U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: **Next-Generation Geothermal Power**

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Comments

The Department of Energy welcomes input and feedback on the contents of this Pathway to Commercial Liftoff Report. Please direct all inquiries and input to liftoff@hq.doe.gov. Input and feedback should not include business sensitive information, trade secrets, proprietary, or otherwise confidential information. Please note that input and feedback provided is subject to the Freedom of Information Act.

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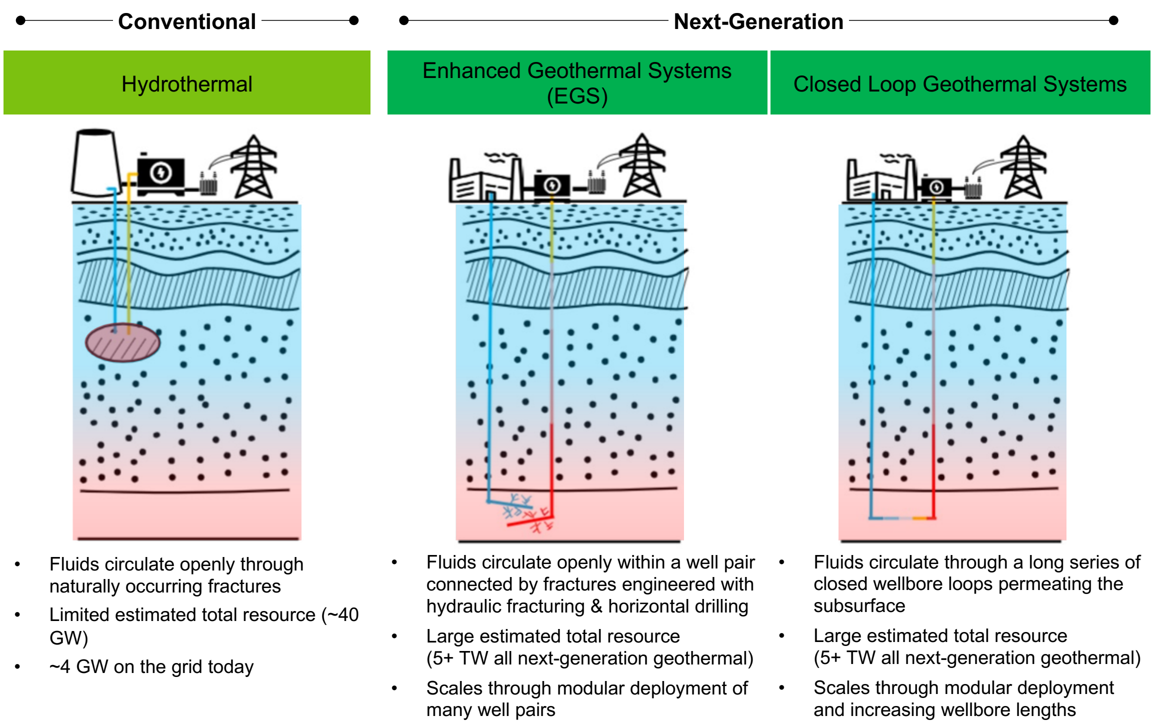
Table of Contents

Executive Summary

Geothermal power technology has shown compelling advances that can enable it to become a key contributor to secure, domestic, decarbonized power generation for the U.S. as a source of clean firm power[a]. Conventional geothermal, although always valued as a source of utility-scale clean firm power, has been dramatically constrained by its geographic limitations, relying on naturally-occurring thermal resources that only exist in niche locations. "Next-generation" technologies (Executive Summary Figure 1) have the potential to engineer effective geothermal resources in commonly found environments, vastly expanding resource availability and potential commercial adoption. Although a nascent industry, next-generation geothermal enjoys several starting advantages, including transferrable technology, supply chains, and workforces from the oil & gas sector, that will help it achieve rapid scale. Recent field-scale pilots already provide a compelling roadmap for cost reductions necessary to achieve widespread commercial adoption of next-generation geothermal power. If the industry can achieve a set of market conditions around cost, demonstrations, value, and community engagement, commercial liftoff is attainable as early as 2030.



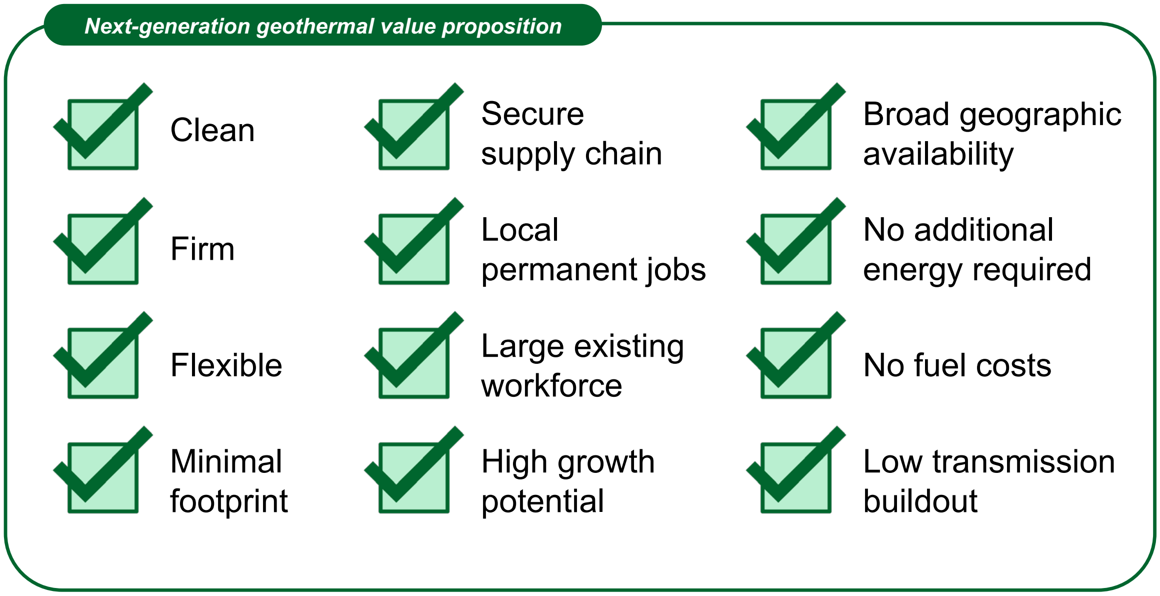
Executive Summary Figure 1: Geothermal technology overview across conventional (left) and next-generation (right) designs [b]

Economywide decarbonization modeling suggests that the U.S. will need an additional 700-900 GW of clean firm capacity to build a decarbonized grid system capable of supporting increased demand. The cost of decarbonizing the electricity system is substantially reduced by simultaneous deployment of variable and firm clean resources, because firm resources reduce the need to overbuild variable renewables capacity.

