Limitations and Potential Improvements to the Effectiveness of Geothermal Energy Implementation in North America

Jacob Hay

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Dr. Marcos Lugo, Ph.D.
Thesis Chair

____
Dr. John Baumgardner, Ph.D.
Committee Member

____
Christopher Nelson, MFA
Assistant Honors Director

____
Date

Abstract

The study of the composition and processes of the interior of the Earth has been the subject of interest in various fields. The analysis of heat transfer in the Earth's interior, in particular, is an area that has tremendous potential to impact other fields, especially that of renewable energy. Geothermal power utilizes the heat beneath the Earth's surface to generate electricity and offers the potential to significantly reduce carbon emissions by lowering the quantity of fossil fuels burned by coal- and gas-fired power plants. This paper analyzes the science behind geothermal energy, including its limitations and potential improvements that could enhance its ability to compete with other technologies.

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Introduction

The subject of heat transfer inside the Earth has long been the object of study by scientists from many fields. Part of the intrigue is heat from within the Earth offers the potential of an abundant, practically unlimited source of energy. Because of this, scientists in recent years have given increased attention to understanding how this heat within the Earth can be transferred efficiently to the surface.

Despite the fact that geothermal energy is an energy source that consumes no fossil fuel and is a means for harnessing the nearly limitless heat inside the Earth, it accounts for only an estimated 0.5 percent of the power produced in the United States (Dhar, Naeth, Jennings, & Gamal El-Din, 2020). The primary hindrances to more widespread exploitation of geothermal power are its high installation costs and severe location constraints. Finding ways to mitigate these challenges could significantly impact the energy industry by providing an essentially limitless clean energy supply.

This paper seeks to analyze and discuss the science behind geothermal energy. It will begin with a background on the heat transfer within the Earth, discuss geothermal power sources, review different geothermal power plant designs, and analyze critical limitations facing geothermal power development. It will conclude with an overview of potential solutions to these issues and improvements that could make geothermal power more competitive.

Background

To understand the specifics of geothermal energy and its applications, it is helpful first to review a few key background topics. These will include heat transfer inside the Earth's interior, sources of geothermal heat, and a survey of designs for geothermal power plants.

Heat Transfer within the Earth

Knowledge about the Earth's internal structure has been minimal for most of human history. As technology has improved, however, scientists have developed new techniques for addressing this need. One of the most successful methods is seismology. Researchers analyze data from earthquakes and the properties of different materials expected to be in the Earth's interior. The seismic information is used similarly to sonar, where vibrations through the planet's interior are analyzed and used to refine interior structure models. Models are constantly being updated, with researchers trying to obtain the most accurate model of the Earth's interior possible.

Current models of the core of the Earth are estimates based on seismology and studies of Earth's moment of inertia, which compare the Earth's observed movements and behaviors with models of a planet with an iron core. The similarities in the behaviors have led scientists to estimate that the core of the Earth is about 95% iron-nickel alloy. The other 5% is believed to be a combination of lighter elements like carbon, oxygen, silicon, and sulfur (Badro, Cote, & Brodholt, 2014).

Convection is the primary means for transferring heat inside the Earth. Silicate minerals that comprise the Earth's mantle are very poor conductors of heat, so conductive heat transfer plays only a minor role within the planet. Similarly, radiation heat transfer only plays a minor role since most minerals found in the mantle are far too opaque for radiation to contribute in a significant manner.

Sources of Heat

The two primary energy sources in the Earth are external heat absorbed from the Sun and internal heat from Earth's core and mantle. The external sources drive processes like weather and the oceans on the surface, while internal heat is responsible for changes and processes beneath the surface of the Earth. According to most secular scientists, the Earth's heat and internal energy were acquired through three primary means. First, heat was acquired from the accretion of infalling meteorites and their potential energy as the Earth was forming. Second, heat was released during the formation of the Earth's core, when gravitational potential energy was converted to heat as iron and other heavy elements sank to the center of the Earth. Third, heat was and still is being produced slowly from the decay of radioactive elements in the Earth.

Convection is the primary method of heat transfer in the mantle. Convection in the mantle mainly occurs when lower-density warm rock rises and higher-density cooler rock sinks. The buoyancy forces acting on these materials cause hotter materials to rise toward the crust and colder materials to sink toward the core. (Boujibar, Driscoll, & Fei, 2020).

Mantle Plumes

One way convection and buoyant forces are expressed is in mantle plumes. A mantle plume is a column of hot rock believed to rise from the core toward the surface. Whether or not mantle plumes actually contain material from the core has been debated (Scherstén, Elliott, Hawkesworth, & Norman, 2004) and will be discussed later. Still, it is widely accepted that they play a significant role in the heat transfer between layers of the Earth. Figure 1 below shows how mantle plumes develop over time and how they can transfer heat from deep within the Earth across broad surface areas.

