International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/
Vol. 50 No. 1 April 2025, pp. 519-542

Geothermal Energy Exploration And Production Techniques: A Review

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Abstract: The internal heat of our planet fuels geothermal energy as a dependable renewable energy that shows extensive potential for sustainable growth. The renewable process of geothermal energy enables its pivotal role in worldwide clean energy development. The initial use of geothermal energy dated back to heating and bathing but now it powers electricity generation and many direct applications. The review delivers an exclusive discussion regarding the fundamental exploration and production methods required for geothermal resource development. The analysis covers geological features as well as sophisticated exploration procedures alongside drilling advancements along with reservoir management practices and the environmental and socioeconomic aspects of building geothermal projects. Research of geological formations requires analysis of heat sources and reservoirs and caprock structures through examination of geochemical methods and geophysical procedures together with remote sensing analysis. The current assessment includes a review of drilling advances that combine horizontality with directionality and the application of Enhanced Geothermal Systems (EGS) for regions beyond hydrothermal natural resources. This analysis includes evaluations of environmental effects as well as social effects and it offers approaches to reduce their impact. The research identifies three essential findings about exploration methods that reduce uncertainty and site selection performance and the value of drilling innovations for saving costs yet increasing outputs and EGS's transformative influence on geothermal production expansion. The review demonstrates geothermal energy's capability to operate across different sectors including power production and direct utilization systems by discussing induced seismic issues and water resource management and greenhouse gas release problems. Geothermal energy establishes itself as an essential basis for producing sustainable power. Continued research, technological advancements, and supportive policy frameworks are essential to overcoming existing barriers and fully realizing its benefits. By addressing environmental and social concerns, geothermal energy can significantly contribute to global clean energy transitions and climate change mitigation.

Keywords: Geothermal energy, exploration techniques, drilling technologies, Enhanced Geothermal Systems (EGS), reservoir engineering, environmental impacts, sustainable energy development.

Introduction: The Significance of Geothermal Energy

Geothermal energy, fundamentally defined as the heat contained within the Earth, derives its name from the Greek words geo (earth) and therme (heat). This heat originates from the continuous production within the Earth's core, primarily through the slow decay of radioactive particles (Howarth, 2024; fig. 1). The Earth's internal temperature is remarkably high, reaching approximately 10,800°F at its inner core (Howarth, 2024). This immense reservoir of thermal energy positions geothermal as a renewable energy source, as the heat is constantly replenished by natural processes. Throughout history, humans have utilized geothermal energy in various forms, notably for bathing and heating buildings, with archaeological evidence suggesting such uses dating back thousands of years.

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The industrial exploitation of geothermal resources began in the 19th century, and the early 20th century marked a significant milestone with the construction of the first geothermal power plant in Italy (Kriger, 2024).

Natural geothermal energy operation continues without interruption thanks to its continuous and self-replenishing systems, which allow reliable baseload power delivery (Chettri and Sankarananth, 2022). Global thermal activity generates continuous heat, enabling geothermal power generation to deliver steady and forecastable electricity without weather disruptions. The built-in reliability aspect stands essential to preserve grid integrity and satisfy uninterrupted power requirements. With such a lengthy record of geothermal energy deployment, society has accepted this power source as enduring while modern technological improvements continue to optimize its capabilities (Jamieson et al., 2024). Geothermal energy has demonstrated a continuous ability to meet human requirements, from its original

functions as a heat source and sanitation system up until its modern application in power generation, as illustrated in fig. 2.

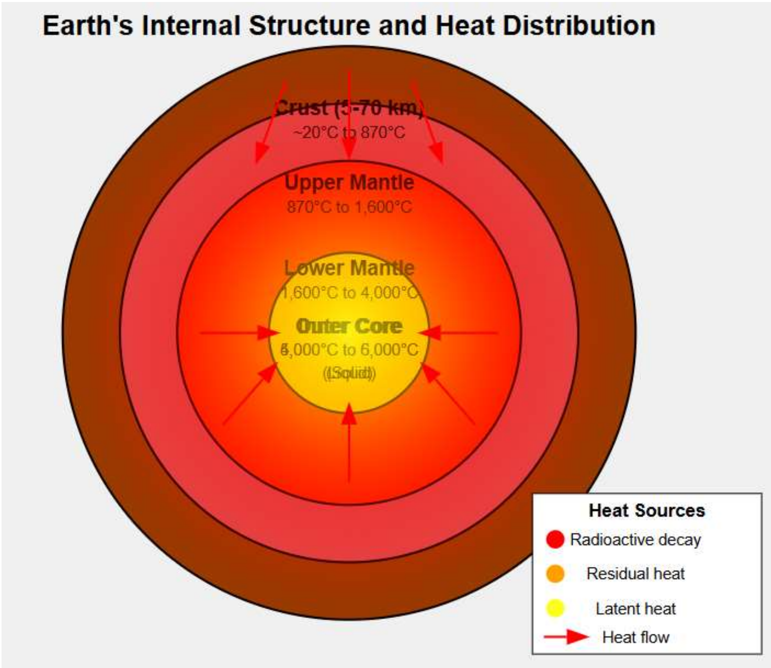

Figure 1: Diagram of Earth's internal structure and heat distribution

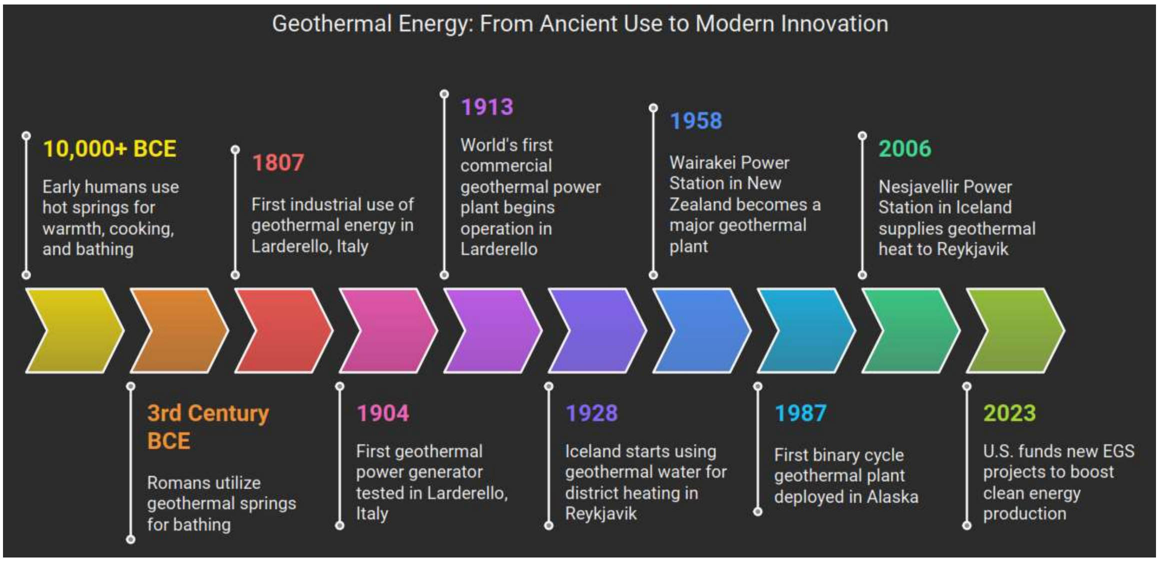

Figure 2: Timeline of historical milestones in geothermal energy utilization.

Challenges in Geothermal Resource Development

Developing geothermal resources presents several complex challenges, beginning with the difficulties in locating and accurately characterizing these subsurface energy sources. High-temperature geothermal resources suitable for electricity generation are often geographically constrained to tectonically active regions, typically found along the boundaries of the Earth's tectonic plates (Zhang et al., 2024; fig. 3). The limited land area situated above accessible pockets of high-temperature water and steam further restricts the potential for large-scale deployment (Wang et al., 2023). Unlike more readily quantifiable renewable resources, the size and characteristics of a geothermal reservoir cannot be directly measured (Sharmin et al., 2023). Instead, resource assessment relies on indirect investigations, including geological, geochemical, and geophysical mapping techniques. Even after the considerable investment in exploratory drilling, substantial uncertainty remains regarding the actual energy potential that can be harnessed from a given site (Sharmin et al., 2023).

High-temperature geothermal resources have proven limited in widespread use because they depend on specific locations (Aljubran & Horne, 2024). The geographical limitation in geothermal energy has required developers to make considerable technological breakthroughs, leading to Enhanced Geothermal Systems (EGS). The unpredictability of underground resource valuation generates major risks and added financial complexity in geothermal energy projects (Sharmin et al., 2023). Establishing complicated exploration methods combined with development stages achieves maximum resource efficiency while reducing resource unpredictability.

The process of locating geothermal resources faces strong resistance from technical difficulties and high initial expenses. Deep-well drilling equipment needed to extract geothermal resources, along with power plant construction tools, demands substantial funding (Wang et al., 2023). Geothermal power generation requires water temperatures above 150°C for efficient operation, and modern technology cannot find these temperatures economically at depths that do not exceed this threshold (Nardini, 2022). Emerging technologies like Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS) currently show higher Levelized Cost of Electricity (LCOE) than standard geothermal power, as well as solar and wind energy systems (table 1 demonstrates; Shelare et al., 2023). The exploration and drilling phases represent a major block of project expenses, as they generally account for approximately fifty percent of total costs (Li et al., 2022).

