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EDITED BY
Wenke Zhang,
Shandong Jianzhu University, China

REVIEWED BY
Giovanni Ciampi,
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Shiyu Zhou,
Shandong Jianzhu University, China
Kexun Wang,
Tianjin University, China

*CORRESPONDENCE
Val Hyginus Udoka Eze,
udoka.eze@kiu.ac.ug

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Recent progress and emerging technologies in geothermal energy utilization for sustainable building heating and cooling: a focus on smart system integration and enhanced efficiency solutions

Val Hyginus Udoka Eze [1]*, Esther Chidinma Eze [2], George Uwadiegwu Alaneme [3] and Pius Erheyovwe Bubu [1]

[1]Department of Electrical, Telecom. & Computer Engineering, Kampala International University, Western Campus, Ishaka, Uganda, [2]Department of Educational Foundations, Kampala International University, Western Campus, Ishaka, Uganda, [3]Department of Civil Engineering, Kampala International University, Western Campus, Ishaka, Uganda

Geothermal energy has gained prominence as a sustainable solution for heating and cooling, driven by technological innovations and the growing global demand for energy efficiency. Geothermal systems, particularly ground-source heat pumps (GSHPs), exhibit high energy efficiency, with coefficients of performance (COP) ranging from 3.5 to 6.0, while deep geothermal systems operate at temperatures of 50°C–200°C, supporting both power generation and large-scale heating applications. Enhanced Geothermal Systems (EGS) use hydraulic, chemical, and thermal stimulation to extract heat from low-permeability formations, significantly expanding the applicability of geothermal resources beyond traditional hotspots. Geothermal heat pumps are capable of achieving energy efficiency levels of 300%–600%, reducing CO_2 emissions by 50%–70% when compared to fossil fuel-based HVAC systems. However, installation costs for GSHPs range from $2,500 to $5,000 per kW, while deep geothermal systems require higher capital investments. Despite these initial costs, operational expenses remain competitive at $0.01–$0.03 per kWh, and geothermal plants exhibit high-capacity factors of 70%–90%, outperforming solar (20%–30%) and wind (30%–50%) in terms of energy production consistency. The return on investment (ROI) for geothermal systems typically occurs within 5–15 years, depending on location and system scale. The integration of smart technologies, such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT), further enhances the efficiency of geothermal energy systems by enabling real-time monitoring, predictive maintenance, and load forecasting, optimizing overall performance and longevity. Hybrid systems, combining geothermal energy with solar, wind, and thermal energy storage, improve grid stability and further enhance energy efficiency. Despite challenges such as geological constraints, high initial costs, and regulatory barriers, policy frameworks and government incentives play a vital role in promoting the expansion of geothermal energy. The global geothermal capacity surpassed 16 GW in 2023 and is projected to exceed 24 GW by 2030, with significant deployments in countries like the U.S., Indonesia, Kenya, the Philippines, and Turkey. Notable geothermal projects include the Olkaria Geothermal Power Plant (800 MW, Kenya), The Geysers (1.5 GW, United States), Hellisheidi (303 MW electricity, 400 MW thermal, Iceland), and the Yangbajain Geothermal Power Station in China (25.5 MW and 100 GWh annual generation). As nations aim for carbon neutrality and energy security, geothermal energy is poised to play a crucial role in achieving sustainable energy transitions and mitigating climate change.

KEYWORDS

geothermal energy, ground-source heat pumps (GSHPs), enhanced geothermal systems, energy efficiency and sustainability, hybrid and smart geothermal technologies IEEE xplore, scopus, web of science, researchgate

1 Introduction

The increasing global demand for sustainable and energy-efficient heating and cooling solutions has intensified the exploration and advancement of geothermal energy technologies (Kassem and Moscariello, 2024). As a renewable and low-carbon energy source, geothermal energy presents a viable alternative to fossil fuel-based heating and cooling systems, particularly in the building sector, which accounts for a significant share of global energy consumption (Romanov and Leiss, 2022). Given that this sector contributes approximately 40% of total energy use and 37% of greenhouse gas emissions, reducing its carbon footprint is crucial for mitigating climate change (Bilgen, 2014). In response to this challenge, recent advancements in geothermal energy utilization have focused on improving system integration, optimizing energy extraction, and enhancing operational efficiency (Sharmin et al., 2023). Traditional geothermal heating and cooling systems, such as ground-source heat pumps (GSHPs) and direct-use applications, have seen significant improvements through the integration of smart control systems, artificial intelligence (AI), and machine learning (ML) algorithms (Thermal work OURS). These technologies enable real-time monitoring, predictive maintenance, and adaptive energy management, leading to increased performance and energy savings. Additionally, innovations in drilling techniques, heat exchanger designs, and hybrid geothermal systems have expanded the feasibility of geothermal energy applications across diverse climatic conditions (Khaleghi and Livescu, 2023).

Further developments in enhanced geothermal systems (EGS), which utilize hydraulic stimulation to increase heat extraction from deep subsurface reservoirs, have emerged as a promising solution to overcome geographical limitations (Rohit et al., 2023). Additionally, the integration of thermal energy storage solutions with geothermal heating and cooling systems has optimized energy utilization and load balancing, ensuring consistent performance and reduced peak demand (Ahmed et al., 2022). The shift toward smart system integration aligns with the broader goals of sustainable development and climate change mitigation. The adoption of Internet of Things (IoT)-enabled sensors and cloud-based analytics facilitates precise control of geothermal systems, ensuring optimal energy distribution and user comfort (Kumar et al., 2022). In alignment with the Paris Climate Agreement, the world has only 27 years to achieve net-zero emissions, requiring a 50% reduction in global building emissions by 2030 and net-zero life-cycle emissions by 2050 (Noorollahi et al., 2019). This urgency has propelled the expansion of net-zero energy buildings, reinforcing the transition toward sustainable architecture. The sector can make significant strides toward sustainability and reducing its environmental footprint by integrating energy-efficient designs, renewable energy sources, and innovative construction materials (Khaleghi and Livescu, 2023). Figure 1 illustrates the global building sector's energy-related CO_2 emissions.

This review paper provides an in-depth analysis of recent progress and emerging technologies in geothermal energy utilization for sustainable building heating and cooling. The discussion focuses on smart system integration, advanced efficiency solutions, and the potential of hybrid approaches that combine geothermal energy with other renewable sources. By highlighting technological advancements, case studies, and future research directions, this study aims to contribute to the ongoing discourse on achieving energy sustainability through geothermal innovations.

This review uniquely contributes to the field by presenting a comprehensive synthesis of recent advancements that collectively redefine geothermal energy deployment. The novelty lies in the strategic convergence of cutting-edge digital technologies such as AI, ML, and IoT, with advanced subsurface engineering techniques like Enhanced EGS, and the integration of hybrid energy models combining geothermal with solar, wind, and thermal storage. Unlike prior reviews that focused narrowly on geological or system design aspects, this work emphasizes how these multidimensional innovations, alongside evolving policy frameworks and investment trends, coalesce to enhance real-time optimization, predictive maintenance, and energy accessibility. It offers a forward-looking framework that positions geothermal energy as a smart, resilient, and scalable pillar of the global sustainable energy landscape.

2 Methodology

2.1 Research design

This study adopts a systematic and multidisciplinary review design to evaluate recent advancements in geothermal energy technologies, with a particular emphasis on their applications in sustainable heating and cooling systems. A mixed-methods approach was employed, integrating qualitative thematic analysis

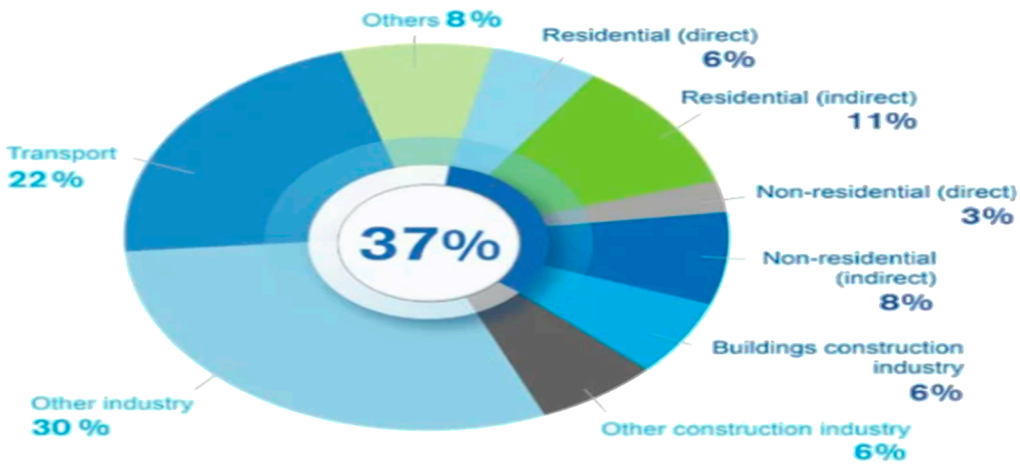

FIGURE 1
Global building sector energy-related CO_2 emissions (Khaleghi and Livescu, 2023).

of scholarly literature with quantitative insights drawn from stakeholder-reported data. The methodology provides a robust foundation for understanding technological, economic, and environmental trends in geothermal applications.

2.2 Study evaluation and categorization using PRISMA framework

A systematic approach guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was adopted to refine the selection of literature. The PRISMA framework in Figure 2 ensured transparency, reproducibility, and rigor in the identification, screening, eligibility assessment, and inclusion of relevant studies. The process followed four structured phases.

2.2.1 Identification

A comprehensive literature search was conducted across five reputable academic databases: IEEE Xplore, Scopus, Web of Science, ResearchGate, and Google Scholar. Search queries combined keywords such as "Geothermal Energy Technologies," "Sustainable Heating and Cooling," "Geothermal Innovations," "Hybrid Geothermal Systems," "Geothermal Energy," "Ground-Source Heat Pumps (GSHPs)," "Enhanced Geothermal Systems," "Energy Efficiency and Sustainability," and "Hybrid and Smart Geothermal Technologies" This process initially yielded 170 records. After removing 12 duplicates and 18 non-peer-reviewed sources, 140 unique studies were identified for preliminary assessment.

2.2.2 Screening

The titles and abstracts of 140 initially identified studies were systematically screened to evaluate their relevance to advancements in geothermal energy. The inclusion criteria emphasized research focused on both heating and cooling applications of geothermal energy. Consequently, studies were excluded if they: (i) focused exclusively on geothermal electricity generation; (ii) did not sufficiently address thermal (heating and cooling) applications; or (iii) constituted non-peer-reviewed literature such as opinion pieces, editorials, or commentaries. Following the application of these criteria, a total of 125 studies met the inclusion requirements and were selected for comprehensive review and further analysis.

2.2.3 Eligibility assessment

Full texts of the 125 shortlisted studies were reviewed for methodological rigor, relevance, and alignment with the study's thematic focus. Twenty studies were excluded for reasons including outdated content, lack of technological context, and geographic bias toward non-representative regions. Ultimately, 105 studies met all eligibility criteria.

2.2.4 Inclusion

A total of 105 high-quality studies were included in the final synthesis. These comprised peer-reviewed journal articles, conference proceedings, industry reports, and government publications from 2015 onward. The included literature provided empirical, technical, and policy-related insights on geothermal advancements in residential, commercial, and industrial heating and cooling applications.