Next-generation geothermal has a unique value proposition, including minimal workforce and supply chain risk, low land use, and flexible generating capability (see Executive Summary Figure 2). The geothermal industry leverages existing fossil energy supply chains and workforce. Geothermal energy may also be stored in the subsurface and dispatched flexibly, enabling it to load-follow variable renewables as long-duration energy storage, providing a needed grid service. Because next-generation geothermal applies subsurface engineering technologies leveraged by the oil and gas industry that have caused environmental harms in the past, such hydraulic fracturing, it can create public concerns. Technology differences between oil & gas and geothermal hydraulic fracturing reduce the actual likelihood of such harms occurring; however,

a "Clean firm power": power that is always available, even under adverse conditions, and emits low to no CO2eq.

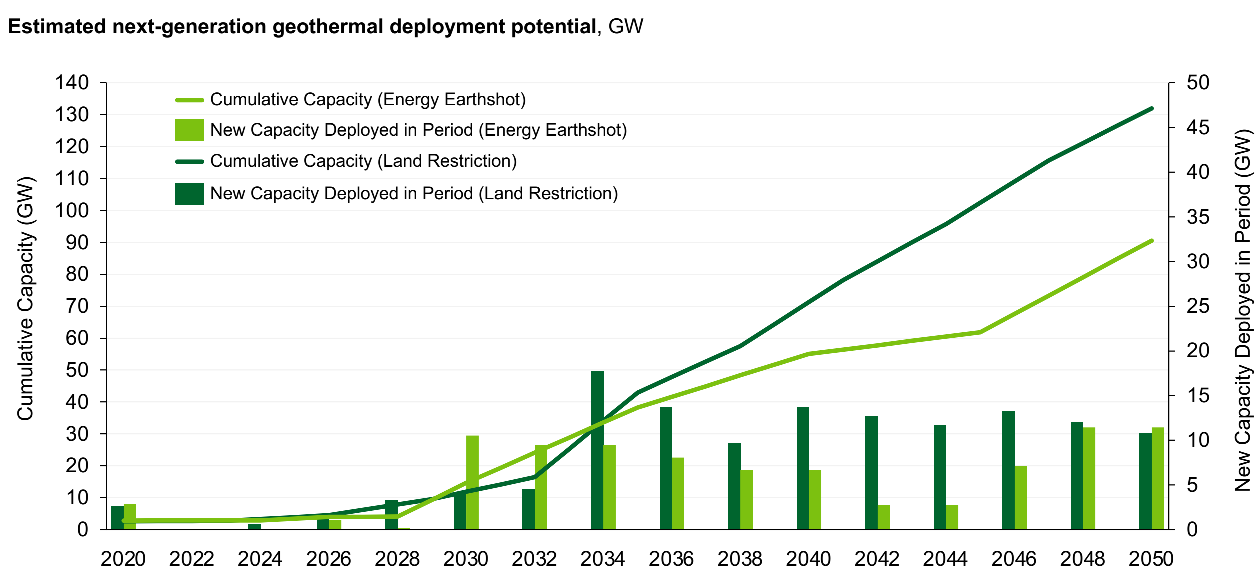
b Graphics adapted with permission from: Next-Generation Geothermal Technologies Are Heating Up | BloombergNEF (bnef.com) transparency and monitoring of environmental health impacts are the fastest path to ensuring that these environmental risks are low and provide a social license to operate.



Executive Summary Figure 2: Next-generation geothermal value proposition

These unique capabilities help enable geothermal energy to command a price premium—**conventional and next-generation geothermal power purchase agreements are signed today for between $70 and $100 per MWh.** These agreements are driven by increasing systemwide recognition of the need for clean firm power. The California Public Utilities Commission, for example, mandated procurement of 1 GW of clean firm power by 2026, resulting in 262 MW of new geothermal power purchase agreements.

Next-generation technologies can expand geothermal power by more than a factor of 20, providing 90 GW or more of clean firm power to the grid by 2050 across the U.S. based on power sector modeling shown in Executive Summary Figure 3. Variation in technical and market factors, such as the availability of land for power generation, the addition of flexible power, and the availability of other nascent technologies, could drive over 300 GW of deployment by 2050.

