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Review

Sustainable Geothermal Energy: A Review of Challenges and Opportunities in Deep Wells and Shallow Heat Pumps for Transitioning Professionals

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Abstract: Geothermal energy has emerged as a cornerstone in renewable energy, delivering reliable, low-emission baseload electricity and heating solutions. This review bridges the current knowledge gap by addressing challenges and opportunities for engineers and scientists, especially those transitioning from other professions. It examines deep and shallow geothermal systems and explores the advanced technologies and skills required across various climates and environments. Transferable expertise in drilling, completion, subsurface evaluation, and hydrological assessment is required for geothermal development but must be adapted to meet the demands of high-temperature, high-pressure environments; abrasive rocks; and complex downhole conditions. Emerging technologies like Enhanced Geothermal Systems (EGSs) and closed-loop systems enable sustainable energy extraction from impermeable and dry formations. Shallow systems utilize near-surface thermal gradients, hydrology, and soil conditions for efficient heat pump operations. Sustainable practices, including reinjection, machine learning-driven fracture modeling, and the use of corrosion-resistant alloys, enhance well integrity and long-term performance. Case studies like Utah FORGE and the Geysers in California, US, demonstrate hydraulic stimulation, machine learning, and reservoir management, while Cornell University has advanced integrated hybrid geothermal systems. Government incentives, such as tax credits under the Inflation Reduction Act, and academic initiatives, such as adopting geothermal energy at Cornell and Colorado Mesa Universities, are accelerating geothermal integration. These advancements, combined with transferable expertise, position geothermal energy as a major contributor to the global transition to renewable energy.

Keywords: geothermal drilling; enhanced geothermal systems (EGSs); shallow geothermal systems; sustainable well design; closed-loop systems; heat pumps; soil hydrology

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1. Introduction

Geothermal energy, derived from the earth's internal heat, offers immense potential for electricity generation and direct heating or cooling in residential and industrial applications. This energy originates from the earth's natural thermal gradient, radioactive mineral decay, and the absorption of solar energy at the surface. Unlike other intermittent renewable energy sources such as solar and wind energy, geothermal energy represents a stable source with minimal greenhouse gas emissions. It also offers weather-independent baseload power with a high capacity factor, smaller land footprint, and higher efficiency [1]. These advantages position geothermal energy use as a major cornerstone of the global energy transition when compared to other methods. Estimates suggest that geothermal resources could supply 127 to 1420 exajoules [10^{18} joules] annually, exceeding the global energy demand by up to 280% [2]. Despite this promise, geothermal energy accounts for only 0.2% of the global primary energy supply due to high development costs and limited access to shallow, high-temperature resources, and the studies in this field remain widely underrepresented and marginal in number compared to other areas of research [3]. Recent advances in drilling technologies and transferable practices from oil and gas operations position geothermal energy as an emerging frontier for transiting professionals. However, realizing its potential requires addressing key challenges and developing strategies and technologies for an effective transition from existing scientific industries to geothermal energy, particularly due to the lack of geothermal energy education degrees [4,5].

Drilling and completion operations account for more than 70% of the cost of geothermal projects, which underscores the importance of optimizing operations to reduce costs and enhance efficiency [6]. Geothermal wells introduce unique challenges, which include extreme temperatures, material durability, complex geomechanics, and fluid thermodynamics [7]. Shallow geothermal systems, unlike deep wells, are influenced by key hydrological factors such as soil properties, groundwater flow, and thermal conductivity. Engineers and scientists must adapt to these conditions by integrating best practices from existing industries, including drilling and completing wells for water, oil, or natural gas. Key factors such as designing drill bits [8] and optimizing drilling fluids [5] significantly influence the success of geothermal wells. A robust drilling plan that anticipates and mitigates worst-case scenarios is critical to achieving operational safety and cost-effectiveness. As the demand for renewable energy grows, the advancement of geothermal drilling techniques will play a key role in meeting global energy needs while minimizing environmental impacts.

In addition to the technical challenges, geothermal energy faces significant challenges in the financial, environmental, and social domains. Technically, geothermal drilling must overcome extreme conditions, such as high temperature and high pressure (HTHP), hard rock formations, and corrosive fluids, which complicate operations and increase costs. Drilling fluids require advanced formulations to ensure thermal stability, maintain well integrity, and prevent formation damage, while materials must withstand casing expansion, corrosion, and cement degradation [9–12]. Financially, exploration and drilling can account for up to 70% of project costs, with geological uncertainties amplifying risks and inefficiencies [13,14]. Regulatory complexities vary across regions and include determining surface and subsurface ownership of land and heat in some countries, tolerating longer timelines with higher uncertainties, and securing funds for higher capital costs [15]. Environmental risks, such as induced seismicity, land subsidence, and freshwater contamination, require robust monitoring and mitigation plans, and gaining public trust remains critical to the success of these projects. Proactive community involvement and addressing environmental concerns are essential to secure a "Social License to Operate" [11]. Tackling these multi-faceted barriers requires innovative technologies, streamlined regulatory frameworks, and coordinated efforts among stakeholders to unlock the full potential of such a sustainable and reliable energy source.

The transition to geothermal energy seems essential, yet significant gaps remain in educational degrees and the research literature regarding transferable skills from other industries and their application to geothermal development. The current literature also largely overlooks the integration of deep and shallow geothermal systems, including hybrid applications for heating and cooling, leaving professionals with limited guidance on navigating the unique demands of this field. This review addresses these gaps by offering a comprehensive analysis of geothermal systems, emphasizing their applications, challenges, and opportunities for industry professionals. It provides insights to help engineers and scientists tackle distinct technical and operational challenges, such as extreme temperatures, hard rock formations, and corrosive environments, using sustainable and innovative solutions. Unlike conventional oil and gas operations, geothermal projects demand a paradigm shift that emphasizes prioritized environmental stewardship and optimized resource utilization. By focusing on key geothermal challenges, sustainable well design, and cutting-edge technologies, this review provides engineers and scientists with a balanced depth and breadth of practical and theoretical insights and strategies to drive advancements in geothermal energy and support global renewable energy goals.

2. Review Method

This review systematically examines the key technical and operational distinctions between geothermal and oil and gas drilling and completions. It also explores the potential of shallow geothermal systems, highlights the role of integrated hybrid systems for heating and cooling, and identifies essential knowledge for professionals entering the field. The potential of artificial intelligence and machine learning in advancing geothermal energy is emphasized. This review addresses challenges such as well design, rig operations, and sustainable practices, focusing on high-temperature conditions, material selection, geomechanics, and emerging technologies. This review explores strategies for addressing extreme downhole conditions in deep wells and surface challenges in shallow systems, such as the use of heat pumps. It highlights the need for energy-efficient technologies and sustainable solutions. Case studies, including those conducted at Utah FORGE and the Geysers in the US, provide practical examples of engineering advances aligned with renewable energy goals.

The methodology used in this study follows the Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines. An exhaustive search was conducted in databases including Google Scholar, ScienceDirect, and OnePetro, in addition to the Stanford IGA Geothermal Conference Database, using search terms such as “geothermal drilling”, “geothermal well design,” “high-temperature geothermal”, “heat pumps”, and “sustainable drilling technologies”. The eligibility criteria targeted studies published in the last 20 years focusing on geothermal energy, transferable knowledge from oil and gas, sustainability, and emerging technologies. Mainly peer-reviewed articles and conference papers were included. We excluded studies lacking technical depth or addressing non-drilling and completion topics, such as power generation. Non-drilling and completion topics, such as power generation and financial modeling, were excluded to maintain focus on technical challenges and solutions. The scope also excludes post-stimulation activities, such as production engineering, pumps, and heat exchanger design. Case studies from the US were included, and other global case studies were beyond the scope of this review, which emphasizes US-based developments to maintain a concise and focused analysis. Each source underwent a quality assessment that included evaluations of methodology, data reliability, and relevance. Data extraction involved a protocol calibrated for consistency, with duplicate reviews to minimize bias. Findings were synthesized to highlight practical insights and solutions for advancing geothermal technologies, address operational challenges, and identify future opportunities for engineers and scientists transitioning to the geothermal sector.

Through the screening process, we identified 124 sources. Figure 1 illustrates the distribution of references used in this review, categorized by topic and publication type. Most references are categorized under “Drilling Challenges and Practices” and “Completion Challenges and EGS”, highlighting the focus on core technical aspects of geothermal energy. The “Shallow System and Heat Pump” category underscores the potential of shallow systems as both stand-alone and integrated solutions. References are divided between journal articles and other publications, with journals dominating in terms of advanced techniques and case studies, reflecting the academic rigor of this review. Including diverse sources ensured a comprehensive analysis of both practical and theoretical advancements in geothermal energy. Figure 1 also highlights the significant increase in geothermal energy publications since 2019, coinciding with the implementation of Utah FORGE in 2019 and the allocation of several US Department of Energy (DOE) funding opportunities during that period. This exponential growth reflects the recognition of geothermal energy's potential as a cornerstone in renewable energy. The rise in journal articles and other publications demonstrates the expansion of research focused on addressing the current technical challenges pertaining to emerging technologies like Enhanced Geothermal Systems and closed-loop shallow systems. This surge underscores the industry's potential to advance sustainable energy solutions, driven by innovations and benefiting from existing skills and knowledge concerning subsurface resources.

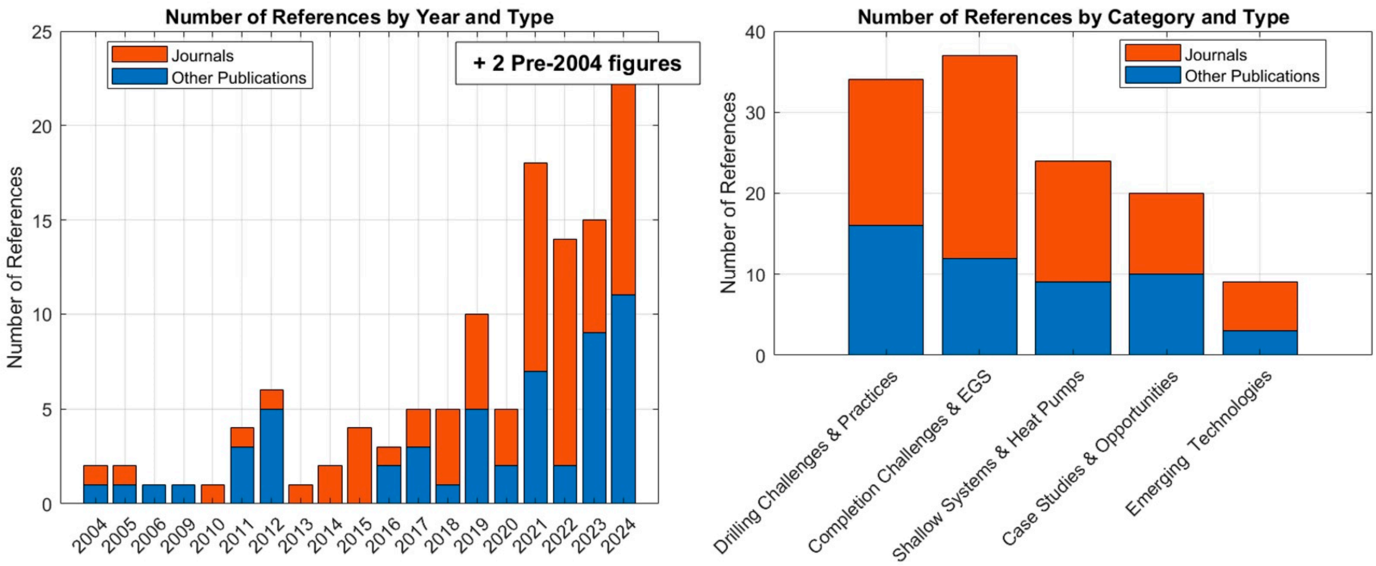

Figure 1. Trends in geothermal publications (2004–2024), illustrating growing research focus on emerging technologies and opportunities (**left**). The right panel shows the distribution of references by category and publication type, including drilling, design, materials, geomechanics, shallow systems, case studies, and emerging techniques in geothermal research (**right**).

This manuscript is structured in a way that provides a comprehensive review of geothermal energy challenges, solutions, and opportunities. The Introduction outlines the significance of geothermal energy and existing knowledge gaps; it is followed by the Review Method Section (Section 2), detailing the systematic approach to the literature analysis. Section 3 examines challenges and sustainable well design, including high-temperature environments and abrasive rock formations. Section 4 covers best practices in drilling and completion operations, addressing drilling materials, rigs, and sustainable solutions. Section 5 focuses on shallow systems and heat pumps, highlighting installation methods and hydrological impacts. Section 6 explores emerging technologies and case studies, such as Utah FORGE and integrated systems at Cornell University. Section 7 discusses opportunities for engineers and scientists transitioning into geothermal energy. Table 1 summarizes the key challenges, operational restrictions, and corresponding solutions in geothermal energy development. These include high-temperature environments, abrasive formations, sustainable well design, and unique issues related to shallow systems. Solutions such as thermally stable polymers, corrosion-resistant alloys, and advanced technologies like managed pressure drilling and Enhanced Geothermal Systems (EGSs) are highlighted.

Table 1. Summary of key challenges, restrictions, and proposed solutions for geothermal energy systems, categorized by drilling operations, well design, completion techniques, and shallow system applications.

