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Geothermal Energy: Unlocking the Earth's Heat for Power

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ABSTRACT

Geothermal energy represents a reliable, renewable, and environmentally sustainable alternative to conventional fossil fuels, drawing heat from the Earth's subsurface to generate electricity and provide direct heating applications. This paper examines the fundamentals, history, and classifications of geothermal energy, including high-, intermediate-, and low-temperature resources. It examines the technological developments in geothermal extraction, the process of energy production, and various environmental and economic implications. Attention is also given to regulatory frameworks and case studies that highlight successful applications and challenges across diverse global settings. Additionally, the integration of geothermal energy into oil and gas infrastructure is presented as a promising pathway to expand geothermal utilization while reducing carbon footprints. Ultimately, this study emphasizes the potential of geothermal energy to support global energy transitions by offering a clean and continuous source of power.

Keywords: Geothermal energy, renewable energy, geothermal technology, thermal energy, direct heating, geothermal power plants.

INTRODUCTION

Geothermal energy is a renewable resource derived from the Earth's natural heat, mainly from thermal energy produced in the outer core. It reaches the surface via volcanic activity and convective transfer. Two key processes, continuous radiogenic heat production and radioactive decay, maintain the thermal energy in the Earth's crust. Geothermal energy is harnessed in three main ways: volcanic geothermal energy, convective geothermal energy, and geothermal energy in conductive rock. Most geothermal power plants are located at Earth's hot spots, converting thermal energy into commercial power through heat exchanges. Convective geothermal energy is crucial for power generation and agricultural applications, such as greenhouse heating and aquaculture. While commercial use focuses on convective geothermal energy, volcanic geothermal energy is limited due to its geographical restrictions. Geothermal energy can be produced through downhole geothermal power generation and underground hot rock geothermal power generation. The geothermal reservoir, surrounded by impermeable rocks, is essential for industrial energy production, with optimal temperatures above 150 °C for effective thermal energy extraction. Geothermal power plants require pre-drilled wellbores for fluid injection and production, with possible horizontal drilling to improve contact in low-permeability reservoirs. Geothermal resources are categorized by temperature: high (above 150 °C), intermediate (90 °C to 150 °C), and low (30 °C to 90 °C). Notable low-temperature examples include the Egyptian thermal springs, Great Geysir in Iceland, and Marmore Water Falls in Italy, while high-temperature resources are often found in active geothermal fields around the Pacific Ring of Fire [1, 2].

History of Geothermal Energy

Geothermal energy is the heat stored in the earth's crust, with historical roots tracing back to hot springs in the Roman Empire. Although many regions had hot springs, serious exploration began in the 19th century. Hungary was the first to harness geothermal energy for swimming pools, followed by Italy for electricity generation. Early exploration focused on shallow geothermal systems, but since the 1970s, attention has shifted to deeper, high-temperature geothermal systems with significantly larger energy storage. Efforts are increasing to maximize geothermal production from drilled oil fields, where temperatures above 200 °C can be accessed at depths of around 2 km. This technique enables the reuse of oil wells globally, allowing for geothermal energy development even in remote areas and less-explored regions of the U.S. Various methods have been developed to exploit geothermal energy, influenced by formation styles and initial conditions. Two primary classes of geothermal energy exploitation exist: downhole solutions that generate steam within the geothermal reservoir and surface solutions that transport thermal energy to consumption sites. The existing technologies will be summarized, along with a discussion on producing added-value products sustainably from aqueous geothermal reservoirs [3, 4].

Types of Geothermal Resources

Geothermal energy extraction technology has progressed alongside oil exploration since the late 20th century. However, geothermal resources lie at different depths from hydrocarbon deposits. They are either found in shallow, low-temperature formations or exceed depths of 5km, making extraction technically challenging. Geothermal energy is categorized into shallow (<3km) and deep (>3km) resources. Shallow geothermal resources are aquifers within 500m of the surface, providing low-temperature heat for district heating and high-temperature heat for power generation. Deep geothermal resources exploit the Primary Type (the 'Hot-dry-rock' concept), with other models ('Fault' and 'Biogenic' concepts) still in pilot studies. Geothermal resources derive energy from the earth, which acts as a reactor producing energy from radioactive decay, redistributing it via conduction, convection, and advection. Increased depth enhances heat transfer from the earth's interior to the surface through these mechanisms, with the geothermal gradient reflecting heat distribution from the core to the crust, usually around 30°/km, and with a maximum crust temperature under 400°C. Natural groundwater circulation exists around geothermal reservoirs, providing the energy source for their formation [5, 6].