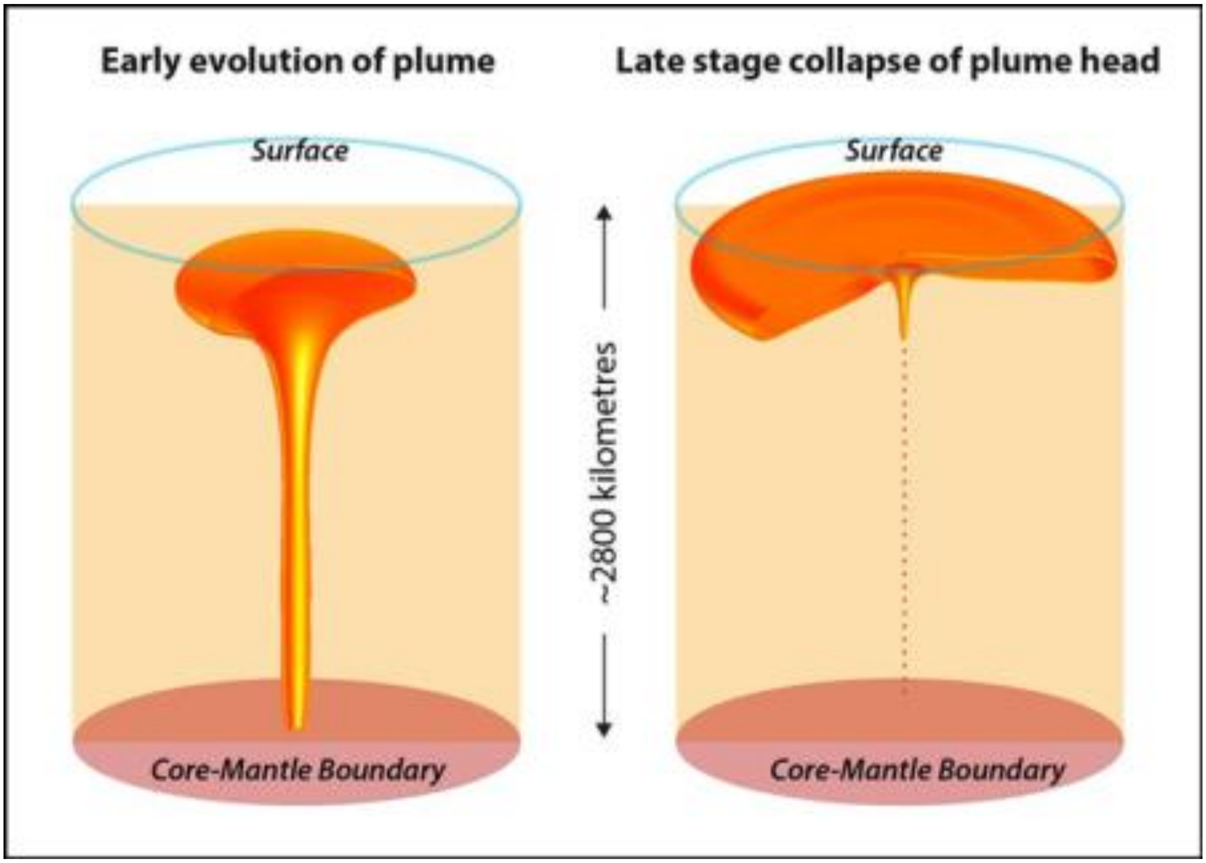

Figure 1 - Evolution and expansion of mantle plumes (Stern, Lamb, Moore, Okaya, & Hochmuth, 2020)

Researchers have identified at least 28 known mantle plumes, most occurring directly below volcanic hot spots. By studying earthquake records using a similar method as was previously mentioned, some researchers believe that they have found evidence that mantle plumes stretch down to the core. The recent estimates are that mantle plumes are 600 to 800 kilometers wide, which is almost three times wider than earlier estimates using simpler models (Hand, 2015). This would mean that mantle plumes can carry significantly more hot material up from the core and disperse more heat than previously thought. The map below in Figure 2 shows the locations of known hotspots with corresponding mantle plumes worldwide.