Main Challenges	Restrictions	Solutions	Reference
Challenges and Sustainable Well Design	High-Temperature Challenges and Material Degradation Hard and Abrasive Rocks and Excessive Tool Wear Sustainable Well Design and Environmental Impact	Thermally stable polymers and additives Polycrystalline Diamond Compact Bits Closed-loop Systems and Repurposing Abandoned Wells	[16–40]
Best Practices in Drilling Operations	Surface Equipment, Energy Consumption, and Carbon Footprint Downhole Material Selection and Corrosive Environment Drilling Problems: Lost Circulation, Stuck Pipes, and Well Control	Automated and Energy-Efficient Equipment Corrosion-Resistant Equipment and Fluids Managed Pressure Drilling	[41–66]
Well Completion and Enhanced Geothermal Systems	Enhanced Geothermal Systems Hydraulic Fracturing and Economic Feasibility Induced Seismic Events	Stimulated Dry and Impermeable Rocks Optimized Spacing and Biodegradable Fluids Geomechanics Modeling and Microseismicity Analysis	[67–78]
Shallow Systems and Heat Pumps	System Installation Methods and Trench Collapse Hydrology and Soil Properties Hot/Cold Climates and Surface Environments	Optimal Machinery for Excavation and Backfill Correlating Moisture Content and Thermal Conductivity Optimal Thermal Performance and Sustainability	[79–94]

3. Challenges and Sustainable Well Design

3.1. High-Temperature Challenges

Geothermal wells are subject to extreme conditions, including temperatures exceeding 400 °C and pressures above 150 bar, which require advanced materials that maintain structural integrity. Specialized high-temperature composite cement, such as the types introduced by [16,17], have been specifically designed to meet the mechanical demands of geothermal applications to ensure durability and performance under harsh thermal and chemical conditions. Accurate bottom-hole temperature (BHT) prediction and measurement are critical in selecting the appropriate materials and designing wells that can withstand these challenges [7]. In addition to technical performance, sustainability is a key consideration in material development. Chemical additives and alternative cementitious materials, mainly industrial natural by-products, have been shown to reduce the environmental footprint of geothermal well cements while improving their long-term stability [18]. Projects like GeoWell have validated cement slurries under simulated and in-situ conditions to prove their efficacy at temperatures exceeding 400 °C [19–21]. Moreover, thermally stable polymers and additives in drilling fluids have enhanced operational efficiency by maintaining rheological properties at temperatures up to 800 °F [427 °C], further supporting supercritical geothermal operations [10,22]. Skills in developing advanced materials are crucial for ensuring both operational reliability and environmental sustainability in geothermal well design. By integrating these materials with precise thermal modeling and sustainable practices, the geothermal industry can effectively address extreme conditions while minimizing environmental risks.

3.2. Hard-and-Abrasive-Rock Challenges

One of the biggest challenges of geothermal energy is drilling through hard and abrasive rocks, such as granite and gneiss, which require advanced technologies and optimized processes to enhance operational efficiency and sustainability. Geothermal drilling typically allows slower rates of 50 to 100 ft/hr [15–30 m/hr] compared to those of up to 1000 ft/hr [305 m/hr] in oil and gas wells, mainly due to the extreme abrasiveness and high compressive strength of geothermal formations. Additionally, geothermal wells require a larger well diameter than a typical oil and gas well due to the higher injection and production flow rates, contributing to drilling complexity and cost. This prolongs drilling time, accelerates tool wear, and increases non-productive time (NPT) [19,21]. Optimizing the key drilling parameters, such as drill bit selection, rotational speed, the weight on the bit, and the circulation rate of the drilling fluids, is critical to achieving a high drilling rate of penetration (ROP). However, maximizing these drilling parameters risks downhole equipment failure [23]. Addressing these challenges requires skills and innovative solutions that balance performance, cost, and environmental impact.

Polycrystalline Diamond Compact (PDC) bits and Roller Cone (RC) bits are the primary types of drill bits employed in geothermal operations. PDC bits have a remarkably higher ROP, achieving up to 700% higher rates in hard granitic formations, such as at the Geysers project in California [8]. However, PDC bits face durability challenges in fractured and abrasive zones, necessitating shorter run lengths compared to RC bits, which are better suited for highly variable formations [8]. Multi-stage bit changes, adapted to specific depth conditions, are commonly employed to leverage the strengths of each bit type. Additionally, skills are needed to advance emerging technologies such as percussive hammers and conical diamond element bits to improve penetration rates and reduce operational costs for abrasive rock formations [24]. Rotary Percussive Drilling (RPD) integrates impact energy with conventional rotary techniques to improve penetration rates and reduce tool wear [25]. Thermal spallation drilling offers a non-contact alternative that uses high heat flux to fracture rocks, significantly reducing mechanical wear and energy consumption [26]. Automation technologies, such as robotic systems, enhance sustainability by monitoring downhole conditions to improve safety and reduce energy usage [7,27]. Geothermal operations can achieve greater efficiency, lower costs, and alignment with renewable energy objectives by integrating these innovations with adaptive drilling strategies.

3.3. Sustainable Well Design

Sustainable practices in geothermal well design prioritize minimizing environmental impacts while ensuring the long-term viability of energy extraction. Geothermal wells are subject to extreme conditions, often exceeding 300 °C, as well as corrosive fluids that require innovative approaches to ensuring well integrity and resource management [7]. Unlike oil and gas, the designers of geothermal wells prioritize durability and sustainability by utilizing advanced materials like corrosion-resistant alloys and high-temperature cement to allow the wells to endure thermal cycling and chemical exposure [28,29]. Flexible couplings and specialized completion techniques further mitigate thermal stress, preserving well integrity and reducing long-term operational costs [16].

Innovative practices such as repurposing abandoned oil and gas wells exemplify the circular economy in geothermal energy development. Repurposing existing wells reduces environmental disruption, leverages established infrastructure, and reduces drilling costs, which can account for up to 70% of total project expenses [30,31]. Sustainable reservoir management strategies also include the systematic reinjection of geothermal fluids that maintain reservoir pressure and thermal stability, prolong resource life, and mitigate ecological impacts. The Paris Basin geothermal district heating scheme illustrates the success of reinjection and monitoring practices in ensuring sustainable operations [32,33]. These measures sharply contrast with oil and gas practices, which often prioritize short-term production at the expense of long-term reservoir deliverability and environmental considerations [13,34]. Closed-loop systems, such as downhole heat exchangers (DHEXs), further distinguish geothermal well design by minimizing resource depletion and environmental damage. These systems conserve water and reduce thermal pollution by circulating working fluids without discharging geothermal fluids to the surface [32], unlike traditional open-loop systems where reinjection of the geothermal fluids is required, including steam, to minimize the sanitary risks associated with the non-condensable gases in the vapor. Furthermore, community acceptance of surface well designs also plays a pivotal role in geothermal projects, addressing public concerns about environmental impacts and fostering social acceptance through the "Social License to Operate" [35]. Community support directly influences the feasibility and success of these initiatives. Acceptance varies globally and is governed by regional environmental concerns and economic expectations. Developers must engage with local communities, addressing environmental and social issues while offering financial and intellectual participation. Integrating geothermal energy with tourism can also boost public interest and support. Skills are needed to integrate innovative materials, adaptive operational strategies, and community-focused practices as well as ensure that geothermal well design aligns with sustainability goals.

Figure 2 illustrates the operational principles of a coaxial and U-shaped geothermal well, which emphasizes the flow dynamics and heat exchange processes between the inner and outer pipes to optimize energy extraction. In coaxial systems, fluid circulates in the annulus, leveraging the larger surface area for enhanced thermal exchange. The heated fluid, after absorbing heat from the outer pipe, experiences minimal thermal loss as it ascends through the inner pipe. This design underscores the focus on sustainability in geothermal systems by optimizing heat transfer while minimizing thermal inefficiencies [36,37]. Compared to conventional oil and gas wells—for which hydrocarbon extraction without reinjection systems is prioritized, leading to potential reservoir depletion and environmental consequences [32]—coaxial geothermal systems circulate fluids in a closed-loop, ensuring minimal environmental impact and long-term thermal stability. Similarly, U-shaped geothermal wells are drilled using advanced directional and horizontal drilling techniques to create a closed-loop system that connects two wellbores downhole. This configuration enhances heat exchange by maximizing the contact area with the geothermal reservoir while maintaining efficient fluid containment. Since this is a relatively new technique, other U-shaped configurations are currently in early development and implementation stages. High-temperature environments and chemically reactive fluids necessitate advanced materials, such as corrosion-resistant alloys and high-temperature cement, to maintain well integrity under extreme conditions [34,38]. These materials and thermal management strategies ensure the long-term sustainability of geothermal wells, in contrast to oil and gas wells, which rely on conventional materials optimized for short-term production [39]. Furthermore, geothermal well designs often incorporate advanced architectures, such as multilateral systems, to optimize heat extraction and improve energy efficiency, introducing complexities rarely encountered in oil and gas wells. Addressing these challenges requires skills in integrating reinjection strategies, innovative materials, advanced well designs, and customized engineering practices tailored to geothermal energy systems.

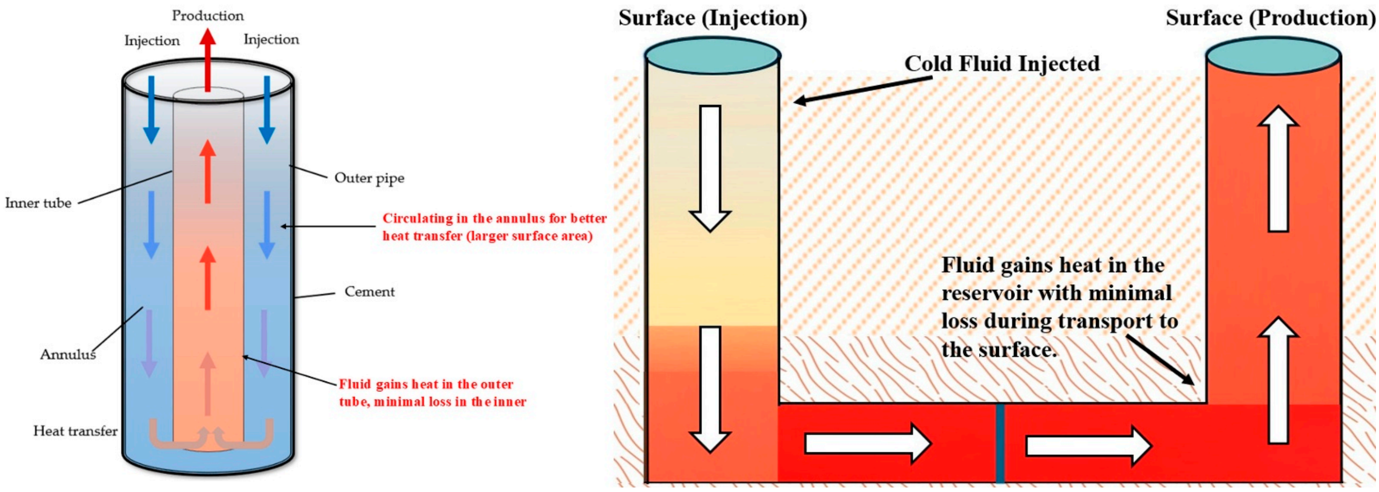

Figure 2. Coaxial and U-shaped geothermal well designs showing the flow of fluid down the annular space or injector well, heat absorption downhole, and the return of fluid to the surface for efficient geothermal energy extraction [40].

4. Best Practices in Drilling and Completion Operations

Geothermal drilling requires specialized strategies for navigating the technical, environmental, and economic complexities of energy extraction [41,42]. Advancements in Enhanced Geothermal Systems, closed-loop designs, and repurposing abandoned oil and gas wells expand the potential of geothermal energy [43,44]. Innovative drilling technologies, including rotary steerable systems, managed pressure drilling, and high-temperature-resistant alloys, enhance operational efficiency and equipment durability in extreme geothermal environments [44]. Moreover, life cycle assessments (LCAs) and stakeholder engagement ensure alignment with sustainability goals and foster public acceptance of geothermal projects [11,45].

4.1. Selection of Drilling Rigs and Surface Equipment

Adopting energy-efficient drilling rigs and surface equipment is critical to reducing carbon footprints and ensuring the sustainability of geothermal projects, particularly in extremely hot and hard-rock environments. Geothermal drilling requires specialized equipment to handle demanding operational conditions, such as Polycrystalline Diamond Compact (PDC) bits, high-strength insulated drill pipes, and advanced cooling systems. Innovations like air drilling and aerated mud systems help reduce cooling requirements and enhance energy efficiency in high-temperature zones. Optimized rig designs tailored for geothermal applications—featuring compact configurations and automated control systems—improve performance, minimize resource use, and reduce environmental impacts [46]. Real-time downhole monitoring technologies enhance well placement. Energy-efficient mud systems contribute to operational sustainability. However, skills are required for designing and handling innovative surface equipment. Geothermal absorption chillers powered by renewable energy and Combined Cooling, Heating, and Power (CCHP) systems utilize geothermal heat to optimize energy use, simultaneously producing power, heat, and cooling while reducing electricity demand and emissions [47,48]. Closed-loop systems, such as downhole heat exchangers (DHEXs), conserve water, prevent groundwater contamination, and maintain reservoir pressure, enhancing environmental stewardship [32]. Heat recovery systems capture and reuse excess thermal energy from drilling operations, lowering operational costs and reducing overall energy demand [49]. Additionally, integrating Permanent Magnet Synchronous Motors (PMSMs) into rigs eliminates intermediate gearboxes, reducing energy consumption and emissions while improving operational efficiency [50].

Automation, robotics, and the reuse of infrastructure further enhance the efficiency and sustainability of geothermal projects. Robotics applications in auto-driller and pipe-handling systems improve safety and operational precision by optimizing parameters in real-time [27]. Repurposing or deepening existing oil and gas wells for geothermal energy extraction provides a cost-effective alternative to drilling new wells, significantly reducing land disturbance, resource consumption, and overall project costs [42,43]. These integrated strategies demonstrate the transformative potential of advanced technologies and sustainable practices in geothermal drilling, positioning the industry to lead the global shift toward cleaner and more sustainable energy systems.

4.2. Downhole Material and Technology Selection

Material and technology selection plays a key role in minimizing the environmental impact of geothermal wells. Corrosion-resistant options like glass-reinforced epoxy (GRE) casing are increasingly favored for their durability, resistance to acidic geothermal fluids, and thermal conductivity, which help prevent corrosion and extend the lifespans of downhole components [51,52]. Customized cementing systems tailored for GRE casings further enhance well integrity under high-temperature-and-high-pressure (HTHP) conditions [51]. Sustainable drilling fluids, like produced-water-based muds (PWBMs), serve as an eco-friendly alternative; consisting of by-products such as red mud, these fluids are used to reduce reliance on toxic polymers to improve rheological properties and minimize fluid loss. Large-scale geothermal production through multi-well layouts has also gained momentum as a clean energy solution. However, optimizing deployment schemes is hindered by a limited understanding of how this approach impacts temperature depletion in geothermal reservoirs. A recent study addressed this gap by developing a 3D multi-well simulation method incorporating 1D line element geothermal well theory to improve calculation efficiency without sacrificing accuracy [10,38].