Geothermal power implementation faces two significant hurdles: drilling operations require significant initial capital outlays combined with extensive drilling expenses (Wang et al., 2023). For geothermal projects to compete economically, it is essential to

International Journal of Progressive Sciences and Technologies (IJPSAT)
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continue innovating technologies and securing financial support mechanisms to improve their affordability (Moore & Gutiérrez-Negrín, 2025).

Ongoing research and development efforts need continuous support to decrease expenses, as advanced technologies like EGS currently have higher costs than conventional geothermal power and fossil fuels (Shelare et al., 2023). Various environmental and social concerns emerge during the development of geothermal energy that require detailed attention. Geothermal development creates various environmental worries relating to site disturbances of land surfaces alongside fluid extraction impacts that produce land subsidence and seismic activity as well as thermal effects on ecosystems and chemical substance emissions (Sharmin et al., 2023; Table 2). Geothermal power production generates lower amounts of greenhouse gas than fossil fuel systems yet drilling operations can trigger the discharge of natural subsurface gases which include greenhouse gas emissions (Nardini, 2022). The main issue with EGS projects involves the risk of earthquake generation (Aljubran & Horne, 2024). Currently applied reservoir management of geothermal sources demands precise fluid extraction controls which maintain replenishment rates above or equivalent to depleting rates (Nardini, 2022). The limited water availability in certain regions causes water requirements for geothermal power plant operations to create disputes with existing water management stakeholders according to Rohit et al. (2023).

Geothermal development remains environmentally friendly compared to fossil fuels but it brings unique environmental concerns (Pambudi & Ulfa, 2024) according to Sharmin et al. (2023). To achieve responsible geothermal energy development organizations must perform detailed environmental impact examinations followed by systematic mitigation procedure execution. Public reaction toward geothermal energy depends largely on environmental concerns especially the seismic risks associated with induced seismicity (fig. 4; Idroes et al., 2024). The lifecycle of geothermal energy projects needs transparent monitoring and community engagement along with strict safety measures because they should guarantee public support.

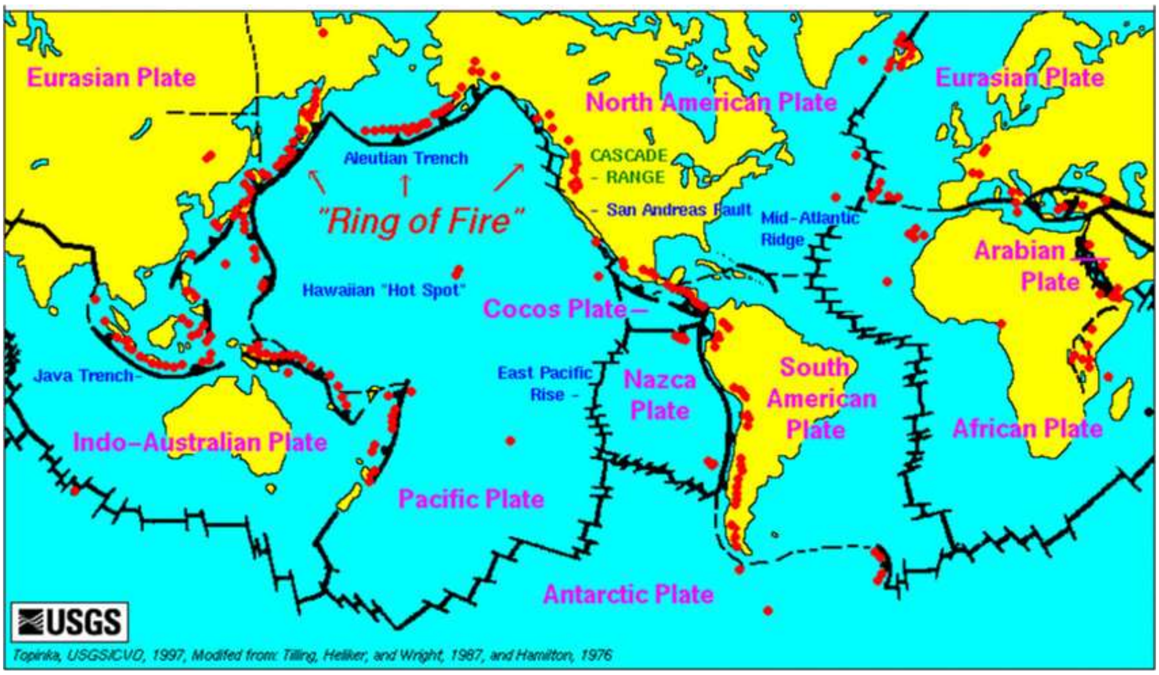

Figure 3: Global Map of Tectonic Plate Boundaries and Geothermal Hotspots (After Fridleifsson et al., 2008).

Volcanic activity takes place mainly along so called plate boundaries (Figure 3). Geothermal fields are very common on plate boundaries, as the crust is highly fractured and thus permeable to water, and sources of heat are readily available. Most of the plate boundaries are below sea level, but in cases where the volcanic activity has been intensive enough to build islands or where active plate boundaries transect continents, high temperature geothermal fields are commonly scattered along the boundaries. A spectacular example of this is the "ring of fire" that circumscribes the Pacific Ocean (the Pacific Plate) with intense volcanism and

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geothermal activity in New Zealand, Indonesia, the Philippines, Japan, Kamchatka, Aleutian Islands, Alaska, California, Mexico, Central America, and the Andes mountain range. Other examples are Iceland, which is the largest island on the Mid-Atlantic Ridge plate boundary, the East African Rift Valley with impressive volcanoes and geothermal resources in e.g. Djibouti, Ethiopia, and Kenya, and "hot spots" such as Hawaii and Yellowstone.

Table 1: Comparison of Levelized Cost of Electricity (LCOE) for Different Energy Sources

Energy Source	LCOE (USD/MWh)	Year	Notes
Conventional Geothermal	37.47	2025	Without tax credits
Conventional Geothermal	35.43	2025	With geothermal tax credits
Conventional Geothermal	71.00	2023	
EGS/AGS	213 - 355	2023	Three to five times higher than offshore wind and solar PV
Natural Gas	75 - 200	2023	
Solar PV	Lower than EGS/AGS	2023	
Wind Energy	Lower than EGS/AGS	2023	

Table 2: Environmental Impacts of Geothermal Development and Fossil Fuels

Environmental Concern	Geothermal Energy	Fossil Fuels (Coal, Oil, Gas)	Comparative Analysis
Land Subsidence	Minor localized subsidence possible due to fluid extraction; mitigated with reinjection (e.g., Wairakei).	Significant subsidence from mining and extraction (e.g., coal mines, oil fields).	Geothermal: Low impact, Fossil Fuels: High impact
Induced Seismicity	Potential for minor, localized induced earthquakes from EGS injection (e.g., Basel, 2006); controlled with monitoring.	Moderate to significant seismic activity from fracking and mining operations.	Geothermal: Controlled, Fossil Fuels: More pronounced
Greenhouse Gas Emissions	Near-zero direct emissions (0–88 g CO_2/kWh), mostly from dissolved reservoir gases.	High CO_2 and methane emissions (Coal: ~820–1000 g/kWh, Oil: ~650–800 g/kWh, Gas: ~400–500 g/kWh).	Geothermal: Minimal, Fossil Fuels: Substantial
Water Usage	Closed-loop systems and water recycling; moderate to high use but efficient.	High water consumption (~20–50 gal/kWh) with potential contamination from spills.	Geothermal: Efficient, Fossil Fuels: Resource-intensive
Habitat Disruption	Minimal surface disturbance (1–8 acres/MW); drilling and plants affect small areas.	Extensive land clearing and ecosystem destruction (10–20 acres/MW, plus broader damage).	Geothermal: Low impact, Fossil Fuels: Significant
Chemical Pollution	Minimal chemical use; some scaling from fluids manageable with treatment.	Extensive chemical contamination from extraction, refining, and spills.	Geothermal: Low risk, Fossil Fuels: High environmental threat
Thermal Effects	Controlled thermal discharge; localized impact on ecosystems (e.g., hot water runoff).	Significant thermal pollution from power plants, altering climates and water bodies.	Geothermal: Managed, Fossil Fuels: Extensive

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Long-term Environmental Risk	Renewable and sustainable; minimal long-term degradation.	Non-renewable; causes long-term environmental degradation (e.g., climate change).	Geothermal: Sustainable, Fossil Fuels: Persistent damage
Air Quality Impact	Negligible air pollution; minor H2S or silica emissions controlled with scrubbers.	Significant air quality degradation (SO2, NOx, particulates, VOCs causing smog).	Geothermal: Minimal, Fossil Fuels: Severe
Carbon Footprint	Extremely low due to renewable nature and low emissions.	Extremely high from combustion and extraction processes.	Geothermal: Minimal, Fossil Fuels: Substantial
Land Use	Moderate (1–8 acres/MW); small footprint compared to fossil fuels.	High (10–20 acres/MW); extensive disruption from mining/drilling.	Geothermal: Low impact, Fossil Fuels: High impact
Waste Production	Low; minimal solid waste, manageable with treatment.	High; ash, sludge, and toxic residues (e.g., coal ash) require extensive disposal.	Geothermal: Low, Fossil Fuels: High