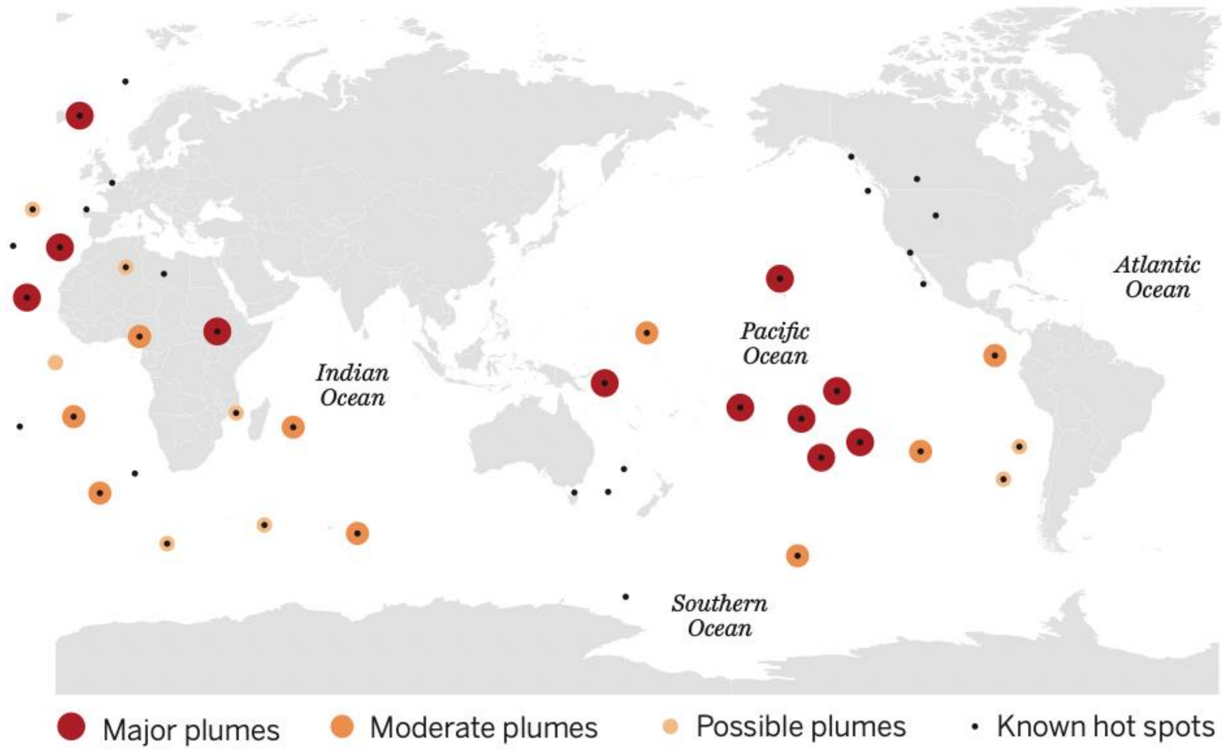

Figure 2 - Locations of known mantle plumes and hotspots (Hand, 2015)

There's considerable debate among scientists about mantle plumes and whether or not they actually originate from the boundary between the core and the mantle or if they just rise from more outer layers. Researchers point to discrepancies between the actual and expected amount of tungsten isotopes in mantle plumes as evidence that they can't originate from the core (Scherstén, Elliott, Hawkesworth, & Norman, 2004). Regardless of the origin of the plumes, they facilitate large amounts of heat transfer in the Earth's interior and create higher temperatures near the planet's surface over these hotspots.

Geothermal Power Sources

The increased temperature at specific locations underground makes geothermal power sources feasible. There are several varieties of geothermal systems, but they all operate under the same basic principles. Heat found deep underground creates steam that turns turbines and generates electricity. In some cases, steam or superheated water from underground is brought to the surface, vaporized, and used in power plants. In other types of geothermal plants, water at temperatures lower than its boiling point is brought up and used to heat another liquid with a much lower boiling point than water. The vapor from this other liquid is then used to turn the turbines. Essentially, geothermal power plants use the same types of turbines and generators as traditional power plants but without the need to burn fossil fuels.

Geothermal Power Plants

There are three main categories of geothermal plants: direct dry steam, flash and double flash cycle, and binary cycle plants. Each functions slightly differently but operates on the same main principles discussed above. The direct dry steam plant is the oldest and simplest style of geothermal power plant. This style of plant taps into underground hydrothermal fluids that are already vaporized or primarily steam. The steam is brought from underground directly into a turbine, which drives the generator that produces the electricity. This style of geothermal plant was first used in Italy in 1904 and can be found worldwide in locations with reservoirs of steam close to the surface. Figure 3 below shows a schematic of a direct dry steam power plant.