Geothermal Energy Technologies

Geothermal energy is a promising renewable source due to its stability, reliability, and long lifespan, but it requires complex equipment and high technology. The earth's temperature rises with depth, a phenomenon known since the 1st century BC. This energy is found in the earth's surface layer, rocks, and magma. Currently, several countries utilize geothermal energy mainly for direct heat use and electricity generation. Direct uses include bathing, space heating, greenhouse heating, food production, and industrial processes. In the USA, geothermal electricity generation uses steam from high-temperature reservoirs to drive turbines. Binary cycle systems pass geothermal water through heat exchangers to heat another fluid, which then drives a turbine. Geothermal resources encompass all heat energy within the earth, primarily for thermal applications, and some countries also use it to generate electricity. Geothermal energy is emitted through steam, water, mud, lava, and gas [7, 8].

Geothermal Energy Production Process

Geothermal energy comes from thermal energy within the Earth, found at various depths where permeable rocks and water-bearing formations exist. Industrial production typically involves extracting energy from pressured geothermal reservoirs by injecting a working fluid that carries heat to the surface. Hot fluids can also be utilized through pre-drilled wellbores. Geothermal resources fall into three temperature categories: high (above 150°C), intermediate (90°C to 150°C), and low (30°C to 90°C). There are two main applications of geothermal energy: direct use and power generation. Direct use involves thermal purposes without energy conversion, such as heating spaces, agriculture, and industry. In contrast, geothermal power generation converts thermal energy into electricity. An injection well accesses the reservoir, allowing fluid at specific temperature and pressure to flow, heating as it moves through the rocks. This heated fluid is pumped to a power plant, expanding rapidly to turn a turbine, which generates electricity. The cooled fluid is reinjected into the reservoir. A geothermal reservoir consists of permeable rocks capped by impermeable layers, allowing subsurface water to reach superheated states, with energy extracted through downhole heat exchangers. The working fluid absorbs heat, converts it into mechanical power, and carries this energy back up through the wellbore [9, 10].

Environmental Impact of Geothermal Energy

As demonstrated by the case studies, geothermal energy can provide substantial benefits to society. While traditional power generation technologies primarily focus on the reduction of carbon emissions from power plants, a more holistic approach is required to consider the wider sustainability of energy systems. This necessitates the assessment of the full life-cycle carbon and environmental impacts of renewable energy sources, particularly for geothermal systems because they can offer ancillary heat-based services, which unlike conventional fossil-based systems, can provide emission-free heat. The Life-Cycle Assessment (LCA) is an efficient tool for analysing processes and comparing their associated environmental impacts. However, traditional LCA is not readily practical for complex time-variable systems such as geothermal ones. Hence, the Geothermal Energy Impact Estimator (GEIE) software tool has been developed to allow for semi-accurate design-space exploration of new systems and refinement of existing ones by calculating the life-cycle GHG emissions and environmental impact indicators of geothermal energy. The key components and workflow of the software, as well as two implementation case studies, were presented as a means of showing its functionality and potential. These are Hellisheidi, a co-generation geothermal plant in Iceland supplying electricity and district heating, and the United Downs Deep Geothermal Power (UDDGP) project, which aims to produce electricity from superheated water with development currently pending. The full description of these plants and their operational conditions is available in [11, 12].

