coring, gas hydrate exploration, and subsurface energy storage. By synthesizing these domains, the article advances a holistic perspective on mines as engineered geothermal systems embedded within complex geological environments. The findings contribute to both academic understanding and practical design strategies for sustainable energy recovery, mine safety enhancement, and the long-term utilization of deep subsurface space.

Keywords: Mine geothermal systems; underground heat transfer; fracture evolution; geothermal energy extraction; deep mining; thermal management; backfill heat storage

INTRODUCTION

The continuous increase in global energy demand, coupled with mounting pressure to decarbonize energy systems, has intensified interest in geothermal resources that were previously considered marginal or auxiliary. Among these, mine geothermal systems have emerged as a particularly promising yet complex category, owing to their unique integration of anthropogenic voids, fractured rock masses, groundwater circulation, and engineered infrastructures. Deep and ultra-deep mining operations generate extensive underground spaces that fundamentally alter the natural thermal regime of the subsurface. These alterations, once viewed primarily as hazards in the form of heat stress and ventilation challenges, are now increasingly recognized as opportunities for geothermal energy extraction and underground heat utilization (Li et al., 2025; Xu et al., 2023).

Historically, the study of underground heat in mines was motivated by occupational safety concerns, focusing on predicting thermal environments in ventilation roadways and mitigating heat hazards for miners. Numerical prediction of mine thermal environments has thus been a long-standing research topic, with models evolving from simplified analytical approaches to sophisticated three-dimensional numerical simulations that incorporate airflow, rock heat conduction, groundwater convection, and operational heat sources (Xu et al., 2023). However, the paradigm has gradually shifted from mere hazard control to energy recovery and sustainability, particularly as mining depths increase and geothermal gradients become more pronounced.

The transformation of mines into geothermal systems is not trivial. Unlike conventional geothermal reservoirs, mines are characterized by highly heterogeneous fracture networks, mining-induced voids, evolving stress fields, and complex hydrogeological conditions. Groundwater flow, in particular, plays a dual role: it acts as a heat carrier that can enhance geothermal energy extraction, while simultaneously introducing uncertainties related to flow pathways, non-Darcy behavior, and thermal breakthrough (Li et al., 2025; Xie et al., 2024). Furthermore, the geological context, including lithology, fault structures, and regional tectonics, exerts strong control over deep geothermal anomalies, as demonstrated in site-specific studies such as those conducted in the Qianjiaying Mine in China (Yang et al., 2020).

In parallel with geothermal exploitation, deep mining research has advanced significantly in understanding fracture evolution, strata movement, and overburden behavior. Mining-induced fractures not only govern ground stability and surface subsidence but also critically influence heat transfer pathways and geothermal performance (Zhu et al., 2022; Zhao et al., 2024). The progressive caving of goafs, the evolution of fracture networks, and the interaction between filled and unfilled voids collectively shape the thermal and hydraulic behavior of the subsurface over the life cycle of a mine (Lu et al., 2024).

Recent studies have proposed innovative engineering solutions that integrate geothermal energy extraction with mine safety and environmental protection. These include multi-level and multi-branch geothermal well systems designed to synergistically exploit geothermal energy while preventing heat hazards (Li et al., 2025), as well as backfill-based heat exchangers that incorporate phase-change materials to enhance thermal storage and extraction efficiency (Zhang et al., 2020; Ning et al., 2025). Such approaches reflect a broader trend toward multifunctional mine design, where waste materials, backfill, and abandoned voids are repurposed as components of an underground energy system.

Despite these advances, significant knowledge gaps remain. Existing studies are often site-specific, focusing on particular mines, geological settings, or technological configurations. There is a lack of integrative theoretical frameworks that connect life-cycle mine evolution, fracture mechanics, groundwater dynamics, and thermal processes into a coherent understanding of mine geothermal systems. Moreover, methodological challenges persist in accurately characterizing in situ conditions at depth, including temperature, pressure, stress, and fluid properties. Developments in in situ coring and pressure-preserving sampling technologies in deep Earth and gas hydrate research highlight both the possibilities and the current limitations of subsurface investigation (Xie et al., 2020; Li et al., 2021).

This article addresses these gaps by developing a comprehensive, theory-driven synthesis of mine geothermal research grounded strictly in the provided literature. Rather than summarizing individual studies, it elaborates in depth on the underlying mechanisms, conceptual linkages, and broader implications of geothermal energy extraction and heat transfer in mining environments. By integrating insights from geothermal engineering, mining geomechanics, thermal science, and deep Earth exploration, the study aims to advance a holistic understanding of mines as dynamic geothermal systems and to identify directions for future research and practical implementation.

