Geothermal: An environmentally friendly alternative to fossil fuel.

by

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Abstract

Geothermal energy promises solutions to many of the challenges posed by reliance on fossil fuels. Demand for energy is not decreasing anytime soon, making the search for environmentally conscious resources of energy a necessary endeavor. However, geothermal also comes with its own set of challenges that must be addressed if the technology is to compete with other alternative energy sources such as wind and solar. Advances such as enhanced geothermal systems and artificial intelligence applications can reduce the obstacles to implementation. One of the biggest advantages of geothermal is the minimal interruptions in the power supply it can provide. Subsidization can also play a role in reducing the issues with riskiness and profitability; however, it does not provide scalability in the same way the private sector would. The success of the ongoing development of solutions to these challenges will determine how geothermal fares in the shift to green energy.

Table of Contents

Table of Figures

Introduction: The Need for a New Energy Source

The International Energy Agency, or IEA, annually releases the World Energy Outlook. In 2022, this report included data on the projected demand for various fossil fuels, extending to

the year 2050. The peak demand lands around 2025 and begins to decline steadily after (see Figure 1). A shift is also occurring in the proportional use of oil, coal, and natural gas to meet the demand. The amount of coal is projected to decrease, natural gas

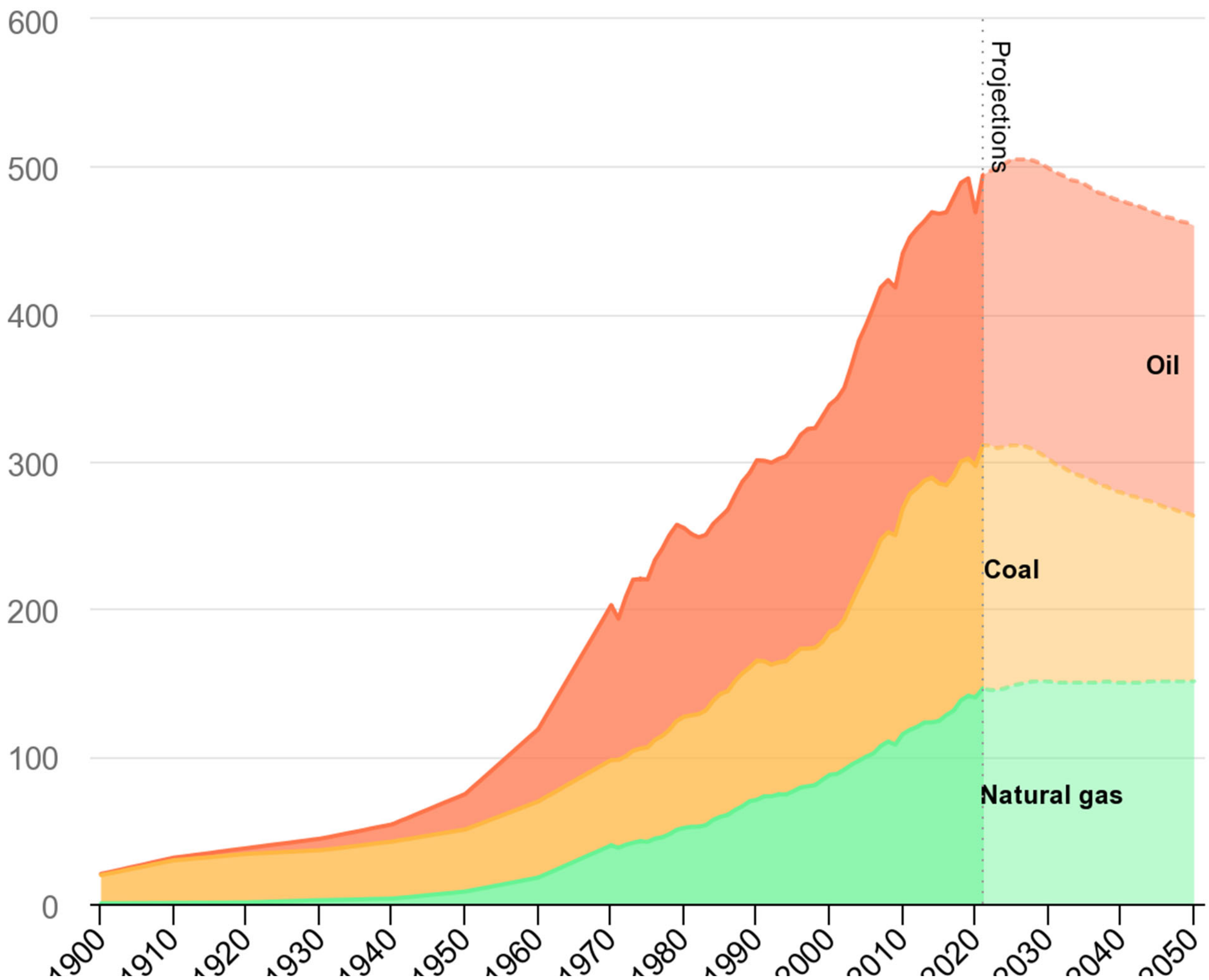

Figure 1, Fossil fuel demand in the Stated Policies Scenario

“Executive Summary”, *World Energy Outlook 2022,* International Energy Agency, 2022 is projected to increase, and the use of oil is supposed to remain consistent. These fossil fuels are harmful to the environment.

As the world’s population grows, so does the demand for energy ("Energy Consumption by Country 2023"). This energy consumption will need to continue to shift away from sources like coal, oil, and natural gas. An alternative energy source will need to replace these fossil fuels and reduce the downsides that currently result from energy production.