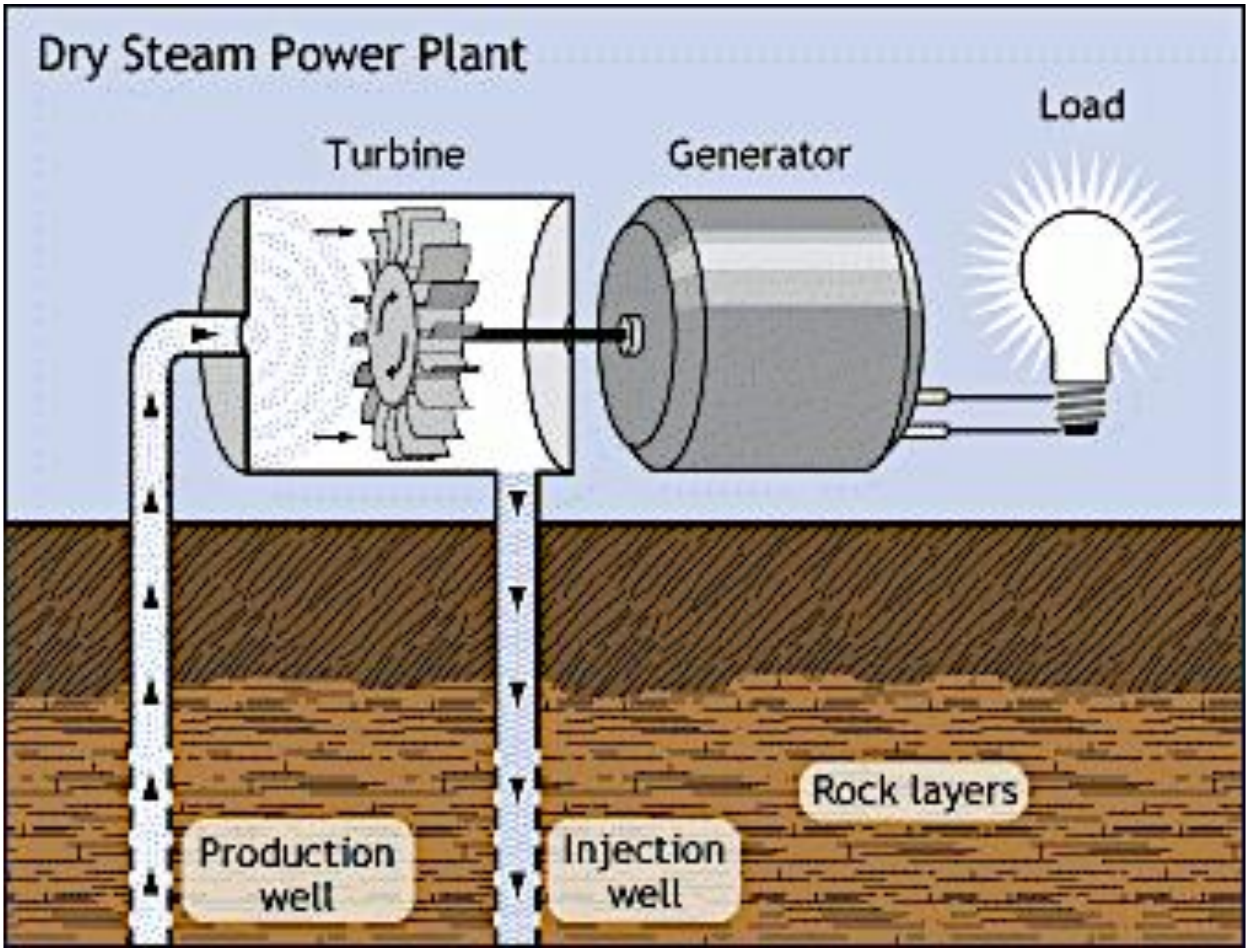

Figure 3 - Schematic of a direct dry steam plant (U.S. Department of Energy, Types of Geothermal Power Plants, n.d.)

Flash and double flash cycles utilize underground hydrothermal fluids that are primarily liquid, but above 360°F (182°C). The fluid is extracted from underground and sprayed into a tank kept at a much lower pressure than the liquid. The sudden pressure difference causes the fluid to rapidly expand and vaporize ("flash") into steam. This vaporized fluid is used to drive a turbine and power the generator. Double flash systems try to improve the efficiency of these power plants by reducing the amount of available energy lost in liquid that isn't vaporized. Double flash systems utilize a second tank to flash any liquid not vaporized initially in the first tank. This allows even more energy to be extracted from the fluid being drawn up from underground. Figure 4 below shows a typical flash cycle power plant schematic.

