

Analysis and Research on the Development of Geothermal Energy and Future Development Trend

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Abstract. Scientists and engineers from all over the world have acknowledged the significance of employing environmentally friendly energy to replace fossil fuels in manufacturing as global warming has gotten worse over the past century. Geothermal energy, which is a form of subsurface energy that is stored as heat and gas, is one of many sustainable energy sources. There are currently three popular exploitation techniques. The Xero-thermal power system is appropriate for regions with shallow heat sources and mild temperature gradients since it generates energy from low-temperature geothermal resources. Flash geothermal power systems are appropriate for locations with hot fluids. Binary cycle generation system employs a secondary working fluid with a boiling point that is lower than water, allowing for power generation from lower temperature geothermal resources, thereby expanding the potential for geothermal energy production. The study then largely focuses on the key elements, such as resource availability, technological hurdles, and market conditions, that can influence the utilization of geothermal energy. Researchers and engineers can more clearly comprehend the benefits and constraints in various resource environments by closely evaluating these elements. While the government should urge the people to pay greater attention to the exploitation and deployment of renewable energy, engineers could improve drilling techniques. The current situation of harnessing and exploiting geothermal energy highlights the necessity for ongoing research and development to fully realize geothermal energy's potential. This essay contributes to the larger conversation on renewable energy and offers insightful information about the significance of geothermal energy.

Keywords: Geothermal, resource availability, influencing factors, technical challenges, economic viability.

1. Introduction

A worldwide concern about climate change and its negative effects has been sparked by the steadily rising amounts of greenhouse gases in the Earth's atmosphere. The greenhouse effect, which traps heat in the atmosphere, is causing ecosystem changes, harsh weather, and rising temperatures. Our search for sustainable and clean energy sources is more important than ever at this pivotal time.

One promising solution lies beneath our feet is geothermal energy. Geothermal energy harnesses the heat stored within the Earth to generate electricity and provide heating and cooling for residential, commercial, and industrial purposes. Unlike fossil fuels, geothermal energy is renewable and emits minimal greenhouse gas emissions during operation, making it an environmentally friendly alternative.

Geothermal energy taps into the planet's internal heat, a natural resource that is virtually limitless and continuously replenished by Earth's core processes. This heat originates from the radioactive decay of elements deep within the Earth, and it steadily conducts towards the surface [1]. This phenomenon is the result of Earth's formation billions of years ago, creating a unique opportunity to capture and convert this natural heat into usable energy. Through the utilization of geothermal power plants, the Earth's heat can be converted into electricity using various methods such as binary cycle, flash steam, and Xero-thermal power generation system systems. These systems efficiently extract the thermal energy from geothermal fluids, which are found deep underground and contain high temperatures and pressures. By utilizing the Earth's heat, geothermal energy provides a continuous and reliable power source that can be harnessed around the clock, regardless of weather conditions.

Although geothermal energy has been exploited between 1910 to 1940, many nations throughout the world have yet to acknowledge its effectiveness and practicality [2]. There is plenty of room for humans to continue using geothermal energy in various fields, as I. Fridleifsson points out, as just a small percentage of it has been developed and utilized [3].

In the past, a lot of essays have mostly concentrated on the advantages that locals may experience from geothermal energy. Some have noted that as drilling methods advance, the cost of electricity generated by geothermal energy may be accessible even in those developing nations [4]. Others point out that, if feasible, geothermal energy utilization can not only lower greenhouse gas emissions but also increase employment prospects and potentially boost regional economic growth [5]. However, because most authors prefer to concentrate on the advantages while taking other viewpoints into account, many of them fail to detect the influencing variables, both natural and artificial.

In this study, the present methods of geothermal energy exploitation are introduced, the key variables that may affect the exploitation process are analyzed, and finally, the long-term prospects of geothermal energy are discussed.