Additionally, many people, especially in underdeveloped countries, do not yet have access to the same resources or technology as others. Over their lifetimes, these individuals consume very little energy when compared to those in places like the United States, Canada, or Australia (see Figure 2). This disparity is likely to decrease over time

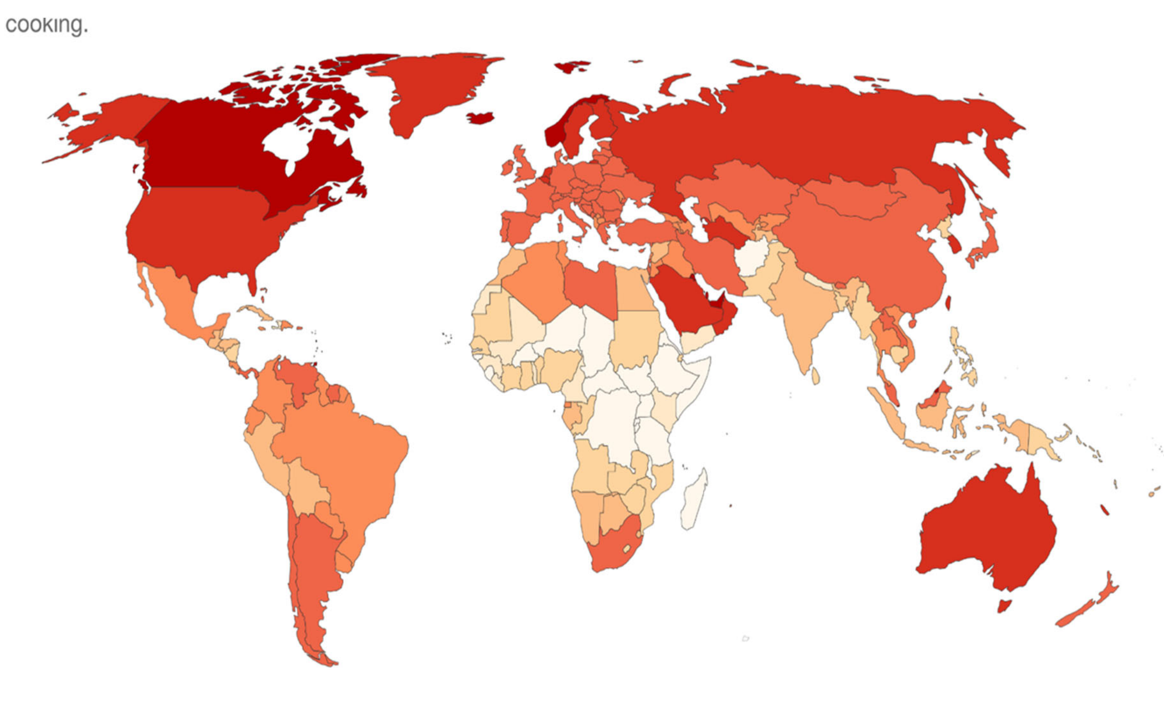

Figure 2, Map of the energy use per person in 2021

“Energy use per person, 2021”, *Our World in Data*, Global Change Data Lab, 2021 as more nations rise out of poverty and into more prosperity. As more nations come out of poverty, more energy is needed to sustain them all.

In addition to a growing population, technology is becoming heavily integrated into everyday life. Objects are being connected to the internet at a high rate, which involves digitization. Online objects constantly gather information and this information feeds into the growing depository of big data. This data comprises the internet of things. The internet of things (IoT) describes the connection between all these devices. All the objects require energy to operate, and the big data repositories require energy to operate.

The combined effect of the growth in the population, increasing energy demand due to decreasing poverty, and the spreading use of technology in nearly every available facet of life contribute to the urgency and importance of replacing polluting and harmful sources with a sustainable energy solution.

The solution needs to have fewer of the downsides that result from the current reliance on fossil fuels. The use of fossil fuels over time has had a significant impact on the environment's health. This impact affects the atmosphere, plants, animals, and people (*World Energy Outlook 2022* 266). It is imperative that another way to satisfy these needs is researched and developed. It must respect the critical characteristics of a power source, such as reliability, scalability, and cost efficiency.

Geothermal energy is an important option to consider in the search for a way to power the increasingly technological world. Geothermal shows promising potential to satisfy all these criteria and become a universally effective energy solution.

What is Geothermal Energy? Geothermal energy is not a recent discovery for humans. In fact, it is one of the oldest. The very first known occurrence of the use of geothermal