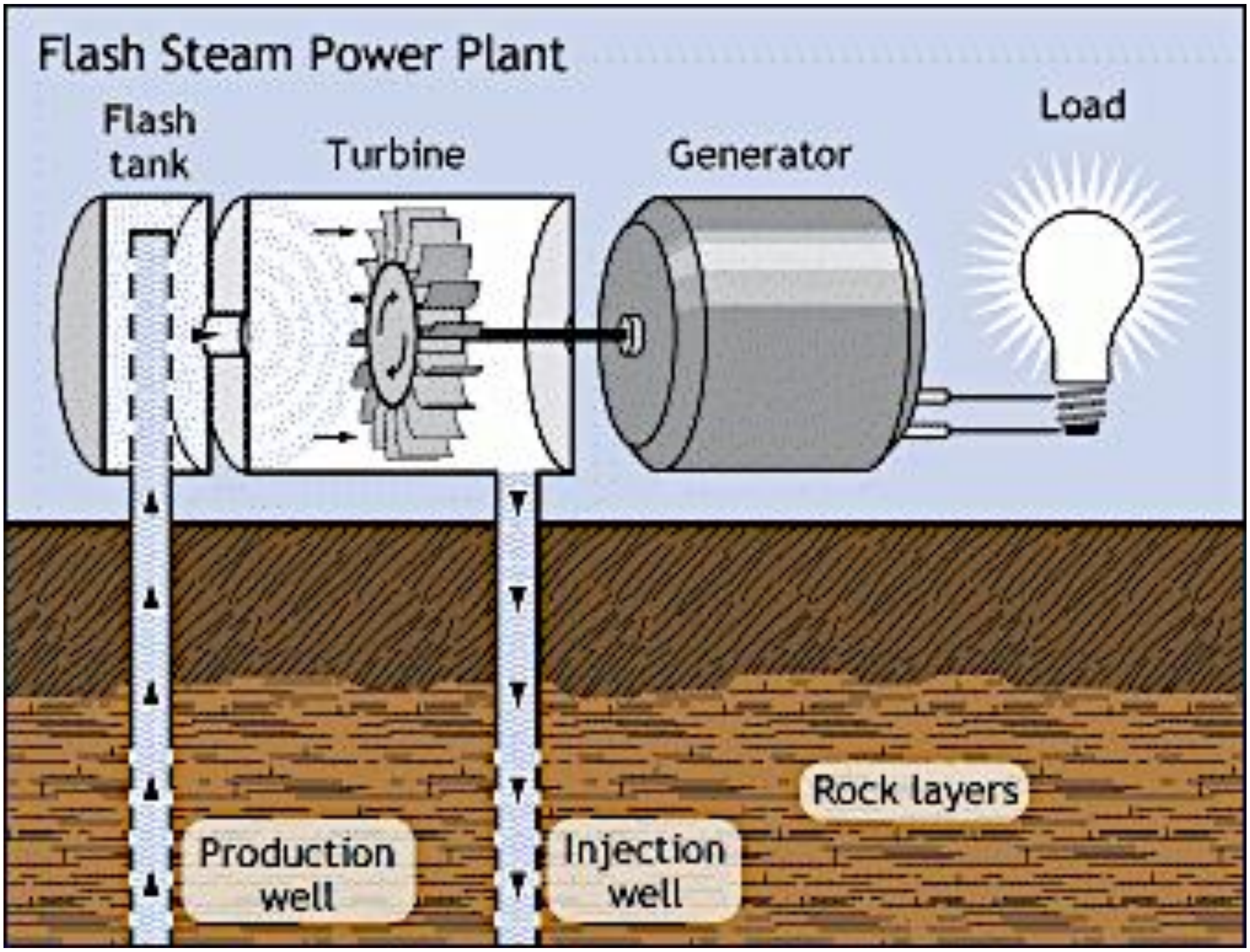

Figure 4 - Schematic of a flash steam power plant (U.S. Department of Energy, Types of Geothermal Power Plants, n.d.)

Some facilities even implement a triple flash system, which builds on the double flash power plant concept. A triple flash plant adds a third flash tank that vaporizes even more of the hydrofluid coming into the tank than a double flash system. This further increases the efficiency of the system and increases its usefulness.

The third common type of geothermal power plant is a binary cycle plant. These plants utilize underground water at cooler temperatures than the other two types of plants (typically below 400°F). The hot fluid is extracted from underground and brought to a heat exchanger on the surface. A secondary, "binary", fluid also passes through the heat exchanger. These binary fluids have a much lower boiling point than the water pumped through the heat exchanger. The heat transfer in the heat exchanger causes the binary fluid to vaporize, which drives the turbines that power the generators. A schematic of this style of geothermal plant can be seen below in Figure 5.

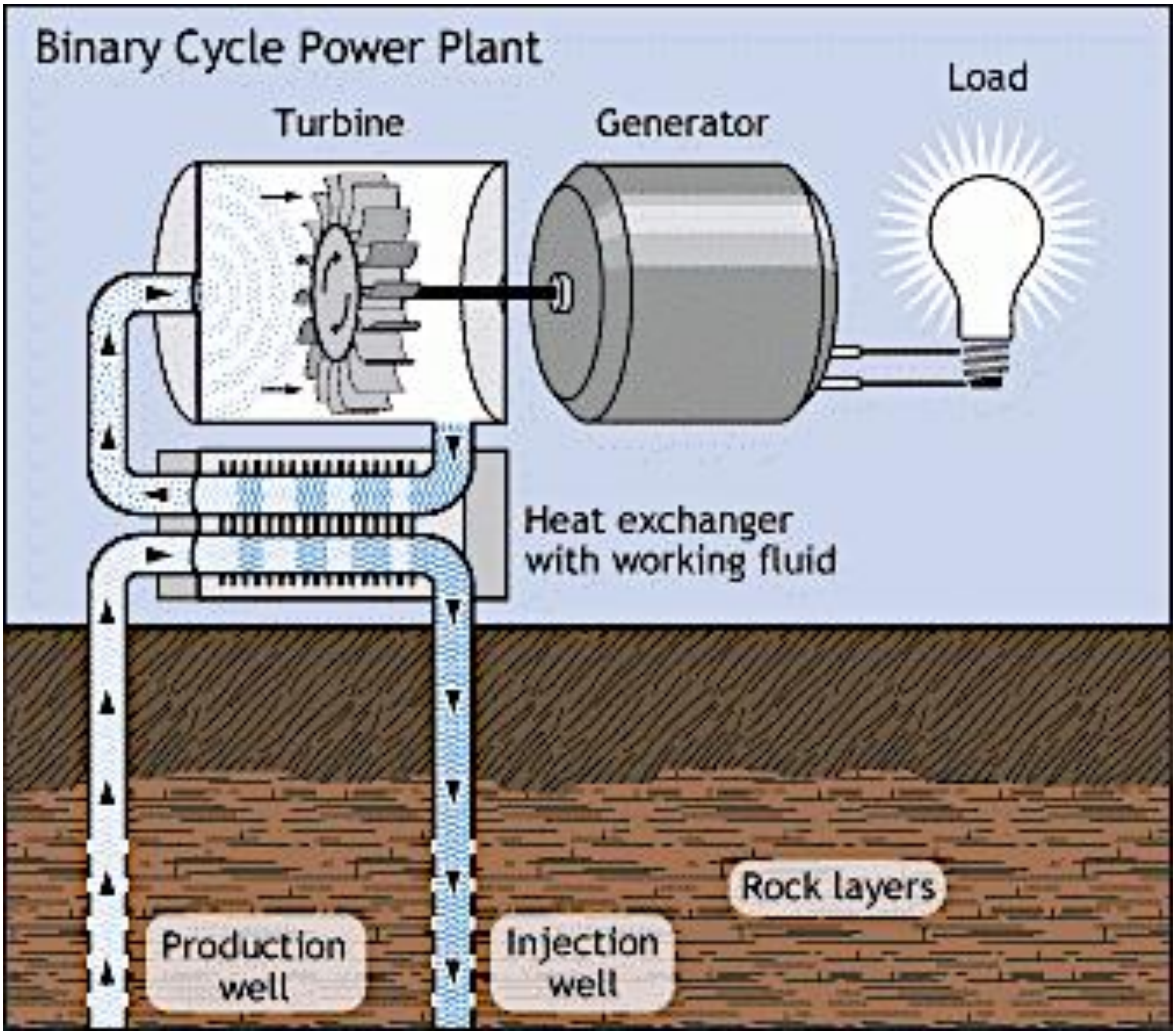

Figure 5 - Schematic of a binary cycle power plant (U.S. Department of Energy, Types of Geothermal Power Plants, n.d.)