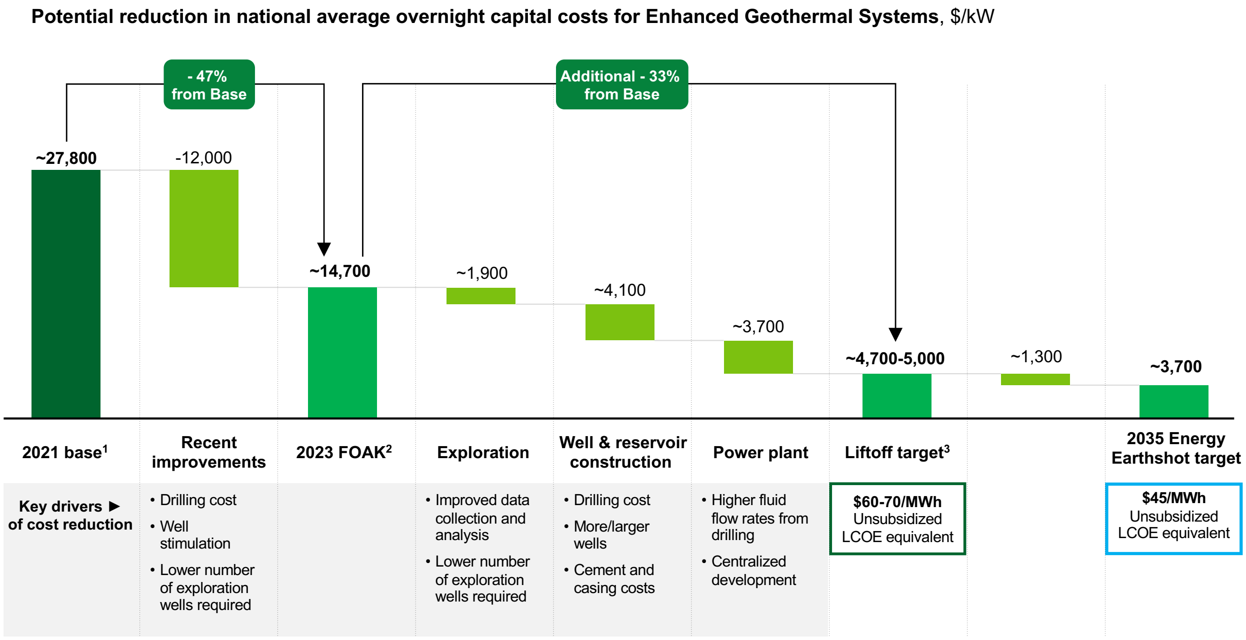


Executive Summary Figure 3: Projected cumulative deployment of next-generation geothermal power until 2050 [left axis] and added capacity in two-year increments [right axis]. Light green scenario represents the projected deployment from the "Energy Earthshot Original" modeling scenario; dark green scenario represents the projected deployment from the "land use restriction" modeling case. See Appendix A for details.

Next-generation technologies change the status quo for geothermal power

Next-generation geothermal technologies make their own reservoirs from ubiquitous hot rock, rather than hunting for naturally occurring reservoirs in unique locations. There is about 40 GW of estimated conventional geothermal resource in the U.S., but only 25 percent of that estimated resource has been located. This need to locate unique geologic environments has limited the geothermal deployment in the U.S. to roughly 4 GW, even though conventional geothermal power today is cost-competitive with most other generation sources. Next-generation geothermal technologies expand geothermal resource potential to 5,500 GW distributed across much of the country and remove the need to search for unique geologic environments.

Next-generation geothermal can soon be broadly cost-competitive with other energy sources. Advancements at field demonstrations in the last two years have reduced estimated project development costs for enhanced geothermal systems (EGS) by almost 50 percent. Reasonable advances expected in drilling, reservoir engineering, and resource exploration largely informed by the existing unconventional oil & gas industry could drive the national average cost of EGS to $60-70/MWh by 2030, implying profit margins of $10-30 per MWh at current PPA prices. These cost reductions are on pace to achieving DOE's Enhanced Geothermal Shot Target of $45/MWh by 2035. More information on the Enhanced Geothermal Shot is provided in Chapter 4.



Executive Summary Figure 4: Cost reduction waterfall for EGS[c]

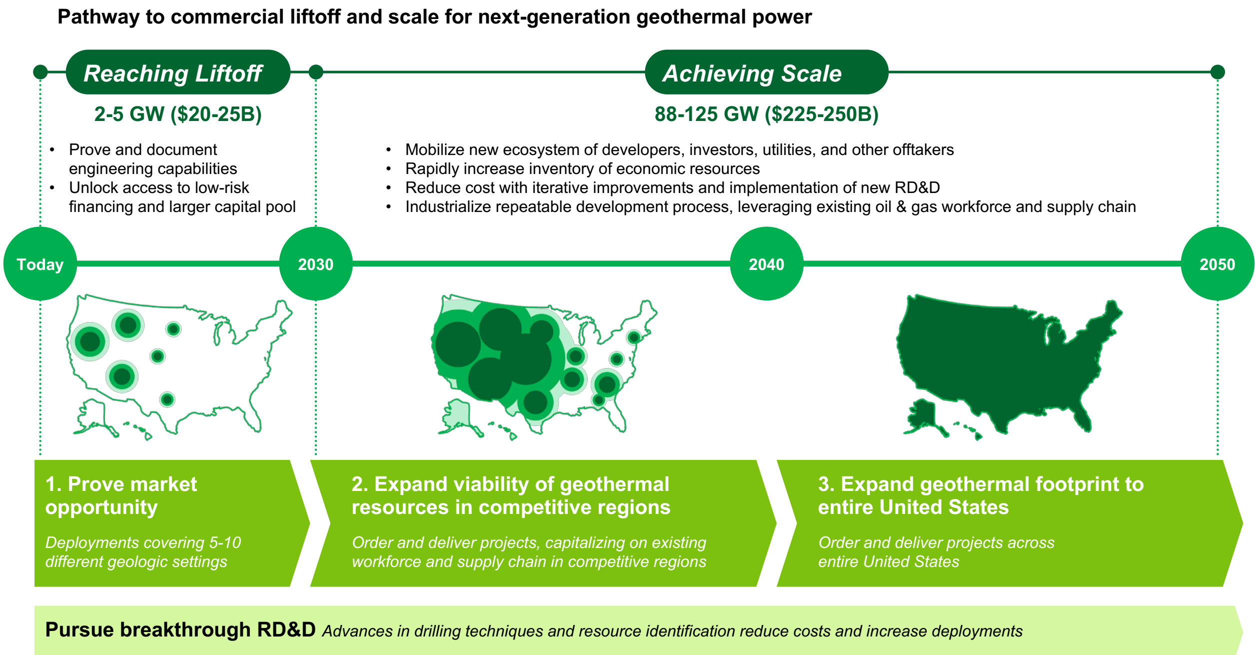
Recent technical successes indicate the industry is on track to achieving ambitious targets. Drilling speeds at the Department of Energy (DOE)'s EGS Demonstration Site "FORGE" improved by over 500 percent in 3 years, and well development costs decreased from $13 million to under $5 million per well between the first two large-scale commercial EGS pilots in the United States. The first field-scale closed loop demonstration project was completed in 2022, and a closed loop commercial pilot in Germany is anticipated to be completed in 2028.