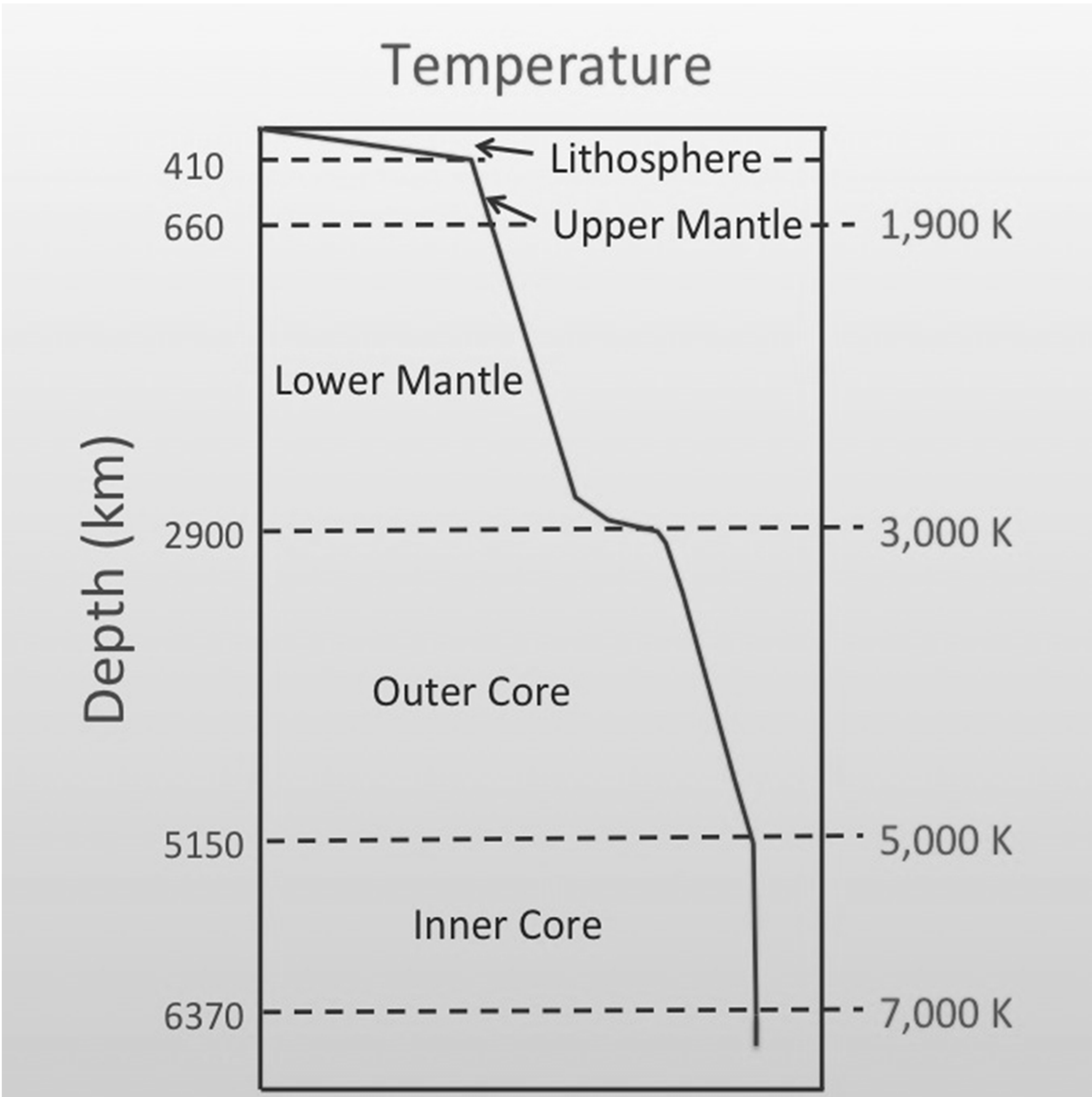

Figure 3, Temperature profile of inner earth, showing the geothermal gradient.

"Melting temperature of the Earth's mantle and core: Earth's thermal structure", *Annual Review of Earth and Planetary Science,* 1996 resources was observed to be by the indigenous people in North America over 10,000 years ago. However, their utilization of geothermal differed tremendously from modern applications like electricity generation. For the indigenous people, "the springs served as a source of warmth and cleansing, their minerals as a source of healing" ("A History of Geothermal Energy in America"). The heat sources were used as both a hygienic and spiritual resource.

The heat that warms these hot springs is from a source called the geothermal gradient. Geothermal gradient describes the heat that flows from the center of the earth to the surface (see Figure 3). For every kilometer from the center to the surface, there is an average temperature decrease of 25° Celsius (Wolfson).

Multiple sources generate the heat that comes from the earth's core. The first of these sources is the heat that has been trapped since the planet's formation, which is referred to as primordial heat. The other type of heat is produced by a reaction that occurs because of the decay of radioactive elements in the lithosphere and mantle ("Geothermal gradient").

The heat that is useful for human energy production is more abundant and accessible in some geographical locations than in others. This is due to many environmental variables. This variance in availability is partially due to the natural fluctuation in altitude along the earth's surface and, thus, distance from the concentration of heat in the core. Soil density, porosity, and others play a role as well (Bedre and Anderson 1255). In some locations, the ground can be penetrated deeply enough to access higher temperatures and find satisfactory conditions for harvesting energy.

In conventional geothermal systems, there is drilling into a naturally existing reservoir of water if it has the high temperatures needed for energy production. However, locations that do not have access to a natural reservoir may be able to benefit from geothermal energy as well. Expanding production in this way necessitates a much more advanced and involved process. One of the most impactful modern advancements in geothermal technology is Enhanced Geothermal Systems (EGS). With EGS, production can be expanded to these previously inaccessibly remote or high-altitude regions and

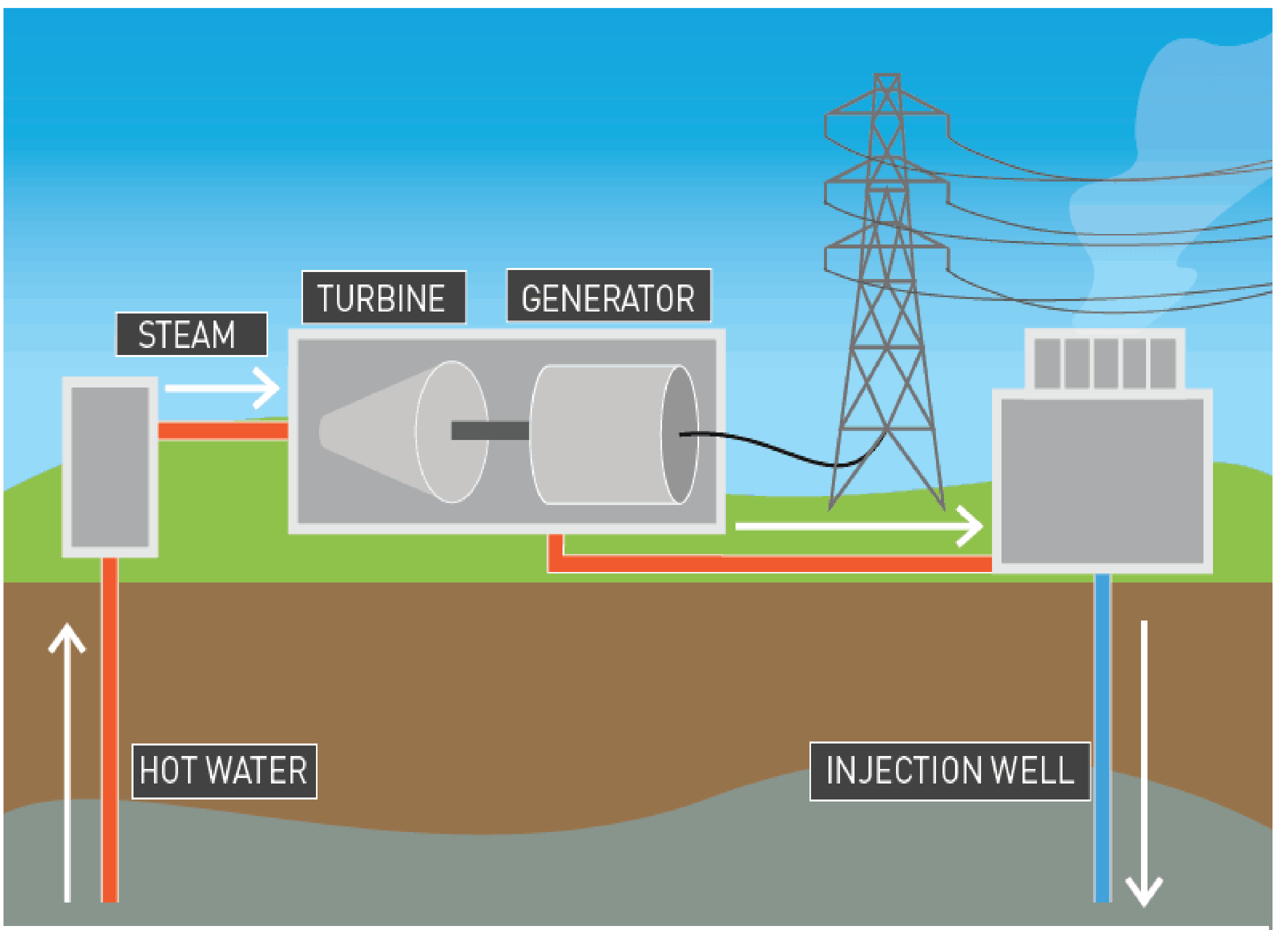

Figure 4, The process for both conventional and enhanced geothermal systems.