2. Exploitation of Geothermal Energy

2.1. Xero-thermal Power Generation System

The Xero-thermal power generation system, also known as the Dry Steam system, taps into high-pressure steam reservoirs found deep within the Earth. In this method, hot steam is directly extracted from underground geothermal reservoirs and used to power turbines, which in turn generate electricity. This system requires a geothermal resource with a high steam content and sufficient pressure. The Xero-thermal power generation systems are most often employed in areas where high-temperature reservoirs are readily accessible. Due to its unique exploiting method, Xero-thermal power generation method can avoid causing emitting toxic chemicals, which can pose a great threat to the human well-being in the long-term development, into the air. Additionally, the electricity generated by xero-thermal power can be more friendly to customers since the price of exploiting and transforming process (6 cents/kW·h) is much lower than that of electricity generated by conventional techniques (23 cents/kW·h) [4].

However, due to the limited drilling technology human have now mastered, it can be quite arduous for engineers to reach places deeper than 6 kilometers. Thus, researchers and engineers should scrupulously calculate the cost and the benefit of the overall project to find the best location to build a Xero-thermal power plant. Moreover, the presence of corrosive gases and minerals in the steam poses challenges at the same time, requiring proper material selection and maintenance while designing the power plants.

2.2. Flash Geothermal Power Generation System

Another prominent method is the Flash geothermal power generation system. This approach involves extracting hot water or brine from the geothermal reservoir and rapidly ‘flashing’ it into steam. According to Boyle’s Law, as the pressure goes down, the boiling point of water goes down as well. With this relationship, it is possible to turn water whose temperature that is under 100°C into steam, which is then used to drive turbines and produce electricity. The remaining water or brine is re-injected back into the reservoir to maintain reservoir pressure. The Flash system is widely applicable since it can be utilized in reservoirs with varying temperatures and depths. This versatility makes it a popular choice for geothermal power generation in many regions around the world. In most of the areas near the Earth surface, the efficiency of transforming thermal energy of steam that is over 130°C into other form of energy is not satisfying by conventional steam engines [6]. By contrast, flash geothermal power generation system can finish this task with a higher efficiency and effectiveness.

However, some reports point out that, even though the long-term generation rate of the electricity is promising and the marginal cost per unit of electricity stays low, the set-up price for a flash

geothermal power generation plant can be extremely expensive, which may lead to serious financial burden on the local government and residents. Furthermore, some critics also point out that the production efficiency of such power plants is much lower than the efficiency in conventional power plants using coal.

2.3. Binary Cycle Generation System

The binary cycle geothermal system represents an innovative and efficient approach to harnessing the Earth's heat for clean and sustainable energy production. This advanced geothermal technology has gained significant attention and widespread adoption due to its ability to tap into lower temperature geothermal resources that were previously considered nonviable for power generation. In a binary cycle system, the process begins with the extraction of geothermal fluids from the underground reservoir, which typically have temperatures as low as 70 °C or even lower [7]. These fluids are then directed to a heat exchanger, where the transfer of thermal energy takes place. The distinguishing feature of the binary cycle system lies in its utilization of a secondary working fluid, which has a lower boiling point compared to water. As the geothermal fluids pass through the heat exchanger, they release their thermal energy to the secondary fluid, causing it to vaporize. The resulting high-pressure vapor drives a turbine, which is connected to an electrical generator to produce clean electricity. What makes the binary cycle system particularly remarkable is its ability to tap into a wide range of geothermal fluid temperatures, including those below the boiling point of water. By employing a secondary fluid with a lower boiling point, power generation becomes feasible even in geothermal fields with relatively low-temperature resources.

This technology offers several notable advantages. First and foremost, the binary cycle system enables the efficient utilization of previously untapped geothermal resources, significantly expanding the potential for geothermal energy production worldwide. It provides a sustainable energy option for regions, where conventional geothermal systems, such as flash steam or dry steam, may not be suitable due to lower temperatures. Furthermore, binary cycle systems have minimal environmental impacts. The process produces virtually no greenhouse gas emissions or air pollutants, making it a clean and sustainable alternative to fossil fuel-based power generation. It aligns with global efforts to combat climate change and transition towards a greener and more sustainable future.

As the world continues to seek reliable and renewable energy sources, the binary cycle geothermal system stands as a remarkable technological advancement in the field of geothermal energy. Its ability to unlock the potential of low-temperature geothermal resources, coupled with its environmental benefits, positions it as a key player in our journey towards a more sustainable and clean energy landscape.

