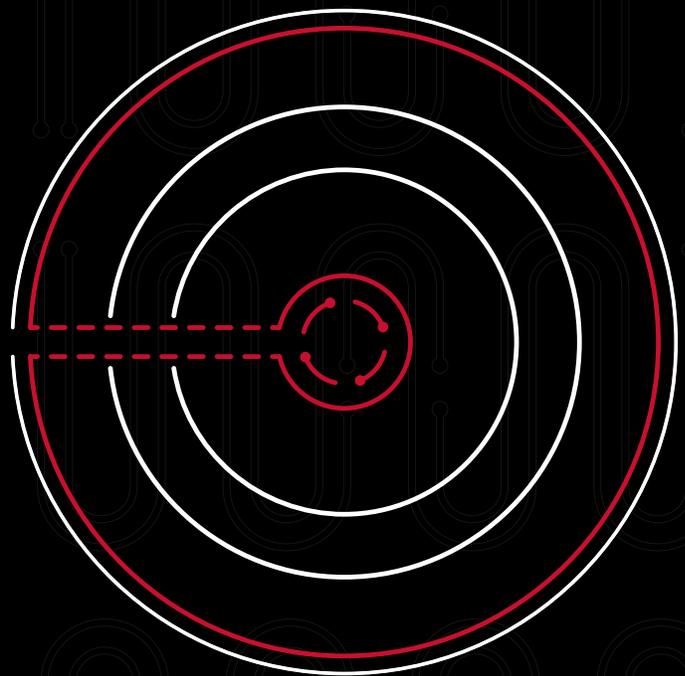


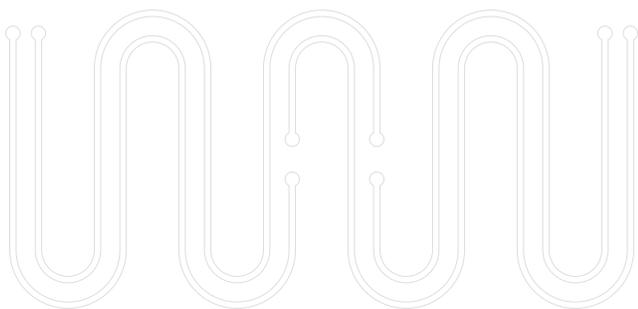
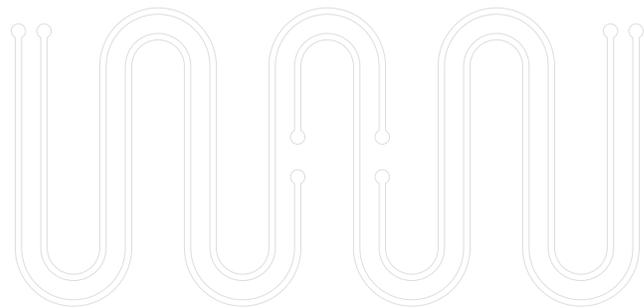
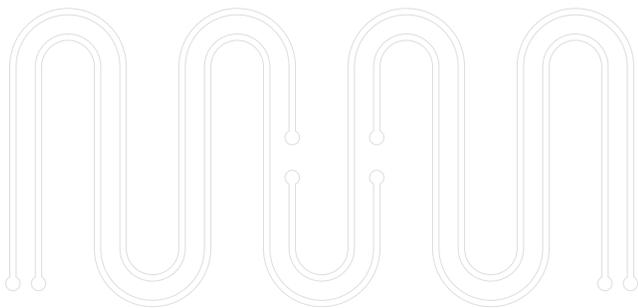
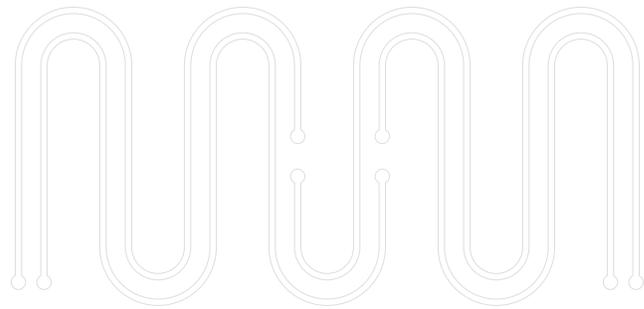
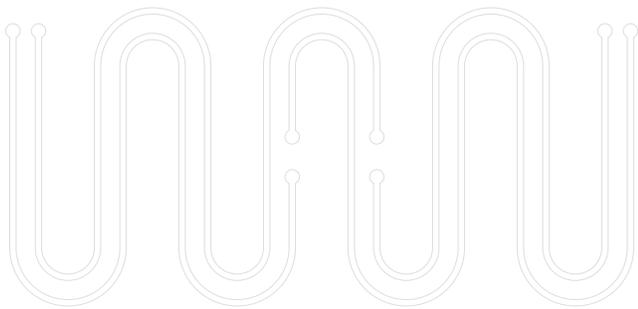
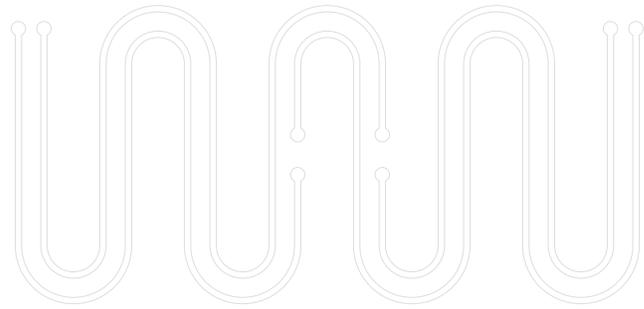
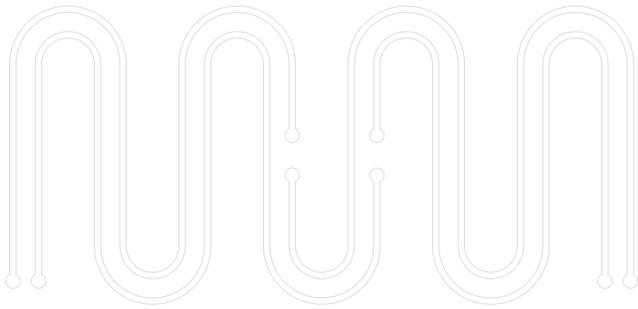
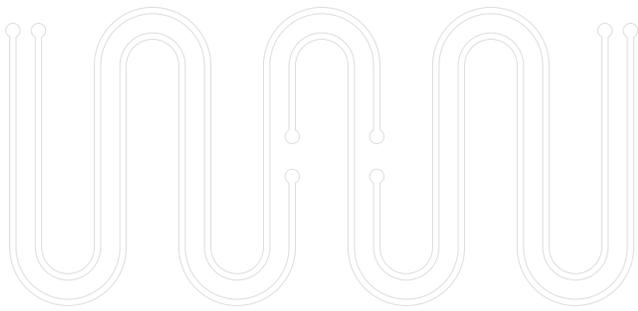
Advanced Geothermal

Opportunities and
Challenges



UH Energy
UNIVERSITY OF HOUSTON

White Paper • February 2026





About

About the Author

Greg Bean is Executive Director of the Gutierrez Energy Management Institute in the Bauer College of Business at the University of Houston. In this position, he is responsible for energy-related curriculum, student experiential learning, research, industry events, and industry outreach at Bauer. He is also faculty director of the Master of Science in Global Energy Management degree program and an adjunct faculty member. His teaching and research focus on the transition to a sustainable energy system. Greg has more than 40 years of energy-related experience in industry, management consulting, and higher education.