"Geothermal Energy Working Diagram", *Learn Mechanical*, 2023 improve their energy availability and the sustainability of the energy ("Climate Investment Funds").

Geothermal Energy Conversion Technology

There are a variety of technologies available for turning geothermal energy into electricity, but overall, geothermal systems can be broken down into two broad categories. The first basic configuration for geothermal systems is those which rely on a heat source that exists naturally (conventional geothermal). An example of this could be the hot springs used by Indigenous people.

The second category is the manufactured reservoirs, referred to as enhanced geothermal systems, or EGS. Both types of reservoirs rely on the same basic process, which involves the extraction of steam from a hot liquid, such as water, to drive a turbine. This turbine then powers a generator, which produces electricity (See Figure 4) ("Geothermal Electricity Production Basics"). The main difference between the two types of systems is the source of the liquid reservoir.

There are very few locations where geothermal is readily available with no additional technology. In other words, conventional geothermal is not easily accessible. This scarcity contributed to the extremely limited scalability of geothermal before the EGS was introduced.

One of the limited locations is The Geysers in the Mayacamas Mountains in northern California. While The Geysers was the location of the United States' first geothermal power plant, it still operates successfully today (Kagel et al. 5). According to the U.S. Geological Survey at The Geysers, "there are 18 geothermal plants which use heat from the earth's interior to produce electricity around the clock. The plants produce about 835 megawatts of electricity." The geothermal plants in California are a valuable example of the benefits that could be available to communities who utilize EGS to take advantage of geothermal technology where they would not have been able to previously.

Only recently has EGS been developed due to the successful creation of manufactured underground water reservoirs. Before this advancement, it was necessary for those constructing the plant to find a pre-existing natural reservoir to drill into. These reservoirs were not necessarily all viable for the high-heat geothermal processes involved in electricity generation, and they were few and far between (Bertani 16). These limitations were not insurmountable once EGS was created. EGS transformed an energy source with limited capacity into an abundant one.

This achievement is demonstrated well by the Chilean geothermal plant Cerro Pabellón. The plan is located in the Atacama Desert, which sits 4,500 meters above sea level. This power plant is at the highest altitude of any plant of its type. The plant has been successful in the community and continues to grow. Cerro Pabellón has provided at least 165,000 households with clean energy. According to the Climate Investment Funds website, this plant has an operational capacity of 47MW, generates 340GWh of power per year, and has eliminated 166,000 tons of CO_2. The level of success seen at Cerró Pabelon, despite the challenging circumstances presented in building a site at the type of location, indicates that the scalability of geothermal using EGS technology would not be as difficult as previously considered before these methods were available (“Climate Investment Funds”).

In the process of geothermal drilling, a conductive liquid material (in the context of geothermal, known as geofluid) is dispensed through the casing. For both types of geothermal wells, the configuration of the casing is important due to the exposure to harsh and destructive conditions it must withstand. For example, the casing needs to remain intact enduring intense thermal loads, a corrosive environment, and fatigue due to constant use, drilling, and pressure (Teodoriu 2).

After the geofluid is sent through the casing, it is then heated to the gaseous state, converted into electricity, then sent back into the earth for continued heating ("Geothermal Electricity Production Basics"). According to a summary of the process provided by the U.S. Department of Energy, "In an EGS, fluid is injected deep underground under carefully controlled conditions, which cause pre-existing fractures to re-open, creating permeability. The increased permeability allows fluid to circulate throughout the now-fractured hot rock, and the fluid becomes hot as it circulates. Operators pump the hot water up to the surface, where it generates electricity for the grid." The continuous reuse of the geofluid is one of the positive and efficient aspects of geothermal.

The process of manually creating the fracture in the underground rock comprises the main difference between conventional geothermal and EGS. According to the National Renewable Energy Laboratory, "The U.S. Geological Survey estimates that potentially 500,000 megawatts of EGS resource are available in the western U.S. or about half of the current installed electric power generating capacity in the United States." The United States uses an average of around 80,000 kWh of energy per person. ("Energy Consumption by Country 2023"). Some extremely high estimates for the theoretical supply of geothermal energy project heat mining could supply the world for a few millennia, provided technology continues to advance. (Sanyal 5). This abundance of potential resources through the avenue of EGS indicates that geothermal is a promising solution.

Determining the Viability of a Prospective Geothermal Power Plant Site

In some cases, though it would be possible to build a geothermal plant and produce some energy, the natural features around the potential plant site may render the area less suitable than other available options. It is crucial to get the selected location correct, both to maximize the output of the plant and reduce the risk of investments being wasted. Failure in the construction or production/operation process due to environmental factors is a common occurrence in EGS.

The limited investment efforts combined with the potential of failure during construction make the forethought and planning portion of the overall life cycle of the plant the main factor in the success of the project. Analysis of the conditions of the potential location for the plant site is necessary for determining whether the benefit of a plant is going to be sufficient to justify the cost. Efficiency in the planning of energy production and the use of capital is vital if geothermal will compete with other energy sources.

The preliminary analysis for land suitability could be broken down into two broad categories. The first consists of a vague search for geothermal potential in a much larger geographic region. The second is a deeper analysis of a narrowed-down location's production capacity, geothermal availability, and potential profitability.

During the first stage in the search for an adequate location, the larger global perspective on geothermal availability should be reviewed. Essentially, this functions as a vetting process to eliminate potential site locations that have characteristics inimical to production. One example of this may be a simple lack of geothermal heat availability. Some of the parameters for determining the suitability of a site include elevation, sediment thickness, and surface air temperature, among others (Coro and Trumpy 3). In the Journal of Cleaner Production, Coro states, "suitability is correlated with the complex combination of these parameters rather than with specific ranges of each parameter."

Though there is a lot of available data, the complicated process of understanding these combinations and their effect on the site is necessary for determining how well a location will produce. This complication is also one of the reasons for the widespread hesitance to adopt these systems. Regardless, these precautionary steps are indispensable to decision-making as the high capital costs combined with the overall riskiness of geothermal are two of the driving factors for low investment. It will be indispensable for the growth of geothermal for investors to overcome the barriers.