Binary power plants offer the most promising future because they function with the lowest temperature geothermal fluid. This allows them to be used in a much wider variety of locations where direct dry steam or flash cycle plants might not be feasible. Binary cycle plants also function in a closed-loop system, meaning there are virtually no emissions, making them an ideal choice from a clean energy point of view. The downside of binary power plants is that they offer a relatively low efficiency – only around 12% (Winters, 2019).

Limitations on Geothermal Energy

While geothermal energy is theoretically an ideal energy source and is very promising in its advantages, several practical limitations make it challenging to implement consistently. These include specific location requirements, high costs, and technical difficulties with drilling.

Requirement of a Suitable Geothermal Reservoir

A suitable geothermal reservoir is one of the main constraints restraining geothermal power from being more widely used. Most areas simply do not have a suitable geothermal reservoir. The development of new technologies in geothermal power plants, like binary plants, has helped to reduce this constraint somewhat, but it is still the primary factor that limits geothermal development. Typically, locations optimal for geothermal power generation are located in tectonically active regions where the outer crust is thinner, and hot rock lies closer to the surface of the Earth.

In the United States, specifically, there are few locations where temperatures underground are suitable for geothermal power plants. Most such sites are in the western United States, for example, California, where there has been recent tectonic activity. Figure 6 below shows the temperatures in the United States at 5500 meters (Blackwell, et al., 2011). This is slightly deeper than most geothermal plants drill, but the map is a helpful representation of how the temperatures are distributed across the continent.

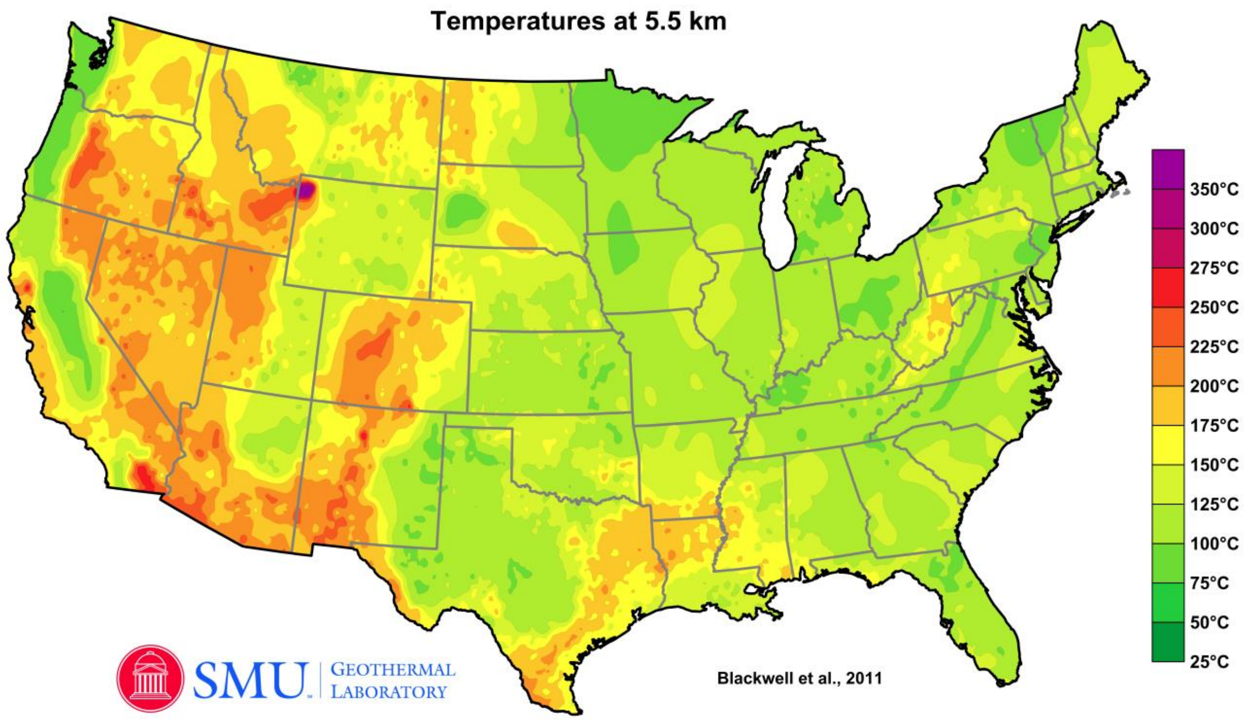

Figure 6 - Temperatures underground in the contiguous United States at 5.5 km (Blackwell, et al., 2011)

As seen above, the western United States and parts of southern states like Texas have the highest temperatures near the surface. This largely corresponds with the Basin and Range province that includes Nevada, much of Idaho, Oregon, California, Utah, and Arizona, as well as the Rio Grande Rift region in New Mexico and Colorado. One of the largest single geothermal fields, The Geysers, is in California, north of San Francisco. This field supports 22 geothermal power plants, which produce 900MW of electricity, enough to power 900,000 homes (Power Technology, 2023).