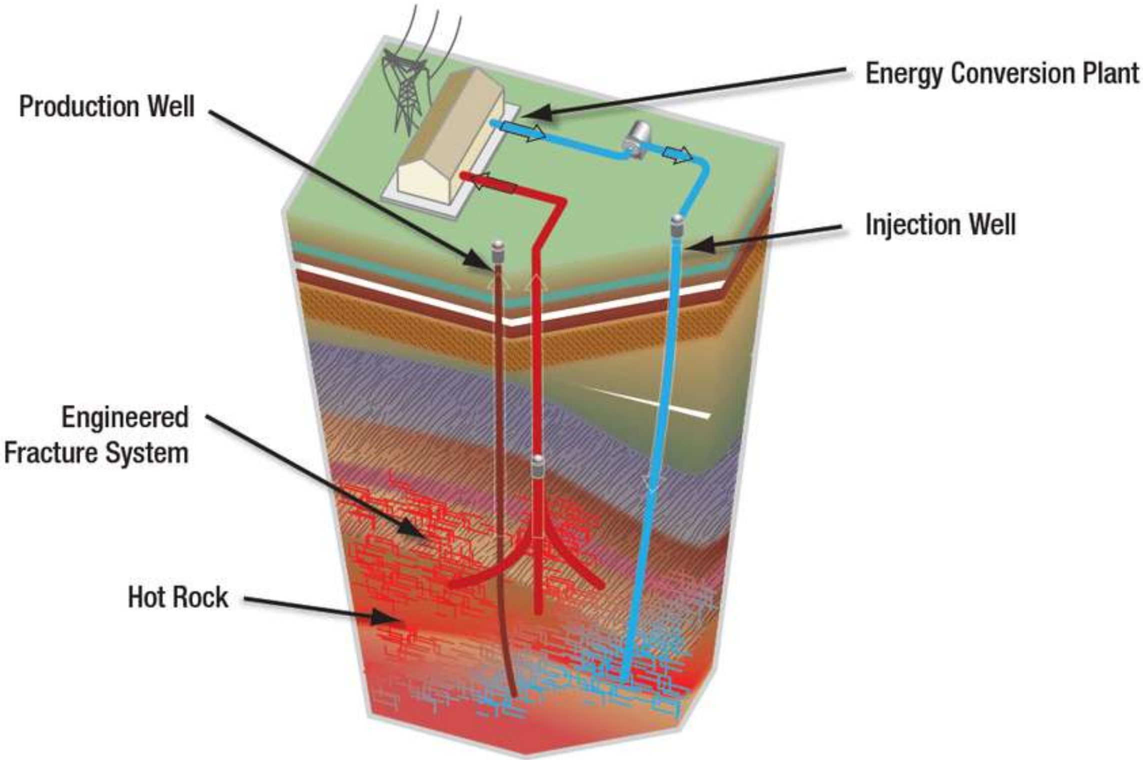

Figure 4: Illustration of Enhanced Geothermal Systems (EGS) Technology (Adapted from Geothermal Technologies Program 2008).

Fluids are pumped at depth of typically around 4 km under high pressure to cause an enhanced fracture network susceptible to fluid flow. Once a permeable fractured network is established the heated fluids are pumped back to the surface through a second borehole to generate electricity from a power plant. Used fluids are then reintroduced to hot rocks at depth.

Purpose and Scope of the Review

This paper conducts a comprehensive evaluation of geothermal energy exploration and production methods that exist today. The scope of this review encompasses several key areas critical to the advancement and sustainable utilization of geothermal resources. The review process starts with an analysis of geothermal system geological features to determine geothermal resource locations while describing research methods for exploration (Sharmin et al., 2023). The exploration assessment techniques section explains multiple detection methods starting from traditional to modern technological methods while emphasizing recent advancements for better accuracy and efficiency (Kumar et al., 2022).

Following the overview the report focuses on standard and new drilling approaches. Various techniques help decrease expenses and boost operational efficiency because they create essential conditions for commercial viability of geothermal energy (Rohit et al., 2023). The paper examines reservoir management principles including Enhanced Geothermal Systems (EGS) together with sustainable practices to sustain geothermal resource productivity (Gkousis et al., 2022).

Geothermal energy development assessments focus on evaluating its social along with environmental impacts in the conclusion. This study analyzes both the key benefits and environmental risks which include land modifications and seismic events and greenhouse gas effects before providing sustainable utilization guidelines (Ahmed et al., 2022; Rohit et al., 2023). The review stresses the requirement to strike a proper balance between power generation and environmental protection together with public participation.

Geological Characteristics of Geothermal Systems and Exploration Techniques

A successful geothermal resource extraction requires multiple essential geological conditions to operate in concert (Khodayar and Björnsson 2024). The necessary elements for geothermal energy extraction comprise a heat source most commonly manifested through magmatic intrusions or regions that generate considerable heat flow from Earth's interior. A reservoir made up of permeable rocks capable of containing hot fluids is required as part of the geological system (fig. 5). The reservoir requires an impermeable geological caprock because it functions to stop the upward movement of heat together with fluids through the reservoir. Geothermal resources build up in locations that experience considerable tectonic activity including tectonic plate boundaries as well as recently active volcanic regions and crustal hot spots (Szanyi et al., 2023; fig. 3). The different types of geothermal fields include convective hydrothermal resources consisting of vapor-dominated and water-dominated systems and hot dry rocks without substantial fluid as well as sedimentary geothermal systems located in sedimentary basins (Figueira et al., 2024; fig. 6). The Earth's crust temperature increases progressively by 25 to 30°C/km throughout its depth as research continues deeper into the subsurface (Figueira et al., 2024; fig. 7).

Effective exploration of geothermal energy relies on in-depth knowledge of different geologic environments and resource features to create specific extraction approaches (Cui et al., 2023). The exploration and production of geothermal resources requires specific methods for hydrothermal systems together with hot dry rocks intended for Enhanced Geothermal Systems (EGS). Every geothermal energy project needs a complete comprehension of geological frameworks in order to achieve success as described by Rohit et al., 2023.

Multiple testing procedures help measure the potential of geothermal resources. Surveying geological formations involves mapping hot spring locations and geyser formations and volcanic areas because their presence indicates concentrated heat within the subsurface (Sharmin et al., 2023). The assessment of natural water and steam and gas flows through geochemical methods determines subsurface properties by measuring both heat levels and fluid chemical compositions (Moraga et al., 2022). The resistivity technology identifies hot regions in the bedrock structure yet seismic technology constructs images of natural geological contours. Three-dimensional seismic data linked to assessments from existing wells improves geological prediction methods for better drilling decisions which lead to overall improvement of the energy sector (AlGaiar et al., 2024). The procedure of thermal gradient drilling facilitates the recognition of modified temperature distributions by shallow drillings which supports analysis of heat flow systems. Scientists monitor surface thermal changes together with generating affected area geological maps through the analysis of satellite imagery and aerial data using remote sensing methods. The development of new advanced methodologies remains focused on inventing better methods to assess resources and blend multiple datasets for more precise and efficient exploration purposes (Yalcin et al., 2023).

The integration of advanced geophysical techniques, particularly the analysis of seismic data, is revolutionizing geothermal exploration (AlGaiar et al., 2024). By providing more precise images of the subsurface, these technologies significantly reduce reliance on extensive and costly exploratory drilling. Leveraging technologies originally developed for the oil and gas industry,

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such as sophisticated seismic surveys, allows for a more detailed understanding of underground geological structures and potential geothermal reservoirs, leading to more efficient and cost-effective exploration efforts.

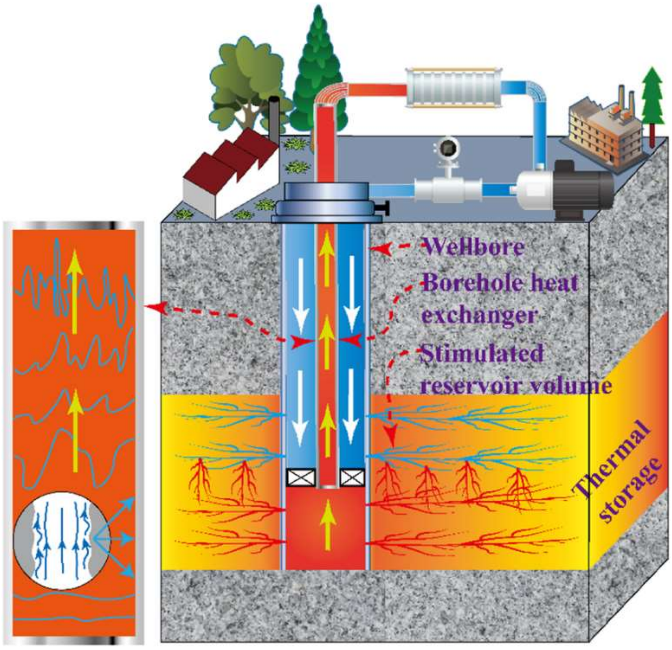

Figure 5: Schematic Diagram of a Geothermal System (After Zhang et al., 2022)

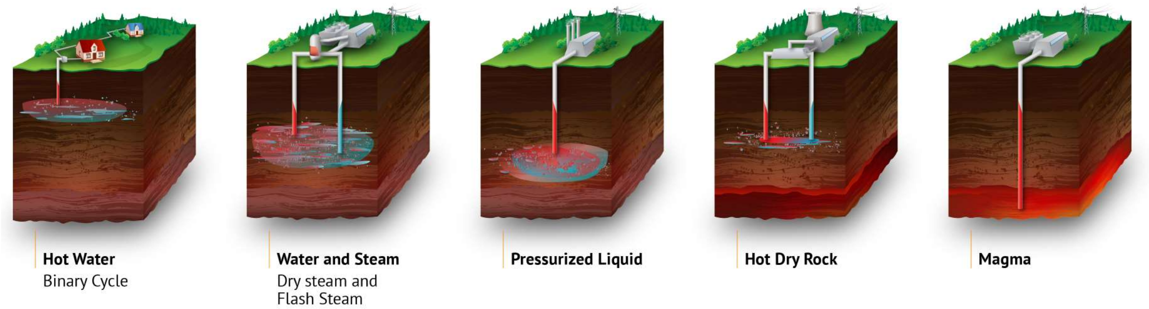

Figure 6: Types of Geothermal Systems (After Energy Encyclopedia 2025.)