2.3 Quality assessment tools

To ensure methodological integrity, each study was assessed using two established tools: the Critical Appraisal Skills Programme (CASP) Checklist and the Modified Joanna Briggs Institute (JBI) Checklist. CASP focused on research clarity, methodological soundness, and coherence of findings, while the JBI Checklist was tailored to assess the reproducibility of methods, technological relevance, and statistical robustness. Studies were assigned a quality score out of 10, with only those scoring 7 and above retained for thematic synthesis.

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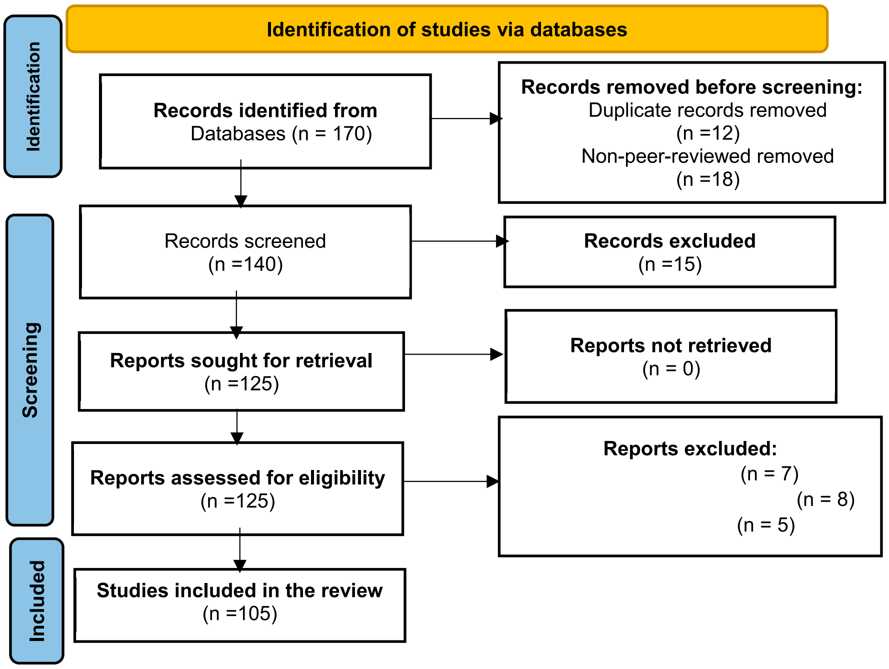

FIGURE 2
PRISMA diagram.

2.4 Thematic coding and data categorization

The selected studies were subjected to a systematic qualitative coding process using NVivo software to ensure rigorous data organization and thematic synthesis. Through iterative thematic analysis, four principal domains emerged: (i) Technological Advancements, encompassing innovations in drilling methods, heat exchanger designs, EGS, and hybrid energy configurations; (ii) Digital Integration, highlighting the application of AI, ML, and IoT technologies in real-time system monitoring, predictive maintenance, and performance optimization; (iii) Environmental and Economic Impacts, focusing on the quantification of carbon dioxide (CO_2) emission reductions, cost-efficiency, and long-term sustainability of geothermal systems; and (iv) Adoption Challenges and Policy Interventions, which addressed barriers such as high initial installation costs, regulatory complexities, and limited public awareness. The use of NVivo facilitated a transparent, traceable, and consistent thematic framework, enhancing the reliability and depth of the analytical process.

2.5 Stakeholder-based data collection

In addition to literature analysis, secondary data were collected from stakeholders, including geothermal research institutions, energy agencies, and system providers. This included information on technological deployments, system performance, regulatory developments, and market trends. These data provided contextual depth and practical validation for the literature-based findings.

2.6 Synthesis and interpretation

The integrated synthesis revealed that recent innovations in geothermal technologies, especially in drilling, heat recovery, hybridization, and digital optimization, have significantly enhanced system efficiency, economic feasibility, and environmental performance. AI, ML, and IoT applications enable smarter geothermal operations, while hybrid systems bolster energy reliability. Challenges such as high initial costs and regulatory inertia persist, but ongoing technological and policy developments are poised to broaden adoption. Figure 2 is the PRISMA diagram showing the systematic rigor evaluations and screening of the data used for this review.

3 Literature review

Geothermal energy has long been recognized as a reliable and sustainable solution for heating and cooling applications, with its utilization dating back to ancient civilizations that harnessed natural hot springs for thermal comfort (Noorollahi et al., 2019). In modern times, advancements in geothermal heat pump (GHP) technology and deep geothermal systems have significantly expanded their role in the built environment (Khaleghi and Livescu, 2023). The integration of geothermal systems in residential, commercial, and industrial buildings has led to a substantial reduction in reliance on conventional fossil-fuel-based energy sources, thereby lowering greenhouse gas emissions and enhancing overall energy efficiency (Elshehabi and Alfehaid, 2025). Unlike intermittent renewable energy sources such as solar and wind, geothermal systems provide stable, continuous, and seasonally independent

TABLE 1 Comparison of geothermal energy systems.

Feature	Shallow geothermal systems (GSHPs)	Deep geothermal systems	Enhanced geothermal systems
Depth	10–400 m	Exceeds 1 km	Typically >3 km
Working principle	Utilizes heat exchange with the ground through closed-loop (horizontal, vertical, pond/lake) or open-loop (aquifer-based) systems	Uses hydrothermal resources (hot water and steam) to generate electricity via binary cycle or flash steam power plants	Extracts heat from dry, low-permeability rock formations through hydraulic fracturing, chemical stimulation, and thermal shock techniques
Temperature range	10°C–25°C	50°C–200°C+	150°C–300°C
Applications	Heating and cooling for residential, commercial, and institutional buildings	Electricity generation, district heating, industrial applications	Power generation in regions without natural hydrothermal reservoirs
Efficiency (COP)	3.5–6.0	Varies based on plant type, typically 10%–20% thermal efficiency for electricity generation	Improved efficiency due to engineered permeability enhancements
Energy output	Low to moderate	High	High
Installation complexity	Moderate (requires drilling and loop installation)	High (deep drilling and plant construction)	Very high (requires advanced drilling and stimulation techniques)
Geographical suitability	Can be implemented in diverse climatic conditions	Requires naturally occurring hydrothermal reservoirs	Can be deployed in areas lacking natural hot water sources
Environmental impact	Low (minimal emissions and land use)	Moderate (possible land subsidence and water usage)	Higher (risks of induced seismicity and fluid injection concerns)
Examples of deployment	Common in Europe, North America, and Asia for residential/commercial heating	Used in Iceland, the U.S., and Germany for power and heating	Experimental and pilot projects in the U.S., Australia, and France
Advancements	Improved heat exchanger designs and refrigerants	More efficient binary cycle technology	AI and ML for optimizing reservoir modeling and reducing drilling risks

heating and cooling solutions, making them a critical component in the global transition toward sustainable energy (Kabeyi and Olanrewaju, 2022). This review provides a comprehensive overview of geothermal energy applications in buildings, classifying different system types, outlining key benefits, and addressing the challenges associated with widespread deployment.

3.1 Classification of geothermal energy systems

Geothermal energy systems for buildings can be broadly classified into three main categories based on the depth of heat extraction and operational mechanisms (Sanyal, 2005; Rajaobelison et al., 2020). Table 1 shows the geothermal energy system comparison.

3.1.1 Shallow geothermal systems (ground-source heat pumps - GSHPs)

Shallow geothermal systems, commonly known as ground-source heat pumps (GSHPs), utilize the relatively stable temperatures of the Earth's upper layers, typically between 10 and 400 m deep, to provide efficient heating and cooling. These systems operate by exchanging heat between the ground and a circulating fluid, which transfers thermal energy through either a closed-loop or open-loop configuration. In closed-loop systems, heat exchangers are placed horizontally, vertically, or in ponds/lakes, with a refrigerant or antifreeze solution circulating through buried pipes (Rajaobelison et al., 2020; Luo et al., 2018). On the other hand, open-loop systems directly extract and discharge groundwater from an aquifer or other underground source. Shallow geothermal systems are widely employed in residential, commercial, and institutional buildings due to their high efficiency, long operational lifespan, and ability to operate effectively across diverse climatic conditions. Studies have shown that GSHPs can achieve a coefficient of performance (COP) ranging from 3.5 to 6.0, substantially outperforming traditional air-source heat pumps and fossil-fuel-based HVAC systems. This makes them a viable option for energy-efficient heating and cooling (Elshehabi and Alfehaid, 2025; Luo et al., 2018). The inherent stability of the ground temperature, which remains constant throughout the year despite surface temperature fluctuations, makes shallow geothermal systems highly adaptable for use in a variety of climates, including both extremely cold and hot regions.

However, the operational performance of shallow geothermal systems can be influenced by various factors in extreme climates.

In cold regions, the system's efficiency may be impacted by lower ground temperatures, reduced soil thermal conductivity, and the need for larger ground loops to maintain heat extraction. Conversely, in hot regions, while the system is efficient in cooling mode, soil conditions, including lower moisture content and the potential for soil overheating, can affect the system's performance (Elshehabi and Alfehaid, 2025). Therefore, while shallow geothermal systems offer robust and versatile solutions, their design and operational efficiency in extreme climates require careful consideration of local environmental conditions. However, some factors affect the performance of the shallow Geothermal system under extreme cold and hot regions, as discussed below.

3.1.1.1 Shallow geothermal systems in extremely cold regions

In extremely cold regions such as the Arctic, subarctic, or high-altitude areas, shallow geothermal systems can still operate efficiently; however, their performance is influenced by several critical factors. Firstly, the ground temperature in colder climates is typically lower, and although it remains more stable than air temperature, it can be colder than in more moderate regions. In some cases, the ground temperature may approach or fall below freezing, reducing the system's efficiency (Sanyal, 2005). Additionally, cold regions often feature soils with lower thermal conductivity, which hinders heat transfer efficiency. Consequently, the geothermal system must work harder to extract or reject heat, resulting in higher energy consumption to maintain operational effectiveness. To compensate for these challenges, systems in cold regions may require larger loop fields, necessitating more drilling and greater installation costs, as the loops need to cover a broader area or extend deeper to access warmer ground layers. Furthermore, in cold climates, heating demands are significantly higher, especially during long winters, putting additional strain on the system and potentially requiring an oversized heat pump or the integration of supplemental heating sources to meet peak heating needs. In terms of operation, shallow geothermal systems in these areas predominantly function in heating mode during most of the year, and as the temperature differential between the ground and air increases, the system needs to work harder to extract heat (Rajaobelison et al., 2020). This can result in a decrease in the system's Coefficient of Performance (COP), particularly if the ground temperature is too low. Moreover, frost penetration into the ground poses a risk, especially if the system's heat exchange design is inadequate, potentially leading to reduced heat transfer efficiency or even system failure in extreme conditions. Finally, the colder climate leads to increased operational costs, requiring more frequent maintenance and additional energy input to extract heat from the colder ground. To mitigate these challenges, auxiliary heating systems, such as electric resistance heaters or biofuels, may be necessary to support the geothermal system during extreme weather conditions.

3.1.1.2 Shallow geothermal systems in extremely hot regions

In extremely hot regions such as deserts or tropical areas, shallow geothermal systems face unique operational challenges, although the heat exchange properties of the ground in hot climates can offer some advantages. The ground temperature in hot regions is typically higher than in temperate climates, which can improve system efficiency when operating in cooling mode, as the ground remains cooler than the surrounding air. This facilitates the transfer of heat from indoor spaces into the ground. However, hot regions often have dry soils with lower moisture content, reducing the soil's ability to conduct heat (Rajaobelison et al., 2020). Dry soils have lower thermal conductivity, which can hinder the system's performance by requiring more energy to reject heat into the ground.