3. Influencing Factors of Geothermal Energy Exploitation

The exploitation of geothermal energy, a renewable and sustainable energy source derived from the Earth's heat, is influenced by a multitude of factors. These factors can significantly impact the feasibility, efficiency, and overall success of geothermal energy projects. Here, this section will introduce three key factors that play a crucial role in the exploitation of geothermal energy.

3.1. Resource Availability and Quality

The availability and quality of geothermal resources are fundamental considerations for geothermal energy exploitation. And it is closely linked to the depth at which they are located. Generally, as the depth increases, the accessibility of geothermal resources becomes more challenging. Shallow geothermal resources, located at relatively shallower depths, are often more accessible and easier to exploit. These resources are typically associated with geothermal heat pump systems used for heating and cooling applications. As the depth increases, accessing the geothermal resources requires drilling deeper wells, which adds complexity and cost of the exploration and exploitation process. High-temperature geothermal reservoirs, which are valuable for power generation, are often

found at greater depths, making their accessibility more challenging. The depth of the geothermal resource influences the selection of drilling techniques, well design, and the overall feasibility of geothermal energy projects. Thus, understanding the relationship between resource accessibility and depth is crucial for effectively planning and executing geothermal energy development initiatives.

The following diagram shows the relationship between each powerplant's construction cost and the average depth of the energy available at the sites. Fig. 1 shows that as the depth of the available resources increases, the cost of building a power plant at the site will rise [8, 9]. Especially, as the resources become deeper, the cost of construction will rise at a more rapid speed. However, these estimated construction costs are approximate using total investment and can vary based on several other factors, including plant capacity, location, technology, and specific project requirements. Specifically, it is essential to consult detailed project reports and feasibility studies for more accurate and up-to-date cost information while constructing more detailed research.

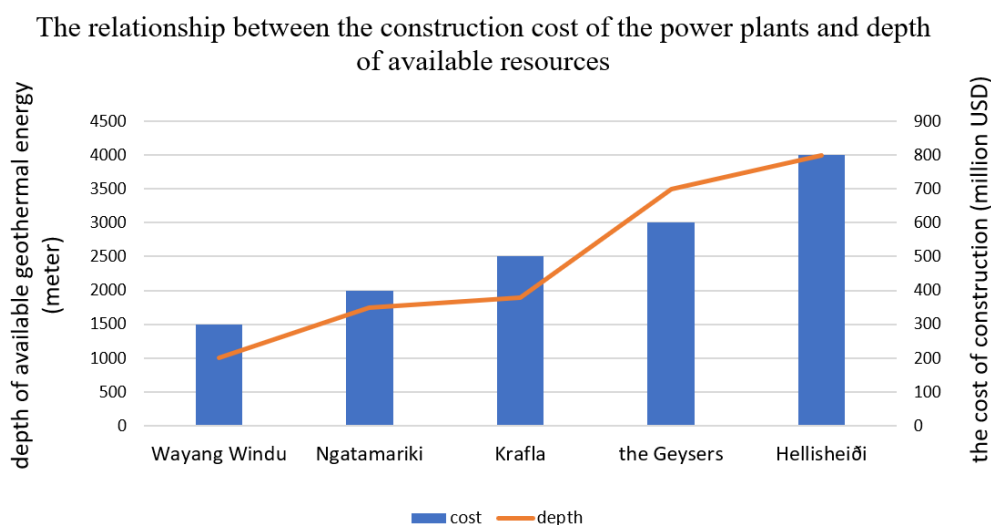


Fig. 1 the relationship between construction cost of the power plants and depth of resources.
(Picture credit: original)

3.2. Technical and Engineering Challenges

The exploitation of geothermal energy presents various technical and engineering challenges that must be overcome to ensure successful and efficient utilization of this renewable energy source. These challenges encompass different aspects of exploration, drilling, power generation, and reservoir management. This section will explore some specific examples of the technical and engineering challenges associated with geothermal energy exploitation.