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Executive Summary

Electricity demand is expected to skyrocket over the next few decades, with much of the growth driven by energy-intensive artificial intelligence and data centers.

Overall, Grid Strategies projects that peak electricity demand in the U.S. will grow by 166 gigawatts over the next five years alone, a 3.7% annual growth rate. Average electricity usage is expected to grow even faster, 5.7% per year over the next five years,¹ boosted by not just the growth of data centers but also the increasing electrification of everything from vehicles to industrial processes (Figure 1).

Much of the demand may initially be filled by a mix of natural gas, solar, and wind, but a growing desire on the part of consumers for low-carbon and firm electricity generation suggests an opening for a century-old technology, updated for the 21st century.

Advanced geothermal energy is well positioned to meet future energy needs. In fact, the U.S. Department of Energy (DOE) projects U.S. advanced geothermal power generation could reach 90 gigawatts by 2050,² 20 times the capacity of existing geothermal power projects. Advanced geothermal also has significant potential for building heating and cooling, with the DOE noting that the technical potential for geothermal heating and cooling systems could equal power demand for about 80 million homes.³ From a policy perspective, geothermal energy is included in the Trump administration’s policy to support development of domestic energy resources and is one of three low-carbon energy resources included along with hydropower and nuclear.

Conventional geothermal energy has been exploited for more than 100 years, used directly to heat buildings or to generate electricity. However, its usefulness has been limited because it relies on a trifecta of subsurface resources that aren’t widely available: high temperatures near the earth’s surface, an aquifer, and naturally occurring fractures.

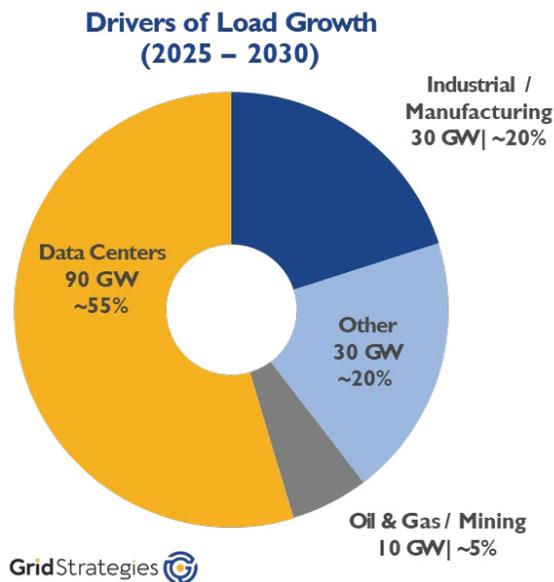


Figure 1. Drivers of Load Growth (2025–2030)

Source: Power Demand Forecasts Revised Up for Third Year Running, Led by Data Centers, Grid Strategies Nov 2025

Areas with the geographic criteria to produce conventional geothermal energy are concentrated along the “Ring of Fire,” a zone circling the Pacific Ocean that is home to most of the planet’s volcanic activity. Although just 10 countries account for 90% of the current global geothermal market, the industry is at a critical juncture. While the DOE conducted much of the early research on advanced geothermal technologies, a number of companies are now engaged in commercial-scale work targeting deeper, hot dry rock. That would allow for widespread deployment in the United States.



A recent symposium at the Gutierrez Energy Management Institute at the C.T. Bauer College of Business at the University of Houston explored the field and suggested key next steps. Among some of the findings:

- Geothermal could meet up to 15% of global electricity demand growth to 2050, if deeper resources can be accessed cost effectively and international markets expanded. This would mean the deployment of as much as 800 gigawatts of geothermal power capacity worldwide, equivalent to the current electricity demand of the United States and India combined.
 - On a global basis, solar is the only low-carbon energy source with a higher technical potential than geothermal.
 - Some advanced geothermal relies on technologies developed for unconventional oil and gas drilling, but there are critical differences, including the fact that geothermal operates at higher temperatures, imposing different design and materials requirements. Unconventional oil and gas wells have the advantage of pay out in one year or less and continue to produce at lower levels for many years, while geothermal wells will be required to operate over a period of 20 to 30 years at constant levels.
 - But their similarities suggest the oil and gas industry has transferable skills, data, technologies, and supply chains that would allow it to play a key role in boosting the cost-effectiveness of geothermal energy. Diversifying into geothermal energy could create new opportunities for the industry in the clean-energy economy.
- Making advanced geothermal economically viable requires overcoming significant hurdles, including developing tools that can withstand temperatures hotter than 250 degrees Celsius and pressures over 3000 psi. The development of high-temperature and high-pressure electronics and other tools is underway.
 - Building stable supply chains and streamlining permitting will present a challenge to establishing geothermal energy plants as well as to securing connections to the grid. In fact, connecting to the grid could take longer than building the plant. Co-locating with large power users, including data centers, could help.

The oil and gas industry has transferable skills, data, technologies, and supply chains that would allow it to play a key role in boosting the cost-effectiveness of geothermal energy.

Symposium Focus

The Gutierrez Energy Management Institute in the C. T. Bauer College of Business at the University of Houston held a symposium and workshop in November 2025 on the potential for advanced geothermal as part of the transition to a low-carbon energy system. The focus spanned key technologies, recent developments, key players, likely challenges, and the ultimate potential of advanced geothermal. The session included a keynote presentation, followed by panel discussions and small group discussions of key questions.

Participants included high-level energy executives, academics, and other energy thought leaders, with sessions conducted under the Chatham House Rule, used around the world to encourage inclusive and open dialogue in meetings. Its guiding spirit is to share the information received without revealing the identity of the source of the information or that of other participants.

This white paper is based on information from the symposium, along with additional research.



Geothermal could meet up to 15% of global electricity demand growth to 2050, deploying as much as 800 gigawatts of geothermal power capacity worldwide, equal to the current electricity demand of the U.S. and India combined.



Evolution to Advanced Geothermal

Conventional Geothermal

Conventional geothermal energy has been around for over 100 years, taking advantage of the earth's internal heat to produce steam or hot water from underground reservoirs in order to generate electricity or to heat and cool buildings directly via heat pumps.

However, conventional geothermal is limited, as it relies on a trifecta of subsurface resources not widely available. These include high subsurface temperatures relatively near the earth's surface, proximity to an aquifer, and naturally occurring fractures. The traditional approach involves drilling a well at one end of the reservoir in an effort to intersect fractures, drilling a second well at the other end to intersect the fractures, and then injecting water into the fractures, with the water heating up as it flows through and ultimately providing the power to spin a turbine and generate electricity.

