Geothermal

An Overview of Critical Factors for Energy Resources

Introduction

America generates energy from a number of sources, but at its most basic level, each method turns a turbine to generate electricity. That power is then fed into the electrical grid to be distributed to homes and businesses. America consumes around 4 trillion kilowatt hours (kWh) of electricity per year. The energy mix to generate this electricity is a blend of public policy and private action. Geothermal was used to generate 0.4 percent of America s electricity in 2023. Geothermal heat-pumps are also used for residential and commercial heating, and its market share is increasing steadily in the United States.

This policy brief will outline eight key factors that shape the current and future utilization of geothermal for American energy needs. To help build a comprehensive picture of geothermal's energy outlook, this brief will examine its energy density, costs to generate energy, availability and reserves, land needed, overall safety record, climate impact, long-term impact, and potential limitations of the energy source.

Basics of Geothermal

Geothermal collects heat energy from underground, typically through pipes of water/steam, and converts it into electricity. Geothermal energy is naturally occurring within the Earth and can manifest naturally on the surface as hot springs and steam geysers. Humans have been utilizing geothermal for millennia for heating and bathing. Today, the geothermal energy industry is expanding, and utility-scale geothermal power plants are being added to the grid every year.

The process of harnessing geothermal energy uses the same concept as most generators: turning a turbine. For utility-scale power generation, cold water is first pumped underground into hotter subsurface areas, sometimes thousands of feet deep. There, the water will be heated up naturally by the earth. Geothermal is utilizing the heat of the Earth's core, the same heat that is responsible for tectonic shift and volcanoes. After the water is heated underground, a production well pumps the hot water and steam back up, where it is used to push a turbine, generating electricity.[1] The steam is collected and cooled back into water before being pumped back down in the injection well once more.

Geography is a limiting factor of utility-scale geothermal power. Geothermal energy requires abundant heat underground that must contain the right amount of rock permeability to allow water to pass through.[2] For these reasons, most utility-scale geothermal energy is located around tectonic plate boundaries, where earth's crust is thinner, and heat is easier to access. Sometimes underground reservoirs can be created in areas where rock permeability is not ideal, but this is also dependent on geography.[3] Over 92 percent of U.S. geothermal energy comes from California and Nevada, with the remaining power coming from Utah, Hawaii, Oregon, Idaho, and New Mexico.

Geothermal heat applications are much more common and are less constrained by geography. Worldwide, geothermal heating is used in various commercial, industrial, and residential applications. Residential heat pumps are becoming increasingly popular in the United States, where a system can save money compared to traditional electric or gas heating.[4] Heat pumps currently make up less than one-fifth of all space-heating systems in the U.S., but are gaining popularity, particularly in the South.[5] However, this paper focuses geothermal electricity generation.

1. Energy Density

The energy density for geothermal is highly variable, depending on the process and geography. Steam is the primary variable pushing the turbine, but ultimately the energy is coming from the heat of the earth. This makes measuring energy density difficult, as volume of water/steam does not directly correspond to the amount of electricity generated, especially between different types of geothermal systems. Geothermal power plants have different processes, depths, temperatures, and amounts of energy generated. A 2008 paper examining energy densities of various energy sources in Joules per cubic meter put geothermal energy at 0.05 joules/m^3.[6] In kWh, this is 0.0000000139, or a little more than one hundred-millionth of a kilowatt-hour per cubic meter. This seems like very little, but geothermal power plants can use thousands of cubic meters of hot rock underground, and it is more energy dense than solar power.[7]

In 2023, 16.462 billion kWh (16.462 TWh) of electricity was produced at utility-scale geothermal facilities. There are approximately 93 utility-scale facilities in the U.S., though numbers vary depending on what qualifies as its own facility.[8, 9] That means the average geothermal plant may produce around 177 million kWh of electricity annually.

To picture the energy density of geothermal power, consider how many plants it would take to power a modern house. The average U.S. household consumes 10,649 kWh of electricity per year.[10] To run the average household for one year using the national average for utility-scale geothermal plants, it would take 0.00006016 of a power plant.

2. Cost

Geothermal energy has a very large capital cost, around $3,000 per kW, but has low operating costs.[11] For reference, solar and wind have capital costs of around $1,300 and $1,700 per kW respectively. The sizable start-up costs have contributed to less investment in geothermal energy compared to other renewables. Despite high initial costs, operational costs of geothermal are quite low, and the unsubsidized levelized cost of electricity (LCOE) is around 7 to 8 cents/kWh.[12] The EIA estimates that by 2027, new geothermal will be dispatched for a highly competitive 4 cents/kWh, similar to solar, natural gas, and wind power.[13]

Current operation and management costs (O&M) are very low, with no commodity-based fuels needed besides water to turn into steam. The amount of water used per kWh is between 0.01 and 0.72 gallons, depending greatly upon the type of power plant.[14] Most of the water is continuously reused in closed-cycle power plants, meaning that water usage is significant but not unusual compared to other steam-based power plants. Other low-temperature plants actually don't use water at all, but a separate special organic fluid in a closed cycle.[15] Overall, O&M costs are typically around 1 to 3 cents/kWh.[16]

At 3.96 cents per kWh, by 2027 it would cost $421.7 per year to power the average U.S. household with geothermal. Or an estimated $905.17 if using 2024 LCOE of 8.5 cent per kWh.