Technical successes have catalyzed substantial recent momentum in the next-generation geothermal market, with increasing market entry and year-over-year increases in the capital raised by developers since 2021.

c Notes: 1. NREL ATB 2021 Base Case 2. NREL ATB Advanced Case 3. 2030 target based on trajectory to DOE Energy Earthshot 2035 target.

Pathway to commercial scale

Full-scale deployment of next-generation geothermal power can proceed in two phases, against a backdrop of continuing R&D in pursuit of technological breakthroughs. Four key market and community enablers can help ensure Liftoff is reached.



Executive Summary Figure 5: Pathway to commercial liftoff and scale. Green dots on maps correspond to representative potential geothermal footprint in terms of power use.

Phase 1: Reaching Liftoff

To reach commercial liftoff, next-generation geothermal developers must first prove the market opportunity. **Industry must demonstrate that the engineering capabilities can be deployed in greenfield conditions**—i.e., locations with no existing geothermal resources. Among the first deployments, successful demonstration projects in five to ten different geologic settings would provide the **validation suite** necessary to demonstrate reduced technological and resource risk, underscoring the large market potential and unlocking debt financing earlier in project development.

Overall deployment of about 2-5 GW across 4-6 states and requiring $20-25B of investment would assemble this validation suite required to reduce the risk of development in new locations.

Four key enablers can help ensure liftoff by 2030:

- Cost reductions that reach national average LCOE of $60-70/MWh by 2030 (corresponding to $40-50/MWh in competitive regions).
- Large-scale demonstrations for new market entries, technical approaches, and geologic settings.
- Well-designed power purchase agreements (PPAs) that reflect the value of clean firm power that next-generation geothermal provides.
- Early and continued community engagement.

Phase 2: Achieving Scale

Achieving commercial scale will require $225-250B in investment while leveraging the hundreds of thousands of existing workers that have transferable expertise.

To achieve scale, the industry could first expand proven Phase 1 developments, and then expand the economic viability of new geothermal resources across the U.S. Unlocking access to lower-risk financing and proving that a large power generation resource is accessible in Phase 1 expands the capital pool available to invest in Phase 2. As in the extraction of other subsurface resources, development of new geothermal resources will have a snowballing effect toward proving the viability of further geothermal resources.

As the next-generation geothermal industry matures, it can expect the entry of new developer classes, sources of investment, and development models that drive deployment. Ultimately, a fully mature and de-risked geothermal industry could develop projects using a traditional project finance model, in which combinations of debt and equity are available early on during a project's lifecycle. Leveraged projects free up capital for other developments, as is the practice for current traditional renewables developers. However, on the path to that model, there are also higher-risk financing strategies that may be in use at the time the industry reaches liftoff.

Challenges & potential solutions

The next-generation geothermal industry faces five major challenges it must overcome to achieve liftoff and scale:

Challenges	Potential Solutions
High up-front costs & risks constraining development capital and limiting geographic reach	About $5 billion out of the $20-25 billion of capital formation in the liftoff phase to finance the validation suite of first-of-a-kind (FOAK) developments in varied geologies, sourced from governments, equity investments, corporate venture or strategic investor-offtakers, or oil & gas Market signals, such as high-valued PPAs, to motivate investment in initial deployments In-field testing and innovation at active geothermal developments through RD&D spending New financial products to reduce drilling costs, such as public/private cost-share agreements and drilling insurance programs
Perceived & actual operability risk for deployments	Strategic demonstration siting and data dissemination from 10+ early deployments to show sustained power production
Long and unpredictable development lifecycles driven by permitting and interconnection	Allowing for combining and streamlining of specific steps in permitting process, where authorized Technology changes that allow certain steps to occur in tandem Centralization of geothermal-specific permitting expertise, where authorized
Existing business models undervaluing the potential of next-generation geothermal	Planning policies that incentivize higher-cost, higher-value power Leveraging flexible geothermal operations to capture highest-value power New offtake models, e.g., subsurface developers providing heat for multiple purposes
Community opposition in some instances	Adherence to long-established induced seismicity and environmental monitoring best practices Early, frequent, and transparent communication

Key Terminology and Abbreviations

Advanced geothermal systems (AGS): See *closed loop geothermal systems.*

ATB: The "Annual Technology Baseline", a data product produced by the National Renewable Energy Laboratory that provides a consistent set of technology cost and performance data for energy analysis. See https://atb.nrel.gov.

BIL: The Bipartisan Infrastructure Law, also known as the "Infrastructure Investment and Jobs Act" (Public Law 117-58).

Binary cycle power plant: a geothermal power plant that can operate at a lower temperature than flash power plants, leveraging organic Rankine cycle (ORC) turbine technology where subsurface fluids are used to heat a secondary fluid to drive a turbine. These plants prevent naturally occurring gas within subsurface working fluids to release into the atmosphere.

BLM: The Bureau of Land Management, the Agency within the United States Department of the Interior responsible for administrating federal lands.

Capacity factor: The ratio of the electrical energy produced by a generating unit for the period considered to the electrical energy that could have been produced at continuous full power operation during the same period.

Closed loop geothermal systems: a subsurface circuit of wellbores containing a fluid heated by a geothermal resource without direct contact with the resource.

Conventional geothermal: See *hydrothermal.*

DOE: The United States Department of Energy.

Enhanced Geothermal Systems (EGS): a subsurface circuit of multiple wells and fractures containing a fluid heated by a geothermal resource through direct contact with the resource.

Firm power: Power or power-producing capacity, intended to be always available during the period covered by a guaranteed commitment to deliver, even under adverse conditions.

Flash power plant: a geothermal power plant that operates at higher temperatures and directly converts geothermal fluids into steam that drives a turbine.

Flow rate: The rate at which a volume of fluid flows through a medium, such as a wellbore or subsurface fracture.

FOAK: "First of a kind".

Geothermal Technologies Office (GTO): The Geothermal Technologies Office (GTO) is the Technology Office within the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy responsible for increasing deployment of geothermal technologies.