But conventional geothermal systems work only in places where subsurface heat between 150 degrees Celsius and 200 degrees Celsius, along with permeable fractures, is found within four kilometers of the earth's surface.⁴ Moreover, geographic constraints aren't the only challenge to expanding conventional geothermal. It also has relatively high subsurface risk, with one of every three geothermal wells being typically unusable.

As a result, geothermal energy today makes only a small contribution to the global energy supply. In 2023, geothermal energy filled about 0.8% of global energy demand. Worldwide, geothermal-generated electricity accounts for about one-fifth of total geothermal energy consumption, with the remainder used for district heating and cooling for networks of residential and commercial buildings. The 10 largest producers of

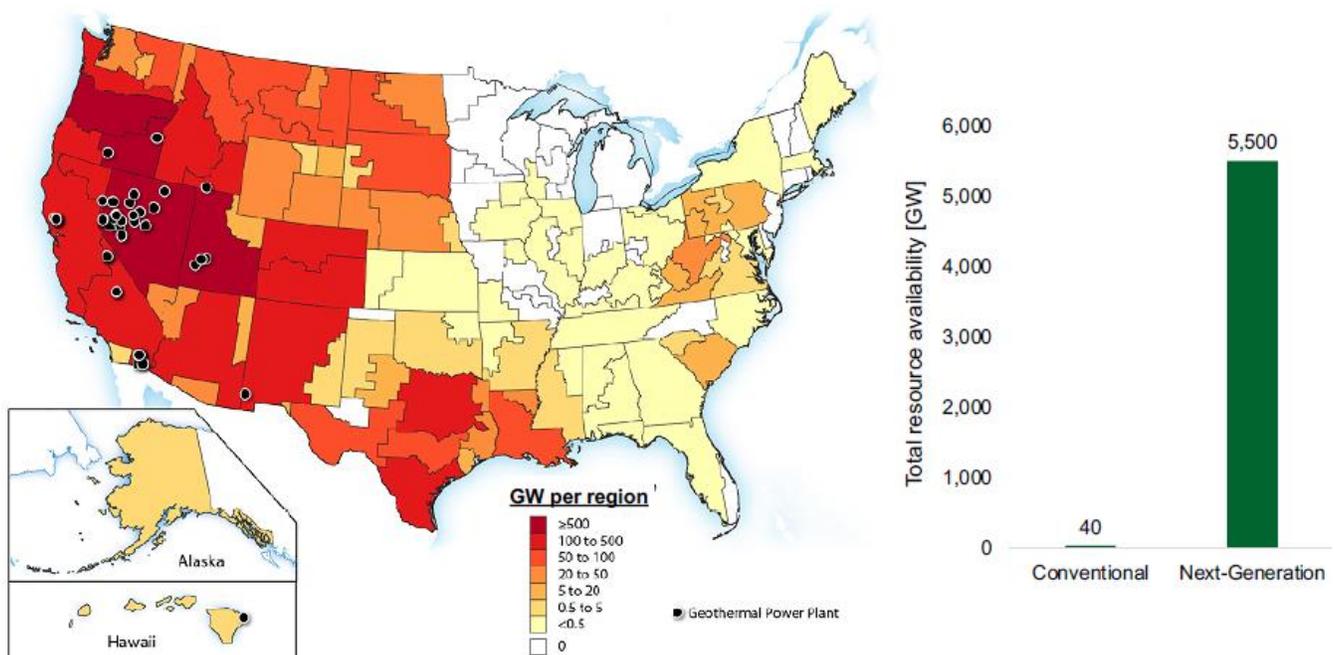


Figure 2. Conventional and Next-Generation geothermal systems in the U.S.

Source: DOE Pathways to Commercial Liftoff: Next Generation Geothermal Power

geothermal energy—China, the United States, Türkiye, Sweden, Indonesia, Iceland, Japan, New Zealand, Germany, and the Philippines—account for almost 90% of the global total. Geothermal penetration is highest in Iceland, meeting almost half the country’s energy demands due to the wide availability of geothermal resources and policies supporting continuous exploration, drilling, and project development since the 1920s.⁵

One company, Zanskar, is using modern prospecting methods combined with artificial intelligence to identify additional conventional resources that can be tapped and turned into electricity-generating plants using conventional technology. It recently announced the discovery of “Big Blind”, a naturally occurring geothermal system in western Nevada with the potential to produce more than 100 megawatts of electricity. It is the first “blind” geothermal system—meaning there are no visible signs of the underground reservoir, such as vents or geysers, and no data history from past exploration—identified for commercial use in more than 30 years.⁶

Advanced geothermal technology is needed to expand the use of geothermal energy beyond areas providing the conventional geothermal trifecta, which are concentrated along the “Ring of Fire,” a zone skirting the Pacific Ocean that is home to most of the earth’s volcanoes. Advanced systems target deeper, hot dry rock, which requires the developer to create an engineered, or artificial, geothermal system. An analysis of thermal gradients shows its widespread geographic potential in the U.S. (Figure 2). While the best advanced geothermal prospects are located in the western US, there are potential opportunities to eventually expand eastward into the south-central region (Texas, Oklahoma, Louisiana, and Arkansas) as well as the south and mid-Atlantic region (from the Carolinas to Pennsylvania).

Analogy to Unconventional Oil and Gas

To produce conventional oil and gas economically, three essential elements are necessary: a source rock with hydrocarbons, a migration path to a reservoir, and a trap to create that reservoir. Without these, conventional hydrocarbons are unrecoverable. Similarly, three elements are also required for conventional geothermal energy: an aquifer, permeability, and heat.

Unconventional oil and gas development started when horizontal drilling and hydraulic fracturing methods were developed to allow production of hydrocarbons directly from the source rock, without a migration path and a traditional reservoir. This allowed a significant expansion of onshore oil and gas production. Geothermal development faces a similar question of how to produce geothermal energy without an aquifer and without permeability. Advanced geothermal concepts focus on addressing this challenge.

Finally, the driver to minimize oil and gas production decline rates is analogous to minimizing the reservoir temperature decline in advanced geothermal.

Key Advanced Geothermal System Concepts

There are two main advanced geothermal system concepts (Figure 3). The first, commonly referred to as Enhanced Geothermal Systems (EGS), involves circulating fluid between well pairs connected through hydraulically fractured connections. In a Closed Loop System (CLS), fluid is circulated through closed loop wellbores that don't require hydraulic fracturing. Because it requires more piping and drilling, CLS is more complex and more costly. While most current work is focused on EGS systems, firms are pursuing CLS in regions where EGS is not an option, either because fracking is banned or water is scarce.

Core enablers of advanced geothermal include drilling, reservoir creation/fracturing, and heat extraction. In the last 10 years, several advanced geothermal technologies have evolved that aim to overcome the challenges of widespread development by allowing access to much deeper and hotter dry heat sources. Some leverage oil and gas drilling and completion technologies, while others depend on newer technologies.

In the last 10 years, several advanced geothermal technologies have evolved aiming to overcome the challenges of widespread development by allowing access to much deeper and hotter dry heat sources.