The sizing of the system is another crucial consideration. In hot climates, shallow geothermal systems may not need deep ground loops, as the surface temperature may be significantly higher than the ground temperature just a few meters below the surface, which enhances heat transfer during cooling. However, proper ground loop design is essential to prevent the system from overheating. If the system is used extensively for cooling, there is a risk that the surrounding soil could warm up over time, diminishing the system's efficiency (Elshehabi and Alfehaid, 2025; Luo et al., 2018). Therefore, the heat exchange rate must not exceed the ground's ability to absorb heat. In terms of heat pump operation, geothermal systems typically operate efficiently in cooling mode in hot climates, rejecting indoor heat into the cooler subsurface. However, if the system runs for extended periods, such as in desert environments, the temperature of the surrounding soil may rise, reducing heat transfer efficiency. A potential issue is overheating, as the heat pump may become less efficient if the ground temperature rises beyond its capacity to absorb the heat, necessitating system shutdowns or periodic recharging. Maintenance and efficiency are also affected in hot climates (Sanyal, 2005). High temperatures lead to faster wear and tear on the heat pump, as it may be operating continuously in cooling mode, which can increase maintenance requirements and operational costs. Additionally, in arid regions, water conservation becomes a critical concern. In closed-loop systems that use water as a heat transfer medium, evaporation can lead to significant water loss, so measures to minimize this are essential.

Overall, both in hot and cold regions, system longevity is a crucial factor. Shallow geothermal systems are designed to last for decades if properly installed and maintained, but extreme climates necessitate careful attention to system sizing and the selection of materials for the ground loops. In both conditions, hybrid systems that combine geothermal energy with other renewable energy sources, such as solar or wind power, can enhance efficiency and reliability. For instance, in cold regions, geothermal systems can be supplemented with solar thermal heating to meet peak heating demands, while in hot regions, solar power can support geothermal cooling, reducing system strain.

3.1.1.3 Cost analysis and implications of installing GSHPs

Shallow geothermal heat exchangers (GSHEs) designed for installation at reduced depths offer a promising avenue for lowering the installation costs of ground-source heat pump (GSHP) systems. Unlike traditional double-U probes, which necessitate drilling depths of approximately 60 m (200 feet) per borehole, these shallow systems typically require depths ranging from 3 to 9 m (10–30 feet), significantly reducing drilling expenses. Drilling costs for deep vertical boreholes can constitute a substantial

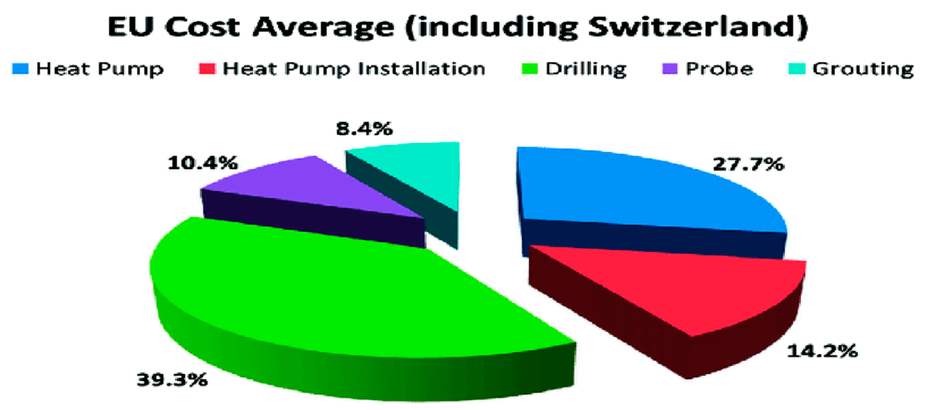

FIGURE 3
European average costs of a standard geothermal installation outside the house heat pump (Müller et al., 2018).

portion of the total installation cost. For instance, in the U.S., drilling a single 60-m borehole can cost up to $3,000, and a typical residential GSHP system requiring two such boreholes may incur drilling costs totaling $6,000. In contrast, shallow GSHEs, such as helical or spiral configurations, can be installed using less invasive methods, avoiding the need to penetrate bedrock or navigate complex hydrogeological conditions, thus offering a more cost-effective solution. Additionally, innovative approaches like large-diameter shallow bore technologies have demonstrated the potential to further reduce installation costs, with some studies indicating reductions of up to two-thirds compared to traditional deep bore systems. These advancements not only make GSHP systems more financially accessible but also expand their applicability across diverse geological settings (Müller et al., 2018).

The installation costs of ground-source heat pumps (GSHPs) are significantly influenced by regional geological variations, which affect both the design and execution of the system. The geological characteristics of a site, such as soil composition, rock hardness, and thermal conductivity, play a crucial role in determining the type of ground loop system, horizontal or vertical, and the associated drilling or excavation methods required. For instance, horizontal ground loops can be installed using standard machinery at relatively lower costs in areas with soft soils or sedimentary rocks (Elshehabi and Alfehaid, 2025; Müller et al., 2018). Conversely, regions with hard bedrock necessitate vertical boreholes, which require specialized drilling equipment and techniques, leading to higher expenses. The depth and diameter of these boreholes further influence costs; deeper and wider boreholes demand more time and resources, thereby increasing the overall installation price. Additionally, the thermal properties of the ground, such as its thermal conductivity and the presence of groundwater, affect the efficiency of heat exchange. In areas with low thermal conductivity or challenging hydrogeological conditions, larger or more numerous boreholes may be necessary to achieve desired performance levels, escalating costs. Therefore, conducting a comprehensive geotechnical site investigation is essential to accurately assess these factors and optimize the design of GSHP systems, ensuring both cost-effectiveness and operational efficiency. Figure 3 is the European average costs of a standard geothermal installation outside the house heat pump (Müller et al., 2018).

3.1.2 Deep geothermal systems

Deep geothermal systems harness high-temperature thermal energy from underground reservoirs at depths exceeding 1 km, where subsurface temperatures typically range from 50°C to over 200°C (Elshehabi and Alfehaid, 2025). These systems exploit naturally occurring hydrothermal resources, such as hot water and steam, to generate electricity and provide large-scale heating through Binary cycle power plants, which use a secondary working fluid with a lower boiling point to generate electricity efficiently and Flash steam power plants, which utilize high-pressure steam to drive turbines (Müller et al., 2018). Deep geothermal energy is particularly suitable for high-energy-demand applications, including industrial heating, district heating networks, and power generation. Countries such as Iceland, the United States, and Germany have successfully deployed deep geothermal systems, demonstrating their viability in supporting sustainable urban energy solutions (Izadi and Freitag, 2025).

3.1.3 Enhanced geothermal systems

EGS represents an advanced engineered approach to geothermal energy extraction, enabling heat recovery from dry, low-permeability rock formations that lack naturally occurring hydrothermal reservoirs (Mindygaliyeva, 2024). This method involves Hydraulic fracturing, where high-pressure fluid injections increase rock permeability. Secondly, chemical stimulation, which dissolves mineral blockages and enhances heat transfer, and finally, thermal shock techniques, which exploit temperature gradients to create microfractures in the rock. EGS technology overcomes geographical limitations associated with conventional geothermal systems, expanding geothermal accessibility in regions without natural hot water reservoirs (Boretti, 2022). Advances in numerical simulations, AI, and ML are now being integrated into EGS operations to optimize reservoir modeling, reduce drilling risks, and enhance heat extraction efficiency.

3.2 Benefits of geothermal energy in building applications

The adoption of geothermal energy in building applications offers numerous benefits in terms of energy efficiency, environmental sustainability, economic viability, and reliability, making it an ideal solution for modern, sustainable infrastructure (Molavi and McDaniel, 2016). One of the key advantages of geothermal systems, particularly ground-source heat pumps (GSHPs), is their exceptional energy efficiency, operating at levels ranging from 300% to 600%. This means they provide 3–6 times more energy than they consume, leading to significant energy savings in residential, commercial, and industrial buildings. GSHPs maintain high efficiency year-round, offering improved seasonal performance that further contributes to reducing heating and cooling demand, ultimately lowering electricity consumption (Vérez et al., 2023). Geothermal energy also promotes environmental sustainability by providing a renewable, low-carbon alternative to fossil fuels, which results in a 50%–70% reduction in CO_2 emissions compared to conventional HVAC systems (Aljashaami et al., 2024). These systems eliminate direct emissions of pollutants like nitrogen oxides (NO_x) and sulfur dioxide (SO_2), and when combined with other renewable energy sources such as solar and wind, they create an even cleaner and more sustainable energy solution. In terms of economic feasibility, geothermal systems offer long-term cost savings due to their low operating and maintenance costs, driven by fewer mechanical components exposed to outdoor elements. The lifespan of GSHP units exceeds 25 years, with underground piping lasting over 50 years, ensuring long-term durability and reliability. Despite their higher initial capital costs, geothermal systems provide attractive payback periods of 5–15 years, depending on location, incentives, and energy prices, making them a financially viable investment. Geothermal energy is also known for its reliability, providing a stable, weather-independent source of heating and cooling, in contrast to solar and wind energy, which are subject to seasonal fluctuations (Umar et al., 2024). This stability ensures consistent performance, even in extreme weather, and reduces reliance on external energy sources, enhancing energy security and reducing exposure to volatile energy markets. Furthermore, geothermal systems enhance indoor comfort by maintaining consistent temperatures, eliminating hot or cold spots, and offering silent operation, which increases acoustic comfort. The ability to provide a reliable, environmentally friendly, and cost-effective energy solution positions geothermal energy as a vital contributor to sustainable building practices.

Table 2 presents a comparative analysis of geothermal energy systems for buildings, highlighting the advantages, disadvantages, and practical applicability of three distinct types of geothermal systems: Shallow Geothermal Systems (GSHPs), Deep Geothermal Systems, and Enhanced Geothermal Systems (EGS). This table summarizes the key factors that differentiate each system, providing insight into their operational efficiency, feasibility, and suitability for various applications in the building sector.

3.3 Challenges in implementing geothermal energy systems

Despite its many advantages, the deployment of geothermal energy systems in buildings faces several challenges that can limit their widespread adoption. These challenges include high initial costs, geological constraints, regulatory hurdles, and issues related to public awareness and adoption (Korucan et al., 2024).