Hydraulic fracturing: a well stimulation technique involving the fracturing of bedrock formations by a pressurized liquid.

Hydrothermal: Also known as conventional geothermal resources, these resources contain both sufficiently hot rock and enough naturally occurring fractures to allow fluid to flow through that hot rock at relatively high rates.

IRA: The Inflation Reduction Act (Public Law 117-169).

ISO: "Independent system operator", an independent, federally regulated entity established to coordinate regional transmission in a non-discriminatory manner and ensure the safety and reliability of the electric system.

LCOE: "Levelized cost of electricity", the present value of the total cost of building and operating a generating plant over its economic life, converted to equal annual payments, and adjusted for inflation.

Next-generation Geothermal: Next-generation geothermal technologies use drilling and/or hydraulic fracturing advances that allow fluid to flow through hot rock that was previously impermeable. Two prominent categories of next-generation geothermal being developed today are closed loop and EGS.

OCC: "Overnight capital cost", the cost of a construction project if no interest was incurred during construction, as if the project was completed "overnight."

Offtaker: entity who buys the product being produced by a project or uses the services being sold by a project, which in the case of the geothermal market is often electric power.

PPA: "Power purchase agreement", a long-term contract between an electricity generator and an offtaker.

R&D and RD&D: "Research and development," "Research, development, and demonstration".

Reservoir: a rock volume that contains naturally-occurring geothermal energy.

Resource: the portion of a reservoir's total geothermal energy that is technically recoverable.

RTO: "Regional transmission organization", an electric power transmission system operator that coordinates, controls, and monitors a multi-state electric grid.

Stimulation: process of enhancing a reservoir via methods like hydraulic fracturing to increase its energy productivity.

Variable Renewable Energy: electricity generation technologies whose primary energy source varies over time. Variable renewable energy sources include solar, wind, and some hydropower generation technologies.

Wellbore: a hole that is drilled to aid in the exploration and recovery of natural resources, including oil, gas, or water. For geothermal, wells are encased by multiple layers of high-grade alloys and cement.

Purpose of Liftoff reports

Liftoff reports describe the market opportunity, current challenges, and potential solutions for the commercialization of interdependent clean energy technologies. Liftoff reports are an ongoing, DOE-led effort to engage directly with energy communities and the private sector across the entire clean energy landscape. Their goal is to catalyze rapid and coordinated action across the full technology value chain. Reports will be updated regularly as living documents and are based on best-available information at time of publication. For more information, see Liftoff.Energy.gov.

Objectives and Scope of this Liftoff report on Next-Generation Geothermal Power

This report is part of a family of reports on geothermal energy. The next report to be published will focus on geothermal heating and cooling. These reports are meant for a diverse audience of stakeholders who can help accelerate liftoff for geothermal energy.

For the audience unfamiliar with next-generation geothermal power, this report aims to build foundational understanding of the technical innovations, value proposition, and business models associated with this set of technologies. Among more experienced audiences, the report aims to catalyze and organize a dialogue between DOE, energy corporations, policymakers, utilities, ISOs/RTOs, research organizations, advocacy groups, and more around challenges and potential solutions for liftoff. Building on this report, future efforts can include near-term actions as well as the development of more detailed, longer-term roadmaps for the rapid, safe, and cost-effective deployment of next-generation geothermal power.

This report is organized as follows:

Chapter 1: Overview and Value Proposition introduces next-generation geothermal technologies and summarizes their value proposition, including the overall potential for scale.

Chapter 2: Next-Generation Geothermal Technology and Market explains fundamental concepts regarding changes to the development potentials and risk landscape for geothermal power thanks to next-generation technologies, and provides an outlook for next-generation geothermal cost declines.

Chapter 3: Pathway to Commercial Scale describes the potential opportunity for next-generation geothermal to reach liftoff by 2030, outlines the key conditions to reach liftoff, and discusses development models at different levels of maturity as the industry reaches full commercial scale by 2050.

Chapter 4: Challenges & Potential Solutions discusses 5 key challenges associated with liftoff and commercial scale and associated potential solutions and actions.

Chapter 5: Metrics to Track Progress suggests metrics for leading indicators, lagging indicators, and goal outcomes for next-generation geothermal power.

Chapter 1: Overview & Value Proposition

Key Takeaways:

- Next-generation geothermal technologies create their own reservoirs from ubiquitous hot rock, which expands the availability of geothermal resources in the United States from 40 GW to over 5,000 GW.
- Next-generation geothermal can economically provide 90 GW of the 700 to 900 GW of clean firm power needed for a decarbonized economy by 2050, and technical and market factors such as limited land available for other renewables and the rate at which other key technologies develop can triple expected deployment to over 300 GW.
- Rapidly increasing projections of electricity demand are driving increased need for clean firm power, which already commands a price premium in some cases; PPAs today are signed between $70-$100/MWh, $20-50/MWh more than the average solar PPA in North America.
- Next-generation geothermal technologies can store energy in the subsurface over long durations, increasing the value proposition of the technology. The economic deployment of next-generation geothermal doubles if this capacity is pursued.
- The next-generation geothermal industry can leverage large and existing workforces and supply chains, reducing key commercial adoption barriers to enable faster uptake.

Geothermal technology overview

Geothermal energy is a naturally occurring and abundant supply of heat within Earth's subsurface. Enough geothermal energy exists to power the entire world thousands of times over. Subsurface temperatures increase with depth; geothermal power plants leverage this gradient by drilling wells that convey fluids from the hot subsurface (below ground) to the surface, using that energy to spin turbines in power plants that generate electricity. Power can be generated from geothermal resources above approximately 90 ºC.[1]

The United States has the most installed geothermal capacity in the world, at 3.7 GW.[2] Commercial geothermal electric power production began in Italy in 1904,[3] and began in the United States in 1960 at The Geysers geothermal field in northern California.[4] The Geysers remains the world's largest geothermal field.