The most common challenge faced by engineers worldwide is the drilling problem. Geothermal drilling involves drilling deep wells into the Earth's crust, which can be technically demanding and costly. High temperatures and pressures encountered at depth pose challenges in terms of drilling equipment durability and selection. Corrosive geothermal fluids can cause material degradation, requiring the use of specialized materials and coatings. Additionally, drilling through challenging geological formations, such as hard rocks or unstable formations, can increase drilling risks and costs. For example, the Cerro Prieto geothermal field in Mexico faced drilling challenges due to the presence of abrasive sands and clays. These formations led to increased drilling wear and tear, necessitating the development of robust drilling techniques and tools.

The second challenge that is usually encountered by constructors is reservoir management. Efficient management of geothermal reservoirs is critical to sustain long-term production and optimize energy extraction. Maintaining reservoir pressure and avoiding fluid depletion are essential considerations. The reinjection of produced fluids, such as brine or condensate, back into the reservoir is often practiced to replenish the resource and maintain pressure. However, reservoir behavior can be complex, with factors like fluid migration and preferential flow paths affecting resource recovery.

The quality of the reservoir may directly relate to the efficiency of energy generation. For instance, The Wairakei geothermal field in New Zealand faced challenges related to reservoir management, including scaling issues caused by the presence of mineral deposits in the geothermal fluids. Scaling reduces the permeability of the reservoir and hampers fluid flow, necessitating scaling prevention and mitigation strategies.

Another crucial consideration is about environmental preservation. Due to the enhanced global warming effect, it has become an international belief to protect the environment. Similarly, geothermal energy exploitation must address environmental concerns to ensure sustainable and responsible development. The extraction and reinjection of fluids may have potential harmful impacts on water resources, local air quality and the farmland around the power plants. Mitigating greenhouse gas emissions, such as hydrogen sulfide and carbon dioxide, is also crucial for minimizing environmental footprints. The Geysers geothermal field in California, USA, for example, faced challenges related to managing hydrogen sulfide emissions, which can pose environmental and health risks. Advanced gas treatment technologies and emission control measures were implemented to reduce the environmental impact.

Finally, which is also the most crucial challenge that is faced by each kind of power plants, is the power generation technology. Converting geothermal heat into electricity requires specialized power generation technologies. Geothermal power plants typically employ binary cycle, flash steam, or dry steam systems, each with its own technical challenges. Ensuring efficient heat transfer, minimizing energy losses, and managing the working fluids are key considerations. Additionally, geothermal fluids often contain dissolved gases, such as carbon dioxide and hydrogen sulfide, which can corrode equipment and require mitigation measures before released into the atmosphere.

The exploitation of geothermal energy involves various technical and engineering challenges. Overcoming drilling complexities, managing reservoir behavior, optimizing power generation technologies, and addressing environmental considerations are key areas that require innovative solutions and continuous advancements. By addressing these challenges, the geothermal industry can unlock the full potential of this clean and renewable energy source and contribute to a sustainable future.

3.3. Economic Viability and Market Conditions

Geothermal energy, harnessed from the Earth's heat, has emerged as a promising renewable energy source with significant economic potential. Its utilization involves tapping into the Earth's natural reservoirs of steam and hot water to generate electricity and provide direct heating. The economic viability and market conditions surrounding geothermal energy are essential factors in determining its widespread adoption and integration into the global energy landscape. This section will explore the economic aspects of geothermal energy and examine the current market conditions that shape its growth and development.

3.3.1 Economic Viability

One crucial aspect of the economic viability of geothermal energy lies in the longevity and stability of its power plants. Geothermal facilities have the advantage of operating for several decades, providing a consistent and reliable source of electricity generation. Unlike fossil fuel-based power plants that require continuous fuel supply and are subject to price fluctuations, geothermal plants harness the Earth's natural heat, resulting in a stable fuel source. This longevity not only ensures a steady stream of revenue for project investors and operators but also contributes to the overall cost-effectiveness and financial attractiveness of geothermal energy as a long-term sustainable solution.