Economic Aspects of Geothermal Energy

Geothermal energy has been used for power generation since the 1900s and, while it currently contributes around 0.3% or 75 GW to global power, it has significant untapped potential. Seventy countries have usable geothermal resources, primarily onshore hydrothermal. Geothermal technology includes ground-source heat pumps for heating and power plants that convert geothermal resources into electricity. Hot water or steam from wells turns turbines, with low-temperature resources around 100 °C utilizing an "organic rankine cycle" (ORC). Recently, the technology of generating electricity using supercritical carbon dioxide cycles has gained attention. Indonesia, the second-largest geothermal producer globally, possesses the largest potential at about 28 GW, making up 40% of the world's total. Studies indicate underutilization of geothermal resources in Indonesia, prompting this thesis to apply quantitative methods for deeper insights. It assesses economic barriers facing geothermal development in the country. Investment includes exploration, power plant planning, construction, operation, and maintenance, but projects often face high exploration costs and initial investments. Test drilling can reach tens of millions of dollars, and about $400 million is needed for a 50 MW plant. The high costs during exploration and construction stages, along with the risk of failure, make it difficult for the private sector to invest. Uncertain production performance increases the risk, leading banks to be hesitant in lending to developers. Moreover, the timeline from exploration to operation exceeds seven years, delaying revenue generation and compounding the financial challenges hindering geothermal development [13, 14].

Geothermal Energy Policies and Regulations

Geothermal development involves projects for direct use of geothermal energy and geothermal power plants that generate electricity. The process is lengthy and intricate. For direct use, it starts with site identification, resource drilling, and, if commercially viable, a lengthy permitting process that can range from 5 to 20 years. Geothermal power plants face additional complexity and investment needs. They require a long-term power purchase agreement or feed-in-tariff, along with the necessary permits for both the resource and the plant. Financing for exploration poses challenges, leading to a potentially extended development timeline compared to direct use projects. In the US, the success of geothermal exploration relies on minimizing capital investment through power purchase agreements and potentially selling the resource to utilities once proven viable. However, globally, smaller developments struggle due to inadequate mechanisms for ensuring returns on exploration investment, particularly when failures occur. Once a resource is deemed viable, a lengthy permitting process ensues, often presenting significant hurdles for developers. The timeline varies by state; smaller states like Nevada and Utah may only need about two years, while larger states like California can take 8 to over 20 years, particularly when engaging with local residents and environmental groups. This multi-faceted process often complicates things further, making permitting a significant challenge for large-scale geothermal projects. However, involving smaller parties with experience, such as those from Norway or Japan, can help navigate local landowner relationships and participate in environmental hearings, aiding in smoother project development [15, 16].

Case Studies of Geothermal Projects

Three case studies were presented to explore the assessment of targeted and innovative downhole geothermal mechanisms and technologies for geothermal power generation in different boreholes, boreholes based on energy extraction from waste drilling fluids, geothermal power generation during borehole widening, and downhole geothermal power generation in oil wells. The considered items, methods, and technologies have been kept within the feasibility of oilfield applications in terms of a wide range of working depths and borehole conditions, manually operated downhole parameters, equipment weight and dimensions, and economic viability. In addition, discussions were held over correlation mechanisms, operational principles, working theories, technical and equipment developments, initial experimental demonstrations, analytical studies and numerical simulations, ongoing engineering tests, potential applications and scalability, and novel designs and conceptual ideas. Future expectations and possibilities were also expressed on the powerful downhole mechanism of energy extraction from waste drilling fluids based on pipe/oil-water cross-flow, new technologies for geothermal power generation during borehole widening in open-hole and cased-hole wells, compatibility issues of oil/water geothermal generating sets with downhole conditions such as high salt content and H_2S gas, and newly-applicable downhole mechanisms and processes for geothermal energy exploitation in offshore Malaysia such as low-pressure water-oil co-axial pipe frictional reduction and energy conversion based on natural gas hydrate. Oil well oil-water separation, downhole waste energy utilisation, and shoe reduction of the wormhole-styled water flooding can be first achieved globally by taking advantage of domestic high-performance drainage/separation filters and a spiral removal-water-locker. Several weight and blade options for spiral wells have also been presented for the industry. Three-dimensional downhole flocculation, emulsion breaking, and waste drilling-fluid energy utilisation can all be conducted in one well by combining a downhole stepped-filter-gravel-pack-housing with a precipitator-nozzle and an electric field. Multi-channel/mode well mouth cooling and downhole vibrating cooling options can also be manufactured to realise the handling of multi-plateau temperature cooling [17, 18].