According to a study done on the screening process of geothermal by Coro, an abundance of invasive and costly procedures is required to conduct a more detailed investigation into a plant site's viability, and consultation of available data before this process may reduce much of this exploratory burden (Coro and Trumpy 1).

The study by Coro created and published one of the available geothermal suitability maps from a global perspective. The map is one of the multiple tools available for this type of analysis. While there are several hurdles in geothermal projects, there are also many available resources for overcoming them. These resources are accessible without extensive access to or involvement in the geothermal field. According to Madhur Bedre of the West Virginia University Department of Chemical Engineering, "Before exploiting a geothermal resource, it is necessary to carry out a preliminary analysis involving knowledge about the geology of the reservoir, general understanding of the potential problems a project might face, and the benefits gained from extracting energy from the resource.” Bedre also states, "reservoir temperature and the geothermal gradient [are] the most important parameters to verify before initializing primary analysis" (1256). Gathering Information about critical geothermal field parameters before initiating a large project for geothermal power is essential, and the data is readily available by consulting the published information.

Once a site is determined to be a viable contender regarding these simpler upfront requirements, a more detailed and thorough investigation into the site's suitability must be conducted. Several naturally varying factors are involved in this secondary investigation, including rock permeability, porosity, and rock thermal conductivity (Bedre 1256). This testing is much more in-depth and requires more invasive procedures to be done to the possible plant site.

There are a few ways for a potential investor to perform site testing. One of these processes was designed and published by Scientists at the Institute and Laboratory of Geotechnics in Germany. The more specific parameters they found for geothermal viability were researched and accordingly published. The result is a systematic and concise series of steps that are intended to serve as a guide for the necessary processes to be included in the testing.

This publication, according to the authors, aims to solidify the legitimacy of geothermal production through standardization and help turn the science into a more established field in the eyes of investors and the public alike. The testing system is aptly named the *Geothermal Response Test* and aims to contribute to the users' understanding of the multiple relevant thermal subsoil properties. The test helps improve the quality of the pre-project testing, as well as guide the user in the appropriate steps to be taken for deeper analysis (Katzenbach et al. 2).

The testing procedure was not very cost-effective as of 2009, when the information in the study was compiled initially, limiting its potential for widespread low-cost use in that form. According to Katzenbach, "the test could be conducted economically up to now only in the course of the preliminary investigation for the construction of bigger facilities." The Geothermal Response Test can be performed based on a relatively small mobile testing unit. This could be done, for example, by using a pickup truck and a trailer for transportation.

In summary, the test involves inserting a borehole heat exchanger into the ground and gathering data on the thermal conductivity of the substrate (Katzenbach et al. 1). The heat exchanger is intended to be as similar as possible to the model the company intends to use in routine operations of the plant. If the testing is done correctly and in conditions that closely resemble what the standard conditions for the plant may be, it is probable that it will accurately indicate the usefulness, efficiency, and quality of both the ground and the equipment.

One example of a parameter involved in soil testing is the thermal conductivity of the soil. In the publication by Katzenbach describing the Geothermal Response Test, thermal conductivity is defined as "a measure for the rate of energy transfer through a borehole heat exchanger for both energy injection and extraction." This conductivity could be affected by numerous variables including but not limited to the groundwater levels and direction of its flow, arrangement and material of the heat exchanger tubes, size of the borehole heat exchanger, and quality of thermal connection to the surrounding soil (Katzenbach et al. 1).

The process of standardization for this testing may be an integral part of attracting increasing investment attention and a small step toward this industry effectively lowering the barrier to entry. For geothermal to be successful, it must continue to improve in efficiency, reliability, and scalability. To improve efficiency and reliability, adequate research, preparation, and planning are necessary. Scalability will likely continue to improve with technological improvements.

One of these critical and modern advancements to the Geothermal Response Test is the modern application of artificial intelligence (AI) or machine learning (Moraga et al. 134-139). The AI models can be formulated to analyze the data that is gathered in any given geothermal test against an extensive repository of previously collected data. The data from the new analysis is then compared to the old data. Then, the correlation that various parameters have to success or failure is analyzed. This is done with AI. The AI program tries to predict how well-suited the environment is for a geothermal plant. The data still must be gathered to be input into a model. Once the model is functional, AI predictions about the suitability of a potential site can be made with increasing accuracy and may decrease the length and complexity of the testing process for people by eliminating the need for much of the current testing.

Some models provide less in-depth information on the overall capacity of the geothermal wells and are more “geared towards the early stages of exploration and only find the footprint of the geothermal resource and not its potential” (Moraga et al. 134-139). Other experimental models with geothermal have been more informative.

One experiment with this machine learning, or AI, was performed at the Laboratory of Soil Mechanics in Lausanne, Switzerland. In this experiment, a model was designed based on data gathered from 174 geothermal thermal response tests throughout Switzerland. The algorithm created used scale predictions to analyze the geothermal potential of different sections of land. The study concluded that "in the future, the model investigated in this work could represent a major opportunity for a partial or complete substitute for thermal response tests, which have historically run to determine the in situ thermo-physical characteristics of the underground” (Bourhis et al. 2-9).

The predictions made in the study by artificial intelligence tended to be accurate once tested against actual data from the site of the projection and represent an optimistic future in the continuous improvement of geothermal testing with machine learning technology. If AI becomes a reliable resource for geothermal operations, it may offer relief to investors from a substantial portion of the exploratory financial burden discussed previously, contributing to more widespread interest.

After these preliminary testing procedures, if a site is determined to be suitable for geothermal production, the developer will then need to begin drilling and construction of the plant. There are various ways for the well casing, drilling, and other aspects of the process to be done. Many of the variables come with risks in one form or another. These critical decisions further complicate the construction. Though some of these risks can be mitigated by proper planning, research, and testing, these measures do not entirely alleviate the issues that builders may face due to several environmental variables that are out of their control. The process of investing in and building the geothermal site can be challenging due to “burdensome regulatory and administrative requirements” (Lund et al. 7).

The construction of the site necessitates a meticulous approach. According to James Southon, who contributed to the Proceedings World Geothermal Congress in 2005, "When a high-temperature geothermal well is completed, there is a risk that the well fails on the first heat up or that there is a delayed failure due to the formation environment like the presence of corrosive fluids." Failures of this type are common in geothermal projects and cause high repair costs that accumulate and diminish the operation's profitability. Southon states, "It is apparent that any oversight or slight deviation in implementing good construction techniques increases the risk of casing failure."