Another significant aspect of the economic viability of geothermal energy is its low level of price variability over time. Once a geothermal power plant is established, the operational costs remain relatively constant. Unlike conventional energy sources that are subject to the volatility of fuel prices, geothermal energy offers a favorable cost structure. This stability in operating costs makes geothermal energy a competitive option, particularly in comparison to other renewable energy technologies. The predictable and consistent cost profile enhances the long-term economic viability

of geothermal projects, making them attractive investments for both private and public entities seeking sustainable and financially sound energy solutions.

The third aspect contributing to the economic viability of geothermal energy is its indigenous nature, free from fuel price fluctuations and geopolitical risks. Geothermal resources are inherent to specific geographic locations and are not dependent on external fuel supplies. This characteristic provides a distinct advantage, as it eliminates the uncertainties associated with imported fuels or geopolitical tensions that can disrupt conventional energy markets. The stability in fuel supply for geothermal power plants ensures cost predictability and reduces vulnerability to global energy market dynamics. This indigenous and self-sustaining feature of geothermal energy enhances its long-term economic viability and resilience, making it a reliable and secure energy option for countries seeking energy independence and stability. structure compared to other renewable energy technologies.

3.3.2 Market Condition

As the greenhouse effect is becoming increasingly severe globally, governments around the world have recognized the importance of protecting the environment. For example, New Zealand put forward a national goal to achieve 100% renewable electricity by 2030, which will greatly take the advantage of the geothermal energy in their future development [10].

Technological innovations have improved the efficiency and performance of geothermal power plants, making them more economically competitive. Enhanced drilling techniques, advanced turbine designs, and improved heat extraction methods have increased energy output and reduced operational costs, further enhancing the economic viability of geothermal projects. According to Wang, it has been possible for China to drill the well designed for exploiting renewable energy that is more than 8000 meters [11]. If this technology can be shared around the world, countries that are lack of advanced drilling technology can benefit from geothermal technology as well.

Additionally, the growing interest in renewable energy investments has opened up opportunities for geothermal energy projects. Institutional investors, venture capitalists, and private equity firms are recognizing the potential of geothermal energy and actively seeking opportunities to fund projects and participate in the industry's growth. Fig. 2 demonstrates the change in global energy investment in clean energy and in fossil fuels from 2014 to 2023 [12]. Investors in recent years tend to prefer clean energy development more than exploiting fossil fuels. Human's awareness about using clean energy has raised much in the last ten years.

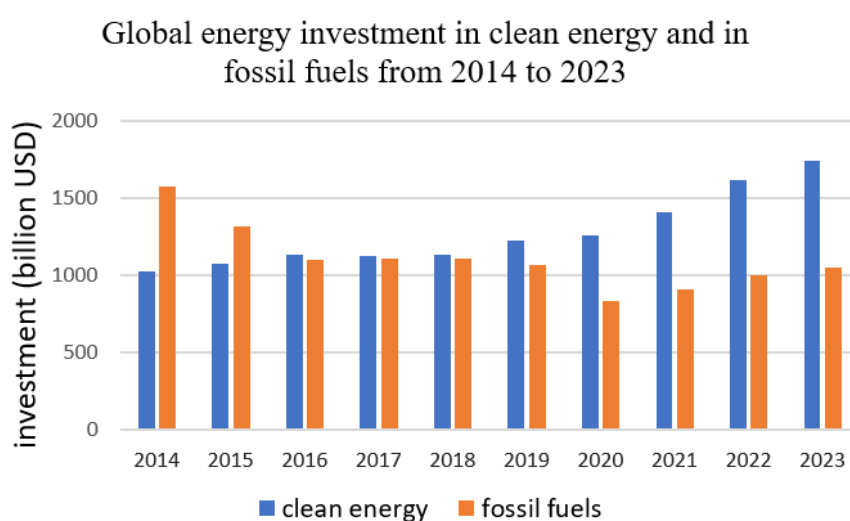


Fig. 2 Global energy investment annually from 2014 to 2023. (Picture credit: original)

4. Geothermal Energy's Impact on the Future Society

Geothermal energy, with its vast potential and numerous advantages, is poised to have a significant impact on future societies. As the world seeks to transition to sustainable and clean energy sources, geothermal energy stands out as a reliable and environmentally friendly solution. Its impact will be felt in various aspects of society, including energy generation, environmental sustainability, economic growth, and job creation.