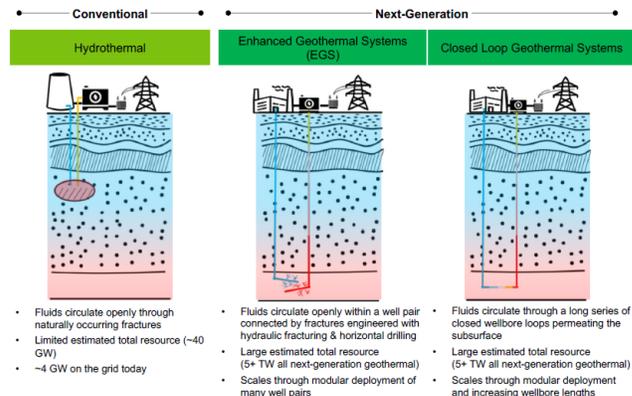


Figure 3. Conventional and Next-Generation geothermal systems

Source: DOE Pathways to Commercial Liftoff: Next Generation Geothermal Power

Much of the early research on advanced geothermal technology was conducted by the Department of Energy. The world's first hot, dry rock Enhanced Geothermal System project was the DOE project at Fenton Hill, New Mexico, which ran from 1971 to 1995. During this demonstration project, the Los Alamos National Laboratory created and tested two reservoirs at depths of 2.8 kilometers to 3.5 kilometers in crystalline rock formations underlying the Fenton Hill site.⁷ Today, the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a field-scale laboratory located in an unpopulated area of southwest Utah. Utah FORGE was established by the DOE to develop, test, and accelerate breakthroughs in technologies and techniques required for commercializing unconventional EGS resources.⁸ Many current advanced geothermal developers are leveraging the lessons from Fenton Hills and FORGE.

Leading Geothermal Companies and Progress So Far

Fervo

Fervo has taken a four-step approach to EGS technologies:

- Drilling vertically and then horizontally
- Hydraulically fracturing the rock to create a controlled, connected reservoir
- Injecting brine, which heats up as it flows through the fractures, and Bringing the brine to the surface to drive power production through an Organic Rankine Cycle (ORC) turbine.
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It's essentially a closed-loop, zero-emission system with a tightly connected fractured reservoir between the injection and production wells. The engineered fractures create strong connectivity so injected brine flows to the producer efficiently, with only a small amount of water loss to the formation. The geofluid heats a secondary working fluid that spins the turbine with brine re-injected. This isolates the geothermal brine from power plant equipment, preventing contamination, scaling, and corrosion, improving reliability and reducing maintenance needs for the turbine and surface facilities.

In 2023, Fervo ran a commercial pilot with Google called Project Red, the most productive EGS project to date. Fervo partnered with an underperforming conventional geothermal plant in Utah and agreed to drill the wells and sell the hot brine to the plant, assuming all risk. Google committed to buy all power produced in pursuit of its corporate zero-carbon goals. The wells achieved and maintained the predicted temperature. The pilot

project reduced risk, demonstrated the technology's scalability, and proved market demand. Project Red remains online with a stable temperature profile more than two years later.

Fervo made significant progress during the course of Project Red: the first two wells were drilled in 70 days and 59 days, respectively. To date, they have drilled more than 30 wells, with the fastest taking only 16 days. In all, Fervo has seen a 70% reduction in drill time and 50% reduction in drilling cost as the continuous drilling enabled rapid iteration and learning, accelerating the cost curve down.

Fervo is now developing its first commercial scale Cape Station project in Beaver County, Utah, with a target capacity of 500 megawatts. All power generated from the project is fully contracted under offtake agreements with utilities, although significant additional demand is emerging from hyperscale data centers as well. One of the key factors in pursuing the Cape Station location was proximity to the FORGE facility, located just 10 miles north of Cape Station. Fervo has been able to use FORGE well temperature data, seismic data, and other resources, which reduced financial risk.⁹

Fervo's pilot project with Google, called Project Red, reduced risk, demonstrated advanced geothermal technology's scalability, and proved market demand.



Quaise

Quaise's goal is similar to other EGS approaches, but at far hotter temperatures and greater depths. Reservoir contact at 425 degrees Celsius instead of 200 degrees Celsius increases power output nonlinearly as the water reaches a supercritical state, significantly improving its energy-carrying capacity. Doubling temperature can increase power output by a factor of 5 to 10. With the potential for up to 10 times more power from the same wellbore, the leveled cost of electricity decreases and project economics improve significantly.

However, drilling at these greater depths requires a breakthrough in drilling technology, as traditional drilling costs typically rise exponentially as well depth increases due to trip-out times for mechanical drill bits, among other factors. To go deeper and hotter, a drilling system that is impervious to heat and scales roughly linearly with depth will be required.

Quaise's solution involves microwave drilling, an approach employing high power, high frequency microwaves to dielectrically heat and vaporize rock. The microwave source sits on the surface, with only a transmission line downhole and no rotating mechanical bit. Microwaves exit at the bottom of the well, heat/vaporize the rock, and purge gas blows ash up the annulus. So far, Quaise has demonstrated the drilling technology at depths greater than 100 meters at a granite quarry in Marble Falls, Texas.

The microwave units are 40,000 times more powerful than a kitchen microwave. The technology originated in fusion experiments at the Massachusetts Institute of Technology. Significant engineering integration was required to adapt the lab systems for harsh field conditions (thunderstorms, snow, hot subsurface environments). The system is now fully integrated into

a standard oil and gas drilling rig to leverage existing supply chains and labor.

Quaise's first commercial project is underway at Newberry, Oregon. The Newberry Complex is a dormant volcano set aside in the 1980s for geothermal development because of its very high geothermal gradient (~100 degrees Celsius per kilometer). While not suitable for conventional geothermal with no suitable aquifers, it is ideal for accessing superhot dry rock. A flow test of a 350 degree Celsius reservoir is planned for the third quarter of 2026. Development is planned for a lease position on the south side of the complex with 50 megawatts under offtake, expandable to one gigawatt.

The well design will use a deviated system. Pure horizontals are an oil-and-gas requirement for thin target zones. For deep hot rock, deeper generally means more power, so horizontals aren't required. Optimal well deviation is around 30 degrees–45 degrees, balancing increased power with depth against lateral exposure, consistent with the DOE's Fenton Hills project findings.

The subsurface concept is to drill an injector and stimulate (fracture) across it, then drill a producer well and circulate water through the reservoir. Quaise reports that it expects significantly lower reservoir leak off compared to traditional systems. The surface concept is initial 50 megawatts via an Organic Rankine Cycle (ORC) to minimize operational risk for investors. At higher completion temperatures of between 315 degrees Celsius and 437 degrees Celsius, water to water heat exchangers become most efficient, enabling use of mature HVAC/refrigeration and broader industrial supply chains. This improves scalability compared to niche geothermal equipment markets, which have limited supplier depth.¹⁰

Sage Geosystems

Sage is focused on harnessing mechanical pressure to create a big underground energy storage system with several times the energy density of pumped hydro plants. Sage, which has a deal to supply power to Meta’s data centers, built an energy storage project that has demonstrated the ability to store and release three megawatts of power to the Texas grid; it is set for further expansion.