High Cost

When installing geothermal power plants, a significant investment is necessary, both financially and in terms of equipment. A measure of energy generation called the "levelized cost of energy," or LCOE, is often used to compare energy sources. This metric essentially tries to consider all the fixed and variable costs of energy generation and compares that to the amount of energy produced and how long that energy production can be sustained. The LCOE of geothermal energy is in the range of $59-$101 per MWh, which is less than sources like coal but more than some other renewable sources like solar or wind power (Energy Monitor Staff, 2023). Figure 7 below compares the cost for various energy sources in terms of dollars of LCOE / MWh.

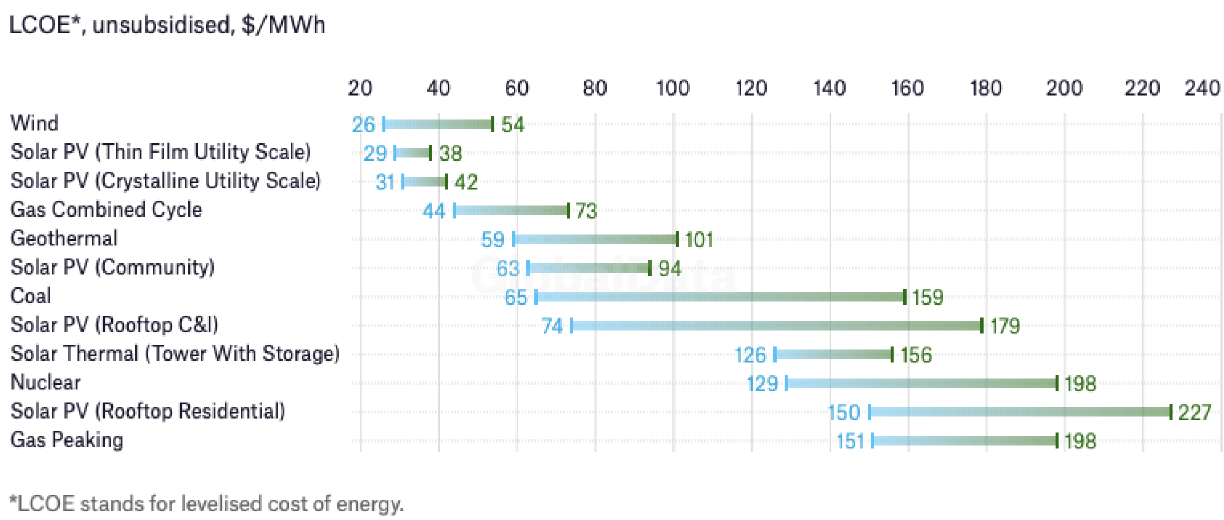

Figure 7 - Levelized cost of energy for different energy sources (Energy Monitor Staff, 2023)

The majority of the cost for geothermal energy is incurred when the system is installed. Data from the Energy Information Administration in 2020 showed that the average cost for installation of a natural gas power plant averaged $1,116/kW. Wind power costs $1,498/kW, the cheapest major renewable energy source in the EIA data. Geothermal energy, however, averaged $3,483/kW, which is by far the highest installation cost in the EIA database (U.S. Energy Information Administration, 2020).

While the low running costs for geothermal power make it an attractive power source once installed, the high price for installation makes it more difficult to justify. Technological improvements or changes that reduce this cost would dramatically increase the appeal of geothermal power.

Changes and Technologies to Improve Geothermal Energy

There are a few key ways in which geothermal power technology can be improved to help resolve some of the common challenges that currently limit its practicality. These include things like improvements in power plant design, the use of fracking, and smarter drilling.

Binary Cycle Powerplants

In terms of improved power plant design, one option is to switch to binary cycle plants, as discussed above. This allows for much lower temperature fluid to be used to drive turbines, but the efficiency of those systems is not as good as dry direct steam plants.

Hydraulic Stimulation

One way to improve rock permeability is hydraulic stimulation. Known more commonly as fracking, hydraulic stimulation has been widely used in the oil and gas industry and has become controversial because of the environmental and seismological impacts it can have. Fracking is the process of drilling into the Earth and injecting fluid at high pressure into the rock at different depths to cause fractures and cracks to form. In the oil and gas industry, this process releases trapped fluids that can be extracted and refined. This allows gas and oil previously trapped in the solid rock to be released and harvested.

The fracking process is controversial, mainly due to its environmental impacts. The process of creating fractures underground often has adverse effects, like increased seismic activity, that have caused many environmental organizations to oppose its use and even caused some countries and states to pass laws banning fracking. The process also requires large volumes of water to be transported to the fracking site and injected underground. This typically requires heavy machinery with large carbon footprints and emitting more pollution than if a site wasn't being fracked.

When it comes to geothermal power plants, fracking can be very beneficial. By increasing the permeability of the rock and increasing the amount of energy that can be harvested, more heat can be drawn from the same section of hot rock. High-pressure fluid can be injected into existing fracture networks, increasing the fractures' size and concentration density. Figure 8 below shows how existing fracture systems can be stimulated with fracking.