Innovative directional drilling and measurement while drilling (MWD) technologies complement material advances by reducing the environmental footprint of geothermal wells. Advanced tools, such as rotary steerable systems and steerable downhole motors, optimize complex well trajectories, minimize surface disruption, and improve drilling accuracy [53]. Real-time monitoring solutions like Cerebro Force in-bit sensing enhance operational precision by tracking critical metrics such as vibration and bit acceleration [54]. Drilling heat maps guide the selection of insulated drill pipes and active temperature management strategies, reduce thermal damage, and improve efficiency in HTHP zones [55]. Simulation-based optimization of multi-well layouts also improves heat extraction efficiency while reducing land use and resource consumption [38]. Advanced geophysical site characterization and exploration methods have been proposed for EGS systems, like using seismic imaging to locate optimal geothermal wells and electromagnetic surveys to limit traditional exploratory drilling and natural habitat disruption, further reducing environmental and financial impacts and constraints [56,57]. These combined strategies and skills ensure that geothermal projects leverage innovative downhole materials and technologies, thereby maximizing sustainability while addressing the unique demands of geothermal environments.

4.3. Drilling Problems and Sustainable Solutions

Geothermal drilling operations face significant challenges, with lost circulation being one of the most costly problems. In mature and naturally fractured fields, lost circulation can account for approximately 10% of total well costs, and this figure increases to over

20% for exploratory wells [7,58]. This problem is exacerbated in geothermal wells due to fractured igneous formations, making fluid loss more frequent and severe. Geothermal-specific loss circulation materials (LCMs), such as polymers and fibrous blends, effectively seal fractures while ensuring environmental safety by reducing contamination risks [59]. Advanced techniques like managed pressure drilling (MPD) could stabilize downhole pressures and mitigate the risk of fluid loss by balancing wellbore and formation pressures, particularly in high-temperature zones [28]. Integrating temperature-activated shape-memory polymers and mixed-material plugs further enhances fluid retention and wellbore stability, aligning with operational efficiency and sustainability goals [60].

Stuck pipes constitute another prevalent issue in geothermal drilling, often resulting from differential pressure sticking across permeable zones, inadequate hole cleaning, or unstable fractured formations. This problem can immobilize the drill string, which leads to the loss of downhole equipment, increased non-productive time (NPT), and higher operational costs. Techniques such as using continuous circulation systems maintain pressure and prevent cuttings from accumulating around the pipe, reducing the likelihood of stuck-pipe incidents [61]. Additionally, proactive measures like conditioning the drilling fluid to ensure proper viscosity and employing optimized casing and drilling programs can help further reduce the likelihood of stuck pipes [62]. Real-time monitoring technologies, including AI-based early warning systems, allow for proactive adjustments in drilling operations to avoid high-risk zones [63]. Real-time optimization of drilling fluid properties and using hydraulically actuated reamers improve borehole quality and stability, minimizing stuck-pipe risks [64]. Enhanced cuttings removal technologies also improve hole-cleaning efficiency by up to 30%, which contributes to safer and more sustainable drilling operations [10].

Drilling into a high-pressure zone presents unique challenges in geothermal drilling due to extreme high-temperature, high-pressure (HTHP) environments, which increase the risk of kicks and blowouts. Managed-Pressure Drilling systems, equipped with temperature-resistant blowout preventers (BOPs) and real-time pressure-monitoring devices, are critical for maintaining wellbore pressures and preventing sudden influxes of subsurface fluids [65]. Narrow-margin drilling fluids tailored to geothermal conditions ensure wellbore pressures remain within safe operational limits, further enhancing safety and reducing the environmental impact of well-control measures [66]. Systematic monitoring, inspection, and optimized casing designs enhance pressure management and reservoir sustainability by reducing the risks of thermal kicks and sudden pressure surges [33]. Developing the skills required to integrate advanced technologies, optimized drilling strategies, and sustainable materials is crucial for managing challenges like lost circulation, stuck pipes, and well control in geothermal drilling.

4.4. Geothermal Well Completion and Enhanced Geothermal Systems (EGSs)

Conventional hydrothermal systems depend on naturally occurring reservoirs involving heat, water, and permeability, which enable energy extraction from fluid circulation. In contrast, EGSs create new or enhance the permeability of pre-existing natural fractures in impermeable, dry rock formations, such as high-heat-producing granite, through hydraulic fracturing stimulation. A carrying fluid, typically cold water, is injected into the stimulated rock, where it exchanges heat and is produced as hot water or steam through this downhole heat exchanger system [67]. The injection of the cold fluid into the hot reservoir can cause cooling-induced stress. It has been found that pore pressure elevation and cooling-induced stress interact significantly and thus affect fracture reactivation, which can be a key initiation factor for induced seismicity [68].

EGSs come with inherent risks of induced seismicity, primarily due to hydraulic fracturing, which alters subsurface stress conditions and can reactivate pre-existing faults. High-pressure fluid injections can destabilize fault planes, triggering seismic activity. This risk highlights the need for careful site selection and rigorous control of injection rates and pressures. Some view induced seismicity as an unavoidable aspect of EGS development, while others argue that it can be minimized with advanced monitoring and risk management. Monitoring microseismicity is critical, as seen in projects like Utah FORGE (discussed in the case studies). These measures are essential to balance the potential of EGSs with public and environmental safety concerns. Another approach to stimulating a geothermal reservoir is to focus on reactivating natural fractures through hydroshearing rather than creating new ones. This technique is geology-dependent and leverages the naturally occurring saline fluids trapped in the fractured basement, eliminating the need to inject cold fluid.

Figure 3 illustrates the operational differences between these systems; it shows fluid production in hydrothermal reservoirs and heat recovery in an EGS through artificially induced fractures in impermeable rock. By enabling energy extraction from dry, impermeable formations, EGSs significantly broaden geothermal resource potential, making them a key innovation for accessing untapped geothermal energy.

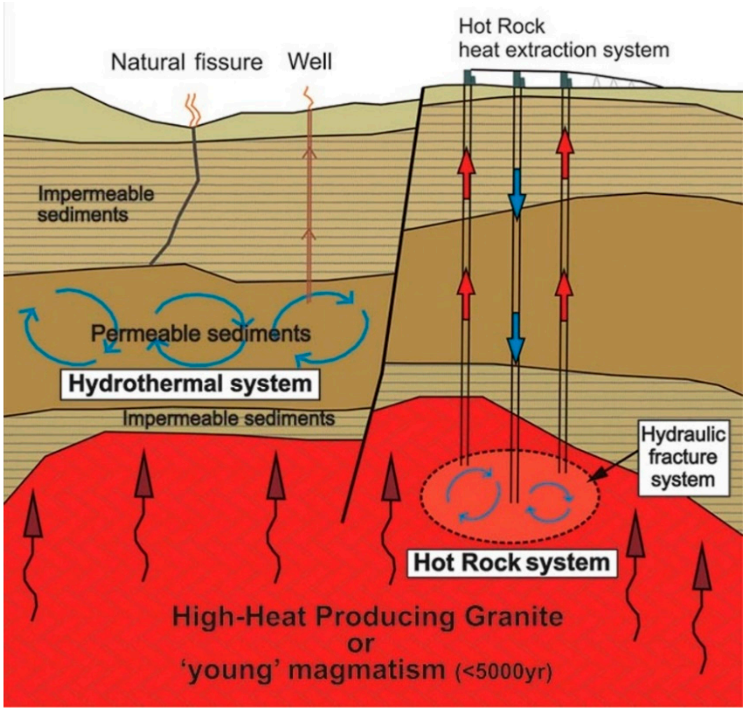

Figure 3. Geothermal energy extraction through hydrothermal and hot-rock systems (EGSs), illustrating fluid circulation in permeable sediments and heat recovery using hydraulic fracture systems within high-heat-producing granite [69].

Hydraulic fracturing in geothermal wells faces unique challenges due to extreme temperatures, variable fracture networks, and high-pressure conditions. These challenges necessitate the use of biodegradable fluids to minimize water usage and chemical contamination risks along with specialized materials capable of enduring intense thermal stress and cycling over extended periods [67]. Advanced completion designs, such as progressively burning propellants and acidizing techniques, are particularly effective in boosting productivity in the low-permeability, high-temperature environments characteristic of geothermal reservoirs [70]. Another critical factor in completion is the spacing between geothermal wells, which significantly impacts thermal performance and economic feasibility. While case-dependent and influenced by reservoir heterogeneity, a spacing range of 300–600 m has been suggested based on economic analysis using the modified Levelized Cost of Heat (LCOH-HT). Wider spacing enhances thermal efficiency by allowing recharged water to absorb more heat but increases hydraulic losses, pressure drops, and pumping costs, ultimately raising drilling and project expenses [71].

Innovative monitoring and modeling methods for fracture networks are critical to managing the complexities of geothermal completions and ensuring sustainable operations. Seismic imaging, for instance, is instrumental in managing induced seismicity and ensuring stable fracture growth under high-pressure and high-temperature conditions [72]. Drilling Dynamic Geomechanics (DDG) technology, which combines machine learning and advanced signal processing, offers continuous high-resolution geomechanical profiles that can optimize fracture propagation and maintain wellbore stability [73]. This is particularly valuable in EGS reservoirs, where traditional well-logging methods fall short due to limited spatial resolution and extreme temperatures. Unlike oil and gas operations, geothermal reservoirs are subject to intensified thermal stresses, with thermo-poroelastic effects causing pore pressures to rise by approximately 1.5 MPa/°C [74]. Cooling generally enhances wellbore stability by reducing compressive failures, whereas heating increases the likelihood of tensile and compressive fractures, which necessitate advanced stability models tailored to geothermal conditions [73]. Cyclic Hydraulic Fracturing (CHF) reduces breakdown pressure and induced seismicity while creating a more complex fracture network than traditional methods [75]. Reinjection strategies, such as geothermal wastewater reinjection, sustain reservoir pressure, enhance heat production capacity, and mitigate resource depletion [76]. Skills are needed to optimize fracture networks, well placement, and thermal–hydraulic–mechanical (THM) interactions using advanced simulation models and comprehensive sustainability frameworks [77,78]. By incorporating these strategies and advanced technologies, geothermal completions and hydraulic fracturing can efficiently extract energy while reducing environmental impacts.

5. Shallow Systems and Heat Pumps

5.1. Types of Heat Pumps and Installation Methods

Shallow geothermal systems utilize the natural near-surface thermal gradient as a renewable energy source. Engineers and scientists play a critical role in designing, optimizing, and conducting hydrological assessments of these systems. The types of heat pumps include Ground-Coupled Heat Pumps (GCHPs), Groundwater Heat Pumps (GWHPs), and Surface-Water Heat Pumps (SWHPs) [79–81]. Like other thermal exchange technologies such as EGSs and hydrothermal systems, these shallow systems rely on transferring heat through natural thermal gradients. The heat transfer would be used either for heating or cooling or in a hybrid system that provides both heating and cooling elements. SWHPs utilize cold bodies of water, such as lakes or ponds, as a heat exchange medium by employing submerged heat exchangers, as shown in Figure 4. Similarly, GWHPs extract heat directly from groundwater, while GCHPs operate through closed-loop systems installed in vertical or horizontal boreholes to harness the earth's thermal energy.

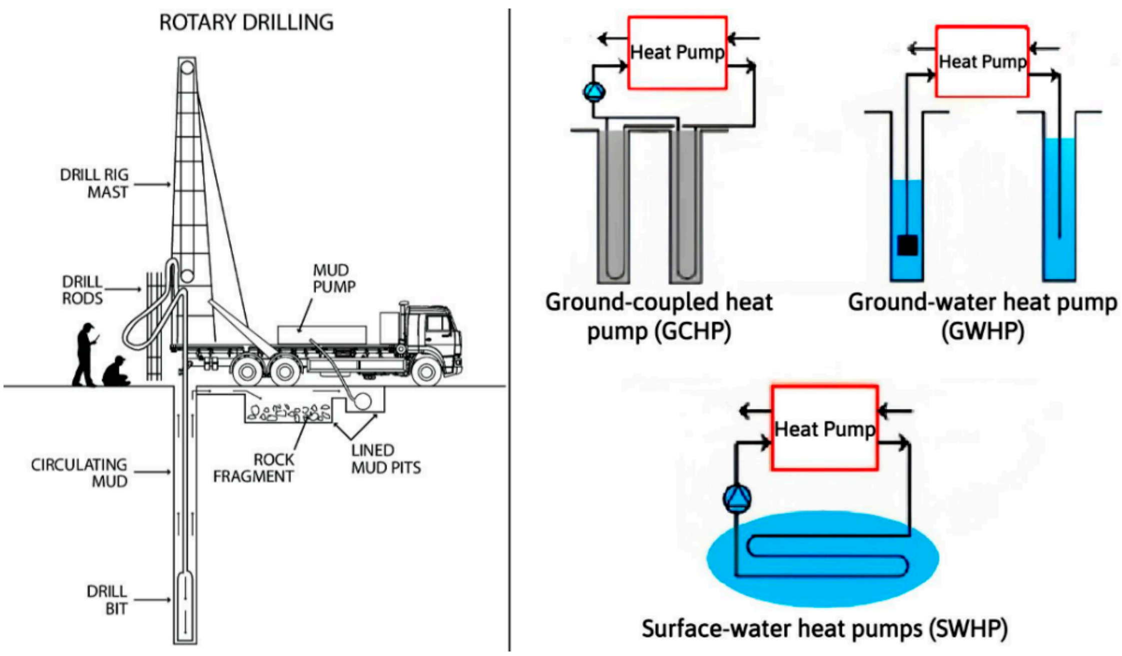

Figure 4. Schematics for a rotary drilling rig, including mud circulation for cooling the drill bit (adapted from [83]). Schematics on the right depict three geothermal heat pump configurations: Ground-Coupled Heat Pump (GCHP), Groundwater Heat Pump (GWHP), and Surface-Water Heat Pump (SWHP) systems (adapted from [80,81] with adjustments to improve labeling and organization).