The firm has drilled about three kilometers deep and fractured the rock to create an underground reservoir. Through a drilled well, water is siphoned from a surface pool and stored under high pressure underground. The well is opened back up when power is required and, thanks to the rock’s natural inclination to close the fracture, the pressurized water moves to the surface. There, it turns a turbine to produce electricity. This “lung”, as the firm calls it, can store power for much longer than lithium batteries and can discharge electricity over a period of four to six hours, compared to the usual two-to-four-hour discharge cycle for lithium-ion batteries. Because Sage’s main hardware costs are fixed, unlike the additive costs of battery blocks, the cost per unit of stored energy drops the longer the system runs. By making electricity generation flexible, this technology could potentially significantly increase the value of the stored power by storing cheap solar power and selling it at a higher price during peak demand periods. This could be especially valuable as grid backup versus costlier peaker gas power generation. Sage is also developing continuous geothermal power generation.¹¹

Eavor

Canada-based Eavor drilled two vertical wells in Germany, both 4.5 kilometers to 5 kilometers deep, linking them with a dozen horizontal wells, each three kilometers long, to create a closed loop “radiator” underground. It announced in October 2025 that drilling the first eight of its 12 lateral wells took more than 100 days and millions of dollars, but drilling times dropped by half for the remaining four wells. Eavor expects to generate its first commercial power soon and hopes to produce more than eight megawatts of electricity and 64 megawatts of district heating for nearby villages within a few years.¹²

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Key Technical Challenges

Many technologies used in unconventional oil and gas are being deployed in advanced geothermal developments today. However, geothermal wells differ from oil and gas wells:

- Geothermal production wells produce at much higher flow rates, on the order of 10 times higher than typical unconventional oil wells.
- Unconventional oil and gas wells have the advantage of pay out in one year or less and continue to produce at lower levels for many years, while geothermal wells will be required to operate over a period of 20 to 30 years at constant levels.
- Geothermal operates at higher temperatures, which imposes different design and materials requirements.
- Roughly half of total capital expenditures is on the surface (power plant and facilities) compared to unconventional fields, where the vast majority of expenditures is in the subsurface.

As a result, reservoir understanding, coupled with the right well architecture and surface systems, is the key to delivering firm, clean geothermal power at scale.



In order to deliver firm, clean geothermal power at scale, the key requirements are reservoir understanding, coupled with the right well architecture and surface systems.



Subsurface Challenges

There are significant subsurface challenges to making advanced geothermal economical over widespread areas.

Reaching deep, superhot dry rock requires drilling through hard rock and overcoming high temperatures. Granitic sections (e.g., at Cape Station) are especially challenging. In super-hot, rough environments, tools need to withstand temperatures above 250 degrees Celsius, which have not yet been commercially proven. For example, downhole electronics available today can operate successfully up to 210 degrees Celsius. However, the industry aims to drill hotter wells under supercritical conditions of nearly 400 degrees Celsius and pressures over 3,000 psi. These conditions necessitate the development of high-temperature and high-pressure electronics.

Handling high-temperature brines is another critical component, as these brines are extremely corrosive and can damage downhole tools. At supercritical conditions, the corrosive environment can cause significant damage to well casing itself.

While improving project economics, there are significant mechanical challenges to drilling larger bore holes and deeper wells, including supporting the additional weight of these wells and creating additional fracking force required. In Texas, the average gradient is only about 25 degrees Celsius per kilometer, which would require drilling approximately 10 kilometers to reach 340 degrees Celsius. This presents both a significant cost challenge and the need to redesign drilling equipment to withstand these loads.

In terms of heat recovery, reservoir temperature management is required over long periods, necessitating accurate reservoir modeling. The communication between injection and production wells relies on fractures, and changes in these fractures could cause premature temperature drawdowns.

Finally, modeling and monitoring for potential induced seismicity is a critical need. There are potentially significant consequences of induced seismicity including liability, regulatory shutdown risk, and insurance cost and availability.

While oil and gas operating and service companies are likely to undertake some of the necessary technology development related to drilling, completion, and subsurface modeling, more general technology development like high temperature electronics is a potential opportunity for public research funding.

Though oil and gas operating and service companies are likely to undertake some of the necessary technology development related to drilling, completion, and subsurface modeling, public research funding can spur more general technology development like high temperature electronics.

Surface Challenges

Unlike an oil and gas project, the saleable product of a large advanced geothermal project is not the produced fluid but electricity or, potentially, heat. This drives the need for significantly larger and more expensive surface facilities than an unconventional oil and gas project. About 60% of capital expenditures for an advanced geothermal development is expected to be in surface facilities (Figure 4).

This points to the importance of the surface facilities, and that managing permitting, financing and construction risks will be critical. Given the growth expected in power generation worldwide, equipment and construction services supply chains are likely to be stretched, potentially delaying project start-ups.



Managing permitting, financing and construction risks will be critical to the success of large advanced geothermal projects.

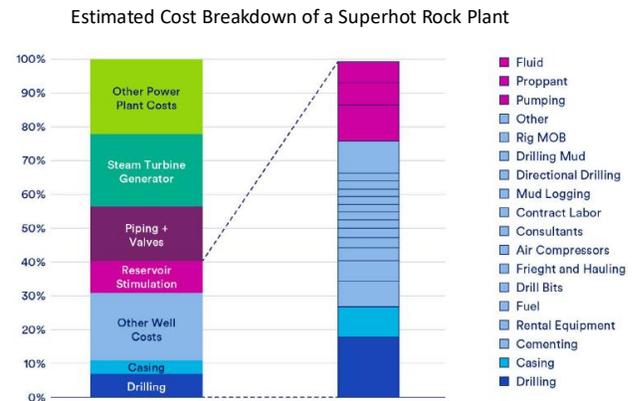


Figure 4. Estimated Cost Breakdown of a Superhot Rock Plant

Source: A Preliminary Techno-Economic Model of Superhot Rock Energy – Clean Air Task Force
Nov 2023

Potential Solutions

Oil and Gas Industry Developments

Key equipment and services suppliers in the oil and gas industry have begun to develop solutions to some of the key challenges of advanced geothermal systems. These include:

- **Advanced thermal-insulation coatings** to protect equipment and maintain fluid temperature profiles
- **Rapidly advancing bit and drilling technology** optimized for granite and high-temperature environments
- **Temperature control equipment** such as chillers and mud chillers to manage fluid and equipment temperatures
- **Downhole technologies to mitigate dysfunctions and vibrations**, improving drilling efficiency, tool and bit longevity, and reducing trips

Lessons from Other Industries

There are global groups, largely outside the oil and gas sector, that have been working on advanced geothermal energy and developing advanced geothermal technologies for the past 20 years. There have been 50 wells drilled to 400 degrees Celsius and five flow tests have been conducted in those conditions in Iceland and New Zealand. While these flow test trials are expensive, in the range of \$60 million, high-temperature cements rated for 500 degrees Celsius are already available in the market.