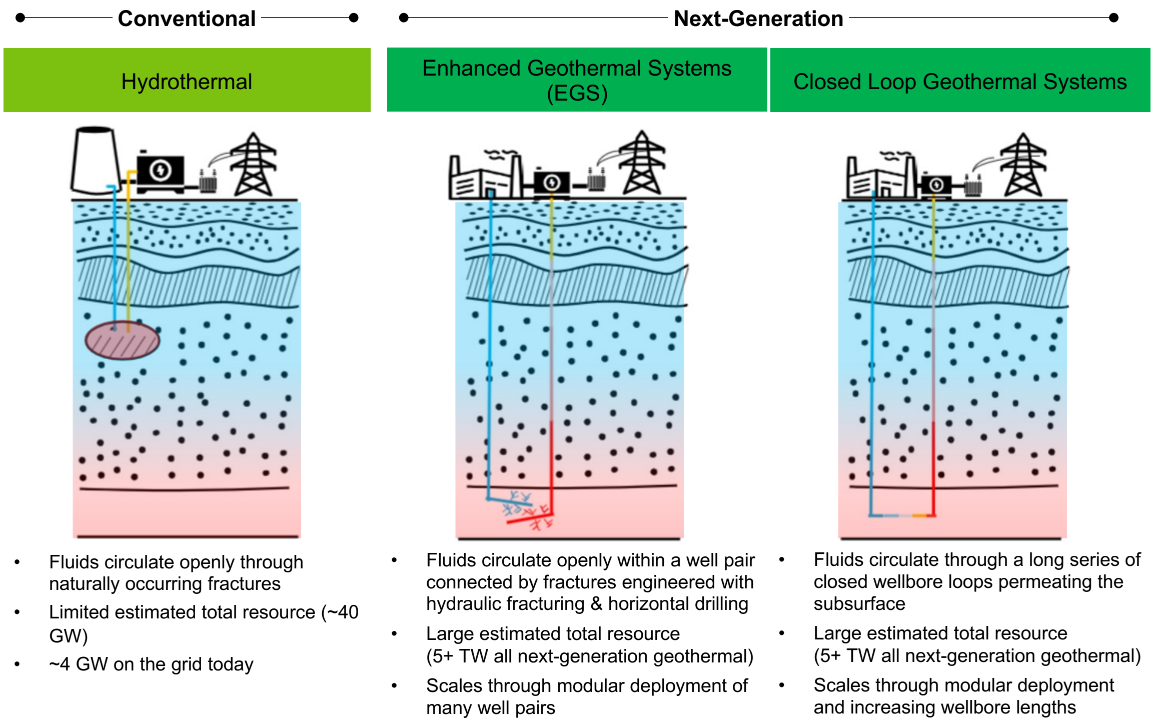


Figure 1: Geothermal technology overview across conventional (left) and next-generation (right) designs[d]

There are two major categories of geothermal power generation: conventional (also known as hydrothermal) and next-generation geothermal (Figure 1). Conventional resources rely on naturally occurring geologic conditions and need minimal subsurface engineering to produce power. These resources contain both sufficiently hot rock and enough naturally occurring fractures to allow fluid to flow through that hot rock at relatively high rates.[5] The unique conditions required mean conventional resources are relatively rare, and absent an obvious surface expression, such as a geyser or hot spring, identifying these resources is a challenge. **Despite an estimated 40 GW of conventional potential in the US, only 9 GW has been identified to date,[6] and only 3.7 GW is producing power.[7]** Forty percent of the U.S. conventional capacity is sourced from one geothermal field (The Geysers).[8] Conventional plants provide most of the geothermal power online today in the U.S., and all conventional developments in the U.S. are in the western contiguous states and Hawaii.

Next-generation geothermal technologies use modern engineering to expand access to geothermal potential across the entire United States. Next-generation geothermal technologies use drilling and/or hydraulic fracturing advances that allow fluid to flow through hot rock that was previously impermeable. Because there is no unique geologic constraint to adhere to, next-generation geothermal technologies have vast potential.

There are an estimated 5.5 terawatts of geothermal energy available for next-generation geothermal development in the United States alone, enough to power the U.S. for thousands of years. The amount of this energy that will ultimately be developed is driven therefore not by a resource constraint but by the techno-economics of geothermal power production. This energy is available nationwide—in addition to terawatts available in the west, there are also hundreds of gigawatts in the eastern U.S. (Figure 2). The two prominent categories of next-generation geothermal being developed today are enhanced geothermal systems (EGS) and closed loop geothermal systems (also known as "advanced geothermal systems" or "AGS") (Figure 1).

d Graphics adapted with permission from: Next-Generation Geothermal Technologies Are Heating Up | BloombergNEF (bnef.com)