Small rotary drilling rigs are commonly used for drilling vertical heat pump boreholes at shallow depths [46]. This method, shown in Figure 4, involves pumping a drilling fluid (mud) slurry, usually containing bentonite clay and other additives, down the rotating drill string to lubricate and cool the cutting head while transporting drilled cuttings back to the surface. The drilling rates for ground loop installations are considered fast compared to other deep drilling operations. Various types of machinery are available for excavating and backfilling horizontal ground loops, depending on the site's specific requirements. For example, bulldozers are suitable when the entire loop field needs to be excavated in a single operation, enabling large amounts of soil to be removed effectively, reducing the installation cost. However, the looser the soil, the higher the risk of trench collapse after digging. Looser soils lack cohesion and are more prone to collapsing under their own weight, especially when affected by moisture, which would increase installation costs [82]. Skills are needed to select the optimum type and installation method for these shallow systems.

5.2. Impact of Subsurface Hydrology and Soil Properties

The skills needed to understand the hydrological and soil context are critical for designing and optimizing geothermal heat pump systems, as depth and soil properties significantly influence thermal stability. In the United States, temperature variations diminish beyond a depth of 5 to 20 m [84], known as the neutral zone, where seasonal temperature fluctuations become negligible. The exact depth of this zone depends on factors such as soil properties, hydrology, and saturation levels, with higher geothermal gradients resulting in shallower neutral zones and deeper depths with lower gradients [84]. To determine the depth of the neutral zone in moderate climates, the equation $z(N.Z.) = 10\lambda^{1/2}$ is approximately used [85], where z(N.Z.) is the depth of the natural zone and λ is the thermal conductivity of the ground. This equation shows the dependency of the depth of the neutral zone on the conductivity of the soil and the properties that control its connectivity, like moisture content, texture, and mineral composition.

Soil moisture content plays a critical role in the efficiency of shallow systems, as wet soils have higher thermal conductivity than dry soils due to water's superior heat transfer properties compared to air [86]. This enhanced conductivity facilitates effective heat transfer and expands the neutral zone, as shown in Figure 5. This effect can enhance the performance of ground-source heat pumps and reduce installation lengths by 25–26% [87,88]. Experimental data indicate that soils with a volumetric water content (VWC) of approximately 20% achieve an optimal balance between thermal conductivity and the coefficient of performance (COP) for heat pump systems [89]. In contrast, dry soils lack sufficient moisture and exhibit low thermal conductivity, leading to inefficient heat exchange. Seasonal variations in precipitation, evaporation, and water table levels can significantly affect soil moisture content, directly impacting geothermal systems' thermal regime and long-term operational efficiency [90]. Other hydrological factors must also be evaluated for GWHP systems; these include aquifer properties, such as groundwater flow, as this can either dissipate heat or introduce thermal energy based on its direction and rate [85,91].

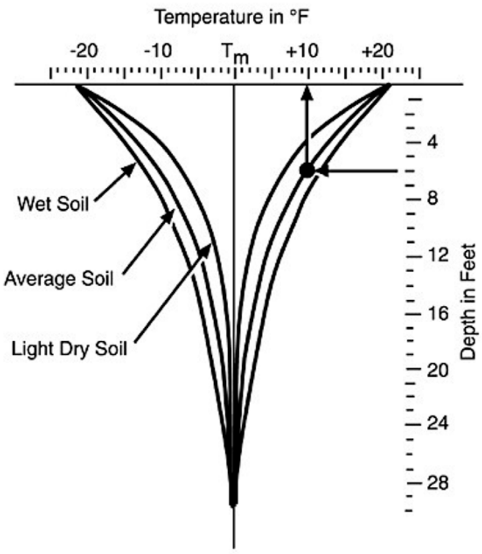

Figure 5. Soil temperature variation with respect to depth for wet, average, and light dry soils. Temperature fluctuations decrease with increasing depth [92].

5.3. Impact of Different Climates and Surface Environments

Optimizing heat pump performance across diverse climates requires careful consideration of factors such as temperature fluctuations. In cold, snowy regions, snow serves as an insulating layer, reducing heat loss from the ground to the atmosphere during winter. Snow's low thermal conductivity stabilizes near-surface soil temperatures, ensuring consistent ground conditions for the efficient operation of shallow geothermal systems [93]. This insulating effect is particularly valuable in mitigating soil cooling under extreme winter conditions, preserving system efficiency, and preventing performance degradation. In sub-arctic environments like Fairbanks, Alaska, heat pump systems placed between the active layer—seasonally freezing and thawing ground—and permafrost, frozen for at least two years, have demonstrated the ability to extract thermal energy from a depth of 2.7 m. While not yet economically viable with current technologies, these systems effectively retain thermal energy, including latent heat released during seasonal phase changes, despite the challenges posed by cold soil and atmospheric conditions [94]. In hot, semi-arid environments, heat pumps have been shown to provide energy-efficient cooling while reducing annual carbon dioxide emissions by up to 40% compared to conventional air-source heat pump systems (ASHPs) [88]. Evaluating hydrological and soil factors during the design and implementation phases is essential for optimizing geothermal systems for thermal performance and long-term sustainability. This creates a compelling opportunity for engineers and scientists transitioning to the renewable energy sector, leveraging their expertise in heat and mass transfer, fluid dynamics, and system design. Foundational skills from the energy sector integrate seamlessly with these technologies, driving innovation and advancing the shift toward sustainable energy solutions.

6. Emerging Technologies and Case Studies

6.1. Emerging Technologies and Sustainable Practices

Geothermal drilling and completion, which can account for up to 70% of total project costs, face significant financial and technical challenges, particularly in hard rock formations associated with slow drilling rates. Emerging technologies like Hydrothermal Spallation Drilling (HSD) and Millimeter-Wave (MMW) drilling offer promising solutions to improve efficiency and reduce costs. In HSD, superheated water and flame jets are used to fragment rock through spallation, allowing penetration rates 5 to 10 times faster than traditional drilling methods along with reduced bit wear and operational downtime. Lab tests have demonstrated drilling rates between 15 and 30 ft/hr [4.6–9 m/hr], facilitating a 15–20% reduction in total drilling costs [6]. However, challenges like heat loss in high-pressure environments, hydrostatic pressure management, and difficulty handling basaltic rocks remain.

MMW drilling was developed in collaboration with the MIT Plasma Science and Fusion Center. In this technique, high-frequency electromagnetic radiation generated by gyrotrons is used to melt or vaporize rock, avoiding the mechanical wear and inefficiencies encountered in conventional drilling. It can facilitate penetration rates over 10 times faster than rotary methods, significantly cutting down the time and costs of geothermal well construction. A key innovation is its ability to produce vitrified borehole linings during drilling, which eliminates the need for traditional casing and enhances borehole stability. This technique also integrates real-time diagnostics and automated control systems to precisely monitor and adjust energy delivery in high-temperature, high-pressure environments. MMW systems transfer energy efficiently, allowing access to supercritical geothermal resources at depths of 10–20 km, where temperatures exceed 374 °C. This capability opens vast untapped reservoirs for renewable energy. However, challenges are faced when using this technique, including the substantial power demand of gyrotrons, which require several megawatts per system, and the need for advanced cooling systems to maintain equipment performance. Addressing these limitations through further optimization of energy efficiency and system integration will be critical to scaling MMW drilling for practical and widespread geothermal applications [95].

Advancing drilling efficiency also involves optimizing drilling fluid formulations and adopting innovative practices. Sustainable and thermally stable drilling fluids, including those based on nanomaterials, mitigate challenges such as lost circulation, stuck pipes, and wellbore instability in high-temperature environments [96]. In thermo-mechanical drilling, flame thermal treatment and rotary drilling are combined to improve rates of penetration in hard rock formations and reduce energy use and environmental impacts [97]. Similarly, drilling auxiliary robots enhance safety and efficiency by minimizing human error and downtime in geothermal operations [27]. Moreover, EGSs, which involve creating artificial reservoirs in hot, dry rock, are gaining traction due to cost reductions and improved performance demonstrated in Nevada and Utah [98]. These advancements are complemented by the reuse of abandoned oil and gas wells for geothermal energy, which minimizes land disturbance and reduces costs, as well as offshore projects that repurpose existing assets for geothermal use [99].

Data-driven optimization and best practices further support sustainable geothermal development. Artificial Intelligence (AI) and Internet of Things (IoT) technologies facilitate real-time monitoring and modeling, enabling smart, real-time decision-making; predictive maintenance; and high operational efficiency [100]. Skills are needed for holistic development approaches, including multidisciplinary research and comprehensive reservoir management strategies, to improve drilling outcomes while balancing environmental and economic sustainability [14,101]. Simulation-based optimization helps determine optimal well locations and operations by accounting for geological uncertainties and energy recovery potential [77]. Furthermore, in reinjection practices, geothermal wastewater is processed to restore heat production capacity and maintain reservoir pressure, enabling resource sustainability and environmental benefits [76]. These technologies and practices underscore the potential of geothermal energy to lead the transition to sustainable and efficient energy systems.

6.2. Exploration Heat Maps and CO_2 Footprint

The heat map in Figure 6 illustrates the geothermal resources of the United States, highlighting regions with varying subsurface temperatures at a depth of 7.5 km. The areas in red and purple indicate the highest geothermal potential, with temperatures exceeding 200 °C, primarily concentrated in the Western United States. Heat maps are the initial exploration tool used to assess an area for geothermal potential, as they are compiled from historical geothermal datasets. In our case studies, two major geothermal sites are marked: The Geysers in California, a renowned conventional hydrothermal field, and Utah FORGE (Frontier Observatory for Research in Geothermal Energy), a leading Enhanced Geothermal System (EGS) research site. These sites showcase the evolution of geothermal technologies in deep wells, from leveraging naturally permeable hydrothermal systems to pioneering EGS in dry, impermeable rocks. Each site highlights unique methodologies, technological advancements, and sustainability challenges associated with harnessing geothermal energy.

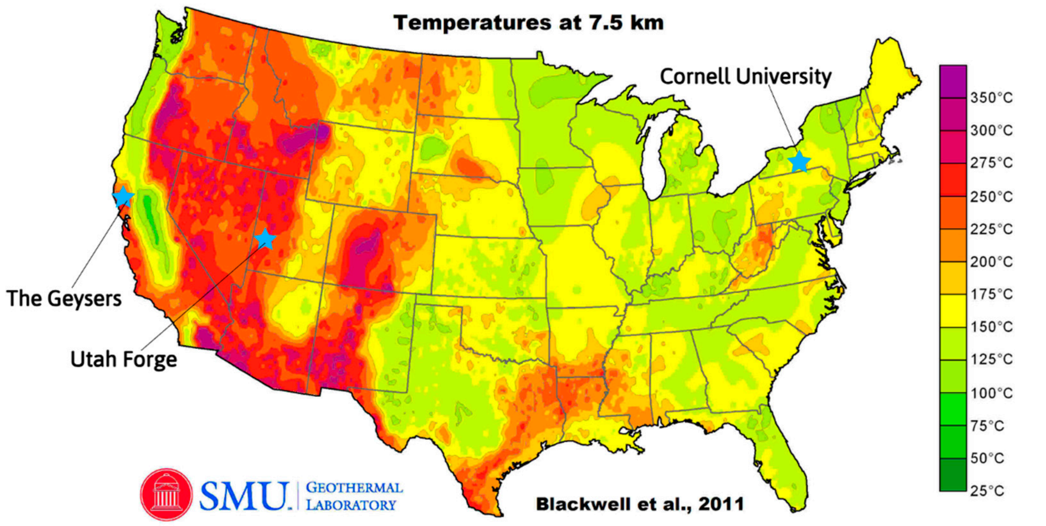

Figure 6. Temperature map at a depth of 7.5 km across the United States, showing geothermal gradients with higher temperatures (red to purple) in the western region. Blue stars indicate case study sites: The Geysers in California, Utah FORGE, and Cornell University. Adapted by highlighting the case study sites from [102].

During the exploration and development phases of geothermal projects, CO_2 emissions are a major factor to be studied and optimized. It is estimated that the exploration phase of geothermal energy leads to the emission of approximately 53.2 kg CO_2-eq/m^2/year, mostly as a result of the use of chemicals and diesel fuel for drilling, as demonstrated in Indonesia [103]. Geothermal power plants, like the Ohaaki project in New Zealand, also release additional CO_2 into the atmosphere while they are in operation; however, long-term modeling indicates that emissions are neutralized over 300 years because of reduced post-shutdown natural degassing [104].

6.3. Case Study 1: The Geysers in California

The Geysers, located in Northern California, is one of the oldest and largest geothermal fields in the United States. Its history dates back to its use by Native Americans well before European settlement [105]. Modern geothermal development began in 1921 and reached a major milestone in 1960 with the establishment of the first US geothermal power plant [105]. The Geysers case benefits from naturally permeable fractured water-bearing rock formations, such as greywacke and felsite. Wells are typically drilled to depths of approximately 8500 feet [2591 m] and operate at temperatures exceeding 188 °C [370 °F]. The natural permeability of these formations enables efficient steam production, making the Geysers a benchmark for hydrothermal resource utilization. To address the challenges of reservoir pressure depletion, advanced reinjection strategies have been implemented; these include horizontal drilling techniques that have extended well productivity and sustainability [8]. More recently, EGS technologies have been applied at the Geysers by reopening and deepening previously abandoned wells, such as Prati State 31 (PS-31) and Prati 32 (P-32), to depths of approximately 11,000 feet [3353 m]. These efforts successfully stimulated a high-temperature reservoir (up to 400 °C/750 °F), with isotopic analyses revealing that 50–75% of the produced steam was injection-derived, demonstrating the feasibility of EGSs even in mature hydrothermal systems [106,107].