There are also potential alternatives to hydraulic fracturing. In deep and super-hot environments, the energy density differential between in-situ water and surface water creates significant pressure differentials. This phenomenon can be observed in nature, especially by volcanologists who study how hydrothermal fractures are formed, which are often exploited by the mining industry.



Academic Research

Many U.S. universities, including the University of Houston, have significant research activity in areas designed to accelerate deployment of advanced geothermal systems. These include:

- **Subsurface characterization:**
 - ◇ Geoscience-led imaging and interpretation to understand the reservoir before and during operations
- **Drilling and subsurface engineering:**
 - ◇ Drilling technology and practices
 - ◇ Heat transfer and fluid-flow modeling
 - ◇ Geomechanics to guide safe stimulation and operation
- **Induced seismicity monitoring:**
 - ◇ Managing injection rates
 - ◇ Borehole geophysics and continuous monitoring to mitigate seismic risks
- **Surface engineering and power systems:**
 - ◇ Mechanical and electrical engineering efforts on surface facilities and power conversion systems

Many different university disciplines are involved, including:

- **Geosciences/geophysics**
 - ◇ Subsurface imaging and fiber-optic sensing to track changes in rock physics over time
 - ◇ Mapping faults, fractures, and fracture connectivity
- **Petroleum engineering**
 - ◇ Modeling and subsurface characterization
 - ◇ Rock properties and rock physics
- **Chemical engineering**
 - ◇ Surface integration
- **Civil engineering**
 - ◇ High temperature cements and materials for well casings
- **Geotechnical engineering**
 - ◇ Geotechnical characterization for heat pumps
 - ◇ Water flow modeling and assessment
- **Electrical engineering:**
 - ◇ High temperature power systems and components including electronics and sensors
 - ◇ Superconducting wires and related logging applications

Non-Technical Risks

Many of the risks associated with advanced geothermal investments are institutional rather than purely technical. As such, there are potential government policy options to accelerate overcoming these challenges.

Developing a geothermal plant requires acquiring acreage, permitting, subsurface characterization, plant design, and plant construction, which can take four to five years in the best-case scenario. In addition to the technical risks described, significant non-technical risks need to be mitigated. Scaling drilling and stimulation supply chains will be a challenge to growing advanced geothermal.

Permitting is a significant challenge, and while strides have been made to address this, each state has different regulations. Often both private and public lands are involved with different geothermal rights. In some states, they are considered mineral rights, while in others, they are surface rights. This inconsistency complicates resource access and increases risks and the likelihood of delays.



Establishing a “clean firm power” priority in some jurisdictions will allow geothermal projects to bypass lengthy interconnection queues.



Another major challenge is power interconnection and transmission, which is currently the biggest bottleneck. An advanced geothermal project can potentially be built in less time than it takes to connect it to the grid, possibly delaying revenue from new geothermal plants. In addition, recent grid expansions have been largely focused on accommodating solar and wind at peak production capacity. However, on average, solar and wind only generate about a 20%–25% capacity factor, potentially leaving significant transmission capacity unused during daily and seasonal variations in production. Geothermal projects, with their high capacity factors, can make much more efficient use of new transmission capacity. There are both regulatory and market-based possible solutions. One regulatory solution is establishing a “clean firm power” priority in some jurisdictions, which would allow geothermal projects to bypass lengthy interconnection queues. A non-regulatory option is co-location with large power loads, which may be considered in the future as large consumers like data centers will have limited options for other clean firm power via the grid. Bloom Energy projects that approximately 30% of all data center sites are expected to use onsite power as a primary energy source by 2030.¹³

Funding early start-ups has been challenging. These have been predominantly privately financed and face competition in the climate tech space. Most climate tech funding has been directed toward solar, wind, and batteries over the last decade due to their lower operational and technological risks.



Business Models and Players

As advanced geothermal evolves, financing and business models will evolve.

Parallels between oil and gas exploration and production investment and LNG plant investments are informative when considering the transition from equity-based early-stage pilot investments to debt-based investments in larger, later-stage commercial infrastructure.

The financing environment of advanced geothermal development is similar to that of independent exploration and production (E&P). The biggest challenge is funding the subsurface. To date, this has primarily been accomplished with equity. However, once individual fields are de-risked, we will likely see the introduction of the same types of financial instruments used in the E&P space, such as reserve-based lending facilities. After overcoming subsurface risk, during power plant construction, project financing or equipment financing will likely become available. The revenue side is analogous to an LNG export facility. LNG plants typically sign long-term offtake agreements with investment-grade counterparts while geothermal developers sign long-term power purchase agreements (PPAs) with utilities or other large power users. Once long-term offtake agreements are secured, developers can tap the debt markets to pay down debt.

Advanced geothermal startups today are looking for initial funding beyond equity or preferred equity to other potentially deeper sources of capital, including private equity funds, infrastructure funds, and large investment banks.

One key to the pace of expansion will be the degree of investment by large oil and gas companies and suppliers. Large oil and gas operators would bring significant lower-cost equity and debt to the advanced geothermal industry as well as accelerate development of key technologies. Large equipment and service providers would bring accelerated technology development and scalable execution capability. The key question is whether the risk–return trade-off of advanced geothermal will be sufficient to attract the oil and gas sector at scale.

The degree of investment made by large oil and gas companies and suppliers will be key to determining the pace of advanced geothermal expansion.

Cost Reduction Potential

The cost reduction challenge with advanced geothermal energy is not managing capital and operating costs but reducing the levelized cost of energy (LCOE). The asset produces energy over a long period, so it is essential to manage both cost structure and production effectively in order to achieve a competitive LCOE. Today, Lazard estimates that new-build geothermal LCOE ranges from \$66 to \$109 per megawatt hour (Figure 5), which is comparable to solar and onshore wind plus battery storage.

Levelized Cost of Energy Comparison \$/MWH

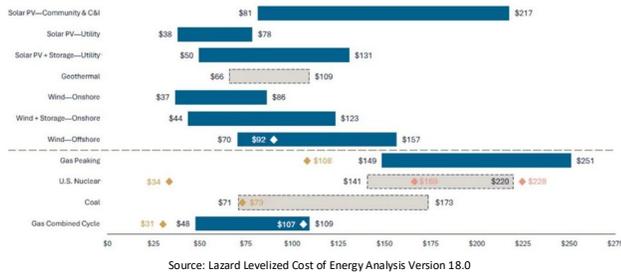


Figure 5. Levelized Cost of Energy Comparison
Source: Lazard Levelized Cost of Energy Analysis Version 18.0

These levelized cost numbers are for current new-build advanced geothermal with 25-year facility life, capital costs of \$5000 to 6800/kw, and capacity factors of 90 to 80% (low to high).