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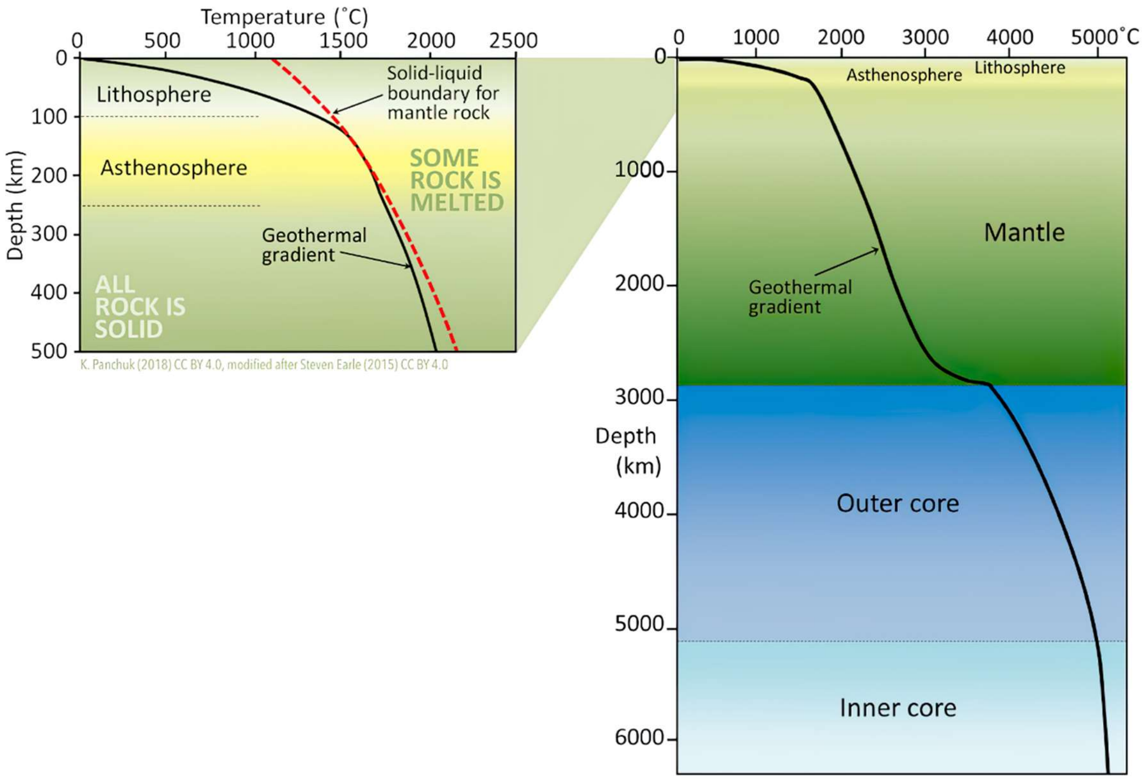

Figure 7: Temperature Gradient Profile with Depth by Karla Panchuk (2018), modified after Steven Earle (2016).

Geothermal gradient (change in temperature with depth). Left- Geothermal gradient in the crust and upper mantle. The geothermal gradient remains below the melting temperature of rock, except in the asthenosphere. There, temperatures are high enough to melt some of the minerals. Right- Geothermal gradient throughout Earth. Rapid changes occur in the uppermost mantle, and at the core-mantle boundary. The red dashed line shows the minimum temperature at which dry mantle rocks will melt.

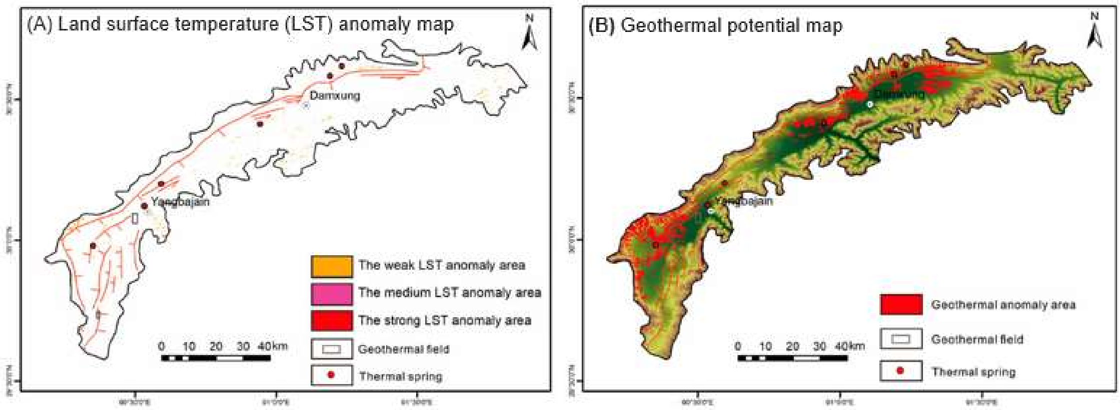

Figure 8: Damxung–Yangbajain basin, Qinghai–Tibet Plateau Thermal Anomalies Identified via Remote Sensing (After Li et al., 2023)

Advancements in Drilling Technologies for Geothermal Energy and Extraction Methods

Conventional drilling methods for geothermal energy largely draw upon rotary drilling techniques that are also widely used in the oil and gas industry (Ahmed & Teodoriu, 2024). However, drilling in geothermal environments presents unique challenges, including encountering high temperatures and abrasive geological formations at significant depths, which can lead to increased wear and tear on drilling equipment (Ahmed & Teodoriu, 2024). Given that drilling expenses can constitute a substantial portion of the overall cost of a geothermal project, cost optimization in this phase is of paramount importance (Sharmin et al., 2023).

Significant advancements in drilling technologies are continually being made to improve efficiency and reduce costs (Dupriest & Noynaert, 2022). Horizontal drilling techniques allow for greater contact with the geothermal reservoir by extending laterally through hot rock formations, potentially increasing the rate of fluid flow and overall energy production (table 3; Sharmin et al., 2023). Directional drilling enables the precise targeting of specific subsurface features and allows for the optimization of well placement to maximize resource extraction (Khodayar & Björnsson, 2024). Developing advanced materials for drill bits and well casing to function under deep geothermal well conditions which require exposure to severe temperatures and pressures constitutes a crucial requirement (Ahmed & Teodoriu, 2024). The drilling industry applies robotics and automation to operations because these integrated systems provide better operational efficiency and safety alongside reduced drilling times (Patel et al., 2025). The exploration of supercritical geothermal systems extends geological drilling beyond 3 kilometers to extract heat from reservoirs that maintain temperatures above 400°C offering increased well energy capacity (Somova et al., 2023).

The application of closed-loop technology brings innovation by using concentric pipes that transport a working fluid which operates independently from the geothermal reservoir according to Khaleghi & Livescu (2023). The technique operates by decreasing water necessities while decreasing ecological dangers of geothermal fluid extraction and re-injection (Sharmin et al., 2023). Geothermal operators successfully implement oil and gas sector technology through their adoption of horizontal drilling methods together with hydraulic fracturing techniques according to Ahmed and Teodoriu (2024). Optimizing wellbore construction expenses remains central because casing and cementing materials and operations compose a primary expenditure part of total costs (Khodayar & Björnsson, 2024). Studies show that advanced electronic and sensored downhole data collection systems demonstrate the ability to shorted drilling operations while minimizing the related expenses (Patel et al., 2025).

Extraction Methods for Geothermal Energy

The production of geothermal energy requires scientists to access underground heat reservoirs to obtain heat energy while delivering it to the electric grid. Different approaches exist to perform this operation.

Enhanced Geothermal Systems (EGS) requires injecting cold fluids into superhot reservoirs to generate microfractures within ductile rocks thus improving their permeability and creating an effective heat transfer region known as a "permeability cloud" (Li et al., 2022). The extraction of geothermal energy becomes possible through this process even when natural rock permeability is minimal (Sharmin et al., 2023).