1. High Initial Costs: One of the primary barriers to the widespread adoption of geothermal energy is the high initial capital investment required for system installation. Ground-source heat pumps (GSHPs) typically cost between $2,500 and $5,000 per installed kW, depending on system size and location. For more advanced geothermal systems, such as deep geothermal and EGS, the costs are significantly higher due to the complex drilling operations, advanced technologies like hydraulic fracturing and reservoir stimulation, and the need for extensive infrastructure. While geothermal systems have low operational costs and offer long-term savings, the steep upfront investment remains a critical barrier, particularly in regions where financial incentives or subsidies are scarce (Noorollahi et al., 2019).
2. Geological Constraints: The feasibility of geothermal energy is highly dependent on site-specific geological conditions, which vary significantly across regions. Factors such as subsurface temperature gradients and rock permeability play crucial roles in determining the viability of geothermal systems. In areas with low-temperature geothermal resources, additional technologies like EGS may be required to enhance efficiency. Low-permeability formations can limit heat extraction and may necessitate more costly methods like hydraulic fracturing. The availability of groundwater is also a key consideration, particularly in open-loop systems. In areas with limited groundwater resources or concerns about water quality, geothermal projects may face significant challenges (Breede et al., 2015). The high costs and complexity of deploying geothermal systems in unfavorable geological conditions reduce their competitiveness compared to other renewable energy sources.
3. Regulatory and Permitting Hurdles: Geothermal energy projects often face complex regulatory and permitting processes, which can lead to delays and increased costs. Environmental impact assessments (EIA) are typically required to assess risks such as land subsidence or groundwater contamination. Land-use and zoning restrictions may also hinder the installation of geothermal infrastructure, especially in densely populated or environmentally sensitive areas (Noorollahi et al., 2019). The permitting process can be lengthy and resource-intensive, as it involves detailed assessments of environmental and geological conditions. Additionally, the variation in policy frameworks across different jurisdictions creates inconsistent regulatory environments, making it more

TABLE 2 Comparative analysis of geothermal energy systems for buildings.

System type	Advantages	Disadvantages	Practical performance
Shallow geothermal systems (GSHPs)	i) High efficiency (COP 3.5–6.0) - Low operational cost ii) Long lifespan iii) Applicable in various climates	i) High installation cost ii) Land requirements for horizontal loops iii) Groundwater access is needed for open-loop systems	i) Ideal for residential, commercial, and institutional buildings ii) Provides both heating and cooling iii) Flexible loop configurations (horizontal, vertical, pond/lake)
Deep geothermal systems	i) High-temperature resource (50°C–200°C) ii) Supports power generation and district heating iii) Stable base-load power with high capacity factor	i) Very high drilling and infrastructure costs ii) Limited to geologically suitable regions iii) Permitting and geological risks	i) Used in geothermal-rich countries (e.g., Iceland, United States) ii) Binary and flash steam plants iii) Suitable for industrial-scale applications
Enhanced geothermal systems (EGS)	i) Expands geothermal access beyond natural reservoirs ii) Advanced stimulation (hydraulic, chemical, thermal) improves heat recovery iii) AI/ML integration enhances system optimization	i) Complex and costly technology ii) Environmental concerns (e.g., induced seismicity) iii) Not yet widely commercialized	i) Suitable for dry, low-permeability rock areas ii) Enables scalable, engineered geothermal energy iii) Promising for future deployment in non-traditional regions

challenging to navigate and secure funding for geothermal projects.

4. Public Awareness and Adoption: Limited public awareness and misconceptions about geothermal energy represent substantial barriers to its adoption. Concerns about drilling-induced seismicity (such as potential earthquakes or ground shaking from drilling or hydraulic fracturing) lead to resistance from local communities. Fears of groundwater contamination, especially in EGS systems, where chemical injections or geothermal fluid leaks could contaminate local water sources, are also prevalent. Additionally, the perception of long payback periods can deter consumers, as geothermal systems are often compared unfavorably to air-source heat pumps or fossil-fuel-based HVAC systems. To address these concerns, targeted outreach programs, policy incentives, and technological advancements are essential to demonstrate the safety, reliability, and environmental benefits of geothermal energy (Kumar et al., 2022). Building public trust through transparent communication, case studies, and clear cost-benefit analyses will help increase awareness and adoption.
5. Limited Public Awareness (Reiteration): The limited understanding of geothermal energy among the public poses a significant hurdle for its wider adoption. Fears about seismicity and water contamination due to the use of chemicals in EGS contribute to misunderstandings. Furthermore, long payback periods compared to more familiar technologies discourage investment in geothermal systems. To overcome these challenges, efforts should focus on educational outreach, demonstrating the safety and environmental benefits of geothermal energy (Kumar et al., 2022; Breede et al., 2015). By sharing successful case studies and providing detailed cost-benefit analyses, stakeholders can build public trust and accelerate market penetration of geothermal systems.

3.4 Recent technological advancements in geothermal systems

As the global demand for sustainable and low-carbon energy sources increases, significant advancements in geothermal energy technologies have emerged. These innovations aim to improve the efficiency of geothermal power generation, expand the accessibility of geothermal resources, and enhance the overall economic feasibility of geothermal systems (Kumari and Ranjith, 2019). This section discusses two key areas of technological progress: innovations in drilling and heat exchanger technologies, and the development of EGS.

3.4.1 Innovations in drilling and heat exchanger technologies

Innovations in drilling and heat exchanger technologies are driving significant advancements in geothermal energy, improving operational efficiency, reducing costs, and enhancing system performance. Drilling remains one of the most critical and cost-intensive components of geothermal energy development, and recent breakthroughs are addressing these challenges (Barbier, 2002). One key innovation is Plasma and Laser-Assisted Drilling, where high-energy plasma or laser beams are used to pre-weak rock formations before mechanical drilling begins. This technique reduces the strength of the rock, minimizing wear on drill bits and significantly lowering operational costs. Plasma-assisted drilling also allows for deeper penetration into hard-to-reach formations that were once difficult or expensive to access, expanding geothermal energy potential (Saxon and Putman, 2003). Another important development is Percussion and Rotary-Percussion Drilling, which combines the rotary motion of traditional drilling with percussive action. This combination enhances penetration rates and speeds up the drilling process, particularly in challenging hard rock formations (Bernardi et al., 2019). This dual approach enables more efficient drilling and shortens the overall time required for installation in complex geological environments. Additionally, Geothermal-Specific Mud and Casing Designs have made significant strides. High-temperature-resistant drilling fluids (geothermal mud) and advanced casing materials have greatly improved borehole stability, especially under extreme pressure and temperature conditions (Bernardi et al., 2019). These innovations mitigate risks such as borehole collapse and fluid leakage, common challenges faced in geothermal extraction, further improving the reliability of geothermal systems.

In addition to drilling technologies, advancements in heat exchanger technologies are enhancing geothermal system efficiency and minimizing environmental impacts. One of the most notable innovations is the use of Closed-Loop Borehole Heat Exchangers (BHEs) in ground-source heat pump systems. BHEs facilitate efficient heat transfer between the ground and the fluid circulating within the system (Price et al., 2023). New designs have optimized heat exchange and expanded their ability to operate in a broader range of geological conditions, improving system performance and making geothermal energy more versatile (Floridia et al., 2020; Banks, 2022). Furthermore, Binary Cycle Power Plants are a breakthrough in geothermal energy extraction. These plants utilize a secondary fluid with a lower boiling point than water, allowing for the generation of electricity from geothermal resources at lower temperatures (Manente, 2011). This innovation makes it possible to tap into previously underutilized geothermal resources, improving energy extraction while minimizing environmental impacts, such as surface emissions (Ziółkowski et al., 2021). Another exciting development is the integration of Nanofluids in Heat Exchangers (Waware et al., 2024). Nanofluids are fluids containing nanoparticles, which significantly enhance thermal conductivity. By improving heat transfer efficiency, nanofluids increase the overall performance of geothermal systems, leading to smaller, more compact systems without sacrificing efficiency. Together, these innovations in drilling and heat exchanger technologies are making geothermal energy more efficient, cost-effective, and environmentally sustainable (Liu et al., 2016). They are transforming geothermal energy into a more viable and competitive option for large-scale, renewable energy production, offering significant potential for the future of global energy solutions.

3.4.2 Enhanced geothermal systems and their potential

Conventional geothermal systems depend on naturally occurring geothermal reservoirs with sufficient permeability and fluid content, such as hot springs or hydrothermal fields. However, the geographical limitations of these resources restrict the widespread deployment of geothermal energy (Olasolo et al., 2016). EGS offers a transformative solution by creating artificial reservoirs in hot, dry rock formations, enabling heat extraction in areas without naturally occurring geothermal resources. This technology has the potential to significantly expand the availability of geothermal energy beyond the limitations of traditional systems (Aghahosseini and Breyer, 2020). EGS technology involves several key processes that allow for efficient heat extraction from deep underground reservoirs. Hydraulic Stimulation is a critical technique in this process, where high-pressure fluid is injected into impermeable rock formations to create or enhance fractures (Li et al., 2022). These fractures increase the permeability of the rock, enabling fluid to circulate more effectively and extract heat. This artificial fracturing method can unlock geothermal potential in regions previously considered unsuitable for conventional geothermal energy production (Moska et al., 2021). Additionally, Advanced Reservoir Monitoring plays a crucial role in optimizing the hydraulic stimulation process (Qun et al., 2019). Real-time monitoring through technologies like seismic imaging and fiber-optic sensors allows for precise control of the reservoir's behavior during stimulation. These technologies provide valuable data on the reservoir's conditions, enabling optimized fluid circulation and efficient heat extraction, improving the overall performance of EGS systems. Another promising development is the exploration of Supercritical Geothermal Systems, where supercritical fluids—substances that exist at extremely high pressures and temperatures—are used to carry more heat and expand faster than traditional steam. This could significantly increase geothermal energy output, unlocking vast untapped geothermal potential, especially in areas without accessible hydrothermal reservoirs (Cipolla et al., 2010).

The potential of EGS is vast, with estimates suggesting that it could tap into geothermal resources many times larger than those available from conventional geothermal systems. However, several challenges must be addressed to unlock this potential fully. One major concern is Induced Seismicity, where the hydraulic stimulation process can occasionally trigger small earthquakes or seismic events, raising safety and environmental concerns (Atkinson et al., 2020). Another challenge is Reservoir Sustainability; maintaining the long-term stability of artificial reservoirs is crucial for EGS's commercial viability. Ensuring that fluid circulation is sustained and preventing the rapid cooling of the reservoir are key factors in the success of these systems. Lastly, the Economic Viability of EGS remains a challenge. The costs associated with drilling, reservoir stimulation, and continuous monitoring are high, and while the technology holds great promise, further research and technological improvements are necessary to make EGS a cost-effective alternative to conventional geothermal systems (National Research Council et al., 2013). In summary, the integration of innovative drilling technologies, advanced heat exchangers, and the development of Enhanced Geothermal Systems positions geothermal energy as a potentially pivotal player in the transition to a sustainable energy future (Porter et al., 2019). Continued advancements in these technologies will not only enhance the efficiency and scalability of geothermal systems but also make them more accessible and commercially viable. As these technologies evolve, EGS could transform geothermal energy into a major contributor to global renewable energy production, addressing both energy needs and climate change mitigation.

3.5 Smart system integration in geothermal energy utilization

The integration of smart technologies in geothermal energy systems has significantly improved their efficiency, reliability, and sustainability (Abu-Rayash and Dincer, 2020). Advanced solutions based on the IoT, AI, and ML enable real-time monitoring, predictive analytics, and automated control mechanisms, leading to optimized energy production and system longevity (Jahan and

Abir, 2024). This section explores the role of these technologies in geothermal system optimization and their application in predictive maintenance and real-time energy management.