3. Availability and Reserves

The availability of geothermal for utility-scale generation is highly dependent on geography. This makes the western United States the ideal spot for geothermal, with utility-scale generation impossible or economically unviable in the large portions of the central and eastern U.S. Additionally, geothermal generators cannot be placed anywhere in the west and require specific site selection within the region itself as well, not unlike geological surveying for oil and gas. However, other users of geothermal energy, such as heat-pumps, can be utilized in many places in the U.S. and are commonly found nationwide.

Geothermal is a truly renewable energy source. The earth's mantle comprises dense molten rock under enormous pressure that continuously releases heat. This heat will never be depleted by humans due to the decay of radioactive particles producing more energy.[17] Geothermal energy has the added advantage of complete reliability and not relying on weather conditions like solar or wind.

Currently just seven states have any installed geothermal capacity for energy generation. A few more, such as Alaska and Texas, may be able to utilize geothermal in the future, but there are no definite plans yet.[18]

4. Land Required

Geothermal energy generation is extremely space efficient, requiring far less land than most other forms of electricity. A study found that geothermal energy takes up a median of 45 ha/TWh/y.[19, 20] A hectare is roughly the size of a track field and surrounding spectator stands, and 100 hectares make a square kilometer. In other words, geothermal takes up 0.45 km^2/TWh/y. According to the study, geothermal has less of a land footprint than any other energy source besides nuclear. Including the spacing and ancillary facilities, natural gas and wind have a land use intensity of 19 and 120 km^2/TWh/y respectively.[21]

Geothermal facilities take up little land, especially relative to their generating output. This is because the above-ground footprint is much smaller than the space needed underground. However, the extreme depth required ensures that the actual land-use footprint is quite tidy. Geothermal plants are normally located on mountainous and rural land, coming with advantages and disadvantages. About 40 percent of geothermal energy production is produced on Bureau of Land Management land, and the National Forest Service also leases land to geothermal energy producers.[22, 23] The BLM manages over 800 geothermal leases, though most are not in production. The federal government owns roughly 46 percent of all land in California and nearly 85 percent in Nevada, the two biggest geothermal energy producers.[24]

As of 2023, there are approximately 93 geothermal energy facilities producing a combined 16.462 billion kWh of electricity.[25] There are no exact publicly available figures regarding the total amount of land used for utility-scale geothermal facilities, but using the median figures from the land use-intensity study we can infer there is around 1,785 acres of land used for geothermal energy production.[26] This acreage is very similar to other estimates from the DOE.[27] Geothermal is very space efficient and only produces a meager 0.4 percent of the nation's electricity. Therefore, a direct energy production to acre land intensity would be 9,222,409 kWh/acre.[28]

In order to power a single average U.S. household for a year with geothermal, 0.0012 acres (above ground) are needed, or 4.67 square meters.

5. Safety

Various reports comparing the fatalities per unit of energy produced consistently rank renewable energy sources as safer than traditional sources, but geothermal is such a small share of the grid that there is limited accident data in the relatively nascent industry. However, a 2021 study concluded that geothermal energy systems will have accident and fatality rates somewhere between offshore wind and solar PV.[29] In other words, geothermal energy is one of the safer forms of electricity, and it has almost no polluting waste product.

Risks still exist for geothermal safety, and accidents can occur during the drilling process or when dealing with the pressurized steam pipelines. Fatalities and serious accidents have taken place both domestically and internationally.[30, 31]

Geothermal has come under fire for another safety concern: earthquakes. Geothermal energy projects can cause earthquakes by the movement of steam through the rocks, slightly destabilizing it.[32] Most of the earthquakes are extremely minor, but earthquakes as large as magnitude 4.5 have been recorded in California. That is not to say that geothermal is entirely responsible for these earthquakes, as there are normally over 10,000 earthquakes every year in California.[33] There is active research on the link between geothermal energy and earthquakes, and many believe that it is a problem that can be overcome. The pumping of fluid underground during oil and gas extraction has also been shown to cause minor earthquakes.[34]

A lack of data makes calculating the total casualty rate for geothermal power per unit of energy produced difficult to state conclusively. It is believed to be comparable to other renewable sources and therefore very low.