The injection of water into superhot rock layers between 3 and 10 km depth transforms the water into supercritical steam with a power output strength of three to four times greater than traditional geothermal steam (Marzouk, 2024). Superhot geothermal steam from deep wells provides ample energy for surface turbines which operate more efficiently than traditional geothermal methods (Somova et al., 2023).

A Closed-Loop System has underground pipes that utilize a working fluid to exchange heat in isolated geothermal networks (Khaleghi & Livescu, 2023). Sustainability advances through the implementation of this technology which reduces environmental damages and eliminates the requirement of fluid injection (Sharmin et al., 2023).

Fractured Reservoir Systems represent a novel technique for obtaining superhot geothermal energy which utilizes tiny fissures instead of large fractures according to Njeru et al. (2024). Research on this method focuses on boosting permeability for continuous fluid transport to extract heat effectively (Zhuang & Zang, 2021).

The process of accessing deep geothermal energy from superhot reservoirs provides both potential advantages and technical obstacles according to Sharmin et al. (2023). Scientists develop millimeter-wave drilling to address extreme-depth drilling challenges as this technology enables the rock vaporization and melting process (Sircar et al., 2023). The search for improved heat extraction methods now focuses on systems which unite authentic fractures with created microcracks and modified reservoirs (Elshehabi & Alfehaid, 2025).

The worldwide energy transition will find significant support through geothermal power due to ongoing advances in drilling technology that will make geothermal power a major contributor away from fossil fuel dependence (Rohit et al., 2023).

Table 3: Comparison of Conventional and Advanced Drilling Techniques

Parameter	Conventional Drilling Techniques	Advanced Drilling Techniques
Definition	Traditional methods using rotary drilling with basic equipment.	Modern techniques incorporating automation, real-time data analysis, and advanced technologies like directional drilling.
Equipment Used	Rotary drills, tri-cone bits, mud pumps, and basic measurement tools.	Advanced drill bits, automated rigs, sensors, Measurement While Drilling (MWD), Logging While Drilling (LWD), and robotics.
Drilling Efficiency	Slower due to manual operations and limited precision.	Faster and more efficient due to automation, real-time monitoring, and optimized drilling paths.
Cost	Lower initial costs but higher operational costs due to inefficiencies and frequent maintenance.	Higher initial investment but reduced long-term costs due to improved efficiency and fewer errors.
Precision	Limited accuracy in targeting specific zones or formations.	High precision with the ability to target specific geological formations and navigate complex reservoirs.
Directional Drilling	Limited ability to drill horizontally or at angles; mostly vertical drilling.	Capable of horizontal, multilateral, and complex wellbore designs for better reservoir access.
Environmental Impact	Higher environmental impact due to excessive mud usage, spills, and inefficient resource extraction.	Reduced environmental impact through optimized resource use, minimal waste, and better control over drilling fluids.
Safety	Higher risk of accidents due to manual operations and lack of real-time monitoring.	Enhanced safety with automated systems, remote operations, and real-time data analysis to prevent hazards.
Data Collection	Limited data collection capabilities; relies on post-drilling analysis.	Real-time data collection and analysis using sensors, MWD, and LWD for informed decision-making during drilling.
Complexity	Simpler and easier to implement but less adaptable to challenging geological conditions.	More complex but highly adaptable to difficult terrains, deepwater drilling, and unconventional reservoirs.
Applications	Suitable for shallow, straightforward wells in conventional reservoirs.	Ideal for deepwater, shale gas, tight oil, geothermal, and other unconventional or hard-to-reach reservoirs.

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Maintenance	Frequent maintenance required due to wear and tear of traditional equipment.	Reduced maintenance needs due to durable materials and predictive maintenance enabled by advanced monitoring.
Energy Consumption	Higher energy consumption due to inefficiencies in drilling processes.	Optimized energy usage through advanced technologies and automated systems.
Examples	Cable tool drilling, rotary drilling, percussion drilling.	Directional drilling, managed pressure drilling (MPD), underbalanced drilling, and laser/ultrasonic drilling.

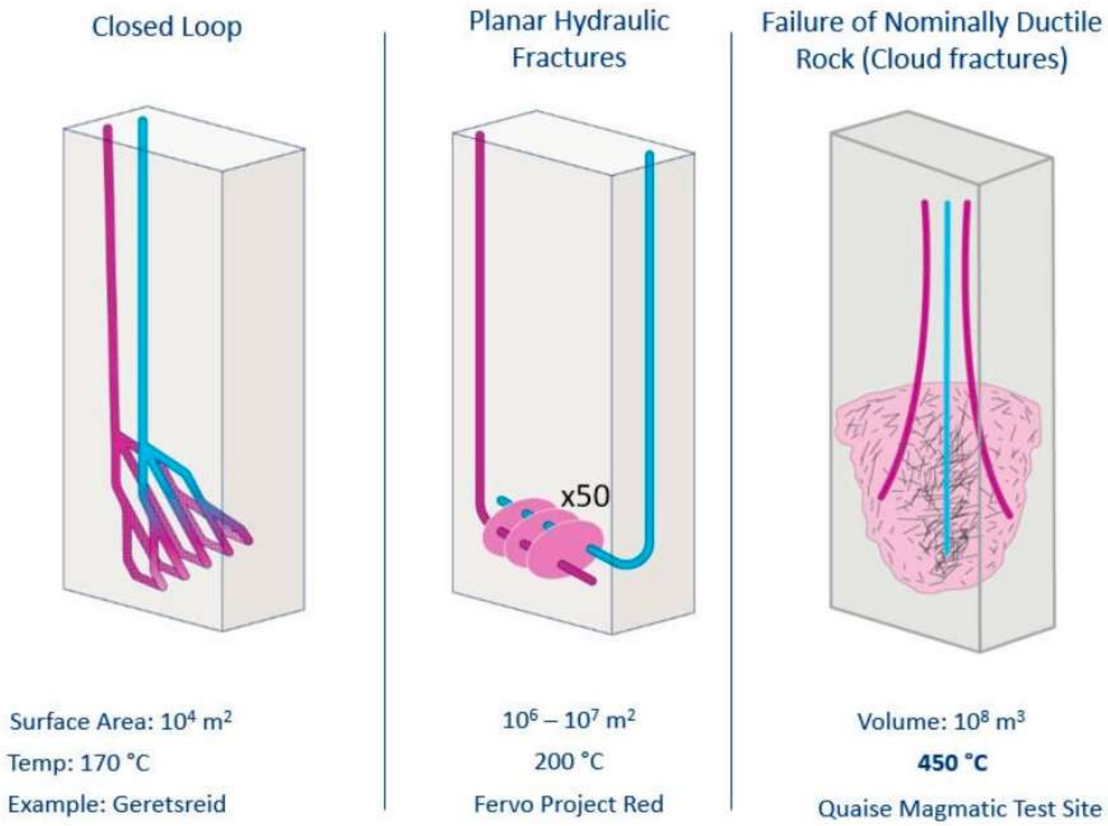

Figure 5: Different concepts for engineered geothermal systems (After Carlo Cariaga. 2024).

Reservoir Engineering and Management in Geothermal Systems

The fundamental properties of geothermal underground reservoirs need characterization according to the rock's permeability and porosity as well as temperature and pressure levels. Geological modeling depends on this fundamental knowledge because it enables accurate predictions about fluid and heat movement during different production stages according to Temizel et al. (2025).

Geo-energy production optimization and sustainable system operation depend on successful reservoir management strategies (Iwe et al., 2023). Strategies for maximizing energy retrieval need implementation during the whole operational period for geothermal fields. The periodic evaluation of reservoir elements through pressure and temperature tests alongside tracer tests allows engineers to make educated management choices. To sustain geothermal power generation properly the stored pressure requires fluid reinjection as an essential practice (Sharmin et al., 2023). Saving the reservoir through reinjection replenishes the system which sustains continuous fluid movement and avoids detrimental subsidence effects in the land surface. Additionally, effective reservoir

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ISSN: 2509-0119.
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https://ijpsat.org/
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management involves addressing operational challenges such as the buildup of mineral deposits (scaling) and the management of non-condensable gases that can affect power plant efficiency (Qin et al., 2023).

Enhanced Geothermal Systems (EGS) represent a significant advancement in reservoir engineering, enabling the creation of human-made geothermal reservoirs in hot, dry rock formations where natural permeability is insufficient for conventional hydrothermal development (Huenges, 2025; fig. 9). The process involves injecting fluid deep underground under carefully controlled conditions to create new fractures in the rock or to reopen existing ones, thereby increasing the overall permeability. Typically, water or another suitable fluid is injected down one well, where it is heated by the hot rock as it circulates through the engineered fracture network. Energy production occurs after bringing the heated fluid back through a different well to the surface for electricity generation (Santos et al., 2022; fig. 9). The potential of EGS technology extends geothermal energy production capabilities outside hydrothermal limitations thus making geothermal power available across wider geographical areas throughout the world (Korucan et al., 2024).

The innovation of Enhanced Geothermal Systems (EGS) enables major developments in geothermal energy resources because they target extensive heat reserves in areas that previously had no geothermal potential (Jolie et al., 2021). The new technology extends geothermal power potential worldwide because it operates independently from naturally occurring hot water or steam reservoirs.