Next-generation and conventional geothermal resource estimates

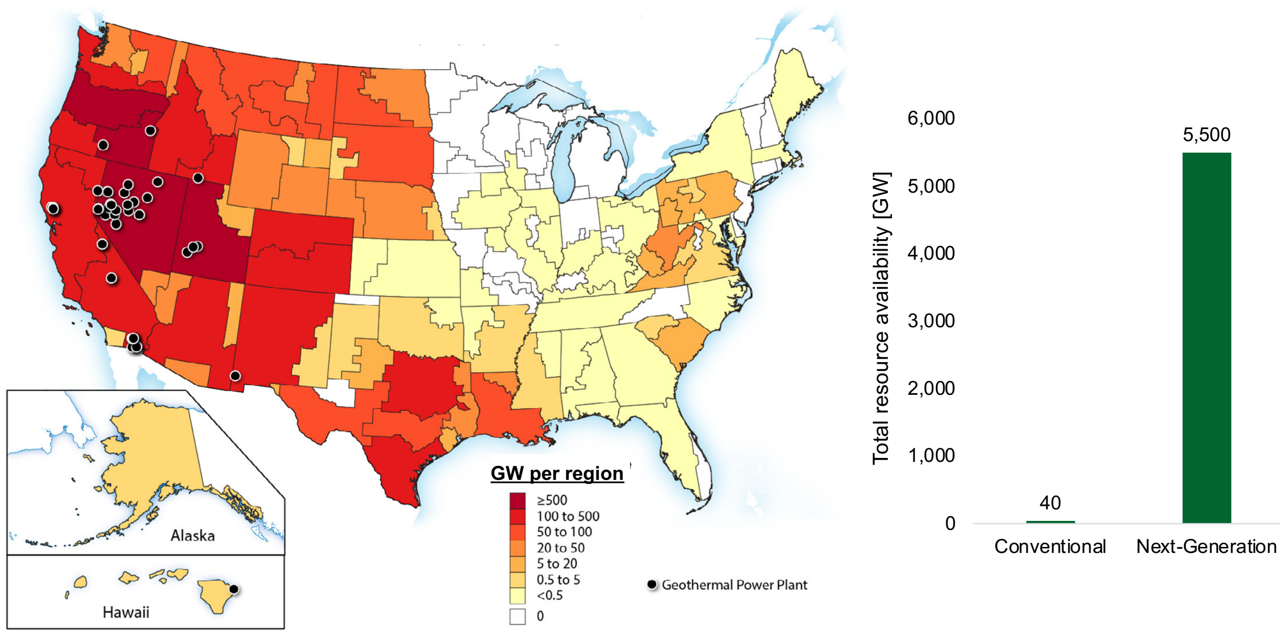


Figure 2: [Left panel] Total next-generation potential across the United States (red shading), overlain by locations of current conventional geothermal plants producing 3.7 GW of power (black dots). [Right panel] comparison between total available resource for conventional geothermal (left) and next-generation geothermal (right).

Enhanced Geothermal Systems (EGS) use proven technology in new environments. EGS applies commercial directional drilling and hydraulic fracturing capabilities developed by the oil & gas industry to target and create fractures in hot, impermeable rock units, allowing fluid to flow where it previously could not. EGS creates many fractures so there is sufficient surface area to allow flowing fluid to conduct enough heat from the rock to produce power. EGS systems are designed to continuously flow fluid in a loop, and therefore differ from hydraulically fractured oil & gas wells, which are only designed for one-way extraction of oil & gas from the rock. Well depths can vary depending on where in the subsurface sufficient temperature and appropriate stress conditions are encountered, but typically are 4,500-12,000 feet.[9]

EGS has been an active area of RD&D for over 50 years, but commercial activity is recent. Research on EGS began in the early 1970s with the Department of Energy (DOE)-funded Fenton Hill project in Los Alamos, New Mexico,[10] and there have been at least 65 EGS projects in 21 countries since then.[11] Commercial applications of EGS have until recently focused on augmenting the capacity of existing conventional plants (“near-field EGS”); these techniques have increased production at several conventional fields in California and Nevada.[12] DOE spurred EGS development through the 2018 commissioning of the “Frontier Observatory for Research in Geothermal Energy”(FORGE), in Milford, UT. FORGE is a collaborative field laboratory and ongoing demonstration project initially spurred by about $200 million in government funding that tests and demonstrates new EGS capabilities, including horizontal drilling and hydraulic fracturing.[13] The first commercial pilot of EGS leveraging these new capabilities is the 3.5 MW “Project Red” completed by Fervo Energy in May 2023 in northern Nevada.[14] Fervo’s next project, which is currently drilling, is adjacent to the Utah FORGE site.[15] That project has a planned output of 400 MW, and the first 10 MW are due online in 2026.

Closed loop geothermal systems circulate fluids entirely within boreholes closed to the environment. Many closed loop geothermal designs are in development, including coaxial systems that inject and produce from a single borehole; U-tube type systems wherein there are separate injection and production wells; and systems that use thermally conductive materials around the wellbore to enhance nearby heat conduction. This report does not intend to analyze all concepts, but rather focuses on the U-tube scenario as a representative view of the approach, as it has been the most robustly tested thus far. In these systems, fluid conducts heat as it flows through one or more boreholes within a hot, impermeable layer of bedrock, emerging at the surface at temperatures sufficient to produce power. Closed loop systems leverage a single drilled pathway, and therefore do not require hydraulic fracturing to create fluid pathways, reducing potential risks to environment and human health associated with hydraulic fracturing fluids. As opposed to EGS, which benefits from having many fracture pathways and thus substantial surface area to allow circulating fluid to conduct heat from hot rock, closed loop systems have only the surface area created by the drilled borehole conveying the fluid. Therefore, to conduct a similar amount of heat, closed loop systems must develop well loops that permeate into deeper, hotter rock.[16] Well loops must also be very long to allow for more contact with the rock, and closed loop system wells may have multiple branches that increase total well surface area.[17] Currently planned closed loop projects propose well depths that far exceed the depths of geothermal wells drilled today, on the order of 5 miles or greater, and will require hundreds of miles of horizontal length for commercial levels of power production.[18] While such depths are within the technical capabilities of drillers today (the deepest well ever drilled is about 7.5 miles deep[19]), these loops would far exceed the deepest well bores that exist today in the geothermal industry.

Like EGS, closed loop geothermal projects have been the subject of R&D for nearly half a century.[20 21] However, unlike EGS, large-scale closed loop geothermal demonstrations, government-funded or otherwise, have just begun to come online. The most notable closed loop geothermal successes in the field are a pilot loop completed by Eavor Technologies in Alberta, Canada ("Eavor-Lite"),[22] and a deep drilling demonstration in New Mexico in 2023.[23] Success at this stage has enabled Eavor Technologies to develop the first-ever large-scale demonstration of closed loop geothermal, in Geretsried, Germany[24] which is scheduled to produce about 8 MW of power from four loops drilled to about 3 miles' depth in 2027. Eavor anticipates drilling over 220 miles of borehole in total for the Geretsried, Germany demonstration project.

Both EGS and closed loop systems increase their efficiencies by permeating into hotter reservoirs. There are targeted efforts to apply these approaches in very high-enthalpy systems where the circ ulating fluid reaches supercritical conditions, known as "superhot rock" geothermal.[25] These systems leverage reservoir temperatures that typically exceed 400C, and thus require more robust drilling and stimulation techniques. EGS and closed loop systems deployed in these conditions can be extremely efficient, but technologies that enable this potential are still in development.