3.5.1 Role of IoT, AI, and ML in geothermal system optimization

The integration of IoT-enabled sensors and smart devices in geothermal energy systems has revolutionized operational efficiency and reliability (Rane et al., 2023). These sensors continuously collect critical data such as temperature, pressure, flow rates, and energy output, enabling real-time monitoring and analysis. When combined with AI and ML algorithms, this data facilitates advanced system optimization and offers several key benefits that improve the performance and sustainability of geothermal energy systems. Optimized Resource Utilization is one of the significant advantages of AI in geothermal systems (Akın et al., 2010). AI-driven models can analyze subsurface conditions in real-time, adjusting extraction rates dynamically to maximize heat recovery while ensuring that the geothermal resource is not depleted or overexploited. By preventing excessive cooling of the reservoir, these models ensure the long-term sustainability of the geothermal system, contributing to its efficiency and longevity (Hemmatabady et al., 2022). In addition, Energy Efficiency Enhancements are realized through the use of ML algorithms (Meng et al., 2018). These algorithms predict geothermal reservoir behavior with high accuracy, allowing power plants to adapt operational parameters such as turbine speed, reinjection rates, and fluid extraction rates. By optimizing these parameters, geothermal plants can operate at peak thermal efficiency, reducing energy consumption and improving overall system performance.

Furthermore, Fault Detection and Anomaly Prediction are critical benefits provided by AI in geothermal systems. AI-powered diagnostic systems monitor drilling operations, heat exchange processes, and fluid circulation in real time to identify any irregularities (Merad et al., 2024). These systems can predict potential faults before they escalate into major failures, allowing for early intervention and reducing costly downtime or repairs. This proactive approach to maintenance not only increases system reliability but also reduces operating costs over the system's lifetime (Frangopol and Liu, 2019). AI-enhanced geothermal reservoir modeling has also transformed geothermal exploration and resource assessment. By integrating geophysical, geological, and operational data, AI models provide highly accurate predictions of geothermal reservoir capacity and longevity. This advanced modeling technique significantly reduces the financial risks associated with geothermal projects by improving site selection strategies and optimizing drilling decisions (Kothamasu et al., 2006; Balac et al., 2013). As a result, the development of geothermal projects becomes more efficient and cost-effective, driving the broader adoption of geothermal energy as a reliable, renewable energy source.

3.5.2 Harnessing AI, ML, and IoT for cost-effective and sustainable geothermal energy systems

Integrating Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) into geothermal energy systems offers significant cost-saving opportunities and operational enhancements across the project lifecycle. In the exploration phase, AI and ML algorithms can analyze vast geological datasets to identify optimal drilling sites, reducing the risk of unsuccessful drilling and lowering exploration costs (Akın et al., 2010; Hemmatabady et al., 2022). For instance, companies like Zanskar are utilizing ML models to evaluate the best locations for geothermal drilling, significantly cutting down exploration expenses and encouraging greater investment in the sector (Merad et al., 2024). During drilling and infrastructure development, AI-driven predictive analytics can optimize drilling operations by forecasting subsurface conditions, thereby minimizing drilling risks and reducing downtime (Frangopol and Liu, 2019). This precision in drilling not only lowers operational costs but also extends the lifespan of drilling equipment. In terms of operational efficiency, IoT devices enable real-time monitoring of geothermal plant components, facilitating immediate detection of anomalies and predictive maintenance. This proactive approach reduces unplanned outages and maintenance costs (Balac et al., 2013). Additionally, AI-powered IoT systems can enhance thermodynamic modeling, leading to more efficient energy production processes.

Moreover, AI models can simulate reservoir behavior under various extraction scenarios, allowing for optimized resource utilization while preserving reservoir health. This ensures the sustainability of geothermal energy as a reliable source over the long term (Frangopol and Liu, 2019). Economically, the integration of AI and ML into geothermal systems has demonstrated potential in reducing operational costs and improving economic efficiency. For example, machine learning applications in geothermal exploration have been shown to lower costs, increase accuracy in identifying subsurface resources, and reduce environmental footprints, thereby favoring social acceptance and accelerating the transition to a sustainable energy matrix (Hemmatabady et al., 2022; Merad et al., 2024). In summary, the integration of AI, ML, and IoT technologies in geothermal energy systems presents a compelling case for cost reduction and efficiency enhancement. These technologies not only streamline exploration and operational processes but also contribute to the sustainable and economically viable expansion of geothermal energy.

3.5.3 Predictive maintenance and real-time energy management

Predictive maintenance is one of the most transformative applications of AI and IoT in geothermal energy systems, offering a shift from traditional fixed-schedule maintenance to data-driven, proactive strategies. Traditional maintenance models, which rely on predefined schedules, can lead to unnecessary downtime or the failure of components at inopportune times. By contrast, predictive maintenance uses real-time data to anticipate failures and reduce operational disruptions (Balac et al., 2013). AI-Based Failure Prediction is central to predictive maintenance in geothermal systems. ML models analyze data from operational sensors to detect early signs of equipment degradation in critical components such as pumps, turbines, and heat exchangers (Soori et al., 2024). This allows for proactive interventions, enabling operators to replace or repair parts before they fail, thus avoiding unplanned downtimes and expensive emergency repairs. Additionally, Vibration and Thermal Monitoring via IoT-based sensors play a crucial role in identifying potential equipment issues. Vibration sensors can detect irregularities in rotating machinery, such as turbines or pumps, signalling potential mechanical failures. Thermal imaging sensors, on the other hand, monitor the temperature of mechanical components, helping to identify overheating or inefficiencies that may lead to catastrophic damage if left unchecked. By catching these anomalies early, geothermal systems can minimize downtime and prevent costly failures (Wang and Jianu, 2009). Moreover, Automated Workflows and Alerts enhance the efficiency of predictive maintenance by leveraging AI-powered diagnostics. These systems automatically trigger maintenance alerts, schedule maintenance tasks, and even optimize spare parts inventory management (Olakotan and Yusof, 2020). This automation reduces the need for manual intervention, streamlining operations and ensuring that critical tasks are addressed promptly.

In addition to predictive maintenance, Real-Time Energy Management systems are crucial for optimizing the efficiency and performance of geothermal plants. By integrating AI and IoT, geothermal systems can adjust in real-time to maximize operational efficiency while maintaining grid stability (Zhou et al., 2014). Balancing Energy Demand and Supply is a key feature of these systems. AI-driven smart grid integration allows geothermal plants to dynamically adjust power output based on real-time electricity demand, ensuring a stable supply to the grid and improving load balancing. This adaptability helps optimize energy generation and consumption across the grid, ensuring that geothermal energy is deployed where it is needed most (Gan et al., 2020). Similarly, Optimizing Heat Distribution is an important aspect of real-time energy management, especially in geothermal district heating networks. AI-based optimization models ensure maximum heat utilization by reducing thermal losses and improving energy efficiency in heating distribution systems. These models enable operators to adjust temperature settings and flow rates to minimize waste and enhance system performance (Keçebaş and Yabanova, 2012). Finally, Enhancing Load Forecasting with Machine Learning-based predictive analytics further improves geothermal plant efficiency. By assessing historical and real-time energy demand patterns, ML models provide accurate forecasts, enabling geothermal operators to make data-driven decisions for energy dispatch. This helps optimize resource allocation and improve financial planning by anticipating demand spikes and adjusting operations accordingly (Rasheed et al., 2023).

3.6 Hybrid geothermal systems and energy storage solutions

The integration of hybrid energy systems has emerged as a promising strategy to enhance the reliability and efficiency of renewable energy sources. Hybrid geothermal systems combine B with other renewable sources, such as solar and wind power, ensuring a more stable and continuous energy supply (Olabi et al., 2020). Additionally, advancements in thermal energy storage (TES) technologies have further optimized the efficiency and flexibility of geothermal power plants. This section explores the benefits of hybrid geothermal systems and the role of thermal energy storage in optimizing geothermal energy utilization (Ding et al., 2021).

3.6.1 Combining geothermal energy with solar, wind, and other renewables

Geothermal energy is a reliable source of baseload power, offering a consistent and stable electricity supply (Kabeyi, 2019). When integrated with intermittent renewable energy sources like solar and wind, geothermal power can significantly enhance both system efficiency and long-term sustainability. Hybrid geothermal systems present several key advantages. First, they provide enhanced grid stability. Geothermal energy acts as a stable and continuous source, helping to mitigate the fluctuations in power generation often associated with solar and wind energy. While solar and wind outputs can vary with weather conditions and time of day, geothermal energy ensures grid reliability by maintaining a steady contribution, thereby balancing these fluctuations (Xu et al., 2022). Second, hybrid systems optimize resource utilization. By incorporating solar and wind energy, these systems maximize energy capture, particularly during periods of peak solar radiation or high wind speeds. When renewable generation is low or when demand surges, geothermal energy steps in as a dependable backup, ensuring a consistent power supply and reducing the reliance on fossil fuels (Al-Mahruqi et al., 2021). Finally, improved energy efficiency is achieved by combining geothermal with other renewable sources. This integration reduces curtailment losses—the practice of discarding excess energy when generation exceeds demand. Hybrid systems can more effectively balance supply and demand, resulting in more efficient power production with minimal waste (Dokmak et al., 2024). By fully utilizing available energy, these systems enhance both the economic and environmental benefits of renewable energy production. In summary, hybrid systems that leverage the complementary strengths of geothermal, solar, wind, and other renewables offer a comprehensive and highly efficient approach to sustainable energy production. These systems contribute to grid stability, optimized energy usage, and reduced waste, making them a promising solution for a sustainable energy future. Figure 4 shows the combination of Geothermal energy with other renewable energy sources.

3.6.2 Common hybrid configurations

Various hybrid configurations can be employed to optimize energy generation and ensure a more reliable and efficient power supply (Olabi et al., 2020; White et al., 2021). Some notable examples include.

- Geothermal-Solar Hybrid Plants: In this configuration, solar thermal collectors preheat the geothermal fluids before they are extracted. This reduces the energy required for fluid extraction, thereby improving the overall efficiency of the geothermal plant by leveraging solar energy to assist in the process (Li et al., 2020).
- Geothermal-Wind Hybrid Systems: Wind turbines generate electricity when favorable wind conditions are present, providing supplemental power during peak demand periods or when geothermal output is variable. This system helps stabilize the energy supply, ensuring a more consistent power generation even during fluctuating conditions (Shah, 2023).
- Geothermal-Biomass Hybrid Plants: Biomass energy is utilized to generate additional heat or electricity, complementing geothermal output. This is especially beneficial in regions where there is an abundance of agricultural waste or forestry residues. The integration of biomass enhances both heat generation and the overall sustainability of the energy system (Thain and DiPippo, 2015).