Modern reservoir engineering and management strategies operate under principles of sustainable operations. The extraction rate of fluid from geothermal reservoirs needs to stay balanced with reinjection rates to preserve long-term reservoir supply according to Sharmin et al. (2023). Water diffusion and environmental impact can decrease through the implementation of closed-loop systems that circulate working fluids within sealed systems according to Santos et al. (2022). Treated wastewater serves as an important water-conservation method when utilized as injection fluid for geothermal systems. Financial and environmental risks linked to the solid materials and sludges produced in geothermal operations require sustainable strategies for their mitigation (Ozowe et al., 2024).

The sustainable management of geothermal reservoirs demands proper conservation between fluid removal and re-introduction and controlled fluid circulation to safeguard the sustainable productivity and environmental stewardship of geothermal power (Sharmin et al., 2023). Reservoir management as a proper practice helps protect geothermal resources from exhaustion while maintaining low water consumption and minimizing environmental hazards that enhance sustainability throughout geothermal power generation.

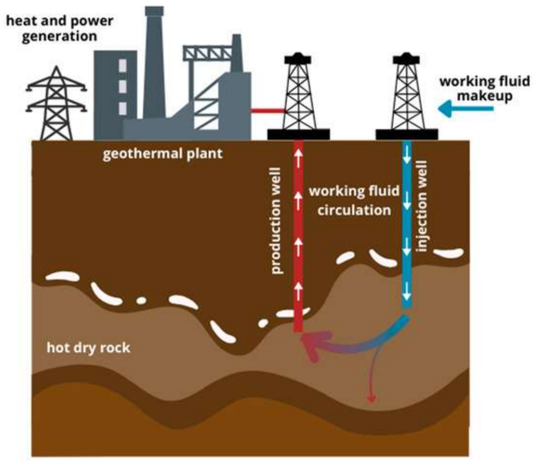

Figure 9: Enhanced Geothermal Systems (EGS) Process (After Gladysz et al., 2024)

Power Generation Technologies and Direct Use Applications of Geothermal Energy

Geothermal energy can be harnessed for electricity generation through several established technologies, each suited to different reservoir characteristics. Dry steam plants directly utilize steam from a geothermal reservoir to power turbines connected to electricity generators (Farajollahi et al., 2023; fig. 10). Flash steam plants, which are the most common type, take high-pressure hot water from deep underground and convert it into steam in a low-pressure tank to drive turbines (Desai et al., 2024). Binary cycle power plants are particularly effective for lower-temperature geothermal resources. In these plants, the geothermal hot water is passed through a heat exchanger to heat a secondary working fluid with a lower boiling point, causing it to vaporize and drive the turbines (DiPippo, 2025). Binary cycle systems are increasingly being used for electricity generation from medium-temperature geothermal fields (Sharmin et al., 2023). Hybrid systems that combine geothermal energy with other renewable energy sources are also being explored to enhance overall efficiency and reliability (fig. 12; Hamlehdar et al., 2024). Notably, binary cycle systems offer an environmental advantage by allowing for the re-sequestration of carbon dioxide back into the underground reservoir (Yilmaz et al., 2023).

Beyond electricity generation, geothermal energy has a wide range of direct use applications that leverage the Earth's heat for various purposes (Tester et al., 2021). District heating systems involve piping hot water from geothermal sources directly into buildings for space heating and hot water supply (fig. 12; Szanyi et al., 2023). Reykjavik, Iceland, serves as a prominent example where a large majority of the city's heating needs are met through such a system (fig. 13; Kumar et al., 2022). Geothermal heat pumps (GHPs), also known as ground-source heat pumps, utilize the relatively constant temperature of the shallow Earth for both heating in the winter and cooling in the summer for residential and commercial buildings (fig. 14; Antoneas & Koronaki, 2024). GHPs are significantly more energy-efficient than conventional heating and cooling systems, often achieving efficiencies three to five times greater (Elkelawy et al., 2025). Geothermal energy also finds applications in various industrial processes, including food dehydration, gold mining, and milk pasteurizing (Idroes et al., 2024). In agriculture, it is used for heating greenhouses, supporting aquaculture (fish farming), and drying crops (fig. 15; Singh et al., 2025). Geothermal energy serves directly by erasing ice from bridges and sidewalks and guests enjoy the convenience of heat in hot springs and spas (Bielicki et al., 2023).

The diverse applications of geothermal energy reach further than electricity generation into various direct usage applications according to Tester et al. (2021). The wide range of applications expands the potential for fossil fuel reduction in multiple sectors of heating, cooling and industrial processes and agricultural needs to enhance both energy

usage and greenhouse gas emission reduction (Korucan et al., 2024).

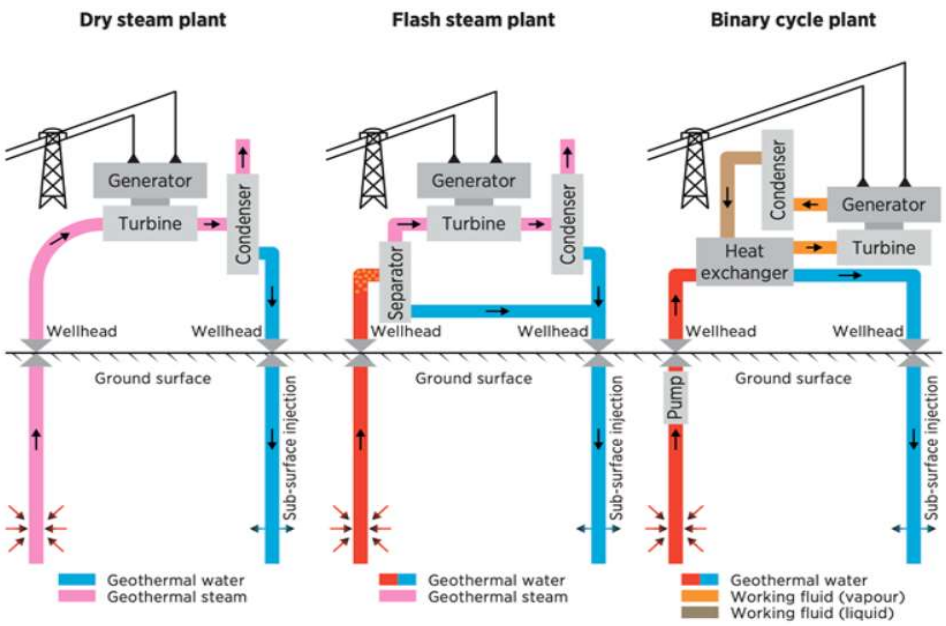

Figure 10: Types of Geothermal Power Plants (After IRENA/IGA 2023)

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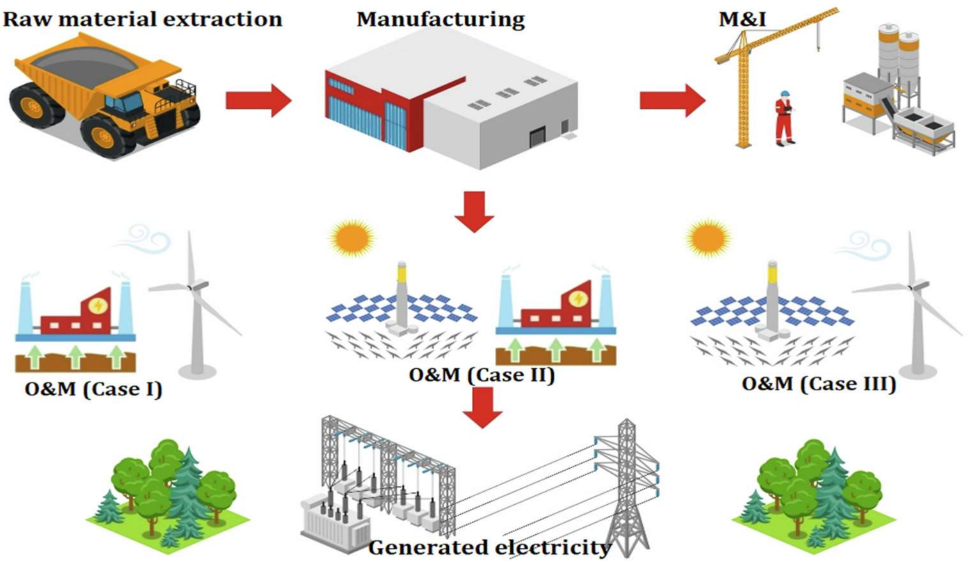

Figure 11: Hybrid Geothermal Systems (after Shamoushaki & Koh, 2024).

This chart shows different life cycle phases of three combined renewable-based power cycles. Case I is combined geothermal-wind, Case II is combined solar-geothermal cycle and Case III is combined solar-wind power plant. This chart displays different assessed phases of these integrated plants which includes raw material extraction, manufacturing of component, installation and assembly of equipment and operation and maintenance (O&M) over plants lifespan to generate low-carbon electricity.