Drilling deeper and wider will create a better production profile, which will help reduce cost. Fervo’s Cape Station Phase 2’s target capital cost is \$4,500 per kilowatt, which would translate to the lower end of that range. The DOE’s Energy Earthshot target projects a 2035 capital cost of \$3,700 per kilowatt, resulting in a LCOE of \$45 per megawatt hour (Figure 6). This would make it fully competitive with natural gas combined cycle at \$3.50 per million BTU gas and current capital costs. In addition, gas plant costs are increasing due to

supply chain shortages of turbines. Large producers like GE Verona report order backlogs of four times annual turbine production capacity.¹⁴

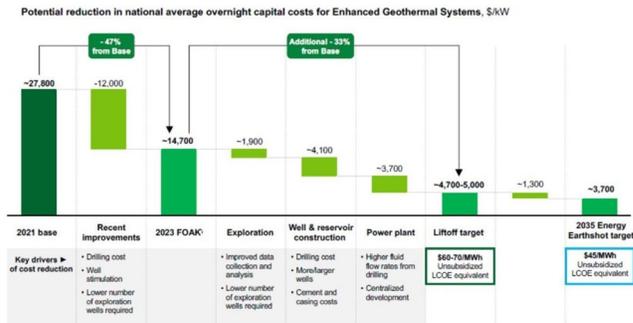


Figure 6. Potential reduction in national average overnight capital costs for Enhanced Geothermal Systems, \$/kW

Source: DOE Pathways to Commercial Liftoff: Next Generation Geothermal Power

In terms of potential improvements, the U.S. unconventional oil and gas analogy can bring perspective in terms of productivity improvements and cost reductions. Since December 2022, the oil-directed rig count has dropped 33% to 397 rigs in October 2025, and the natural gas-directed rig count has declined 23% to 120 rigs over the same period. This was driven by declines in crude oil prices from \$76 to \$64/bbl and gas prices from \$5.50 to \$3.00 per million BTU over the December 2022 to September 2025 period. Nonetheless, crude oil production increased from 13.3 to 13.8 million barrels per day, and natural gas production increased from 100 billion cubic feet per day to 108 billion cubic feet per day from December 2022 to September 2025. In the face of the price decline, operators have focused on the most productive plays, drilling longer lateral lengths to access more hydrocarbons and using more efficient completion techniques.¹⁵

The Potential of Advanced Geothermal

As advanced geothermal creates its own reservoir, the number of areas that can be successfully developed could be significantly expanded. This potential is primarily within the U.S. initially, given the experience in unconventional oil and gas.

Expansion will require activating the equipment and services supply chain, capital stack, and labor force. There are again parallels to the unconventional oil and gas industry development. Shale gas started in the Barnett, then moved to the Haynesville, Fayetteville, Marcellus and Eagle Ford, ultimately expanding to oil in the Bakken and Permian. From 2005 to 2015, the oil and gas sector released about eight million barrels per day of oil and significant volumes of gas. Depending on power conversion efficiencies, this equates to around 500 gigawatts of power from a new energy source released by the oil and gas supply chain over a 10-year period.

Similarly, geothermal is starting in Nevada, Utah, Oregon, and Idaho. The reason for this focus is that higher gradients mean we don't have to drill as deep, which improves economics and reduces operational and technical risks. In fact, estimated 2024 LCOE in many regions today is below the national average cost of energy (Figure 7). As project costs reduce and de-risk, advanced geothermal could expand across the country. One major target is to reach the PJM grid area in the Northeast, where data center concentration, urban density, and load demand are highest.

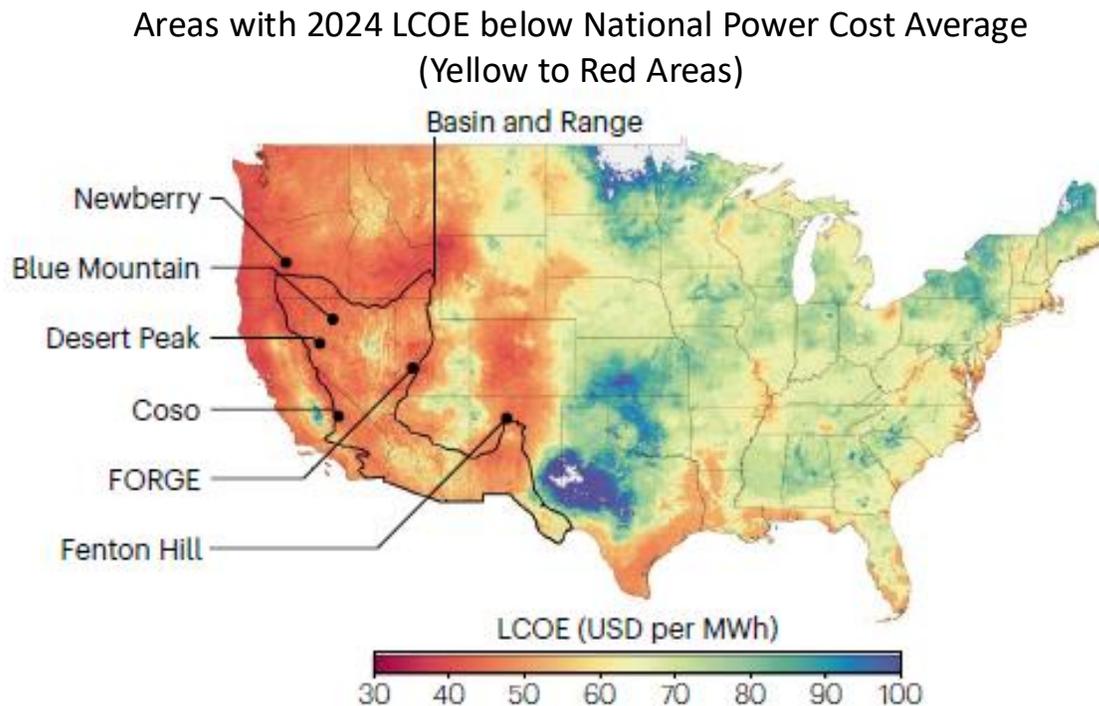


Figure 7. Estimates EGS systems based on 2024 drilling costs at optimal depth

Source: Enhanced geothermal systems for clean firm energy generation, Horne et al – Nature Reviews Clean Technology Feb 2025

There are also opportunities to use advanced geothermal projects to generate clean firm district heat. Cornell University is developing its Earth Source Heat project to directly warm the sprawling campus with geothermal energy pulled from deep underground. The project has drilled a nearly 10,000-foot-long borehole that slices vertically through layers of rock to reach sufficiently high temperatures to create an artificial heat reservoir. Cornell is using data from the site to develop a system that will replace the school's fossil gas-based heating network, potentially by 2035. Cornell received about \$7 million from the DOE for the project, which cost around \$14 million to deploy. With additional funding, Earth Source Heat wants to reopen the borehole, deepen it, and use fiber-optic cables and other tools to study how the rock responds to stress and high-pressure injections of water, data that will inform the design of the final system.¹⁶

Advanced geothermal is maturing on a timely basis. U.S. power demand has begun to grow, and some customers are willing to pay a premium for quick access to power and/or low-carbon firm power. For a nascent industry with these features, like next-generation geothermal, this is an opportunity to become established while reducing costs in order to sell power at competitive rates across the country in 10 or 15 years. As a result, geothermal energy in the US could reach 100 gigawatts by 2050 (Figure 8).