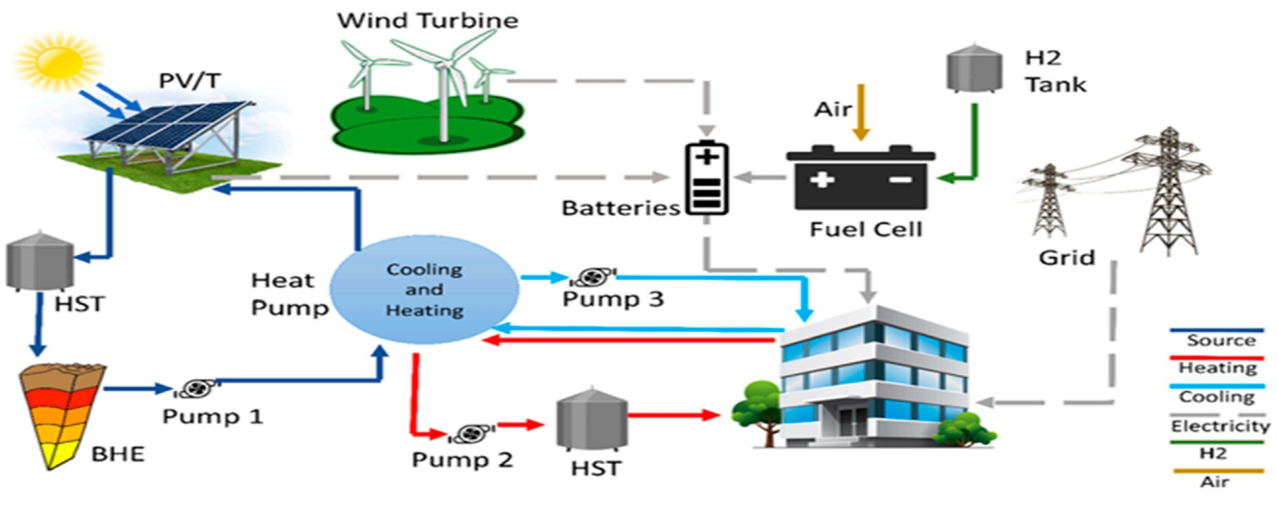

FIGURE 4
Geothermal energy sources with other renewable energy sources (Dokmak et al., 2024).

3.6.3 Thermal energy storage and its impact on efficiency

Thermal Energy Storage plays a critical role in optimizing the utilization of geothermal energy by capturing excess heat and releasing it when demand arises (Zhang et al., 2013). This capability significantly enhances both the efficiency and operational flexibility of geothermal power plants in several key ways. First, load balancing and demand response are greatly improved by TES. By storing thermal energy for later use, geothermal plants can release heat during peak demand periods, reducing the need for additional power generation. This not only stabilizes the grid but also minimizes fluctuations in supply and lowers the operational costs associated with meeting high demand. Second, increased power plant flexibility is another significant benefit of TES (Sifnaios et al., 2023). The system allows geothermal plants to store excess heat during low-demand periods, ensuring that this energy is available when demand rises. This ensures a consistent power output even when intermittent renewable sources such as wind or solar energy are insufficient. Finally, TES improves system efficiency by optimizing heat recovery and minimizing heat loss (Dincer, 2002). This results in enhanced overall energy conversion efficiency, making geothermal power generation more reliable, cost-effective, and adaptable to varying operational conditions. Ultimately, TES enables geothermal power plants to operate more sustainably, enhancing their role in the broader renewable energy mix.

3.6.4 TES methods used in geothermal applications

TES methods are employed in geothermal applications to optimize energy storage and improve efficiency in energy utilization. One common method is sensible heat storage, where thermal energy is stored in solid or liquid materials, such as hot water tanks or molten salts, and later released when needed. This method is cost-effective and scalable, making it ideal for load balancing in geothermal plants (Shah et al., 2024). Another method is latent heat storage, which utilizes phase-change materials (PCMs) that absorb and release heat during phase transitions, such as from solid to liquid or *vice versa*. This approach is highly efficient for thermal regulation, as it requires less space and reduces the overall storage volume, making it an effective solution for space-constrained applications. Lastly, Aquifer Thermal Energy Storage (ATES) is a method that leverages underground aquifers to store and extract heat. This method enhances the sustainability of geothermal heating and cooling systems by utilizing natural subsurface reservoirs, thereby minimizing the environmental impact of the storage process (Tester et al., 2007). These TES methods collectively enhance the overall efficiency, sustainability, and scalability of geothermal energy systems.

3.7 Economic and environmental impact of geothermal energy

Geothermal energy has emerged as a cost-effective and environmentally sustainable alternative to fossil fuels, providing long-term economic and environmental benefits. While initial capital investment in geothermal projects can be high, a detailed cost-benefit analysis demonstrates its economic viability over time. Moreover, geothermal energy significantly contributes to carbon footprint reduction, aligning with global climate goals. This section explores the financial and environmental implications of adopting geothermal energy (Kristmannsdóttir and Ármannsson, 2003).

3.7.1 Cost-benefit analysis and return on investment

The economic feasibility of geothermal energy is influenced by various factors, including resource availability, drilling costs, plant design, and operational efficiency. A comprehensive cost-benefit analysis typically incorporates several key elements. First, capital costs, which represent the largest upfront expense, include the costs of exploration, drilling, and infrastructure construction (Idroes et al., 2024). These costs can range from $2,500 to $5,000

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per kilowatt (kW), depending on the scale and location of the project. Second, operational and maintenance costs are relatively low for geothermal power plants, typically ranging from $0.01 to $0.03 per kilowatt-hour (kWh). This is primarily due to the minimal fuel requirements compared to fossil fuel-based plants (Casebeer et al., 1997). Geothermal plants also benefit from high energy generation potential, operating at capacity factors of 70%–90%, which significantly outperforms solar (20%–30%) and wind (30%–50%) energy. This high-capacity factor ensures a stable and continuous power supply, making geothermal energy a reliable source of baseload power. In terms of Return on Investment (ROI), although geothermal projects incur high upfront costs, they offer long-term profitability. The payback period for geothermal projects typically ranges from 5 to 10 years, and with a lifespan extending beyond 30–50 years, they provide a solid ROI. Additionally, government incentives, tax credits, and carbon pricing mechanisms can improve the financial viability of geothermal projects, enhancing their attractiveness as investments for both private and public sectors. These factors collectively contribute to the financial feasibility and long-term economic viability of geothermal energy as a sustainable power generation solution (Cordes, 2017).

3.7.2 Contribution to carbon footprint reduction and climate goals

Geothermal energy is a low-carbon and sustainable energy source that plays a crucial role in mitigating climate change and advancing global climate goals (Owusu and Asumadu-Sarkodie, 2024). The environmental benefits of geothermal energy are substantial. One of the most significant advantages is its minimal greenhouse gas emissions. Geothermal plants emit less than 5% of the CO_2 produced by coal-fired power plants, with emissions as low as 50 g CO_2 per kWh, compared to coal's approximate 1,000 g CO_2/kWh. This stark reduction in emissions directly supports efforts to reduce the carbon footprint of energy production. Another key contribution of geothermal energy is its reduction of fossil fuel dependency. By replacing coal and natural gas in electricity generation and direct heating applications, geothermal energy not only cuts carbon emissions but also helps reduce air pollution, contributing to cleaner and healthier environments. Furthermore, geothermal energy promotes sustainable resource management (Stevens et al., 2020). With effective reservoir management, geothermal resources can be continuously replenished, providing a long-lasting, renewable energy source while ensuring minimal ecological disruption.

Geothermal energy also aligns with global net-zero goals. Countries such as the United States, Iceland, and Kenya have integrated geothermal energy into their national climate strategies, utilizing it to drive carbon neutrality and transition toward sustainable energy systems (Roberts et al., 2023). Geothermal's potential to support these goals makes it a critical player in achieving global climate objectives. However, despite its many benefits, geothermal energy faces challenges that need to be addressed. Issues such as land use concerns, induced seismicity, and water consumption must be carefully managed through improved regulatory frameworks, enhanced environmental monitoring, and technological innovations (Friedmann et al., 2020). As advancements in drilling, energy storage, and hybridization further enhance geothermal efficiency, the energy source will continue to be a vital component in the global shift toward a low-carbon, sustainable energy future. In conclusion, geothermal energy offers a compelling economic and environmental case, delivering high long-term returns while making significant contributions to global carbon reduction efforts.

3.8 Policy, regulations, and market trends

The growth and widespread adoption of geothermal energy are largely shaped by government policies, regulatory frameworks, and shifting market dynamics. Supportive policies, including financial incentives and research funding, have been instrumental in advancing geothermal energy technologies (Chen and Huang, 1993). Additionally, market trends underscore the increasing importance of geothermal energy as the world transitions toward renewable energy. This section delves into the role of government incentives, regulatory frameworks, and the current trends influencing the global geothermal sector.

3.8.1 Government incentives and support for geothermal adoption

To expedite geothermal energy deployment, many governments have implemented policy mechanisms and financial incentives aimed at reducing risks and stimulating investment. These include.

- Tax Credits and Subsidies: Countries around the world offer investment tax credits (ITCs) and production tax credits (PTCs) to geothermal developers, helping mitigate the financial risks of large-scale projects. For example, the U.S. Investment Tax Credit (ITC) provides a 30% deduction on eligible geothermal project costs, significantly reducing initial investment burdens (Pan et al., 2019).
- Grants and Research Funding: Government funds support exploration, drilling, and research into advanced geothermal technologies, reducing the risks associated with early-stage development. The European Union and U.S. Department of Energy (DOE), for example, have allocated millions for EGS research to unlock new geothermal resources (Kriger, 2024).
- Feed-in Tariffs (FiTs) and Power Purchase Agreements (PPAs): Some countries guarantee fixed electricity rates for geothermal power producers, ensuring long-term financial viability. For example, Kenya and Indonesia have introduced favorable FiTs and PPAs, attracting private investors by providing long-term stability in revenue generation (Kriger, 2024).
- Risk Mitigation Strategies: Governments offer various risk mitigation mechanisms, such as exploration risk insurance and loan guarantees. Programs like GEORISK (EU) and the African Union's Geothermal Risk Mitigation Facility (GRMF) provide financial protection against unsuccessful drilling attempts, thereby encouraging investment in geothermal energy (Winters and Cawvey, 2015).

3.8.2 Global trends and future outlook in geothermal energy

The global geothermal energy market is experiencing rapid growth, fueled by technological advancements, rising energy security concerns, and robust climate policies. In 2023, global geothermal capacity surpassed 16 GW, with projections indicating it will exceed 24 GW by 2030 (Rybach, 2022). Leading countries such as the U.S., Indonesia, Kenya, the Philippines, and Turkey are leveraging their geothermal resources to meet increasing energy demands and promote sustainable energy solutions. EGS are further expanding geothermal energy's potential by unlocking resources in regions lacking natural permeability, broadening its global reach. Hybridizing geothermal with solar, wind, and energy storage systems is enhancing grid stability, balancing intermittent energy sources, and improving overall efficiency (van der Zwaan and Dalla Longa, 2019). Geothermal energy is also gaining momentum in direct-use applications like district heating, greenhouse agriculture, industrial processes, and desalination, contributing to economic growth and sustainable development. Geothermal's clean, renewable nature makes it a crucial tool in global decarbonization efforts, helping countries meet their net-zero emissions targets and diversify their energy mix. Additionally, market liberalization and deregulation are fostering public-private partnerships, attracting foreign investment, and driving innovation. These developments are making geothermal energy more accessible, financially viable, and competitive (Korucan et al., 2024). With strong government support, technological innovation, and evolving market trends, geothermal energy is poised to play a central role in the global transition to a sustainable, low-carbon energy future.

3.9 Case studies and real-world implementations

The successful deployment of geothermal energy projects across different regions provides valuable insights into best practices, challenges, and innovative solutions. Examining these projects helps in understanding the technical, economic, and policy factors that contribute to their success. This section highlights notable geothermal projects worldwide and key lessons learned for future geothermal development.