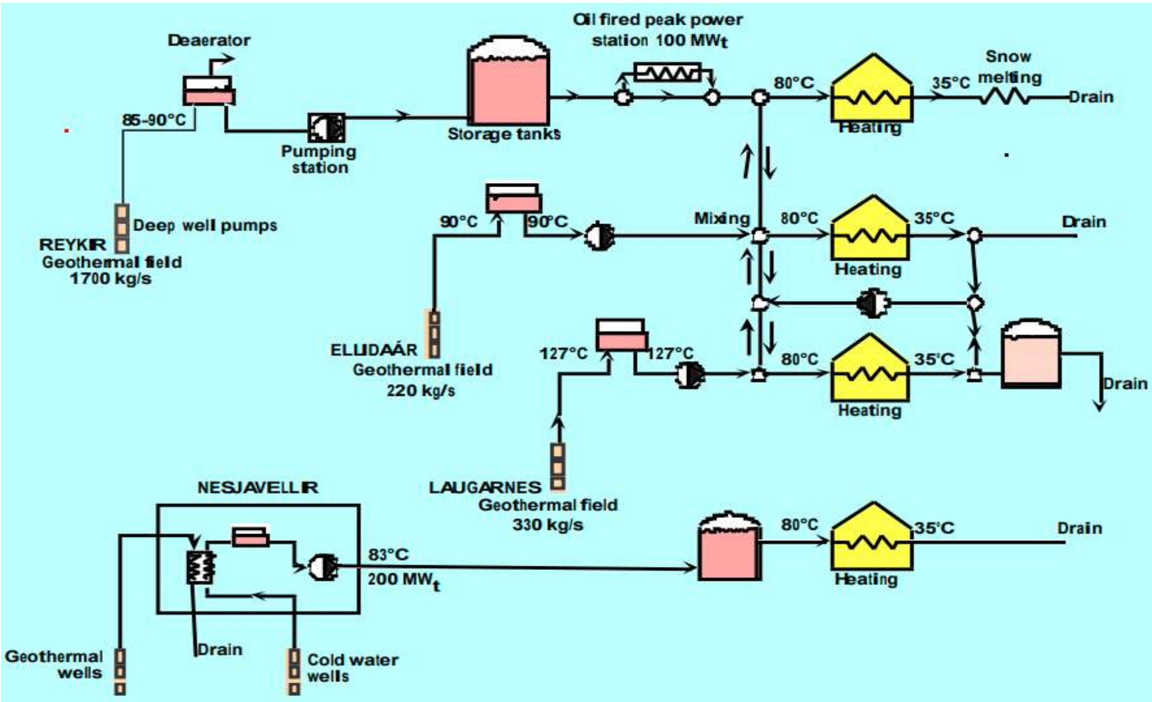

Figure 12: District Heating System Example (After Gunlaugsson & Reykjavíkur 2004)

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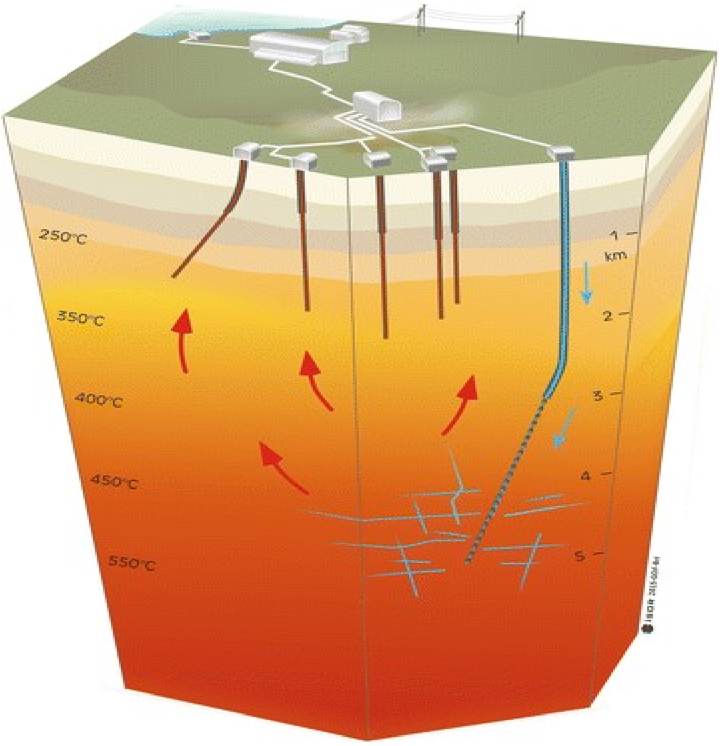

Figure 13: Conceptual model of the Reykjanes geothermal field showing conventional geothermal wells (brown) and the Iceland Deep Drilling project-2 well (blue) (After Friðleifsson et al. 2016)

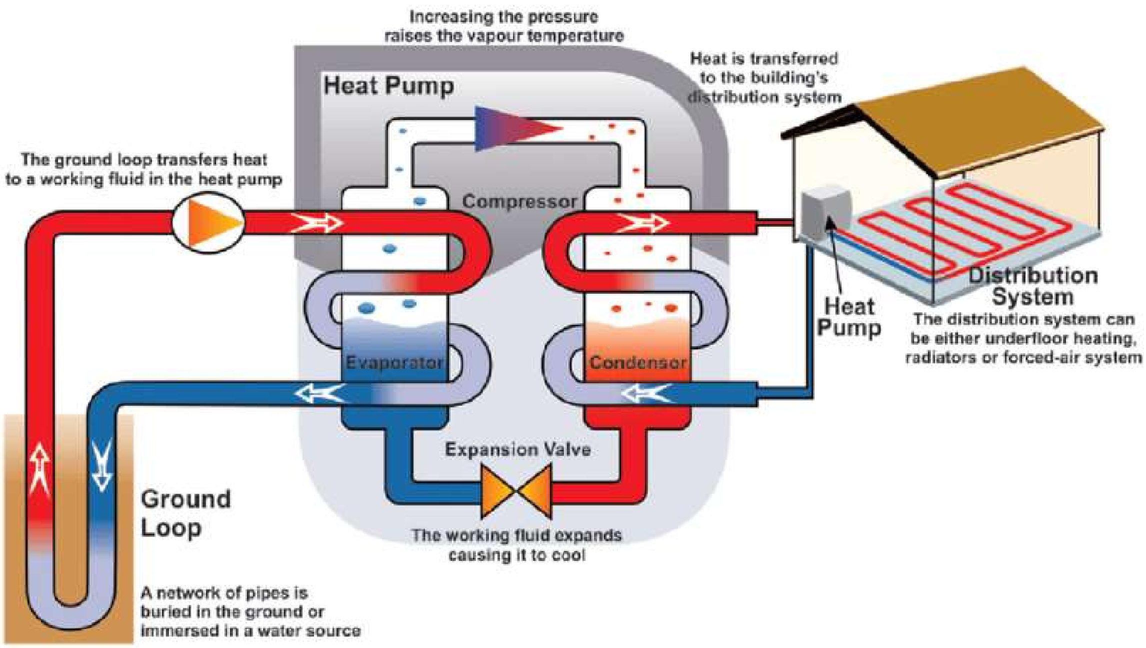

Figure 14: Geothermal Heat Pump (GHP) System (After Climo, 2021)

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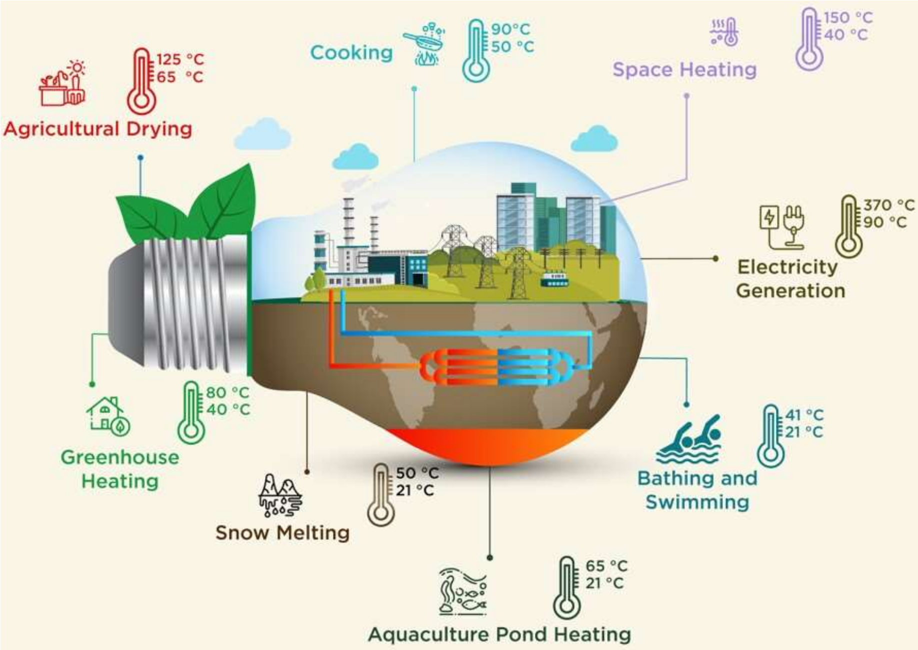

Figure 15: Applications of Geothermal Energy (Okoroafor et al., 2023)

Environmental and Social Impacts of Geothermal Energy Development

The development and utilization of geothermal energy offer numerous environmental and social benefits. Compared to fossil fuels, geothermal power plants produce significantly lower greenhouse gas emissions (fig. 16; Ghezelbash et al., 2023) and minimal conventional air pollutants such as particulate matter, sulfur dioxide, and nitrogen oxides (table 2; Alsaleh et al., 2023). Geothermal installations typically have a smaller land footprint compared to other energy generation technologies, with conventional geothermal having the second smallest footprint after nuclear energy (Umar et al., 2024). As a consistently available energy source, geothermal contributes to energy security and reduces dependence on volatile fuel markets (Sbrana et al., 2021). The development of geothermal resources can also stimulate economic growth and create job opportunities, particularly in rural areas where these resources are often located, providing long-term, stable employment (Ouerghi et al., 2024).