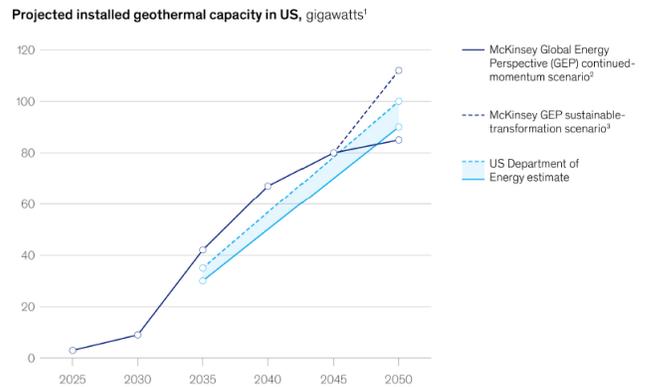


Figure 8, Projected installed geothermal capacity in US, gigawatts¹

Source: McKinsey *Is Geothermal Energy Ready to Make Its Mark in the US Power Mix?*

U.S. power demand is growing, and some customers are willing to pay a premium for quick access to power and/or low-carbon firm power. For next-generation geothermal, this is an opportunity to become established while reducing costs.

However, advanced geothermal is also beginning to generate international interest, especially in Europe and Asia. In the U.S., a major gas exporter, geothermal ultimately competes with low-cost natural gas for the firm generation market. As importers of natural gas, Europe and Asia often face prices that are 50%–100% higher than in the U.S. As a result, realizations from power purchase agreements there could be substantially higher. There is also significant interest in geothermal for district heating in Europe, which could expand geothermal development.

If deeper resources can be accessed cost effectively and international markets expanded, geothermal could meet up to 15% of global electricity demand growth by 2050. This would mean the cost-effective deployment of as much as 800 gigawatts of geothermal power capacity worldwide, producing almost 6,000 terawatt-hours per year, equivalent to the current electricity demand today of the United States and India combined.¹⁷

On a global basis, solar is the only low-carbon energy source with a higher technical potential than geothermal (Figure 9).

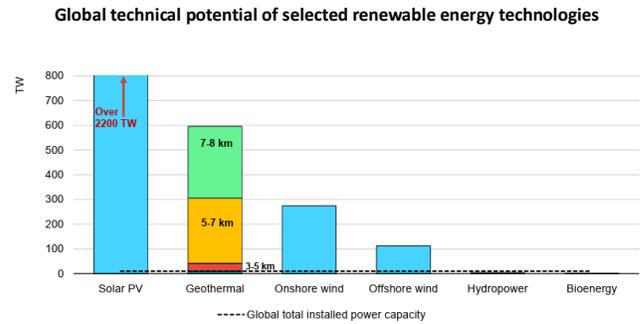


Figure 9. Global technical potential of selected renewable energy technologies

Source: *The Future of Geothermal*, IEA Dec 2024

The Role of the Oil and Gas Industry

The oil and gas industry can play a key role in boosting the cost-effectiveness of geothermal energy.

Up to 80% of the investment required in a geothermal project involves capacity and skills that are common in the oil and gas industry.¹⁸ The industry has transferable skills, data, technologies, and supply chains that make it central to the prospects for next-generation geothermal.

Diversifying into geothermal energy could be of great benefit to the oil and gas industry, providing opportunities to develop new business lines in the fast-growing clean energy economy.



Up to 80% of the investment required in a geothermal project involves capacity and skills that are common in the oil and gas industry.



Conclusion

As a widely distributed energy source, advanced geothermal has the potential to be the largest source of firm, low-carbon intensity electricity in the U.S. and internationally. Advanced geothermal has many advantages in the growth and decarbonization of electricity grids (Figure 10). Technologies for advanced geothermal, many based on unconventional oil and gas, have evolved rapidly, mainly in the U.S.

Given expected cost reductions and other advantages, advanced geothermal is expected to become a major source of low-carbon electricity over the next 25 years.

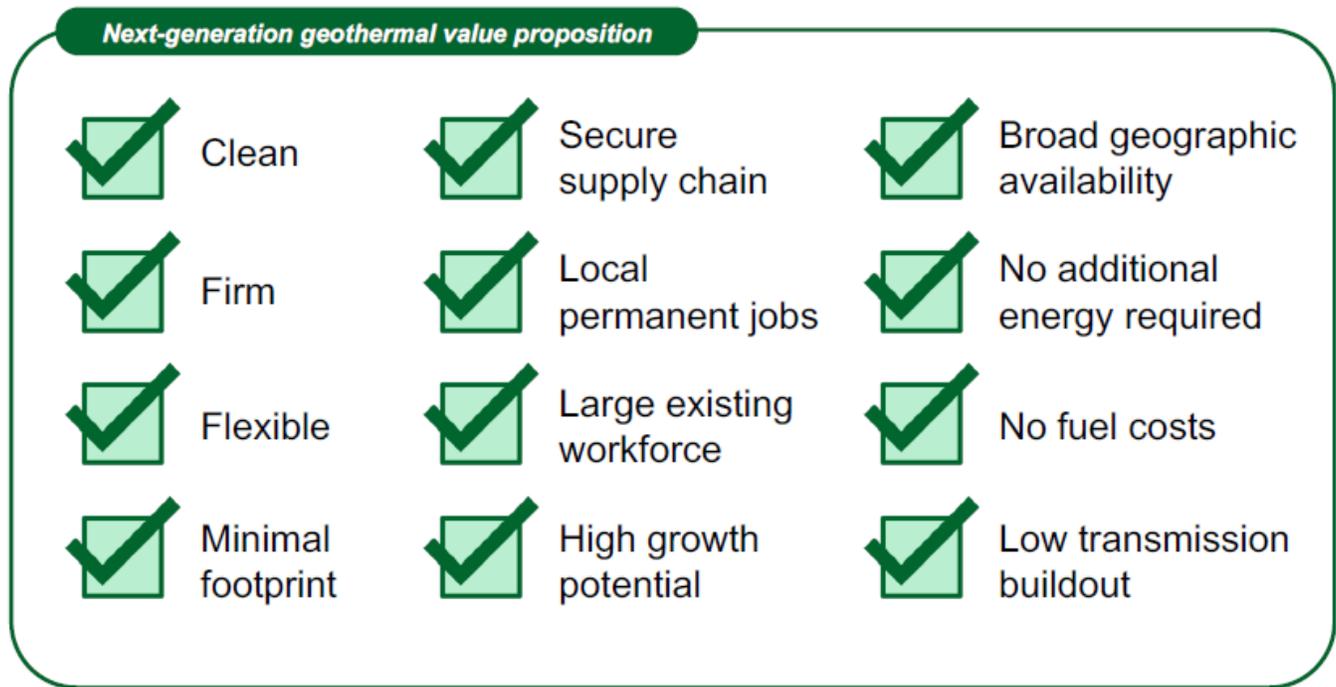


Figure 10. Next-generation geothermal value proposition
Source: DOE Pathways to Commercial Liftoff: Next Generation Geothermal Power

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