Future of Geothermal Energy

Exploration of geothermal energy within oil and gas fields presents a long-term opportunity for site utilization, minimizing major drilling and completion costs. Specifically, hydrocarbon regions can target deep, warm reservoirs for geothermal exploration. Utilizing downhole heat exchangers in injection wells to extract heat from hot reservoirs makes this approach economically attractive. Recently, there has been renewed interest in converting oil and gas wells to geothermal production wells, allowing for the possibility of continued oil production alongside power generation. This transition will require adaptations to the material properties of both the oil retrieval and geothermal production systems. The interaction of brine and steam in the well system also needs further examination. Designing an optimal thermodynamic system for converting oil and gas fields into geothermal sites is essential. This integration can be viewed as a network of systems, including wells contacting reservoirs, production facilities extracting fuel, and power plants generating usable energy. Expanding geothermal power into oil and gas fields entails converting reservoir settings into geothermal systems and establishing new geothermal facilities and power plants, thus transforming both existing and new systems from fossil fuel to geothermal energy production [19, 20].

Public Perception and Awareness

Geothermal energy, despite its potential, remains largely untapped, contributing only 0.4% to global energy supply. Key reasons for underdevelopment include insufficient public acceptance regarding rental contracts and drilling, particularly in deep geothermal projects. Informed communities tend to accept geothermal initiatives more readily, while misinformation leads to distrust and resistance to development. Environmental concerns also influence this acceptance. Thus, enhancing public knowledge and awareness about geothermal energy is essential for its adoption. A recent survey in Poland assessed the public's understanding and acceptance of geothermal energy, revealing insights into perceptions and methods to improve acceptability. The study analyzed demographics, including occupation, education, gender, and age, to better understand attitudes toward geothermal energy. Research revealed that traditional ground-source heat pumps and deep geothermal systems (up to 10 km) are predominantly used, especially for power generation. There is strong public acceptance for low-temperature geothermal energy and ground-source heat pumps, though Poland's use of these systems remains limited compared to medium- and high-temperature alternatives. The analysis also considered the future evolution of both onshore and offshore geothermal energy systems by 2050, highlighting the need for increased deployment in Poland [21-24].

Geothermal Energy Vs. Other Renewable Sources

Technological advances have enabled the exploration of new geothermal energy resources, notably enhanced geothermal systems, which attract significant interest. These systems utilize geothermal energy in areas without reservoirs but with high thermal gradients, expanding the potential for geothermal production to vast regions. While they offer low-carbon energy possibilities, there are uncertainties about environmental impacts, necessitating a life-cycle assessment of this technology. A software was created for this purpose. Geothermal energy exists beneath the earth's surface in large thermal reservoirs, which can be tapped depending on geological conditions. The first commercial electricity generation occurred in Larderello in 1942, prompting other countries to adopt similar practices. The heat source can stem from high-temperature magmatic intrusions or low-temperature systems, with reservoirs composed of hot, permeable rocks allowing circulating fluids to extract heat. Geothermal fluid, typically water with chemicals and gases, is involved in this process. Enhanced geothermal systems necessitate improving natural rock permeability, where injected water is heated and returned to the surface via production wells [25-27].

CONCLUSION

Geothermal energy holds immense potential as a clean, renewable energy source capable of providing continuous base-load power and direct heating. From its historical use in ancient civilizations to modern applications in electricity generation and industrial processes, geothermal energy has demonstrated adaptability and sustainability. While technological advancements have improved the efficiency of extraction and utilization, economic and regulatory challenges remain, particularly in exploration, permitting, and financing. Nonetheless, successful case studies and the emerging synergy with oil and gas infrastructure suggest a promising future for geothermal energy expansion. With further investment, policy support, and innovation, geothermal energy can significantly contribute to a resilient and decarbonized global energy mix.

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