However, geothermal energy development also carries potential environmental and social risks. While emissions are generally low, geothermal plants can release non-condensable gases such as hydrogen sulfide and carbon dioxide (Ghezelbash et al., 2023). The main concern in the case of Enhanced Geothermal Systems (EGS) is the possibility of induced seismicity (Leontidis et al., 2023). However, this risk can be mitigated through strict regulatory frameworks and robust management procedures (Leontidis et al., 2023). For water-disadvantaged regions, geothermal power plant water usage (typically less than fossil or nuclear fuels) could still pose a concern (Kabeyi & Olanrewaju, 2022). Land subsidence, resulting from extracting geothermal fluids, can sometimes occur but can mostly be prevented by reinjecting spent fluids back into the reservoir (Mahmoud et al., 2021). Improper drilling and operation techniques may also pose a risk of groundwater contamination (Richardson & Webbison, 2024). Drilling and power plant noise together with operational changes to the landscape represent problems that mostly affect specific areas yet remain controllable (Colucci et al., 2022).

The success of geothermal energy projects throughout planning and implementation requires full assessment of both potential advantages and possible risks. Accomplishing environmental protection through best practices remains essential during geothermal energy exploitation that also yields socioeconomic advantages.

International Journal of Progressive Sciences and Technologies (IJPSAT)
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Table 4: Environmental Impact Comparison of Geothermal and Fossil Fuels

Environmental Indicator	Geothermal Energy	Fossil Fuels
Greenhouse Gas Emissions	97-99% less CO2 than fossil fuel plants	Significant CO2, SO2, NOx emissions
Acid Rain Compounds	97% less sulfur compounds than fossil fuel plants	Major source of sulfur compounds
Air Pollutants	Minimal to no particulate matter, SO2, NOx	Significant particulate matter, SO2, NOx emissions
Water Usage	Less than coal, oil, or nuclear plants	High water consumption
Land Footprint	Smaller than most renewables, second to nuclear	Larger land requirements for extraction and power plants
Waste Generation	Less solid waste than coal, natural gas, or nuclear	Significant solid waste, including ash and other byproducts

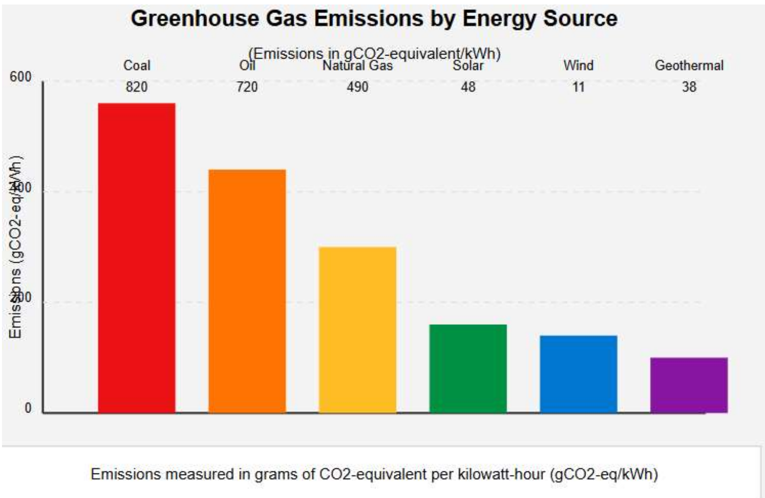

Figure 16: Comparison of Greenhouse Gas Emissions from Energy Sources

Future Directions and Research Opportunities in Geothermal Energy

The production of geothermal energy will expand dramatically as scientists create newer second-generation technology solutions. Scientists now have access to large amounts of untapped geothermal resources through the development of Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS) and closed-loop geothermal systems according to Sharmin et al. (2023). Drilling and reservoir engineering methods for accessing superhot rock geothermal show great promise because they enable scientists to explore deep thermally intense resources exceeding 400°C (Rohit et al., 2023). Future geothermal research remains essential because it enables scientists to develop improved technology for resource location and description (Tester et al., 2021). Geothermal development across its entire lifecycle needs cost reduction measures that should address drilling operations as well as well completion methods and power generation equipment technology (Sharmin et al., 2023). As part of the Enhanced Geothermal Shot™ program the objectives state that EGS costs will reach 90% reduction by 2035 (Bashir et al., 2023). The current usage of

International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

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geothermal power requires a fusion between geothermal infrastructure and solar and wind systems to build hybrid energy networks which rely on geothermal energy storage capabilities and system balance functions (Islam et al., 2022). Through dynamic reservoir simulation and machine learning technology companies can optimize their reservoir operations while increasing their energy output potential (Sadeghi, 2022). Geothermal energy deployment advancement depends profoundly on supportive policy frameworks that must contain government-supported research together with simplified permitting processes and fiscal rewards (Santos et al., 2022). Researchers need to dedicate additional effort toward studying sedimentary geothermal systems to evaluate their capacity for generating electric power and enabling direct use applications (Rohit et al., 2023). The substantial technological capabilities of oil and gas belong to an enormous platform that facilitates rapid geothermal power development and cost reduction (Ramzan et al., 2024).

Future progress of geothermal energy depends on continuous next-generation technology research at EGS and superhot rock geothermal systems (Sharmin et al., 2023; fig. 17). These technological advancements provide the fundamental capability to tap into huge geothermal heat reserves which were beyond reach thus expanding global geothermal energy potential. Research continuation that focuses on lowering costs and developing improved exploration practices and better resource management strategies is needed to make geothermal energy economically viable for full-scale global adoption in the energy transition process (Tester et al., 2021).

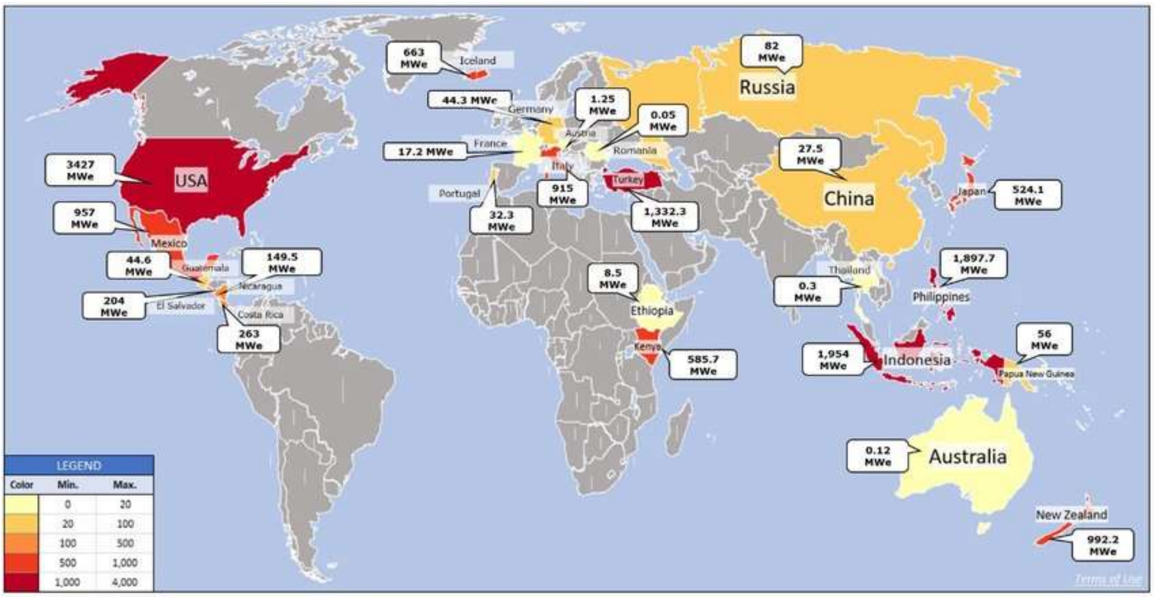

Figure 17: A world map showing regions with untapped geothermal resources (After Kamila, 2021)

Conclusion:

This review has highlighted the significant role of geothermal energy as a clean, reliable, and versatile renewable resource with the potential to contribute substantially to global sustainable energy development. While challenges remain in exploration, production, and cost competitiveness, significant progress is being made through advancements in drilling technologies, reservoir engineering, and the development of next-generation geothermal systems. The inherent reliability and high-capacity factors of geothermal energy make it an invaluable asset in a diversified clean energy portfolio, capable of providing baseload power and complementing intermittent renewable sources like solar and wind. The versatility of geothermal energy extends beyond electricity generation to a wide array of direct use applications, offering opportunities for decarbonization across various sectors. Addressing the environmental and social impacts through careful planning and mitigation strategies is crucial for ensuring the responsible and sustainable development of geothermal resources. Continued research, technological innovation, and supportive policy frameworks are essential to fully realize the immense potential of geothermal energy in achieving a sustainable energy future and mitigating the impacts of climate change.

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