Figure 7 presents the wellbore schematics for Prati State 31 and Prati 32 at the Geysers geothermal field in California. The Prati State 31 schematic (left) shows detailed casing and liner specifications that include perforations and the high-temperature zones (260 °C/500 °F) encountered between 7677′ and 7966′ [2340–2428 m]. The well includes a 30-inch conductor, a 20-inch surface casing, a 13-3/8-inch intermediate casing, a 7-inch liner with perforations from 6776 to 7696 feet [2065–2346 m], and a 10-3/4-inch tieback to the surface. The bottom section has slotted and open-hole completions reaching 10,034 feet [3058 m]. The Prati 32 schematic (right) provides a similar overview, indicating casing collapse issues, cementing details, and the slotted liner configuration extending to a depth of 11,115′ [3388 m]. The high-temperature zone is marked at around 8400′ [2560 m], which emphasizes the extreme thermal conditions typical of geothermal reservoirs. The design includes a 26-inch cemented conductor, 20-1/2-inch surface casing, 13-3/8-inch tieback, and a 7-inch slotted liner from 6801 to 11,115 feet [2073–3388 m], with open-hole completions to 11,143 feet [3396 m]. These designs ensure structural stability while allowing efficient reservoir access and higher steam production rates. Notably, the majority of oil and gas wells in the US are completed with production casings of 4.5 to 5.5 inches in diameter. These diagrams illustrate the skills needed for and the complexities of well design, completion, and thermal management in deep geothermal systems.

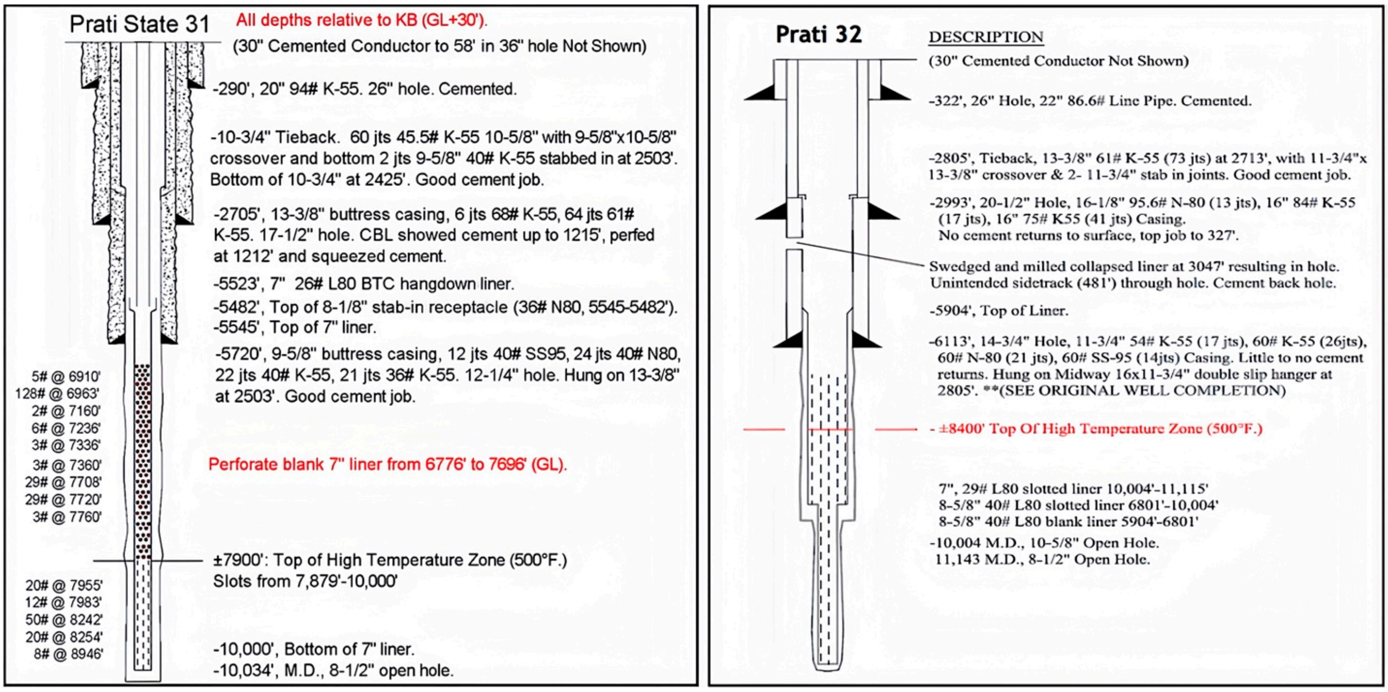

Figure 7. Wellbore schematics for Prati State 31 and Prati 32 at The Geysers, highlighting casing designs, liner configurations, and high-temperature zones critical for geothermal reservoir management [107].

6.4. Case Study 2: Utah FORGE

Utah FORGE (Frontier Observatory for Research in Geothermal Energy) represents the cutting edge of geothermal innovation in Enhanced/Engineered Geothermal Systems (EGSs). Unlike at The Geysers, Utah FORGE targets hard and dry crystalline rocks, such as granite, at depths reaching 10,987 feet [3349 m], with temperatures reaching approximately 228 °C/442 °F [108]. The project aims to develop and test technologies for creating permeable reservoirs in impermeable rocks through advanced directional drilling and hydraulic fracturing techniques [72]. Real-time monitoring and simulation tools are used to refine these techniques to optimize stimulated reservoir volume (SRV) and heat extraction efficiency [109]. Additional advancements include fracture network modeling, machine learning applications used to generate high-resolution temperature maps, and discrete fracture network (DFN) modeling conducted to control fracture properties [110,111]. Utah FORGE proves EGSs to be a scalable and eco-friendly solution for geothermal energy [112,113]. To better understand the FORGE area, the project was thoroughly studied and explored using traditional geological mapping and geochemical assessments, in addition to geophysical methods like seismic reflection and gravity surveys, to assess the subsurface and to implement advanced microseismic monitoring for the stimulation process [112,113].

These case studies underscore the diversity and potential of geothermal energy. The Geysers showcases the historical success of hydrothermal systems, utilizing naturally permeable formations and incorporating EGS techniques to enhance productivity. Meanwhile, Utah FORGE demonstrates the future of geothermal energy through its advancements in EGS technologies to provide solutions to unlock geothermal potential in previously inaccessible formations. Building upon existing skills, these developments in geothermal drilling reflect a transformative shift in geothermal energy to address current energy needs and future sustainability goals.

6.5. Case Study 3: Integrated Geothermal System—Cornell University

Cornell University is pioneering the integration of shallow heat pump systems and deep geothermal technologies to create a comprehensive renewable energy model on a single campus. A key component of this approach is the Lake Source Cooling project, in which the naturally cold temperatures of Cayuga Lake are being used to replace conventional air conditioning with an environmentally friendly alternative. The system operates as a closed-loop, extracting water at 39–41 °F [3.8–5 °C] from the lake's depths and transporting it to a central heat exchange facility (Figure 8). There, it cools a secondary water loop for campus buildings before returning the water to the lake at a slightly elevated temperature of 48–56 °F [8.9–13.3 °C], preserving the lake's thermal balance and minimizing the environmental impact [114].

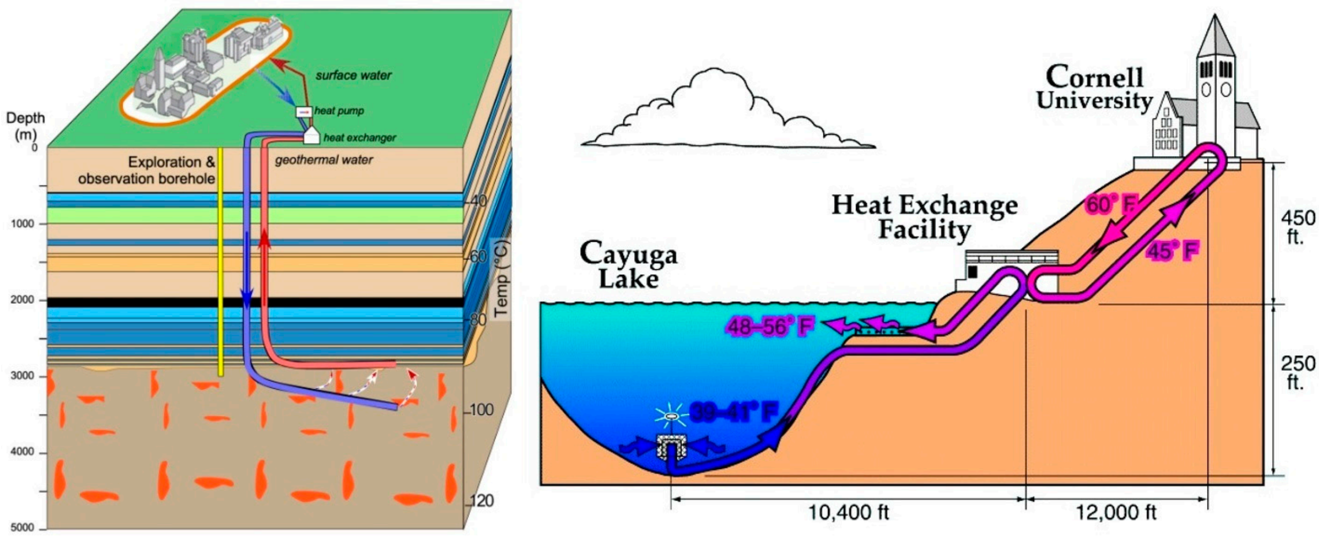

Figure 8. Geothermal systems at Cornell University. **Left**, a schematic of Cornell's Earth Source Heat, featuring planned production and injection wells [115]. **Right**, a schematic of the Lake Source Cooling System [114].

In addition to the Lake Source Cooling project, Cornell University has also launched the Earth Source Heat project, which aims to tap into geothermal energy from deep underground formations to provide heating for the campus. A crucial component of this project is the Cornell University Borehole Observatory, drilled in 2022 to a depth of nearly two miles [3.2 km]. This observatory well assesses the potential for extracting heat from deep geothermal reservoirs (Figure 8). Looking ahead, the project will involve further drilling into the basement rock to conduct fracture injection tests (DFITs) and to determine the ideal depths for optimal reservoir access. These efforts will inform the design of future geothermal injection and production wells and thus ensure the long-term sustainability of the energy source. The envisioned system will use one well to inject water into hot rock formations and another to extract heated water for transfer to the campus heating network via a heat exchanger [115]. The integration of these two projects at Cornell demonstrates one of the ways shallow and deep geothermal systems can work together to meet both cooling and heating demands efficiently. This combination reduces fossil fuel use, lowers emissions, and provides a practical, scalable solution for sustainable renewable energy.

7. Opportunities for Engineers and Scientists in Geothermal Energy

Geothermal energy presents significant opportunities for many STEM (Science, Technology, Engineering, and Mathematics) professionals, including oil and gas engineers, leveraging their expertise in deep drilling and subsurface exploration. The technical similarities between geothermal energy development and oil and gas extraction, which include well design, directional drilling, and hydraulics, enable a seamless transition for both seasoned professionals and recent graduates. Meeting the workforce demands of this growing sector is substantial, as developing a single 50-megawatt geothermal plant requires 697 to 862 workers [116]. Additionally, advances in technology and infrastructure could allow the US geothermal industry to support up to 60 gigawatts of energy generation by 2050 [117]. However, petroleum engineers transitioning to geothermal energy must adapt to alternative environments and unique challenges. Leveraging existing skills requires a deeper understanding of cost dynamics and adaptability to meet sustainable geothermal energy demands [4,118]. Given the lack of geothermal energy educational degrees, specialized training programs focusing on the unique challenges of geothermal drilling—such as high-temperature conditions and complex geological formations—are essential. Scenario-based certifications could bridge this education gap and enhance safety, efficiency, and adaptability to equip engineers and scientists with the tools required to handle these industry-specific demands effectively [119].

Government incentives could further accelerate the adoption of geothermal technologies, particularly geothermal heat pumps (GHPs). Federal and State programs, including tax credits, grants, and rebates under the Inflation Reduction Act, reduce upfront costs and encourage institutional and residential adoption of geothermal systems [120]. These incentives support the decarbonization of heating and cooling systems, creating momentum for geothermal energy as a sustainable solution. Universities across the United States are also leading a shift toward geothermal energy. Colorado Mesa University implemented geothermal heating as part of a district energy system in campus operations [121]. Similarly, Cornell University's Earth Source Heat project aims to harness deep geothermal energy for campus-wide heating, combining cost savings with emissions reductions and setting a model for the large-scale academic adoption of renewable energy [122]. Most importantly, geothermal energy presents untapped potential for direct industrial heat applications, such as food processing, plastic manufacturing, and even automotive production, with companies like Daimler and Volkswagen exploring geothermal wells to supply heat for their operations [123]. Furthermore, geothermal energy offers transformative potential as a sustainable power source for energy-intensive data centers in the generative AI and blockchain applications era.

Geothermal energy strategies, however, vary significantly between Europe and the United States. Europe leads in government-driven district heating projects, such as the Paris Basin network, heating thousands of homes, and Iceland's Hellisheiði plant, supplying electricity and heat. Although the European techniques eliminate the need for hydraulic fracturing, for its environmental concerns, expertise and equipment from the oil and gas industry remain essential for identifying, planning, drilling, and completing geothermal projects [123]. The US, in contrast, focuses on private-sector innovation to advance EGS and closed-loop technologies. Key US initiatives include Utah FORGE's EGS research, the Salton Sea's geothermal energy–lithium recovery integration, Fervo Energy's South Utah project targeting data centers, and Ormat Technologies' Nevada facilities. Data centers represent a compelling growth area for geothermal energy. Europe's progress is exemplified by Microsoft's geothermal-energy-powered data center in Finland, while US partnerships between oil majors and tech firms aim to align geothermal energy with low-carbon goals. Europe's policy leadership has driven adoption, but the US's entrepreneurial model showcases scalability and innovation, as seen in projects like The Geysers and Cornell University's campus-wide geothermal heating initiative. These efforts highlight geothermal energy's dual role in decarbonizing heating systems and supporting energy-intensive industries [123,124]. Engineers and scientists can play a pivotal role in advancing geothermal energy by combining their expertise with innovative technologies and benefiting from strong policy and legislation support. These opportunities emphasize geothermal energy's potential as a cornerstone of a sustainable energy future.