METHODOLOGY

The methodological approach adopted in this study is fundamentally integrative and interpretative, reflecting the complex, multidisciplinary nature of mine geothermal systems. Rather than relying on original field experiments or numerical simulations, the research develops an original analytical framework through systematic theoretical elaboration and critical synthesis of existing studies. All methodological insights are derived strictly from the referenced literature, ensuring conceptual fidelity while allowing for original interpretation and extension.

At the core of the methodology is a life-cycle perspective on mine geothermal systems. This perspective treats the mine not as a static structure but as a dynamically evolving system in which excavation, fracture development, backfill placement, and post-mining stabilization continuously reshape thermal and hydraulic conditions (Li et al., 2025; Lu et al., 2024). By adopting this temporal lens, the methodology enables analysis of how geothermal energy extraction potential changes from the active mining phase through closure and post-closure periods.

A second methodological pillar is the conceptual coupling of thermal, hydraulic, and mechanical processes. Numerical investigations reported in the literature consistently demonstrate that heat transfer in mines cannot be understood in isolation from groundwater flow and rock deformation (Xie et al., 2024; Zhao et al., 2024). The present study therefore synthesizes modeling approaches that account for fracture evolution, non-Darcy flow behavior, and stress-dependent permeability changes. Although no equations are presented, the underlying assumptions and implications of these models are examined in detail, highlighting how different parameter choices influence predicted thermal performance.

The methodology also incorporates a comparative analysis of engineered geothermal solutions proposed in recent studies. Multi-branch geothermal well systems, backfill heat exchangers, and phase-change heat storage backfill are examined not merely as technical devices but as manifestations of broader design philosophies aimed at integrating energy extraction with mine safety (Li et al., 2025; Zhang et al., 2020; Ning et al., 2025). By comparing these approaches across different geological and operational contexts, the study identifies common design principles and trade-offs.

In addition, the methodology draws on insights from adjacent fields, particularly deep Earth exploration and gas hydrate research, to contextualize challenges in in situ measurement and subsurface characterization. Advances in pressure-preserving coring, thermal insulation during sampling, and deep drilling technologies provide valuable analogies for mine geothermal research, especially in relation to understanding true in situ thermal and hydraulic conditions (Xie et al., 2020; Hu et al., 2022; Kubo et al., 2014).

Throughout the methodological process, emphasis is placed on critical interpretation rather than aggregation. Conflicting findings, methodological limitations, and uncertainties reported in the literature are explicitly discussed, and alternative explanations are considered. This approach ensures that the resulting analysis is not only comprehensive but also reflective of the ongoing debates and evolving understanding within the field.

RESULTS

The integrative analysis reveals several emergent patterns and insights into the behavior of mine geothermal systems that transcend individual case studies. One of the most prominent findings is the critical role of groundwater flow in governing both the magnitude and sustainability of geothermal energy extraction from mines. Studies that incorporate groundwater dynamics consistently demonstrate higher heat extraction rates compared to conduction-dominated scenarios, underscoring the importance of advective heat transport (Li et al., 2025). However, this enhancement is accompanied by increased complexity and uncertainty, as flow pathways are strongly influenced by fracture networks that evolve over time.

Another key result concerns the life-cycle thermal response of mines. During active mining, continuous excavation exposes fresh rock surfaces and generates extensive fracture networks, leading to increased heat release into mine workings. As mining progresses and goafs develop, the thermal regime becomes increasingly heterogeneous, with localized hotspots associated with deep strata and reduced ventilation efficiency (Xu et al., 2023). Post-mining, the placement of backfill and the cessation of ventilation fundamentally alter heat transfer pathways, creating conditions conducive to long-term geothermal energy extraction, particularly when engineered heat exchangers are integrated into backfilled stopes (Ghoreishi-Madiseh et al., 2015; Ning et al., 2025).

The analysis also highlights the significance of fracture evolution and non-Darcy flow effects. Numerical investigations in complex fractured rock demonstrate that traditional Darcy-based assumptions can substantially underestimate or misrepresent heat transfer performance in enhanced geothermal systems (Xie et al., 2024). As fractures dilate, connect, or become partially filled during mining and backfilling, flow regimes transition between laminar and non-linear behavior, affecting both thermal breakthrough times and overall extraction efficiency.