One of the most significant impacts of geothermal energy on future society is its contribution to meeting the growing demand for electricity. As populations increase and energy needs rise, geothermal power plants can provide a consistent and continuous supply of clean electricity. Unlike solar or wind power, geothermal energy is not subject to intermittent availability or weather-dependent fluctuations. This reliability ensures a stable energy supply, reducing reliance on fossil fuels and mitigating the risks associated with energy shortages and price volatility. Geothermal energy can play a vital role in diversifying the energy mix and ensuring a sustainable and resilient power grid.

Moreover, geothermal energy's low carbon footprint and minimal greenhouse gas emissions make it an essential tool in combating climate change. As societies strive to reduce their carbon emissions and limit the environmental impact of energy generation, geothermal energy offers a renewable alternative that is virtually emissions-free. By tapping into the Earth's natural heat, geothermal power plants produce minimal air pollutants and contribute to cleaner air quality. The widespread adoption of geothermal energy can significantly reduce greenhouse gas emissions, helping to mitigate climate change and promote a more sustainable future.

In addition to its environmental benefits, geothermal energy has the potential to drive economic growth and create job opportunities. The development and operation of geothermal power plants require a range of skilled professionals, from engineers and technicians to project managers and geoscientists. As geothermal projects expand, local communities can benefit from job creation and economic development, stimulating local economies and providing sustainable employment opportunities. Moreover, geothermal resources are often found in regions with limited access to traditional energy sources. Harnessing these indigenous resources can enhance energy security and foster local self-sufficiency, reducing dependence on imported fuels and driving economic resilience.

Geothermal energy's impact on future society also extends to the realm of sustainable urban development. District heating systems that utilize geothermal energy can provide efficient and cost-effective heating and cooling solutions for residential and commercial buildings. By leveraging the Earth's natural heat, geothermal systems can significantly reduce energy consumption and greenhouse gas emissions associated with traditional heating and cooling methods. This promotes sustainable urban planning and helps create energy-efficient cities with reduced environmental footprints.

Furthermore, geothermal energy can have a transformative effect on remote and off-grid communities. Many regions around the world, particularly in developing countries, lack access to reliable electricity. Geothermal power plants, with their ability to operate continuously and independently of external factors, can provide electricity to these underserved areas. This access to clean and affordable energy can improve living conditions, support education and healthcare services, and spur economic development in remote communities. Geothermal energy can be a catalyst for social progress and upliftment, ensuring a more equitable distribution of energy resources.

In conclusion, geothermal energy's impact on future society is multi-faceted and profound. It offers a reliable, clean, and sustainable energy solution that can address the challenges of increasing energy demand, environmental degradation, and climate change. From providing a stable electricity supply to promoting economic growth, job creation, and sustainable urban development, geothermal energy has the potential to shape a more resilient, equitable, and environmentally conscious future society. By embracing and expanding the use of geothermal energy, societies can unlock its vast benefits and pave the way for a sustainable energy transition.

5. Conclusion

Clean energy will eventually replace fossil fuels entirely as time goes on. People from diverse domains should collaborate in order to accomplish this goal. The cost of constructing a power plant at the site will typically grow as the depth of the available resources decreases. Furthermore, the cost of building will increase more quickly as the resources are dug up deeper. It then appeals to scientists and engineers to carry out additional study on improving drilling methods. Governments should implement measures to promote increased investment in the market for clean energy and geothermal extraction in the interim. Residents should be informed by their local media on the benefits of using various renewable energy sources. The benefits of clean energy for human life are numerous. It can support economic growth, fight climate change, and meet the rising need for electricity. There is little doubt that if geothermal energy can be used effectively and efficiently, humans can make progress toward the building of a civilization that is sustainable. This study contributes to the larger conversation about renewable energy by providing substantial insights into the significance of geothermal energy and shedding light on the evolution of geothermal energy utilization.

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