8. Conclusions

This review underscores geothermal energy's essential role in the global energy transition, offering a sustainable, low-emission alternative to traditional energy sources. It comprehensively examines both deep and shallow geothermal systems, identifying critical challenges and opportunities for advancement. By exploring cutting-edge technologies, sustainable practices, and case studies across diverse climatic conditions, this review provides actionable insights to propel geothermal energy forward. In light of the educational gaps in this field, this review serves as a vital resource fostering innovation and empowering professionals from oil and gas and other STEM (Science, Technology, Engineering, and Mathematics) disciplines to contribute meaningfully to a cleaner, more sustainable energy future. The following key conclusions have been drawn from this analysis:

- Geothermal energy provides stable, renewable power essential for addressing global energy demands and achieving climate goals while minimizing environmental impacts.
- Deep geothermal drilling aligns naturally with the expertise of oil and gas engineers, enabling them to apply skills in wellbore stability, directional drilling, and advanced completions to drive innovation and overcome geothermal-energy-specific challenges.
- Shallow geothermal systems depend on efficient heat transfer and require careful consideration of soil, climatic, and hydrological properties as well as environmental factors to optimize performance across diverse climates.
- Engineers and scientists from diverse STEM fields can significantly contribute by integrating shallow heat pump systems with deep geothermal technologies, fostering a multidisciplinary approach to geothermal energy solutions.
- Emerging technologies, including Enhanced Geothermal Systems (EGSs), closed-loop designs, Hydrothermal Spallation Drilling (HSD), and Millimeter Wave (MMW) drilling, are revolutionizing geothermal energy by expanding its applicability and efficiency.
- Sustainable practices, such as reinjection strategies and the use of corrosion-resistant alloys and advanced cementing materials, enhance well integrity, reservoir sustainability, and environmental stewardship.
- Case studies, including The Geysers, Utah FORGE, and Cornell University's hybrid geothermal systems, illustrate successful implementations of hydraulic stimulation, fracture modeling, and innovative reservoir management.
- Government incentives, such as tax credits for geothermal heat pumps, and academic initiatives are accelerating geothermal adoption, driving innovation, and fostering collaboration across disciplines to support the global energy transition.

Future work should concentrate on enhancing both shallow and deep geothermal systems by addressing their shortcomings, their distinct physical mechanisms, and the ways to integrate them. The mechanism of deep systems is tied to high-pressure, high-temperature environments in addition to controlling and monitoring fractures and injection-induced seismic events for EGS systems, while shallow systems rely on effective heat transfer and moisture content in addition to the local environmental and climatic conditions. As a reliable, low-carbon source, geothermal energy is key to energy security and decarbonization. Advancing both deep and shallow systems will improve efficiency, lower costs, and scale deployment. Enhanced Geothermal Systems (EGSs) unlock deeper, hotter reservoirs by increasing permeability through hydraulic stimulation. Optimizing fracture management, mitigating seismic risks, and improving heat extraction remain key research priorities. Advances in drilling, well construction, and thermal modeling will further enhance performance and cost-effectiveness.

Future research should also focus on optimizing both subsurface and surface geothermal production systems to improve efficiency, longevity, and economic feasibility. Subsurface advancements should prioritize well design, casing durability, and downhole pump integration to maintain stable flow rates and enhance heat extraction. The interaction between production and reinjection wells must be carefully managed to prevent thermal breakthroughs and pressure imbalances. On the surface, future work should explore advanced power plant configurations, including improved flash and binary cycle systems, to maximize energy conversion. Heat exchangers and pumping systems should be optimized for higher thermal efficiency and reduced environmental impact. Monitoring and control technologies need further development to enhance real-time resource assessment and operational performance. Integrating geothermal energy with carbon capture, automation, and hybrid renewable systems presents an opportunity for expanding its role in sustainable energy solutions.

Hybrid geothermal systems incorporating solar energy, heat pumps, and hydrogen production are emerging as efficient solutions. Extracting lithium and other critical minerals from geothermal brines presents new economic opportunities. Community engagement is crucial for project success, requiring transparency on environmental impacts and benefits. High upfront costs remain a challenge, but improved drilling, reservoir management, and repurposed oil and gas wells offer cost-effective solutions. Geothermal energy is essential for carbon neutrality and energy independence.

Future research must also refine heat transfer in shallow systems, enhance fracture monitoring in deep systems, and develop energy storage solutions. Interdisciplinary collaboration among engineers, geologists, and policymakers will drive geothermal energy's expansion. As technology, economics, and public acceptance improve, geothermal energy is set to become a cornerstone of sustainable energy. Future research on geothermal energy should focus on integrating machine learning and artificial intelligence with remote sensing technologies and the feasibility of transforming abandoned oil and gas wells into a single-well geothermal system. Future projects will require continued interdisciplinary collaboration that includes engineers, geologists, hydrologists, geophysicists, and geomechanics experts to unlock the full potential of geothermal energy as a sustainable energy source.

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Abbreviations

AI	Artificial Intelligence
ASHPs	Air Source Heat Pump Systems
BHT	Bottomhole temperature
BTC	Buttress Thread Connection
CBL	Cement Bond Log
CCHP	Combined Cooling, Heating, and Power
CHF	Cyclic Hydraulic Fracturing
COP	Coefficient Of Performance
DDG	Drilling Dynamic Geomechanics
DHEX	Downhole Heat Exchangers
EGS	Enhanced Geothermal Systems
FORGE	Frontier Observatory for Research in Geothermal Energy
GCHP	Ground-Coupled Heat Pumps
GHPs	Geothermal Heat Pumps
GL	Ground Level
GRE	Glass Reinforced Epoxy
GWHP	Groundwater Heat Pumps
HSD	Hydrothermal Spallation Drilling
HTHP	High-Temperature, High-Pressure
IoT	Internet of Things
Jts	Joints
KB	Kelly Bushing
LCAs	Life Cycle Assessments
LCOH-HT	Levelized Cost of Heat
MD	Measured Depth
MMW	Millimeter Wave
NPT	Non-productive time
PDC	Polycrystalline Diamond Compact
PMSMs	Permanent Magnet Synchronous Motors
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
ROP	Rate Of Penetration
RPD	Rotary Percussive Drilling
SRV	Stimulated Reservoir Volume
STEM	Science, Technology, Engineering, and Math
SWHP	Surface Water Heat Pumps
THM	Thermal–Hydraulic–Mechanical
VWC	Volumetric Water Content

References

1. Li, K.; Bian, H.; Liu, C.; Zhang, D.; Yang, Y. Comparison of Geothermal with Solar and Wind Power Generation Systems. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1464–1474. [CrossRef]
2. Eberle, A.; Heath, G.A.; Carpenter Petri, A.C.; Nicholson, S.R. *Systematic Review of Life Cycle Greenhouse Gas Emissions from Geothermal Electricity*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2017.
3. Josiane, J.; Jello, J.; Başer, T. Repurposing Abandoned Oil and Gas Wells for Geothermal Applications. In Proceedings of the Applied Energy Symposium: MIT A+B, Cambridge, MA, USA, 5–8 July 2022. [CrossRef]
4. Cao, J.; Lye, J.; Gonzalez, M.M.; Magalhaes, M. Exploring the Synergy: Leveraging Oil and Gas Drilling Solutions for Enhanced Geothermal Drilling. In Proceedings of the 49th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 12–14 February 2024.
5. Collins, I.R.; Cano Floriano, D.; Paevskiy, I.; Wee, J.; Boek, E.S.; Mohammadi, M.K. Transition from Oil & Gas Drilling Fluids to Geothermal Drilling Fluids. *Geoenergy Sci. Eng.* **2024**, *233*, 212543. [CrossRef]

6. Wang, M.; Zhang, S.; Gouemo Niangui, J.E. Hydrothermal Spallation Drilling Technology: An Alternative Method of Geothermal Energy Development. In Proceedings of the 2017 2nd International Conference on Electrical, Automation and Mechanical Engineering (EAME 2017), Shanghai, China, 23–24 April 2017. [CrossRef]
7. Finger, J.; Blankenship, D. *Handbook of Best Practices for Geothermal Drilling*; SAND2011–6478; Sandia National Lab.: Albuquerque, NM, USA, 2012.
8. So, P.; Wriedt, J.; Mclennan, J.; Deo, M.; Noynaert, S.F.; Raymond, D.; Schneider, M. Evaluation of Physics-Based Limiter Redesign Drilling and Alternative Bit Design at the Geysers. In Proceedings of the 49th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 12–14 February 2024.
9. AlGaiar, M.; Afolabi, J. Enhancing Geothermal Wells Integrity: Key Considerations and Challenges from Drilling to Production. In Proceedings of the SPE Symposium: Well Integrity, Al-Khobar, Saudi Arabia, 21–22 May 2024; p. D021S005R001. [CrossRef]
10. Ba Saloom, S.; Ba Geri, M.; Suhail, M.; Ge, X. Advancements in Drilling Fluid Optimization for Enhanced Geothermal Energy Extraction. In Proceedings of the SPE Eastern Regional Meeting, Wheeling, WV, USA, 8 October 2024; p. D021S002R003. [CrossRef]
11. Barich, A.; Stokłosa, A.W.; Hildebrand, J.; Elíasson, O.; Medgyes, T.; Quinonez, G.; Casillas, A.C.; Fernandez, I. Social License to Operate in Geothermal Energy. *Energies* **2022**, *15*, 139. [CrossRef]
12. Błaż, S.; Zima, G.; Jasiński, B.; Kremieniewski, M. Increasing the Thermal Resistance of Water-Based Mud for Drilling Geothermal Wells. *Energies* **2024**, *17*, 4537. [CrossRef]
13. Cano, N.A.; Céspedes, S.; Redondo, J.D.; Foo, G.; Jaramillo, D.; Martinez, D.; Gutiérrez, M.; Pataquiba, J.; Rojas, J.; Cortés, F.B.; et al. Power From Geothermal Resources as a Co-Product of the Oil and Gas Industry: A Review. *Acs. Omega* **2022**, *7*, 40603–40624. [CrossRef]
14. Mensa-Wilmot, G.; Cotanda, R.; Pazziuagan, D. Geothermal Drilling—Collaborative and Holistic Applications Specific Solutions Drive Consistent Improvements in Drilling Efficiency and Operational Costs. In Proceedings of the SPE/IADC International Drilling Conference and Exhibition, Stavanger, Norway, 7 March 2023; p. D031S020R003. [CrossRef]
15. Meirbekova, R.; Bonciani, D.; Olafsson, D.I.; Korucan, A.; Derin-Güre, P.; Harcouët-Menou, V.; Bero, W. Opportunities and Challenges of Geothermal Energy: A Comparative Analysis of Three European Cases—Belgium, Iceland, and Italy. *Energies* **2024**, *17*, 4134. [CrossRef]
16. Kaldal, G.; Thorbjornsson, I.O.; Guðmundsson, L.; Reinsch, T.; Lipus, M.; Wollenweber, J.; Orlic, B.; Gislason, T.; Stefánsson, A.; Pálsson, B.; et al. Thermal Stress Mitigation Testing of Externally Cemented Flexible Coupling in Geothermal Steam. In Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, 24–27 October 2021.
17. Allahvirdizadeh, P. A Review on Geothermal Wells: Well Integrity Issues. *J. Clean. Prod.* **2020**, *275*, 124009. [CrossRef]
18. Bergen, S.L.; Zemberekci, L.; Nair, S.D. A Review of Conventional and Alternative Cementitious Materials for Geothermal Wells. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112347. [CrossRef]
19. Mohamed, A.; Salehi, S.; Ahmed, R. Significance and Complications of Drilling Fluid Rheology in Geothermal Drilling: A Review. *Geothermics* **2021**, *93*, 102066. [CrossRef]
20. Ragnarsson, A.; Durst, P.; Randeberg, E.; Reinsch, T.; Thorbjornsson, I.; Wollenweber, J.; Jong, W.d.; Sørlie, C.F.; Sigurdsson, O.; Vercauteren, F.; et al. GeoWell—Innovative Materials and Designs for Long-Life High-Temperature Geothermal Wells 2021. *Oil Gas Eur. Mag.* **2018**, *44*, 14–16.
21. Stutz, G. Geothermal Drilling Challenges: 3 Things I Wish I Knew Transitioning From O&G to Geothermal. In Proceedings of the IADC DEC Q2 Technology Forum, Virtual via Zoom, 30 June 2021.
22. Bageri, M.; Cascone, A.; Vordick, T. Drilling Fluid Design for Safe, Efficient Resource Delineation in XHT Geothermal Reservoirs. In Proceedings of the SPE Annual Technical Conference and Exhibition, New Orleans, LA, USA, 20 September 2024; p. D011S006R006. [CrossRef]
23. Snyder, N.K.; Visser, C.F.; Alfred, E.I.W.; Baker, W.; Tucker, J.; Quick, R.; Nagle, T.; Bell, J.; Bell, S.; Bolton, D.; et al. *Geothermal Drilling and Completions: Petroleum Practices Technology Transfer*; NREL/TP-6A20--72277; National Renewable Energy Laboratory: Golden, CO, USA, 2019.
24. Iskandar, F.F.; Fanti, D.; Liang, T.T. Innovative Conical Diamond Element Bits Deliver Superior Performance Drilling a Geothermal Well in the Philippines. In Proceedings of the Offshore Technology Conference Asia, Kuala Lumpur, Malaysia, 22–25 March 2016. [CrossRef]
25. Trivedi, A.; De La Fuente Valadez, J.; Kandala, S.S.; Mai, A.; Shor, R.J.; Vetsak, A. Experimental Study for the Validation of Drilling Optimization Model for Improved Performance in Hard Rock Formations. In Proceedings of the 56th U.S. Rock Mechanics/Geomechanics Symposium, Santa Fe, NM, USA, 26–29 June 2022.
26. Zhang, W. Feasibility Analysis of Drilling with Liquid Nitrogen in High Temperature Geothermal Wells. *Acad. J. Sci. Technol.* **2023**, *6*, 119–124. [CrossRef]
27. Zhang, J.; Yang, S.; Yan, H.; Xiao, B.; Niu, H. Research on Key Technologies of Drilling Auxiliary Robots for Geothermal Drilling Platforms. *Int. J. Front. Eng. Technol.* **2023**, *5*, 27–34. [CrossRef]