There are ways to mitigate these risks, one of which is a focus on the quality and appropriateness of the equipment selected (Ngugi 2-5). When failure occurs, it makes the length of the construction process increase. Geothermal projects are already time-consuming before failure occurs. The long time span is because of the necessity for project managers to ensure minor details are being done correctly.

One demonstration of the high rate of complication is the Hengill geothermal field in Iceland. At the field, “14 of the 73 wells encountered unusual problems which led to additional cost,” and “the difficulties were mostly due to anomalous geological conditions" (Thorhallsson and Sveinbjornsson 2). There is constant scrutiny of the quality of the work performed, but certain complications are more difficult to guard against.

Government Subsidization and Intervention

Various steps have been taken over time, both to promote but also regulate geothermal energy in the United States. The interaction an industry has with the government will always have an impact on the way it runs. For geothermal, both positive and negative impacts can be observed.

One of the ways regulations have been implemented is through the process of the requirement to prepare a Categorical Exclusion (CE), Environmental Assessment (EA), Environmental Impact Statement (EIS), or a Finding of No Significant Impact (FONSI) if a geothermal plant is to receive any government funding or be permitted by a federal agency (Lund et al. 2) For an energy sector like geothermal, where government subsidization is often a large part of the success of the project, additional reporting requirements have a large impact on the process.

The requirements add to the administrative burden associated with the project. According to Lund, "For geothermal projects, the EIS can require considerable time and funding to complete and is often contested, causing additional delays" (2). These regulations can add to the obstacles in geothermal and may be discouraging to investors, though these measures are for environmental protection purposes.

Government promotion of geothermal energy first occurred in the late 1960s and early 1970s, with the first act to "establish a legal framework for leasing, exploration, and development of geothermal resources" being the California Geothermal Resources Act of 1967. In this act, various policy issues are addressed, such as ownership of resources, operational regulation, taxation, and others. Notably, the federal government also arranged programs for risk reduction and subsidization of geothermal, one of the most ambitious being the American Recovery and Reinvestment Act of 2009 (ARRA). The ARRA provided "90% of the total aggregate project cost providing that the applicant was an electric, housing or other cooperative or municipality" and was capped at $100 million (Lund et al. 5)

The Costs of Geothermal Energy

The drilling costs associated with geothermal energy are a much riskier investment than drilling for oil and mining other fossil fuels. These costs are also higher than the initial costs of oil drilling (see figure 5) and often account for as much as 60% of the entire capital investment for a geothermal power plant, while other sources of electricity have capital investment costs that are not as proportionally large (Blankenship et al.).

According to a cost analysis study on well drilling done by the Massachusetts Institute of Technology Chemical Engineering Department, "[The] cost of drilling and completing [hydrothermal] wells is considerably more expensive than for oil and gas wells over the depth intervals considered." The total costs of exploration and construction can sum up to $7 million, which constitutes half of the total expenses (Igwe 661). Because these large investments are required upfront, thorough analysis (like ample environmental research) is needed to determine whether the operational benefits of geothermal outweigh the sizeable upfront investment costs.

To make good comparisons involving the costs of energy sources, the Levelized Cost of Electricity (LCOE) must be understood. LCOE is the most widely used reporting measure. According to the U.S. Department of Energy, the LCOE "Allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities" (Energy.gov). This calculation determines the present value of all the costs to be incurred over the entire life of the project and divides that by the amount of energy. This calculation ideally produces

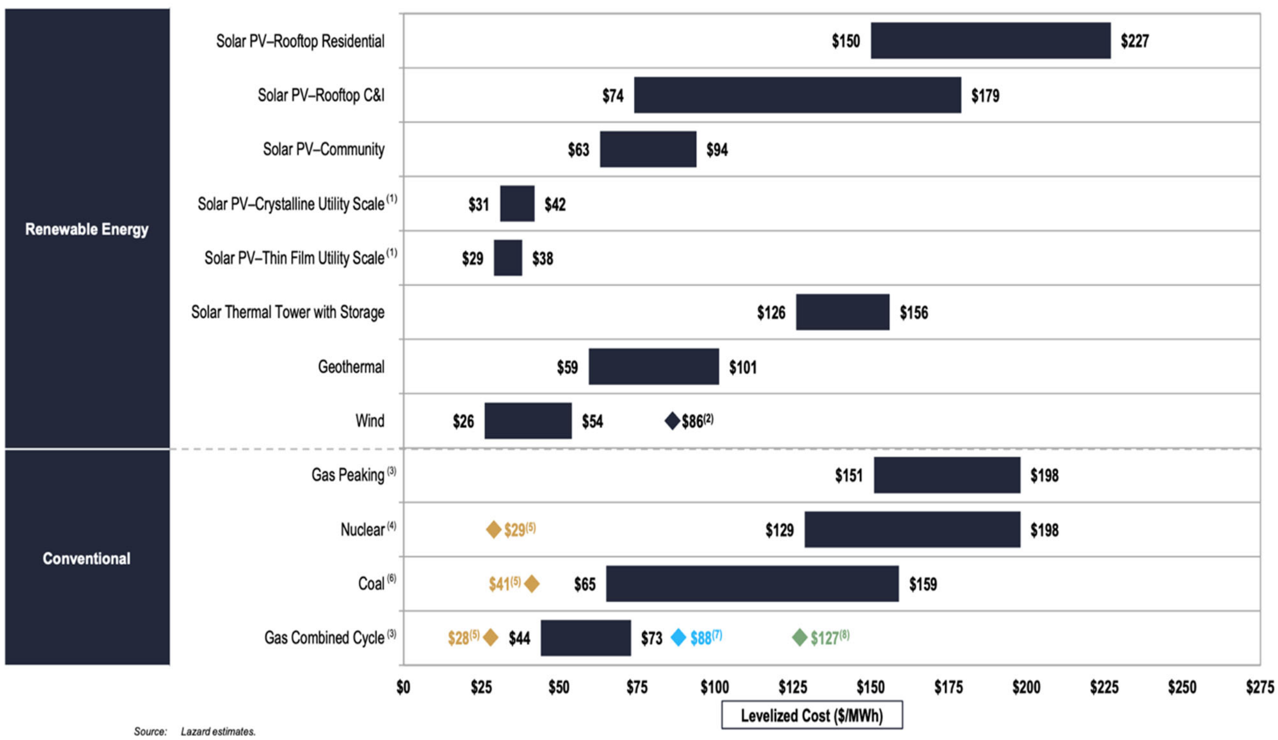

Figure 5, Comparison of the Levelized Cost of Energy for selected energy sources, categorized as Renewable Energy or Conventional Energy.