Geological controls emerge as another dominant factor. Site-specific studies show that lithological contrasts, fault systems, and regional stress fields strongly influence deep geothermal anomalies and heat distribution (Yang et al., 2020). Mines located in regions with favorable geothermal gradients and permeable structures exhibit significantly higher energy extraction potential, while those in low-permeability or highly anisotropic formations face greater challenges.

Engineered solutions such as multi-branch geothermal wells and phase-change heat storage backfill demonstrate considerable promise. Multi-level well systems enable simultaneous heat extraction from different strata, effectively increasing the contact area between the geothermal fluid and the surrounding rock mass (Li et al., 2025). Phase-change materials incorporated into backfill enhance thermal buffering capacity, smoothing temperature fluctuations and improving the temporal stability of heat supply (Zhang et al., 2020; Ning et al., 2025).

Finally, the analysis reveals a convergence between mine geothermal research and broader subsurface energy and resource studies. Techniques developed for in situ coring, gas hydrate sampling, and deep drilling provide methodological insights that could significantly improve characterization and monitoring of mine geothermal systems (Xie et al., 2020; Li et al., 2021).

DISCUSSION

The results underscore the necessity of viewing mine geothermal systems as inherently dynamic and multidisciplinary. One of the central implications is that effective geothermal energy extraction from mines cannot rely on static design assumptions. Instead, it requires adaptive strategies that account for the evolving nature of fracture networks, groundwater flow, and thermal regimes throughout the mine life cycle.

A critical discussion point concerns the balance between geothermal energy extraction and mine safety. While enhanced heat extraction can mitigate underground heat hazards by reducing ambient temperatures, aggressive manipulation of groundwater flow or fracture networks may introduce geotechnical risks, including increased subsidence or instability (Zhu et al., 2022; Rafiee et al., 2015). The literature suggests that synergistic designs, such as those integrating backfill and geothermal infrastructure, offer a promising pathway to reconcile these objectives.

Another important consideration is scale. Many numerical studies focus on representative sections of mines or simplified fracture networks, raising questions about scalability and representativeness. The heterogeneity of real mines, both geological and operational, poses significant challenges to model validation and generalization. Advances in in situ measurement and monitoring technologies, inspired by deep Earth and gas hydrate research, could help address these challenges by providing more reliable data on subsurface conditions (Hu et al., 2022; Kvenvolden et al., 1983).

Uncertainty remains a pervasive issue. Parameters such as fracture permeability, thermal properties of backfill materials, and long-term groundwater behavior are often poorly constrained. Sensitivity analyses reported in the literature highlight the potential for small parameter variations to produce large differences in predicted thermal performance (Xie et al., 2024). This underscores the need for robust, probabilistic approaches to design and assessment.

From a broader perspective, the integration of mine geothermal systems into regional energy strategies aligns with emerging concepts of subsurface multifunctionality. Mines, once abandoned, can serve as long-term energy assets, contributing to heating networks, seasonal thermal storage, and even hybrid systems that combine geothermal extraction with carbon dioxide storage or hydrogen storage in subsurface formations (Ding et al., 2023; Chai et al., 2023).

Future research directions suggested by this discussion include the development of unified modeling frameworks that couple thermal, hydraulic, mechanical, and chemical processes across scales; enhanced field monitoring to validate long-term performance; and interdisciplinary collaboration between mining engineers, geothermal scientists, and energy system planners.

CONCLUSION

This study has developed a comprehensive, theoretically grounded analysis of geothermal energy extraction and heat transfer in mining systems, strictly based on the provided literature. By synthesizing advances in numerical modeling, geological analysis, engineered design, and subsurface investigation, the article demonstrates that mines can be effectively reconceptualized as dynamic geothermal systems with significant energy potential.

The findings highlight the central roles of groundwater flow, fracture evolution, geological controls, and engineered interventions in shaping thermal performance. They also emphasize the importance of life-cycle thinking, adaptive design, and multidisciplinary integration. While significant challenges remain in characterization, modeling, and uncertainty management, the convergence of mining science and geothermal engineering offers a promising pathway toward sustainable subsurface energy utilization.

Ultimately, the transformation of mines into geothermal assets represents not only a technological opportunity but also a conceptual shift in how society views the legacy of mining. By embedding energy recovery, safety enhancement, and environmental stewardship into mine design and closure strategies, it is possible to unlock enduring value from deep subsurface spaces.

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