28. Magzoub, M.; Salehi, S.; Li, G.; Fan, J.; Teodoriu, C. Loss Circulation Prevention in Geothermal Drilling by Shape Memory Polymer. *Geothermics* **2021**, *89*, 101943. [CrossRef]
29. Moumin, A.O. *Geothermal Well Design*; United Nations University: Reykjavik, Iceland, 2013; pp. 660–668.
30. Caulk, R.A.; Tomac, I. Reuse of Abandoned Oil and Gas Wells for Geothermal Energy Production. *Renew. Energy* **2017**, *112*, 388–397. [CrossRef]
31. Tuschl, M.; Kurevija, T. Revitalization Modelling of a Mature Oil Field with Bottom-Type Aquifer into Geothermal Resource—Reservoir Engineering and Techno-Economic Challenges. *Energies* **2023**, *16*, 6599. [CrossRef]
32. Kaplanoğlu, M.A.; Baba, A.; Gokcen Akkurt, G. Use of Abandoned Oil Wells in Geothermal Systems in Turkey. *Geomech. Geophys. Geo-Energ. Geo-Resour.* **2019**, *6*, 2. [CrossRef]
33. Ungemach, P. Carbonate Geothermal Reservoir Management in France. In Proceedings of the International Geothermal Days POLAND 2004, International Geothermal Association (IGA), Zakopane, Poland, 13–17 September 2004.
34. Frick, S.; Regenspurg, S.; Kranz, S.; Milsch, H.; Saadat, A.; Francke, H.; Brandt, W.; Huenges, E. Geochemical and Process Engineering Challenges for Geothermal Power Generation. *Chem. Ing. Technol.* **2011**, *83*, 2093–2104. [CrossRef]
35. Lukawski, M.Z.; Silverman, R.L.; Tester, J.W. Uncertainty Analysis of Geothermal Well Drilling and Completion Costs. *Geothermics* **2016**, *64*, 382–391. [CrossRef]
36. Falcone, G.; Liu, X.; Okech, R.R.; Seyidov, F.; Teodoriu, C. Assessment of Deep Geothermal Energy Exploitation Methods: The Need for Novel Single-Well Solutions. *Energy* **2018**, *160*, 54–63. [CrossRef]
37. Molen, J.v.d.; Peters, E.; Jedari-Eyvazi, F.; Gessel, S.F. van Dual Hydrocarbon–Geothermal Energy Exploitation: Potential Synergy between the Production of Natural Gas and Warm Water from the Subsurface. *Neth. J. Geosci.* **2019**, *98*, e12. [CrossRef]
38. Liu, Y.; Guo, L.; Wang, Y.; Liao, Y.; Zhao, G. Numerical Simulation and Design Optimization of Large-Scale Geothermal Production Based on a Multiwell Layout in Xianxian Geothermal Field. *Lithosphere* **2022**, *2021*, 2929551. [CrossRef]
39. Lux, M.; Szanyi, J. Effects of Vertical Anisotropy on Optimization of Multilateral Well Geometry. *J. Pet. Sci. Eng.* **2022**, *208*, 109424. [CrossRef]
40. Chai, Y.; Chen, Z.; Yin, S. Numerical Simulation of Geothermal Energy Development at Mount Meager and Its Impact on In Situ Thermal Stress. *Energies* **2024**, *17*, 3466. [CrossRef]
41. Chettri, N.; Sankarananth, S. Geothermal Energy: Definition and Its Applications. *Technoarete Trans. Renew. Energy Green Energy Sustain.* **2022**, *2*, 12–17. [CrossRef]
42. Mehmood, A.; Yao, J.; Fan, D.; Bongole, K.; Liu, J.; Zhang, X. Potential for Heat Production by Retrofitting Abandoned Gas Wells into Geothermal Wells. *PLoS ONE* **2019**, *14*, e0220128. [CrossRef]
43. Camp, E.; Jordan, T. Feasibility Study of Repurposing Trenton–Black River Gas Fields for Geothermal Heat Extraction, Southern New York. *Geosphere* **2017**, *13*, 22–35. [CrossRef]
44. Rossi, E. Advanced Drilling Technologies to Improve the Economics of Deep Geo-Resource Utilization. In Proceedings of the MIT Applied Energy Symposium: MIT A+B, Cambridge, MA, USA, 12–14 August 2020. [CrossRef]
45. Parisi, M.L.; Douziech, M.; Tosti, L.; Pérez-López, P.; Mendecka, B.; Ulgiati, S.; Fiaschi, D.; Manfrida, G.; Blanc, I. Definition of LCA Guidelines in the Geothermal Sector to Enhance Result Comparability. *Energies* **2020**, *13*, 3534. [CrossRef]
46. Bernardi, A.; Pockelé, L.; Sanner, B.; Cicolin, F.; Bobbo, S.; Carli, M.D.; Galgaro, A.; Urchueguía, J.; Mezzasalma, G.; Pasquali, R.; et al. Innovative Drilling Methods, Heat Pumps and Tools to Address Shallow Geothermal in the Built Environment: H2020 Project—GEO4CIVHIC. In Proceedings of the European Geothermal Congress 2019, Den Haag, The Netherlands, 1–8 June 2019; p. 1.
47. Nutakki, T.U.K.; Kolsi, L.; Eladeb, A.; Abbas, A.; Ahmed, M.A.; Ayadi, M.; Muhammad, T.; Bai, W. Simulation and Comprehensive 4E Study of a High-Efficient CCHP Arrangement Utilizing Geothermal Energy and Eco-Friendly Heat Recovery. *Geothermics* **2024**, *118*, 102916. [CrossRef]
48. Maragna, C.; Altamirano, A.; Tréméac, B.; Fabre, F.; Rouzic, L.; Barcellini, P. Design and Optimization of a Geothermal Absorption Cooling System in a Tropical Climate. *Appl. Energy* **2024**, *364*, 123102. [CrossRef]
49. Shin, J.-H.; Cho, Y.-H. Development of a Variable Water Flow Rate Control Method for the Circulation Pump in a Geothermal Heat Pump System. *Energies* **2018**, *11*, 718. [CrossRef]
50. Wang, Y.; Liu, J.; Li, C.; Liu, W.; Guo, K. Investigation on the Application of Permanent Magnet Synchronous Motor in Geological Drilling Rig. In Proceedings of the Second International Conference on Advanced Manufacturing Technology and Manufacturing Systems (ICAMTMS 2023), Nanjing, China, 26–28 May 2023; Volume 12744, pp. 308–322.
51. Lummer, N.R.; Block, R.; Yadigarov, Y. Specially Customized System for Cementing Glass Reinforced Epoxy GRE Casings—Development and Field Trials in a Geothermal Project. In Proceedings of the SPE/IADC Drilling Conference and Exhibition, The Hague, The Netherlands, 14–16 March 2017. [CrossRef]
52. Tayactac, R.; Manuel, M.C. Understanding Material Selection Challenges in Geothermal Well and Systematic Qualification Approach. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1046*, 012007. [CrossRef]

53. Sugiura, J.; Lopez, R.; Borjas, F.; Jones, S.; McLennan, J.; Winkler, D.; Stevenson, M.; Self, J. Oil and Gas Drilling Optimization Technologies Applied Successfully to Unconventional Geothermal Well Drilling. In Proceedings of the SPE Annual Technical Conference and Exhibition, Dubai, United Arab Emirates, 21 September 2021; p. D031S055R006. [CrossRef]
54. Fathi, E.; Liwuitekong Dongho, G.B.; Heidari, B.; Carr, T.R.; Belyadi, F.; Bilgesu, I. Optimizing Deep Geothermal Drilling for Energy Sustainability in the Appalachian Basin. *Sustainability* **2024**, *16*, 8053. [CrossRef]
55. Khaled, M.; Chen, D.; Ashok, P.; van Oort, E. Drilling Heat Maps for Active Temperature Management in Geothermal Wells. *SPE J.* **2023**, *28*, 1577–1593. [CrossRef]
56. Zheng, Y.; Wang, Y. High-Resolution Reflection Seismic Imaging to Reveal Subsurface Geologic Structures of a Deep Geothermal Reservoir. *Geophysics* **2023**, *88*, WB37–WB43. [CrossRef]
57. Börner, J.H.; Bär, M.; Spitzer, K. Electromagnetic Methods for Exploration and Monitoring of Enhanced Geothermal Systems—A Virtual Experiment. *Geothermics* **2015**, *55*, 78–87. [CrossRef]
58. Saleh, F.; Teodoriu, C.; Salehi, S.; Ezeakacha, C. Geothermal Drilling: A Review of Drilling Challenges with Mud Design and Lost Circulation Problem. In Proceedings of the 45th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 10–12 February 2020.
59. Kibikas, W.; Chang, C.; Bauer, S.; Nakagawa, S.; Dobson, P.; Kneafsey, T.; Samuel, A. Time-Dependent Thermal Degradation of Lost Circulation Materials in Geothermal Systems. *Geothermics* **2024**, *121*, 103038. [CrossRef]
60. Shehata, A.M.; Kalia, N.; Comer, R. Advancing Isolation Techniques for Geothermal Wells: Development of Polymer and Nanoparticle System. In Proceedings of the SPE Canadian Energy Technology Conference and Exhibition, Calgary, AB, Canada, 13 March 2024; p. D021S015R001. [CrossRef]
61. Purba, D.; Adityatama, D.W.; Siregar, F.; Solehudin, M.; Al Asy'ari, M.R.; Adi Wicaksana, A.; Umam, M.; Alamsyah, D.; Asokawaty, R. Integrated Stuck-Pipe-Prevention Campaign in Geothermal Drilling Project in Indonesia: A Proactive Approach. In Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, 24–27 October 2021.
62. Marbun, B.; Somawijaya, A.; Novrianto, A.R.; Hasna, H.; Anshari, M.R. Study of Prevention and Mitigation of Stuck Pipe in Geothermal Drilling. In Proceedings of the 41st Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 22–24 February 2016.
63. Sarwono, S.; Lukas, L.; Kartawidjaja, M.; Wardana, R. Stuck Pipe Detection For North Sumatera Geothermal Drilling Operation Using Artificial Neural Network. *J. Migasian* **2022**, *6*. [CrossRef]
64. Nkwocha, C. Designing a Fully Customizable Low Pressure, High-Speed Rotating Reamer Shoe System for Tubular Deployment. In Proceedings of the SPE Nigeria Annual International Conference and Exhibition, Lagos, Nigeria, 5–7 August 2024. [CrossRef]
65. Sammat, E.; O'Shea, S.; Innes, G.; Kemenyfy, J.G.; Piscevic, D. Successful Controlled Pressure Drilling Application in a Geothermal Field. In Proceedings of the All Days, Milan, Italy, 20 March 2012; p. SPE-156895-MS. [CrossRef]
66. Delong, Z.; Jun, J.; Yuwen, H.; Wei, W.; Wenjian, Z. Study on Well Control Technology of High Temperature Geothermal Drilling. *Procedia Eng.* **2014**, *73*, 337–344. [CrossRef]
67. Kumari, W.G.P.; Ranjith, P.G. Sustainable Development of Enhanced Geothermal Systems Based on Geotechnical Research—A Review. *Earth-Sci. Rev.* **2019**, *199*, 102955. [CrossRef]
68. Fan, Z.; Parashar, R. Analytical Solutions for a Wellbore Subjected to a Non-Isothermal Fluid Flux: Implications for Optimizing Injection Rates, Fracture Reactivation, and EGS Hydraulic Stimulation. *Rock Mech. Rock Eng.* **2019**, *52*, 4715–4729. [CrossRef]
69. Ayling, B.F.; Budd, A.R.; Holgate, F.L.; Gerner, E. Electricity Generation from Geothermal Energy in Australia; Geoscience Australia Fact Sheet, GEOCAT #65455; Canberra, 2007. Australian Government, G.A. Australia. 2018. Available online: http://www.ga.gov.au/image_cache/GA10663.pdf (accessed on 18 December 2024).
70. Aydin, H.; Junesompitsiri, C.; Hunkar, F.; Schmidt, J.; Schmidt, R.; Schmidt, A. Boosting the Performance of Geothermal Wells Using Progressively-Burning Propellant and High-Rate Acidizing. In Proceedings of the SPE Western Regional Meeting, Palo Alto, CA, USA, 9 April 2024; p. D021S010R004.
71. Sun, W.; Zhang, W.; Zhao, Z.; Huang, Y.; Ren, Y.; Ren, L.; Yan, Y.; Ji, S.; Wang, S.; Kong, Y. Qualitative Assessment of Optimizing the Well Spacings Based on the Economic Analysis. *Geotherm Energy* **2024**, *12*, 16. [CrossRef]
72. Niemz, P.; McLennan, J.; Pankow, K.L.; Rutledge, J.; England, K. Circulation Experiments at Utah FORGE: Near-Surface Seismic Monitoring Reveals Fracture Growth after Shut-In. *Geothermics* **2024**, *119*, 102947. [CrossRef]
73. Gentry, E.; Batir, J.; Soroush, H.; Hoffman, O.; Madyarov, A. Utilizing Downhole Drilling Dynamic Data to Characterize Geomechanics of Enhanced Geothermal Reservoirs at FORGE. In Proceedings of the 48th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 6–8 February 2023.
74. Ghassemi, A. A Review of Some Rock Mechanics Issues in Geothermal Reservoir Development. *Geo. Geol. Eng.* **2012**, *30*, 647–664. [CrossRef]
75. Li, N.; Xie, H.; Hu, J.; Li, C. A Critical Review of the Experimental and Theoretical Research on Cyclic Hydraulic Fracturing for Geothermal Reservoir Stimulation. *Geomech. Geophys. Geo. Geo-Resour.* **2021**, *8*, 7. [CrossRef]