“Levelized Cost of Energy Comparison- Unsubsidized Analysis”, *Lazard’s Levelized Cost of Energy Analysis – Version 14.0,* Lazard, 2020

a per-unit cost for power (Lazard)

According to Lazard's LCOE unsubsidized analysis, geothermal energy ranges from $59-$101/MWh. The analysis divides the energy comparison into conventional energy sources and renewable energy sources, highlighting the importance of a technology's sustainability levels in cost analysis. When looking at the LCOE, geothermal energy seems to land around the center of the data. The most expensive type of energy is Solar PV-Rooftop Residential at $150-$227/MWh, while the least expensive is wind at $26-$54/MWh. Some alternative sources, like solar, contain large cost discrepancies between different versions of the technology. Because of these cost differences, a one-to-comparison is more difficult than a one-to-one comparison with, for example, coal which in the Lazard report has one LCOE calculation.

In China, as the country moves toward decreased reliance on fossil fuels in its Five-Year Plan, there has been a success with geothermal projects. However, geothermal plants are not economically feasible in China without government subsidization due to a combination of difficult working conditions and an overall lack of commercial sustainability (Zhang et al. 7).

The study surveying geothermal energy in China concluded that "considering its favorable environmental competitiveness, attractive subsidy policies, and the support of scientific research to continue technological innovations can help geothermal power become another valuable alternative to coal in China" (7). The situation in China suggests that there is a long way to go before wholly commercial geothermal production is feasible, but there are also promising characteristics to the project.

Throughout the world, other countries have also subsidized and promoted geothermal energy. Between 2015 and 2020, 1,159 geothermal wells intended for power generation were constructed in over thirty countries (Huttrer 1). This means there is a considerable amount of available data on the performance of these geothermal sites, including their investment return, costs and profits, and environmental impact.

Studying the cost of geothermal is necessary to weigh out all the components of an energy source decision but does not make up the whole of the decision. If energy sources were to be based solely on cost moving forward, much of the discussion of renewable energy might not take place. The factors discussed before, like environmental friendliness, sustainability, reliability, scalability, etc., all play a role.

Across the United States, there is an abundance of abandoned wells that were not properly disposed of and sit vacant today as a liability to companies who drilled them. According to Yong-Le Nian, "at least 1.2 million wells had been abandoned in the US in 1987" (1). Laws have since been put into place that prevents these wells from being abandoned without being plugged. The abandoned wells that were not properly disposed of in the past, estimated to be in the hundreds of thousands in the state of Pennsylvania, could potentially be transformed into geothermal source sites with some renovation (Carroll).

Using this type of equipment could drastically lower the cost of establishing a geothermal site, as much as by half, and clean up what is otherwise an abandoned site of unusable infrastructure with risk as a liability to the companies who hold onto them (Templeton 367). It would also contribute to solving the unintended waste caused by abandoned wells, which can release methane into the atmosphere and into the groundwater (Carroll).

Environmental Considerations

While geothermal energy is widely considered to be a very clean form of renewable energy, it is not without the capacity to harm the environment. Because of these risks, analyzing these potential effects is an integral part of improving technology, spreading awareness, and mitigating these adverse effects while the technology moves forward.

In the discussion surrounding geothermal energy, concern has been discussed about the high temperatures that make up the most fundamental aspect of energy production and play a part in affecting the quality of the soil. However, the impact is limited primarily to high-heat geothermal operations, as low heat does not disturb the microorganisms as severely.

In 2015, a study was conducted to observe the effect of various temperatures on microbial diversity at the Tengchong Geothermal Field in China. The results of this study found that "Microbial communities in high-temperature environments are often dominated by a few types of microorganisms and are often significantly less diverse than those in lower temperature habitats" (Li et al. 7). This suggests that there could be adverse effects occurring when soil is heated to a very high temperature. From a discussion on the relationship between microbial biodiversity and human health, "The diversity of microorganisms is critical to the functioning of the ecosystem because there is the need to maintain ecological processes such as decomposition of organic matter, nutrient cycling, soil aggregation and controlling pathogens within the ecosystem" (Panizzon 138).

As is the case with many different environmental components throughout the world, the health of the soil is directly related to the health of people around the plant.

However, this is likely a concern with any large-scale construction or high-heat process and is not uniquely applicable to geothermal.

The air quality of a geographical area has a significant and direct impact on the lives of all the organisms living around it. A geothermal plant had a measurable effect on the air in the form of emissions, though an important question is how these emissions compare to the levels that would be produced if other forms of energy production were used. Over time, technological advancements have created a lot of growth in the efficiency and cleanliness of geothermal processes, so the impact these advancements have on the atmosphere depends on several plant-specific factors.

One example of advancement is that modern geothermal plants have fewer emissions than older plants and fewer undesirable effects. One noticeable impact caused by older geothermal plants that required a constant release of steam was that they had the power to change the cloud and weather patterns in the area it was located. The intensity of these effects depended on the local topographic and meteorological conditions, but these effects on the weather are not favorable (Dhar 8).

There are still emissions from geothermal sites, but fossil fuels, which are currently the primary source of energy, are more harmful in comparison. Data from the International Geothermal Association (IGA) indicates that geothermal plant CO2 emissions average 122 g/kWh, which is lower than that of fossil fuel power plants, and according to Dhar, "These values are considerably lower than CO2 emissions of fossil fuels such as natural gas (~550 g kWh-1), coal (994-1130 g kWh-1) and oil (~758 g kWh-1) power plants."

According to a report published by the U.S. Department of Energy, "[greenhouse gas] emissions that exist for renewable systems tend to be dominated by plant construction, although flash geothermal emissions are primarily attributable to fugitive [greenhouse gases] from the geofluid during the plant operation stage of the life cycle." Greenhouse gas emissions are produced in much more significant quantities because of burning fossil fuels as compared to geothermal and many other renewable energy sources (Sullivan et al. 40).

Studying the Geothermal District Heating Plants in the Polish Lowlands or Podhale region in Poland provides an additional example of the improvement that geothermal plants have over the emissions put out by alternative fossil fuels. The carbon dioxide emissions were decreased by 530 thousand tons within a span of twenty-five years (Sowiżdżał 112). Overall, evidence on what harmful emissions are released by geothermal indicates that it is still a considerable improvement over the emissions produced by fossil fuels.