3.9.1 Olkaria geothermal power plant (Kenya)

The Olkaria Geothermal Power Plant in Kenya is Africa's largest geothermal facility, boasting a generation capacity of over 800 MW. As a pioneering project in renewable energy, Olkaria plays a crucial role in Kenya's power sector, contributing more than 40% of the nation's electricity supply and significantly reducing dependence on fossil fuels (Miller, 2016). The plant's success is attributed to a combination of strong government support, well-structured public-private partnerships (PPPs), and strategic investments. The Kenyan government played a pivotal role by implementing feed-in tariffs (FiTs) and fostering private-sector participation, creating a favorable investment climate. Additionally, financial backing from international institutions, including the World Bank and the African Development Bank, was instrumental in securing the necessary funding for the plant's expansion. Beyond infrastructure and financing, the project prioritized local workforce development, ensuring long-term sustainability and efficient plant operation through targeted training programs (Abdi et al., 2024). The Olkaria project serves as a model for geothermal energy development in Africa, demonstrating how policy support, international collaboration, and human capital investment can drive large-scale renewable energy initiatives.

3.9.2 The Geysers geothermal complex (United States)

The Geysers Geothermal Complex in California, United States, is the largest geothermal field in the world, with a generation capacity of approximately 1.5 GW. Having been in operation since the 1960s, it remains a significant contributor to clean and renewable energy in the United States. A key factor in the longevity and sustainability of The Geysers has been the implementation of advanced reservoir management techniques, particularly the re-injection of treated wastewater to maintain underground pressure and sustain steam production (Dobson et al., 2020). Additionally, regulatory incentives, such as tax credits and renewable energy mandates, have played a crucial role in attracting investment and fostering the expansion of geothermal power generation. Beyond technological advancements and policy support, community engagement and environmental monitoring have been instrumental in addressing concerns related to seismic activity and land use, ensuring the project's long-term viability. The Geysers stands as a global benchmark for geothermal energy development, showcasing how innovative reservoir management, supportive policies, and proactive community involvement can enhance the sustainability of large-scale geothermal power projects.

3.9.3 Hellisheidi geothermal power plant (Iceland)

The Hellisheidi Geothermal Power Plant in Iceland is one of the most advanced geothermal facilities in the world, with a generation capacity of 303 MW of electricity and 400 MW of thermal energy. As a key pillar of Iceland's energy sector, Hellisheidi contributes significantly to the country's impressive geothermal utilization, supplying nearly 90% of its heating needs and 27% of its electricity (Mikhaylov, 2020). A defining feature of the plant is its integration with carbon capture technology (CarbFix), which enables the permanent storage of CO_2 in basalt rock formations, effectively making the plant a negative-emission facility. Additionally, Hellisheidi maximizes energy utilization through direct-use applications, supplying geothermal heat for district heating and industrial processes. The Icelandic government has played a crucial role in the plant's success by making substantial investments in research and innovation, driving continuous advancements in geothermal efficiency and sustainability. As a result, Hellisheidi stands as a global model for the future of geothermal energy, demonstrating how carbon capture, direct-use applications, and government-backed innovation can enhance both environmental and economic benefits.

3.9.4 Sarımehmet geothermal plant (Turkey)

The Sarımehmet Geothermal Plant in Turkey is a notable example of the country's expanding geothermal energy sector, with a generation capacity of 50 MW. As part of Turkey's push toward increasing its renewable energy capacity, the plant plays a crucial role in diversifying the country's energy mix. One of the key technological advancements at Sarımehmet is the use of binary cycle power plants, which enable efficient energy conversion from low- to medium-temperature geothermal resources, making previously untapped reservoirs viable for power generation (Oyan et al., 2023). To encourage private sector participation, Turkey has implemented risk mitigation programs, including exploration drilling insurance, which has significantly reduced investment uncertainties and attracted private investors. Additionally, local government initiatives have supported the expansion of geothermal district heating, providing communities with a reliable and cost-effective heating solution while boosting public acceptance and economic benefits. The success of the Sarımehmet plant underscores the importance of innovative technology, investment security, and supportive local policies in accelerating geothermal development in emerging markets (Oyan et al., 2023).

3.9.5 Yangbajain geothermal power station (China)

The Yangbajain Geothermal Power Station in Tibet is China's most prominent geothermal facility, with an installed capacity of 25.2 MW and an annual electricity generation of approximately 100 GWh. Commissioned in 1977, it was the first geothermal power plant in China and remains the largest, supplying about 30% of Lhasa's electricity needs. Situated at an elevation of around 4,300 m, it is among the highest-altitude geothermal plants globally (Xue et al., 2023). The plant utilizes medium-temperature geothermal resources from a shallow reservoir, with temperatures ranging between 140°C and 160°C. To address declining pressure in the shallow reservoir, deeper wells have been drilled to tap into higher-temperature resources, with temperatures up to 329.8°C recorded at depths of approximately 1,500 m. Beyond electricity generation, the facility contributes to direct-use applications, such as heating greenhouses and washing sheep's wool (Zhang et al., 2019). The development of the Yangbajain Geothermal Power Station was supported by significant government investment, including its designation as a key project in China's Fifth Five-Year Plan, with over 200 million RMB allocated for its construction. This strategic investment underscores China's commitment to advancing geothermal energy as a sustainable and reliable energy source.

3.9.6 Lessons learned and best practices for future geothermal development

The success of geothermal power projects worldwide offers valuable insights for future developments, emphasizing several key factors. A robust policy and regulatory framework, including government incentives like feed-in tariffs, tax credits, and risk mitigation funds, is crucial for attracting investment and ensuring project sustainability. Advanced resource management techniques, such as reservoir re-injection, along with the integration of carbon capture and storage (CCS) technologies, ensure long-term resource availability and contribute to climate change mitigation (Akhigbe, 2025). Expanding geothermal's role through hybridization with solar, wind, and energy storage systems, as well as direct-use applications like district heating and industrial processes, increases both economic and environmental benefits. Public-private partnerships and international collaboration are vital for funding and accelerating technological advancements, while community engagement ensures that stakeholder concerns are addressed, fostering trust and local support. By incorporating these best practices, future geothermal projects can enhance their efficiency, sustainability, and public acceptance, solidifying geothermal energy's position as a reliable and clean energy source in the global transition to renewables.

3.10 Future research directions and emerging trends in geothermal energy

As the global demand for sustainable and low-carbon energy solutions grows, geothermal energy research is evolving to overcome existing challenges and unlock new opportunities. Innovations in drilling technologies, reservoir management, hybrid renewable systems, and interdisciplinary applications are driving the future of geothermal energy. This section highlights potential breakthroughs in geothermal technology and explores interdisciplinary approaches that can enhance geothermal applications.

3.10.1 Potential breakthroughs in geothermal technology

Potential breakthroughs in geothermal technology are poised to significantly enhance the sector's efficiency and scalability. Advanced drilling techniques, such as plasma and laser drilling, offer faster penetration rates and deeper access to geothermal reservoirs, reducing operational costs and equipment wear. AI-assisted drilling optimization, leveraging ML algorithms, improves precision, subsurface imaging, and material selection, further boosting efficiency. EGS innovations are overcoming natural permeability limitations by improving hydraulic stimulation techniques and exploring supercritical geothermal fluids, which can yield up to ten times more energy than conventional systems. Geothermal-integrated energy storage solutions, including TES and geothermal battery systems, enable on-demand electricity generation and enhance grid stability by storing excess heat for later use. Hybrid and multi-source renewable systems, such as geothermal-solar-wind plants and geothermal-powered hydrogen production, are further revolutionizing geothermal energy by integrating multiple renewable sources for more reliable power generation and contributing to decarbonization efforts. These advancements make geothermal energy a more viable, flexible, and sustainable energy solution in the transition to a renewable-powered future.

3.10.2 Interdisciplinary approaches for enhanced geothermal applications

3.10.2.1 Artificial intelligence and machine learning in geothermal optimization

AI and ML are playing a pivotal role in optimizing geothermal energy production by enhancing operational efficiency and long-term field management. AI-driven predictive maintenance and fault detection systems are significantly improving plant efficiency by proactively identifying potential issues before they lead to costly downtime, thereby reducing maintenance costs and ensuring continuous power generation. Additionally, ML-based techniques are being applied to reservoir modeling, well placement, and fluid flow prediction, leading to better energy extraction rates and more effective management of geothermal fields. By analyzing vast amounts of data, these technologies can optimize drilling locations, predict reservoir behavior, and improve fluid dynamics, ensuring that geothermal resources are used sustainably and efficiently for long-term energy production.

TABLE 3 Summary of the related literature.

Contributions	Main findings	Research gap	References
Systematic review of geothermal-powered district heating and cooling networks; highlights sustainability benefits.	Demonstrates that geothermal district systems offer high energy efficiency and reduced emissions, supporting climate-resilient urban heating strategies.	Limited empirical data on real-world performance.	Kassem and Moscariello (2024)
Explores geothermal energy applications at various depths for district heating and cooling.	Identifies depth-specific performance metrics and suggests deep systems yield higher thermal outputs under specific geological conditions.	Focuses on existing building stock, limiting applicability to new constructions.	Romanov and Leiss (2022)
Comprehensive review of geothermal energy extraction methods (conventional, hybrid, enhanced systems).	Outlines the advantages of hybrid and enhanced systems in achieving scalable and stable thermal outputs.	Lacks cost analysis and economic feasibility discussion.	(Thermal work OURS)
Reviews vertical closed-loop geothermal systems, emphasizing subsurface factors.	Emphasizes the influence of soil type, thermal conductivity, and borehole spacing on vertical system efficiency.	Does not address horizontal system comparisons.	Khaleghi and Livescu (2023)
Traces geothermal energy research evolution and future trends.	Highlights increased R&D investment and emerging hybrid and AI-enhanced geothermal technologies.	Lacks field-specific case studies.	Abu-Rayash and Dincer (2020)
Critical review of shallow geothermal energy systems for heating and cooling.	Shows significant thermal efficiency in shallow systems with minimal surface disruption in temperate zones.	Focuses primarily on Europe, limiting global applicability.	Ahmed et al. (2022)
Discusses technological advancements and challenges in geothermal energy systems.	Reveals that material science and control automation significantly improve geothermal system performance.	Limited focus on policy and regulatory barriers.	Izadi and Freitag (2025)
Analyzes deep wells and shallow heat pumps for sustainable geothermal energy.	Confirms potential for large-scale adoption but emphasizes site-specific customization for optimal performance.	Insufficient real-world case study evaluations.	Gan et al. (2020)
Focuses on sustainable energy transitions, including geothermal energy.	Contextualizes geothermal energy as a critical contributor to low-carbon energy transitions.	Does not provide specific geothermal system case studies.	Kabeyi and Olanrewaju (2022)
Examines resource assessment and management for various geothermal systems.	Advocates for improved thermal reservoir modeling and data acquisition to enhance deployment accuracy.	Primarily theoretical, lacks practical implementation insights.	Izadi and Freitag (2025)
Reviews enhanced geothermal systems (EGS), particularly hot dry rock engineering.	Demonstrates potential of EGS in extending geothermal viability to low-permeability regions.	Does not extensively cover economic viability.	Xu et al. (2022)
Highlights EGS as a key component of a renewable-energy grid.	Shows EGS systems can offer reliable baseload power, enhancing grid stability.	Lacks discussion on technical and regulatory challenges.	Boretti (2022)
Explores thermal energy storage benefits in geothermal applications.	Identifies significant potential of subsurface storage in demand-side load balancing.	Limited experimental validation of proposed benefits.	Vérez et al. (2023)
Discusses recent HVAC improvements integrating renewable energy for zero-energy buildings.	Suggests geothermal integration in HVAC can lower building energy consumption by up to 40%.	Focuses more on general HVAC than specific geothermal applications.	Aljashaami et al. (2024)
Examines geothermal energy's relationship with carbon emissions reduction.	Projects a strong inverse correlation between geothermal adoption and CO_2 emission intensity.	Relies heavily on statistical models, lacking experimental data.	Mikhaylov (2020)

(Continued on the following page)

TABLE 3 (*Continued*) Summary of the related literature.