76. Gan, H.; Liu, Z.; Wang, X.; Zhang, Y.; Liao, Y.; Zhao, G.; Zhao, J.; Liu, Z. Effect of Temperature and Acidification on Reinjection of Geothermal Water into Sandstone Geothermal Reservoirs: Laboratory Study. *Water* **2022**, *14*, 2955. [CrossRef]
77. Xu, T.; Zhao, Y.; Zhao, J.; Zhang, L.; Liu, S.; Liu, Z.; Feng, B.; Feng, G.; Yue, G. Heat Extraction Performance and Optimization for a Doublet-Well Geothermal System in Dezhou, China. *Energy Explor. Exploit.* **2022**, *40*, 619–638. [CrossRef]
78. Maeda, Y.; Ogata, S.; Fukuda, D.; Inui, T.; Yasuhara, H.; Kishida, K. A Framework of Coupled Thermal-Hydraulic-Mechanical Analysis for Simulating Hydraulic Fracturing Based on Explicit and Implicit Methods. In Proceedings of the 57th U.S. Rock Mechanics/Geomechanics Symposium, Atlanta, GA, USA, 25 June 2023; p. ARMA-2023-0759.
79. Hepbasli, A.; Akdemir, O. Energy and Exergy Analysis of a Ground Source (Geothermal) Heat Pump System. *Energy Convers. Manag.* **2004**, *45*, 737–753. [CrossRef]
80. Sarbu, I.; Sebarchievici, C. General Review of Ground-Source Heat Pump Systems for Heating and Cooling of Buildings. *Energy Build.* **2014**, *70*, 441–454. [CrossRef]
81. Yang, H.; Cui, P.; Fang, Z. Vertical-Borehole Ground-Coupled Heat Pumps: A Review of Models and Systems. *Appl. Energy* **2010**, *87*, 16–27. [CrossRef]
82. Berry, C. *A Guide to OSHA Excavations Standard*; Occupational Safety and Health Division. N.C. Department of Labor: Raleigh, NC, USA, 2009. Available online: https://www.safety.duke.edu/sites/default/files/ig14.pdf (accessed on 18 December 2024).
83. American Ground Water Trust. *Ground Water: A Source of Wonder*; American Ground Water Trust: Concord, NH, USA, 2003.
84. Mao, R.; Zhao, Z.; Tian, L.; Wang, X. Mapping the Distribution of the Neutral Zone in Assist of Shallow Geothermal Applications in the United States. In Proceedings of the Stanford Geothermal Workshop, Stanford, CA, USA, 12–14 February 2024.
85. Rybach, L. 7.06—Shallow Systems: Geothermal Heat Pumps. In *Comprehensive Renewable Energy*; Sayigh, A., Ed.; Elsevier: Oxford, UK, 2012; pp. 189–207. ISBN 978-0-08-087873-7.
86. Côté, J.; Konrad, J.-M. A Generalized Thermal Conductivity Model for Soils and Construction Materials. *Can. Geotech. J.* **2005**, *42*, 443–458. [CrossRef]
87. Bigdelou, P.; Pourfayaz, F.; Noorollahi, Y. Investigating the Effect of Soil Type and Moisture on the Performance of a Ground Source Heat Pump System Used for a Greenhouse in Iran. *J. Therm. Sci. Eng. Appl.* **2018**, *11*, 011009. [CrossRef]
88. Tambe, V.; Reddy, T.A.; Kavazanjian, E. Evaluation of Ground Coupled Heat Pump Systems in a Hot and Semi-Arid Climate. In Proceedings of the PanAm Unsaturated Soils 2017, Dallas, TX, USA, 12–15 November 2017; pp. 381–393. [CrossRef]
89. Liu, Z.; Du, Y.; Song, C.; Yang, X.; Yan, J. Effect of Soil Moisture Content on Thermal Performance of Ground Source Heat Exchangers: An Electromagnetism Topology-Based Analysis. *Energy Rep.* **2023**, *10*, 3914–3928. [CrossRef]
90. Wu, Q.; Xu, S.; Zhou, W.; LaMoreaux, J. Hydrogeology and Design of Groundwater Heat Pump Systems. *Environ. Earth Sci.* **2015**, *73*, 3683–3695. [CrossRef]
91. Guo, Y.; Zhao, J.; Liu, W.V. Effects of Varying Heat Transfer Rates for Borehole Heat Exchangers in Layered Subsurface with Groundwater Flow. *Appl. Therm. Eng.* **2024**, *247*, 123007. [CrossRef]
92. Bose, J.F.M.; Parker, J. *Design/Data Manual for Closed-Loop Ground-Coupled Heat Pump Systems*; American Society of Heating, Refrigerating and AirConditioning Engineers Inc.: Peachtree Corners, GA, USA, 1985.
93. Nikitin, A.; Farahnak, M.; Deymi-Dashtebayaz, M.; Muraveinikov, S.; Nikitina, V.; Nazeri, R. Effect of Ice Thickness and Snow Cover Depth on Performance Optimization of Ground Source Heat Pump Based on the Energy, Exergy, Economic and Environmental Analysis. *Renew. Energy* **2022**, *185*, 1301–1317. [CrossRef]
94. Garber-Slaght, R. Performance Considerations for Ground Source Heat Pumps in Cold Climates. In *Proceedings of the Report Number: NREL/CP-5600-79479*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2021.
95. Houde, M.; Araque, C.; Oglesby, K.; Woskov, P. Rewriting the Limits for Deep Geothermal Drilling: Direct Energy Drilling Using Millimeter Wave Technology. In Proceedings of the World Geothermal Congress 2020+1, Reykjavik, Iceland, 24–27 October 2021.
96. Martín-Alfonso, M.J.; Pozo, J.; Delgado-Sánchez, C.; Martínez-Boza, F.J. Thermal and Rheological Properties of Hydrophobic Nanosilica in Sunflower Oil Suspensions at High Pressures. *Nanomaterials* **2021**, *11*, 3037. [CrossRef] [PubMed]
97. Ji, Y.; Wang, L.; Zheng, Y.; Wu, W. Temperature-Dependent Abrasivity of Bukit Timah Granite and Implications for Drill Bit Wear in Thermo-Mechanical Drilling. *Acta Geo.* **2021**, *16*, 885–893. [CrossRef]
98. Hamm, S.G.; Anderson, A.; Blankenship, D.; Boyd, L.W.; Brown, E.A.; Frone, Z.; Hamos, I.; Hughes, H.J.; Kalmuk, M.; Marble, A.; et al. Geothermal Energy R&D: An Overview of the U.S. Department of Energy's Geothermal Technologies Office. *J. Energy Resour. Technol.* **2021**, *143*, 100801. [CrossRef]
99. Okoroafor, E.R.; Smith, C.M.; Ochie, K.I.; Nwosu, C.J.; Gudmundsdottir, H.; (Jabs) Aljubran, M. Machine Learning in Subsurface Geothermal Energy: Two Decades in Review. *Geothermics* **2022**, *102*, 102401. [CrossRef]
100. Ezhilarasan, K.; Jeevarekha, A. Powering the Geothermal Energy with AI, ML, and IoT. In *AI-Powered IoT in the Energy Industry*; Springer: Cham, Switzerland, 2023; pp. 271–286. ISBN 978-3-031-15043-2.
101. Buster, G.; Siratovich, P.; Taverna, N.; Rossol, M.; Weers, J.; Blair, A.; Huggins, J.; Siega, C.; Mannington, W.; Urgel, A.; et al. A New Modeling Framework for Geothermal Operational Optimization with Machine Learning (GOOML). *Energies* **2021**, *14*, 6852. [CrossRef]

102. Blackwell, D.; Richards, M.; Frone, Z.; Ruzo, A.; Dingwall, R.; Williams, M. Temperature-At-Depth Maps For the Conterminous US and Geothermal Resource Estimates. *GRC Trans.* **2011**, *35*, GRC1029452.
103. Joni S, A.; Biswas, W.; Haque, H. Life Cycle Based Carbon Footprint Assessment of Indonesia s Geothermal Energy Exploration Project. *Chem. Eng. Trans.* **2021**, *83*, 61–66. [CrossRef]
104. O'Sullivan, M.; Gravatt, M.; Popineau, J.; O'Sullivan, J.; Mannington, W.; McDowell, J. Carbon Dioxide Emissions from Geothermal Power Plants. *Renew. Energy* **2021**, *175*, 990–1000. [CrossRef]
105. Lund, J.W. 100 Years of Geothermal Power Product. In Proceedings of the Thirtieth Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 31 January–2 February 2005.
106. Garcia, J.; Walters, M.; Beall, J.; Hartline, C.; Pingol, A.; Pistone, S.; Goyal, K.; Wright, M.; Conant, T. Overview of the Northwest Geysers EGS Demonstration Project. In Proceedings of the Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 30 January–1 February 2012.
107. Walters, M.; Hartline, C. *Northwest Geysers Enhanced Geothermal System Demonstration Project*; Calpine Corporation's Second Public Informational Meeting Reporting Progress on the U.S. Department of Energy's and Calpine's Enhanced Geothermal System (EGS) Demonstration Project Underway at The Geysers; 4-November 2011. Available online: https://dnnt93026.blob.core.windows.net/portals/1/Documents/11042011_Calpine_EGS_Demonstration_Community_Update.pdf?sr=b&si=DNNFileManagerPolicy&sig=z3/L79yDnKmBcvwztmDx2/e6P8GJTUm0pPVzfhJJkBU= (accessed on 18 December 2024).
108. Katis, C. *Utah FORGE Successfully Completes Drilling of First Deviated Deep Well*; Salt Lake City, UT, USA. 2 February 2021. Available online: https://utahforge.com/wp-content/uploads/2021/02/Drilling-Completed-Press-Release-Feb2_2021.pdf (accessed on 18 December 2024).
109. Ghassemi, A.; Kumar, D. Hydraulic Fracturing in Petroleum and Geothermal Reservoirs with Reference to the Utah FORGE Stimulation. In Proceedings of the 48th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 6–8 February 2023.
110. Vivas, C.; Salehi, S. Real-Time Model for Thermal Conductivity Prediction in Geothermal Wells Using Surface Drilling Data: A Machine Learning Approach. In Proceedings of the 46th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 15–17 February 2021.
111. Janiga, D.; Kwaśnik, J.; Wojnarowski, P. Utilization of Discrete Fracture Network (DFN) in Modelling and Simulation of a Horizontal Well-Doublet Enhanced Geothermal System (EGS) with Sensitivity Analysis of Key Production Parameters. *Energies* **2022**, *15*, 9020. [CrossRef]
112. Moore, J.; McLennan, J.; Pankow, K.; Simmons, S.; Podgorney, R.; Wannamaker, P.; Rickard, W.; Xing, P. The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): A Laboratory for Characterizing, Creating and Sustaining Enhanced Geothermal Systems. In Proceedings of the 45th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 10–12 February 2020.
113. Moore, J.; Mclennan, J.; Allis, R.; Pankow, K.; Simmons, S.; Podgorney, R.; Wannamaker, P.; Rickard, W. The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): An International Laboratory for Enhanced Geothermal System Technology Development. In Proceedings of the 44th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 11–13 February 2019.
114. The Research Foundation, *Assessing the Feasibility of a Central New York Naturally Chilled Water Project*; The State University of New York: Albany, NY, USA, 2011. Available online: https://www.cnyrpdb.org/docs/reports/CNYCWP_Final_Report_June_6_2011R.pdf (accessed on 18 December 2024).
115. Fulton, P.; Clairmont, R.; Fulcher, S.; Pinilla, D.; Purwamaska, I.; Jamison, H.; Fresonke, M.; Puthur, R.; Torres, J.; Heaton, T.; et al. Subsurface Insights from the Cornell University Borehole Observatory (CUBO): A 3km Deep Exploratory Well for Advancing Earth Source Heat Deep Direct-Use Geothermal for District Heating. In Proceedings of the 49th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 12–14 February 2024.
116. Liming, D. *Careers in Geothermal Energy*; U.S. Bureau of Labor Statistics: Washington, DC, USA, 2012.
117. Office of Energy Efficiency & Renewable Energy. *GeoVision: Harnessing the Heat Beneath Our Feet*; U.S. Department of Energy: Washington, DC, USA, 2019.
118. Augustine, C.; Tester, J.W.; Anderson, B. A Comparison of Geothermal with Oil and Gas Well Drilling Costs. In Proceedings of the Thirty-First Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 30 January–1 February 2006.
119. Bavadiya, V.; Srivastava, S.; Teodoriu, C.; Salehi, S. Geothermal Drilling Training and Certification: Should It Be Different? In Proceedings of the 44th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 11–13 February 2019.
120. Malhotra, M.; Li, Z.; Liu, X.; Lapsa, M.; Bouza, T.; Vineyard, E. Heat Pumps in the United States: Market Potentials, Challenges and Opportunities, Technology Advances. In Proceedings of the 14th IEA Heat Pump Conference, Chicago, IL, USA, 14 April 2023.
121. Oh, H.; Beckers, K. *Cost and Performance Analysis for Five Existing Geothermal Heat Pump-Based District Energy Systems in the United States*; NREL/TP--5700-86678; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2023.

122. Tester, J.; Gustafson, O.; Beyers, S.; Jordan, T.; Fulton, P. Geothermal Direct Use for Decarbonization—Progress Towards Demonstrating Earth Source Heat at Cornell. In Proceedings of the 48th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 6–8 February 2023.
123. European and US Efforts to Develop Geothermal Energy Are Headed in Different Directions. Available online: https://jpt.spe.org/european-and-us-efforts-to-develop-geothermal-energy-are-headed-in-different-directions (accessed on 18 December 2024).
124. Big Oil Eyes Powering Big Tech's Data Center Demand. Available online: https://jpt.spe.org/big-oil-eyes-powering-big-techs-data-center-demand (accessed on 18 December 2024).