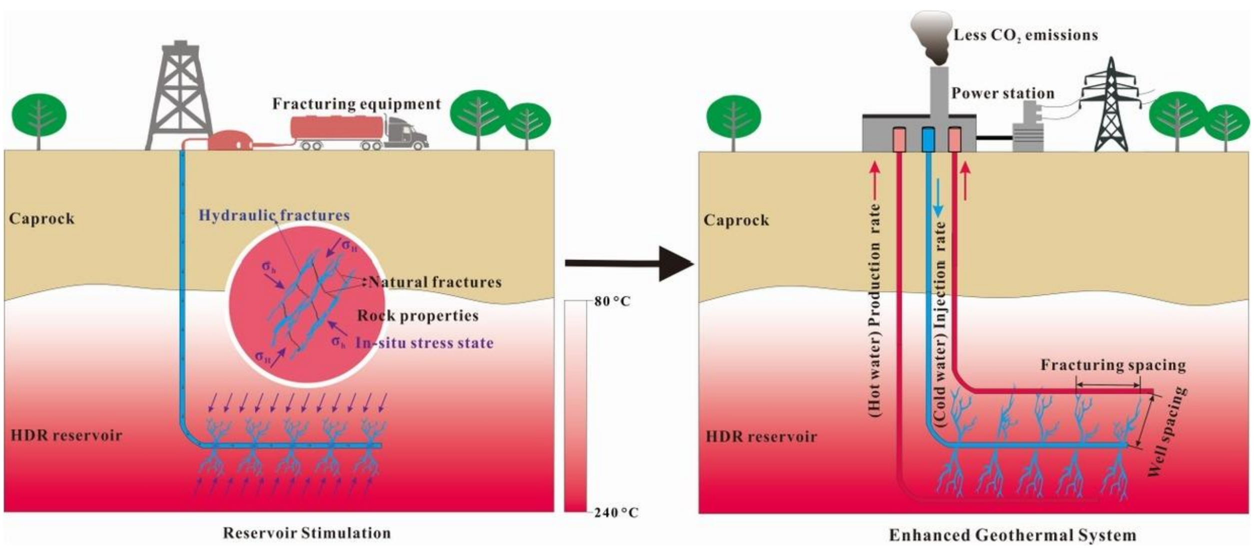

Figure 8 - Implementation of hydraulic stimulation at geothermal power plants (Lei, et al., 2020)

A basic understanding of geothermal systems shows that larger, more expansive fracture systems underground allow more heat and energy to be drawn from the hot rock under the surface. It follows logically that increasing the size and permeability of these fracture systems would only increase the efficiency and potential for geothermal sites.

In some situations, fracking can create large fracture systems from only the small cracks that are present naturally. This could allow geothermal plants to be used practically anywhere, as long as sufficient depths are drilled to have high enough temperatures in the rocks. This type of system is known as an enhanced geothermal system, or EGS. The Department of Energy estimates that, by 2050, EGS-powered plants could reach 90GW of electricity (U.S. Department of Energy, DOE Analysis Highlights Opportunities to Expand Clean, Affordable Geothermal Power, 2023) (which is less than 10% of current generation capacity).

Drilling and Technical Solutions

Most of the technical challenges facing EGS drilling involve the high temperatures associated with the geothermal environment. Higher temperature increases the rate that the components of the drilling rigs wear down and fail. The drill bit is the most critical component, and several options address different issues regarding drill bit failure (Sircar, Solanki, Bist, & Yadav, 2022). Figure 9 below outlines some of the most common bits used in industry and shows the uses each has for geothermal drilling.

Bit type	Challenges emerged during geothermal drilling	Potential of Geothermal
Roller cone	Bearing and seals	Suitable bit type for hard rocks
Polycrystalline diamond compact (PDC)	Hard rock	Possible improvement with water jets
Water/ abrasive jet cutting	Pumping seals and high pressure	limited
Percussion	Maintaining Gage, good data	Good if gage problem can be solved
Flame jet	Water quench, System difficulties, Costs for deep wells	Hot dry rock reservoir (Granite)

Figure 9 - Different types of drill bits used for geothermal drilling (Sircar, Solanki, Bist, & Yadav, 2022)

Further research into drilling techniques and technology will inevitably result in faster drilling and longer drill bit lifespan. This could potentially reduce the initial installation costs for these power plants by a significant amount. One such technology is spallation, which uses intense flames to heat the surface of rocks, which causes them to “spall” or fragment (Sircar, Solanki, Bist, & Yadav, 2022). Another improvement being developed is projectile drilling, which utilizes steel balls that are propelled at the rock to disintegrate and remove chunks of rock. A third emerging advancement is chemical drilling. This uses powerful acids that dissolve certain rock types and often can be combined with other traditional drilling techniques. None of these technologies is commercially available at the moment, but each offers a significant upside that could drastically reduce the high cost of installing geothermal power plants.

Conclusions

Geothermal power is theoretically an ideal clean energy source that draws on the relatively limitless heat contained within the Earth. By tapping into this heat and converting it into electricity, power can be produced at relatively low costs while having almost zero carbon footprint.

Currently, several issues face geothermal energy that restrict its use and make it challenging to implement. Among these challenges are the high installation costs, specific location constraints, and the technological difficulties of drilling to great depths under high temperatures. Researchers and engineers in the industry are working to address these challenges. Some potential solutions include using hydraulic stimulation to create more favorable fracture systems for geothermal power, utilizing binary cycle plants to use geothermal power in locations with lower temperatures underground, and making advancements in drilling technology to reduce drilling costs.

If these strategies successfully solve the main issues facing geothermal power, more and more people may benefit from the clean energy provided by geothermal technology. This would ultimately result in a more environmentally friendly power source that is ultra-sustainable and has the potential to reduce energy costs in areas where it is implemented.

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