Water use is important for both the construction and operational stages of geothermal production. The amount of water necessary varies between projects depending on different factors, including the type of geothermal plant, scale, water availability at the site, temperature, etc. (Dhar 11). In conventional geothermal sites, there is usually a pre-existing body of water, which would decrease the amount of water to be added to the process. However, despite the high involvement of water in geothermal, the requirements are an improvement on some other technologies.

According to the Office of Scientific and Technical Information within the U.S. Department of Energy, "geothermal power plants consume less water per kilowatt-hour of lifetime energy output than other electric power generation technologies." The highest water consumption rate, measured in gal/kWh, is Carbon Coal, which uses over one gal/kWh, while Flash Geothermal and Wind both measure at 0 gal/kWh for operation. Some types of geothermal energy require more water, with the highest being EGS at about an average of 9 million gallons a day (Clark et al. 13). The decrease in water usage from the most demanding electric power generation method to geothermal is by half.

There are a variety of available recommendations for reducing the amount of water usage, such as re-using water, evaluating the sources of consumption, shifting water sources, and opting for systems that are more water-efficient from the beginning of the project (Clark et al. 50).

The amount of water used in the geothermal process is not the only concern related to water usage in the process. In a report on water use in geothermal systems, Clark states, "comparison of the geofluid composition with U.S. drinking water standards concluded that geothermal waters pose a large potential risk to water quality if released into the environment, due to high concentrations of toxics including antimony, arsenic, lead, and mercury." These dangers point to concerns about how geothermal operations affect the water already in use and whether it is adequately contained to prevent contamination.

The need for proper due diligence by construction crews and planners when considering this containment is another example of the meticulous nature needed in the geothermal plant process and why it is often risky and difficult to predict. Clark adds to the discussion on contamination, "the risk of release can be virtually eliminated through proper design and engineering control" (Clark et al. 50). As with other components of geothermal energy, water use efficiency may be improved further with the quickening advancement of technology.

Production Capacity Advantage

While the focus lies a lot in the environmental harm reduction perspective of green energy, it is essential to consider how functional it could be for people in their everyday lives and the efficiency with which it will meet their energy needs. One significant concern about alternative green energy sources such as wind or solar power is the reliability of power generation and situations where rationing may need to occur as a result. For example, in periods where there is consistent cloud cover, it might not be feasible to rely on solar energy continuously. Similarly, if there is not an abundance of wind, it would not be functional for the people who rely on wind energy. Perhaps one of geothermal's most important but less often considered advantages is its ability to run consistently around the clock for much of the time, which allows for a significant decrease in the number of interruptions in the power supply (Dhar 3).

As mentioned previously, this advantage is seen playing out in the Geysers in California, which do not have the same fluctuations in availability as other environmentally friendly resources ("Geothermal Electricity Production Basics"). The situation is similar when looking at the Cerró Pabellon plant site, which has provided the Chilean community with consistent electricity that does not rely on the patterns of weather ("Climate Investment Funds").

Disadvantages of Geothermal Energy

In the available literature, some critical analyses of geothermal emphasize the scarcity and erratic placement of the geothermal heat, as well as inaccessibility at some depths (Azarpour et al. 317). However, the increasing pace of technological development within the geothermal field may allow for seemingly unconquerable barriers like challenging or erratic locations to become less restrictive to growth and development. This type of rapid improvement can be exemplified in the rapid invention and adoption of EGS and its ability to access geothermal resources that were previously thought to be entirely out of reach.

As discussed previously, decreasing the investment riskiness plays an essential role in geothermal gaining widespread traction. The components that go into investment riskiness encompass most of the process, including preliminary research and testing, construction, and operation and maintenance.

One unique risk to geothermal energy is that no two geothermal fields are the same. This lack of uniformity makes it more challenging to understand and quantify the risk. The Kenyan geothermal field Olkaria is proof of this lack of uniformity. In this geothermal location, different areas within the same field exhibit different characteristics like chemistry, output, and drilling challenges (Ngugi 2). The high levels of variation as well as the combination of many variables in measuring the conditions of a geothermal site contribute to the need for such complex assessment procedures as the ones discussed previously, such as the Geothermal Response Test and AI implementation.

A broad, summarizing perspective on the most significant challenges to geothermal energy lends to the conclusion that a substantial portion of the hesitation from potential investors in development is tied to its ability, or lack thereof, depending on the data, to generate a profit without subsidies. The comparatively environmentally friendly nature of geothermal has its array of benefits. However, the motives involved for the potential investors are not as likely to be well aligned with the environmentalist perspective. According to Ngugi, "the overarching goal of a geothermal development is the successful implementation of the project that will generate a good return to its owners, as well as meeting its other financial obligations." The technologies being intermingled with geothermal to improve the process will be the way for investors to feel more confident.

Final Discussion

In surveying the overall state of the geothermal energy process and its standing in the search for alternative energy sources, it seems there are a few significant and fundamental challenges to the technology that must be overcome to compete with alternative environmentally friendly resources. However, there is ample precedent for success and growth in the geothermal energy sector. In 2022, as more people are looking toward clean energy efforts, there is more discussion and interest in geothermal investment. A portion of the increase in interest may be attributable to the growing popularity of integrating AI into many different types of processes to maximize efficiency however possible.

Progress made with EGS, as seen at Cerró Pabelon and other geothermal sites, is one example of the use of technology to improve geothermal capabilities ("Climate Investment Funds"). The demand for energy is increasing, and this trend is considered unlikely to reverse for a long time, giving these technologies growing importance (“World Energy Outlook 2022”). As reliance on energy increases, researching and advancing environmentally conscious ways of harnessing energy is the only path to implementing a sustainable solution to meet the demand.

Geothermal energy, in some cases, has a higher LCOE than wind and solar, but other advantages of geothermal play a role in the analysis (Lazard). The minimal interruptions in operation and minimal environmental effects are two of the biggest advantages. While wind and solar may provide more cost efficiency in some circumstances, their ability to generate power is inconsistent. The power generation from wind and solar is also dependent on uncontrollable conditions like weather. In the big picture, these technologies will likely all play a role in cultivating a sustainable and reliable energy system for the future.

Whether geothermal energy is one of the right paths for long-term investment depends on its ability to grow and overcome the challenges with profitability and riskiness. These two factors relate strongly to each other. Government subsidization has been one of the solutions to this problem, as seen in China. However, this subsidization does not provide the same level of scalability as commercialized energy sources and is still risky for those who are paying.

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