Based on studies and drawing on international statistics, deaths from powering the average U.S. home for a single year with geothermal would be around 0.000000016 deaths per year. Inclusion of injury incidents would make a marginal though not significant increase.

6. Climate Impact

Geothermal is a renewable and extremely clean source of energy, but it technically does not have zero-emissions. Very small amounts of hydrogen sulfide, carbon dioxide, ammonia, methane, and boron can be emitted from open-loop geothermal systems.[35] The amount released is magnitudes smaller than coal-powered plants, and the majority of geothermal power plants are closed-loop.

In a modern open-loop system, the operating carbon emissions are estimated at about 45g CO_2eq/kWh, roughly one-tenth that of natural gas.[36] In a closed loop system, there are virtually no emissions other than during the construction process.

Other environmental concerns with geothermal power include location, water use, toxic emissions, and drilling.

As mentioned, geothermal plants often require large amounts of water, and even closed-loop systems can have water loss over time.[37] This can be an issue in the west, where water is a precious resource.[38] The remote locations of most geothermal sites means that development into areas of wildlife may also be required. Isolated locations can result in longer transmission infrastructure, which brings further development into remote natural forests and mountains.

Some open-loop geothermal systems can result in significant mercury emissions into the environment.[39] Mercury and other heavy metals can be extremely toxic and cause environmental damage. These unwanted emissions can be collected using scrubbers, but the captured materials must be properly disposed at hazardous waste sites.[40] The complicated drilling process during construction of a geothermal power plant has also been cited as a possible environmental concern. Drilling can release underground emissions and the process can be damaging to the surrounding landscape.[41]

The National Renewable Energy Laboratory (NREL) estimated the lifecycle emissions of three different forms of geothermal, concluding that all forms had median total emissions below 50g CO_2eq/kWh.[42] The overall average between all forms (adjusting for number of facilities) is 31.1g CO_2eq/kWh.

Emissions generated to power a single American household from geothermal would total 730.7 pounds of carbon dioxide per year.

7. Long-Term Impact

As discussed, the major long-term concerns for geothermal are the issues from the remote location and possible earthquake problems. Isolated locations of any power plant present extra challenges for operating costs, construction, and transmission infrastructure. Renewable power projects across the nation often get stuck in long queues to determine if the project is viable and available to hook up to power.[43] These queues can last years and have a huge impact on grid expansion.

The geothermal plants themselves are relatively low maintenance and can last several decades if properly maintained.[44] Some may last 20 years, while others can last upwards of 50 years. The applied technology is still relatively new, so new advancements and mechanical replacement of older parts may extend the lifespan ever further.

Geothermal does not generate significant greenhouse gas emissions, but development into previously wild and remote areas can contribute to habitat destruction and ecological damage.

8. Limitations

Despite a decent amount of media attention, the share of geothermal energy has not increased significantly in the U.S. since the 1980s.[45] This is due to a multitude of reasons, including a lack of supporting policy, the high up-front capital cost, and geographic challenges.[46] More than 80 percent of the U.S. population lives in the eastern half of the nation, so development of energy resources that can only be used by a fraction of the population gets less attention than other renewables. Private investment into geothermal has also been nowhere near the level as wind and solar. The high upfront costs of geothermal can be seen as riskier by investors, and the extreme site-specifics can add complications to installation.[47, 48] Maintaining a geothermal generator is relatively easy, but the construction is a demanding and highly technical process. Solar and wind technologies are far more straightforward and less complicated.

A serious limitation of geothermal power is the location requirements. Utility-scale geothermal power is only possible in the western United States, and often in mountainous and remote areas. Like the expansion of other renewables, outlying geothermal power plants will need transmission connections that can take years to complete.[49]

Technological progress is also needed to utilize geothermal to be economically competitive with gas and other renewables. Currently geothermal power LCOE is not expensive, but it is not as cheap as other sources either. Despite humans using geothermal energy for thousands of years, utility-scale electricity generation technology is still in its infancy. Research on the severity of geothermal-caused earthquakes and if they can pose any danger to nearby population centers needs to be studied thoroughly.

Unlike other renewables, geothermal power is not reliant upon weather conditions for generation, but it does come with slightly higher lifetime emissions compared to wind and solar.[50]

Conclusion

Geothermal is an exciting renewable energy source that has inherent advantages over other renewable energy technologies. Its reliability compared to other renewables should make it extremely desirable, yet expansion has been sluggish over the past several decades.

Despite these challenges, geothermal knowledge and expertise is constantly improving, and the industry is still projected to grow significantly in the coming years.[51] The low emissions combined with constant power production may become more valuable in the future as reliance on energy storage increases from other renewables.[52] The benefits of geothermal are evident, but it still has challenges to overcome before it can become a foundation of the energy grid.

Citations and Notes

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