Contributions	Main findings	Research gap	References
Provides a detailed roadmap for geothermal well construction technology development.	Introduces drilling automation and novel casing materials to reduce costs and improve safety.	Lacks specific implementation strategies for various geothermal systems.	Price et al. (2023)
Thorough review of nanofluid applications in heat exchangers, highlighting energy efficiency.	Reports nanofluid-enhanced exchangers achieve up to 15% thermal performance gains.	Limited practical application data in real-world scenarios.	Waware et al. (2024)
Focuses on innovative integration of AI and IoT for building energy management.	Demonstrates potential for 20%–30% efficiency gains using AI-driven system optimization.	Overemphasis on theoretical applications without extensive case studies.	Abdi et al. (2024)
Proposes a novel hybrid energy management solution integrating solar and geothermal.	Shows simulation-based evidence of hybrid systems reducing peak energy demand.	Limited testing or demonstration of proposed systems in real-world environments.	Jahan and Abir (2024)
Exploration of non-thermal power generation systems as an alternative to conventional methods.	Suggests theoretical models support economic benefits of magneto-hydro and piezoelectric geothermal coupling.	Lack of detailed analysis on the economic feasibility of these systems.	Shah (2023)
Comprehensive review of geothermal energy development prospects worldwide.	Finds growing international interest but emphasizes disparity in technical capabilities among regions.	Limited focus on technological challenges in the implementation of geothermal systems.	Rybach (2022)
In-depth review of geothermal energy storage methods and their applications in energy systems.	Indicates underground storage achieves higher long-term thermal retention than most conventional systems.	Lacks a clear comparison of geothermal energy storage efficiency against other methods.	Shah et al. (2024)
Provides a detailed classification and hybridization of geothermal systems.	Classifies over 10 hybrid models and identifies configurations with optimal COP under different climates.	The complexity of the hybrid systems may limit practical implementation in diverse environments.	Dokmak et al. (2024)
Explores the intersection of carbon emissions reduction and astronomy.	Discusses theoretical planetary models with geothermal parallels, offering analogies but little direct applicability.	Not directly related to geothermal energy, making it less applicable to the field.	Stevens et al. (2020)

3.10.2.2 Geothermal-carbon capture synergies

Geothermal-CO_2 storage, or geo-sequestration, is an emerging field where geothermal reservoirs are being explored for permanent carbon dioxide storage, aligning with global efforts to achieve carbon neutrality. This approach offers a promising solution to mitigate the effects of CO_2 emissions by securely storing them underground in geothermal reservoirs, reducing the greenhouse gases in the atmosphere. Additionally, Carbon Capture Utilization and Storage (CCUS) technologies are demonstrating the potential of geothermal energy in advancing negative emissions technologies. For instance, Iceland's Hellisheidi power plant has already implemented the process of mineralizing CO_2 into basalt rock formations, converting the captured CO_2 into solid minerals. This not only helps in reducing emissions but also utilizes geothermal heat to enhance the process, positioning geothermal energy as a key player in combating climate change. These innovations are crucial in the global transition to a low-carbon future.

3.10.2.3 Geothermal desalination and water-energy nexus

Geothermal desalination is gaining attention as a sustainable solution for providing clean water in arid regions, where freshwater resources are limited. Geothermal energy is being tested for use in desalination technologies, harnessing the Earth's natural heat to power the desalination process while simultaneously generating electricity. This dual benefit makes geothermal a promising solution in regions where both energy and clean water are scarce. Additionally, hybrid geothermal-membrane distillation systems are being explored to enhance energy efficiency and reduce costs. These systems combine geothermal heat with membrane distillation technology to provide more energy-efficient and cost-effective water purification, making it a viable and sustainable solution for addressing water scarcity in geothermal-rich regions. By integrating water and energy systems, the geothermal-water-energy nexus holds great potential for improving resource management and sustainability.

3.10.2.4 Bio-geothermal integration

Bio-geothermal integration is a promising approach that combines geothermal energy with biological processes to enhance energy production and support sustainable practices. One area of focus is Microbial-Enhanced Geothermal Energy (MEGE), where scientists are studying thermophilic microbes—microorganisms that thrive in high-temperature environments—to improve heat extraction and aid in mineral recovery from geothermal reservoirs. These microbes can enhance the efficiency of geothermal systems by accelerating natural processes and helping to extract valuable minerals, making geothermal energy production more efficient and cost-effective. Additionally, geothermal waste heat is being harnessed for algae and biomass cultivation. By utilizing the excess heat from geothermal systems, controlled environments can be created for growing algae and biomass, which can, in turn, support biofuel production and boost agricultural productivity. This integration not only enhances geothermal energy output but also contributes to sustainable bioenergy and agricultural practices.

These advancements and interdisciplinary approaches hold immense potential for transforming geothermal energy into a more efficient, flexible, and widely applicable renewable energy source. As research continues, breakthrough technologies, AI integration, and hybrid energy systems will play a crucial role in enhancing geothermal's contribution to global clean energy goals.

Table 3 summarizes the reviewed literature, highlighting the contributions and limitations of each study. It provides an overview of the strengths and weaknesses of these contributions within the context of energy systems, geothermal technologies, and related innovations.

4 Findings

Geothermal energy, particularly through Ground-Source Heat Pumps (GSHPs), offers remarkable efficiency with Coefficients of Performance (COP) ranging from 3.5 to 6.0, equating to energy efficiency levels of 300%–600%. This leads to significant reductions in electricity consumption. Furthermore, geothermal systems can lower CO_2 emissions by 50%–70% compared to traditional fossil fuel-based HVAC systems. Geothermal power plants, emitting less than 5% of the CO_2 produced by coal-fired plants, further illustrate their environmental benefits. Economically, GSHP installation costs range from \$2,500 to \$5,000 per kW, while operational costs are minimal at \$0.01–\$0.03 per kWh. The return on investment (ROI) is realized within 5–15 years, with infrastructure lifespans ranging from 30 to 50 years. On a global scale, geothermal capacity exceeded 16 GW in 2023 and is expected to surpass 24 GW by 2030, with leading contributions from countries like the U.S., Indonesia, Kenya, the Philippines, and Turkey. Technological advancements, including plasma and laser-assisted drilling, rotary-percussion drilling, and high-temperature-resistant fluids, have made geothermal drilling more efficient and cost-effective. Additionally, AI and ML models now optimize system performance, aiding in real-time monitoring, predictive maintenance, and adaptive energy management. The development of EGS has further expanded the potential of geothermal energy by allowing heat extraction from impermeable rock formations, and AI-driven modeling is enhancing heat recovery and reducing drilling risks. Hybrid geothermal systems, integrating solar, wind, and biomass, have further improved energy reliability. Geothermal-solar systems use solar collectors to preheat geothermal fluids, while geothermal-wind hybrids help stabilize energy supply during variable demand periods. Thermal Energy Storage technologies, including sensible heat storage, phase-change materials (PCMs), and aquifer thermal energy storage, have enhanced the efficiency and stability of grid systems. Successful geothermal projects, such as the Olkaria Geothermal Power Plant in Kenya, The Geysers in the U.S., and Hellisheidi in Iceland, highlight the significant impact of geothermal energy. However, challenges such as high initial costs, site-specific geological constraints, regulatory complexity, and public concerns over seismic activity and groundwater contamination remain barriers to wider adoption. These findings underscore the importance of ongoing advancements in policy, hybridization, and drilling technologies to unlock the full potential of geothermal energy as a sustainable, efficient, and resilient solution for heating and cooling.

5 Conclusion

Geothermal energy continues to emerge as a highly sustainable and technically viable solution for meeting heating, cooling, and electricity demands across diverse geographies. It offers considerable advantages in energy efficiency, carbon emission reduction, and long-term cost effectiveness. Ground-source heat pumps (GSHPs) demonstrate coefficients of performance (COP) ranging between 3.5 and 6.0, achieving efficiencies of 300%–600%, while geothermal systems in general reduce CO_2 emissions by 50%–70% when compared to conventional heating, ventilation, and air conditioning (HVAC) systems. The integration of geothermal with renewable resources such as solar, wind, and biomass in hybrid energy configurations further enhances system reliability and operational efficiency. Notably, geothermal-solar hybrid systems help reduce the energy requirements associated with subsurface heat extraction. Moreover, the incorporation of thermal energy storage strategies, including sensible and latent heat storage, contributes to system flexibility and cost-effective load balancing.

This review makes a unique contribution by synthesizing recent multidimensional innovations that collectively redefine geothermal energy deployment. Central to this transformation is the convergence of advanced digital technologies, namely, Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT), with cutting-edge subsurface engineering techniques, such as Enhanced Geothermal Systems (EGS). These innovations enable real-time optimization, predictive maintenance, and improved system control, positioning geothermal energy as an intelligent and adaptive infrastructure component. Furthermore, evolving policy frameworks and increasing investment trends are facilitating the transition of geothermal energy from a niche application to a scalable solution in national and regional energy portfolios.

However, despite these advancements, several challenges remain. The high initial installation cost, estimated between USD 2,500 and 5,000 per kilowatt for GSHPs, alongside geological constraints and regulatory barriers, continues to impede widespread adoption. Nonetheless, successful utility-scale projects, such as the Olkaria Geothermal Power Plant in Kenya (800 MW capacity) and The Geysers in California, United States (1.5 GW capacity), serve as benchmarks for the scalability, reliability, and economic viability of geothermal energy systems. These plants consistently achieve capacity factors of 70%–90%, significantly outperforming solar (20%–30%) and wind (30%–50%) technologies. Moreover, geothermal facilities emit less than 5% of the carbon dioxide produced by coal-fired power plants, aligning with global decarbonization targets.

Countries such as the United States, Iceland, and Kenya have demonstrated strong commitments to integrating geothermal energy into their national strategies, guided by the objectives of achieving net-zero emissions and enhancing energy security. Looking ahead, the intelligent hybridization of geothermal systems, the expansion of advanced thermal storage solutions, and the digital transformation of energy infrastructure will collectively underpin the broader adoption and evolution of geothermal energy. When supported by robust regulatory policies, financial incentives, and international collaboration, geothermal energy is poised to play a central role in shaping a clean, resilient, and sustainable global energy future.

5.1 Actionable recommendations

1. Strengthen Policy and Regulatory Frameworks: Governments must establish robust, transparent, and supportive policies to reduce permitting delays, lower investment risks, and offer financial incentives (e.g., tax credits, feed-in tariffs). These measures are essential to create a favorable environment for both public and private geothermal development.
2. Invest in Cost-Reduction and Digital Innovation: Prioritize funding and R&D for technologies that reduce capital costs, such as advanced drilling, modular GSHPs, and prefabricated components, while also supporting integration of AI, ML, and IoT for system optimization, predictive maintenance, and smart energy management.
3. Promote Hybrid Renewable Energy Integration: Encourage the deployment of hybrid geothermal systems combined with solar, wind, or biomass to maximize system reliability, energy output, and land use efficiency, particularly in remote, off-grid, or variable-demand regions.

Author contributions

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