Refining geothermal resource estimates

Notably, resource estimates for next-generation geothermal have substantial room for improvement, particularly in the Eastern and Central states, Alaska, and Hawaii. Subsurface temperature measurements, the backbone of geothermal resource estimates, are expensive and are rarely known in areas without a history of subsurface exploration (i.e., oil & gas extraction or mining). For example, while there are about 56,000 measurements of subsurface temperature in Texas, there are 29 measurements in Georgia.[26] Eighteen U.S. states have fewer than 100 subsurface temperature measurements, 14 have fewer than 20, and 6 have none at all. Hawaii, a state created by volcanoes, only has two measurements, and Alaska, three times the size of Texas with a volcanic history of its own, has 26. These states have lacked the type of industrial-scale subsurface industry that drives robust public data collection; however, the advent of next-generation geothermal technologies may spur a renewed public interest in subsurface understanding, and significantly improve the potential of next-generation geothermal resources in these data-sparse locations.

Geothermal market development to date in the United States

The conventional geothermal industry in the U.S. is composed of 93 power plants providing 3.7 GW of total capacity in California, Nevada, Oregon, Idaho, Utah, New Mexico, and Hawaii. While a generation source of regional importance—geothermal sources provided 6 percent of power in California[27] and 4 percent of power in Nevada in 2022[28] – the industry provides only 0.4 percent electricity on the U.S. grid overall.[29] Between 2016 and 2021, seven new geothermal plants with a cumulative capacity of 186 MW were brought online, although only one of those plants was at a truly new resource. In the same span, 11 plants retired, subtracting 103 MW. These retirements were driven by the age of the existing geothermal power plant—nearly half the geothermal plants online today are more than 30 years old. In some cases, retired "flash" plants—in which subsurface fluids are hot enough to boil and directly drive a turbine at the surface—were replaced with newer "binary" plants,[30] in which subsurface fluids are used to heat a secondary fluid to drive a turbine. There are eight major conventional geothermal developers, although the top three developers represent more than 75% of the market.[31] Recent clean firm mandates in California have spurred new power purchase agreements in California since 2021 (see Chapter 2).

Overall geothermal attributes & value

Next-generation geothermal could capture a significant share of the power market because of multiple value propositions. It is clean firm[e], flexible; requires a small land footprint and no additional energy input; and is exposed to minimal supply chain risk (Figure 3). It is among the few options that can provide the clean firm power necessary to enable widespread deployment of variable renewables, such as solar and wind energy. It is also positioned to deliver that power flexibly, effectively offering needed long-duration energy storage grid benefits by storing energy in the subsurface when demand is low and releasing it when demand is high. These capabilities make it both a useful grid asset and a potential generation source for other power users like behind-the-meter industrial centers with high electricity demand, data centers, or direct air capture facilities.[32] Geothermal technologies require some of the smallest land area per kilowatt of any energy technology, firm or renewable.[33] Next-generation geothermal can also scale supported by the availability of workers with translatable skillsets, many from the oil & gas sector.

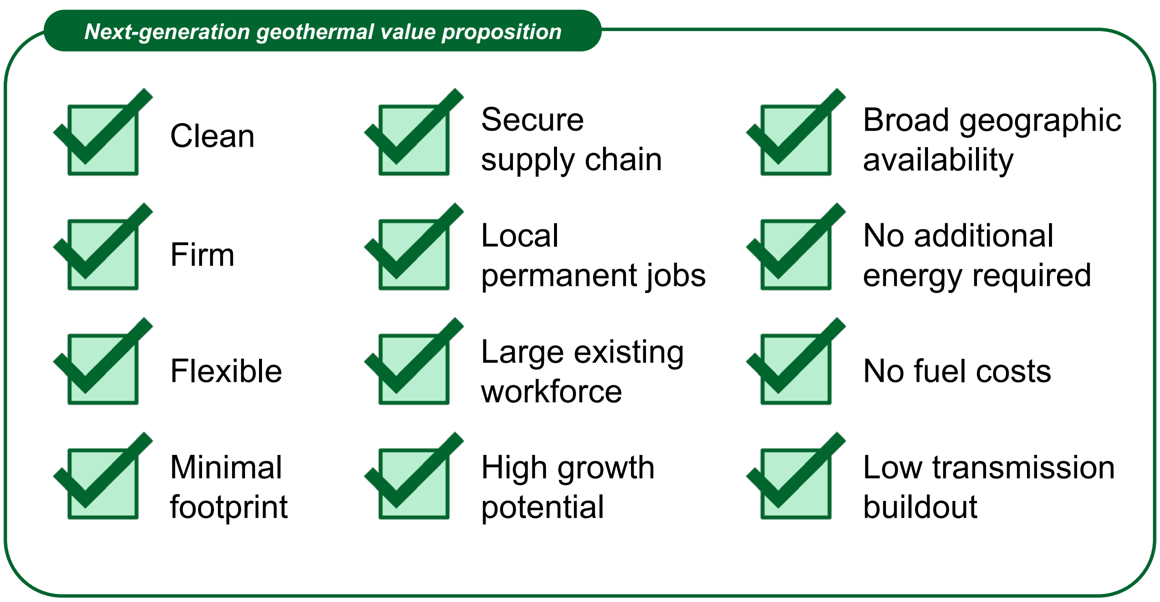


Figure 3: Features of next-generation geothermal power

Market for clean firm power

System-level decarbonization modeling suggests that the U.S. will need to quadruple the existing clean firm power supply available on the grid today, adding between 700 and 900 GW by 2050 to build a decarbonized, functioning grid system capable of supporting wind and solar buildout and increased demand (Figure 4). Throughout this report, we define "clean firm" generation sources as technologies that have a high capacity credit[f] and low carbon emissions. Increased reliance on weather-

e see: www.eia.gov/tools/glossary/index.php?id=F

f Capacity credit is a measure of the contribution of a power plant to resource adequacy, meaning the ability of a system to reliably meet demand during all hours of the year.

dependent renewable energy sources has made it more challenging for grid operators to balance electricity supply and demand. Daily fluctuations in electricity supply from solar and wind sources can exceed 100%, requiring systems to drastically cut and increase power supply over the course of the day to ensure the load on the grid is balanced.[34] Clean firm power facilitates grid balancing while furthering progress towards decarbonization targets.

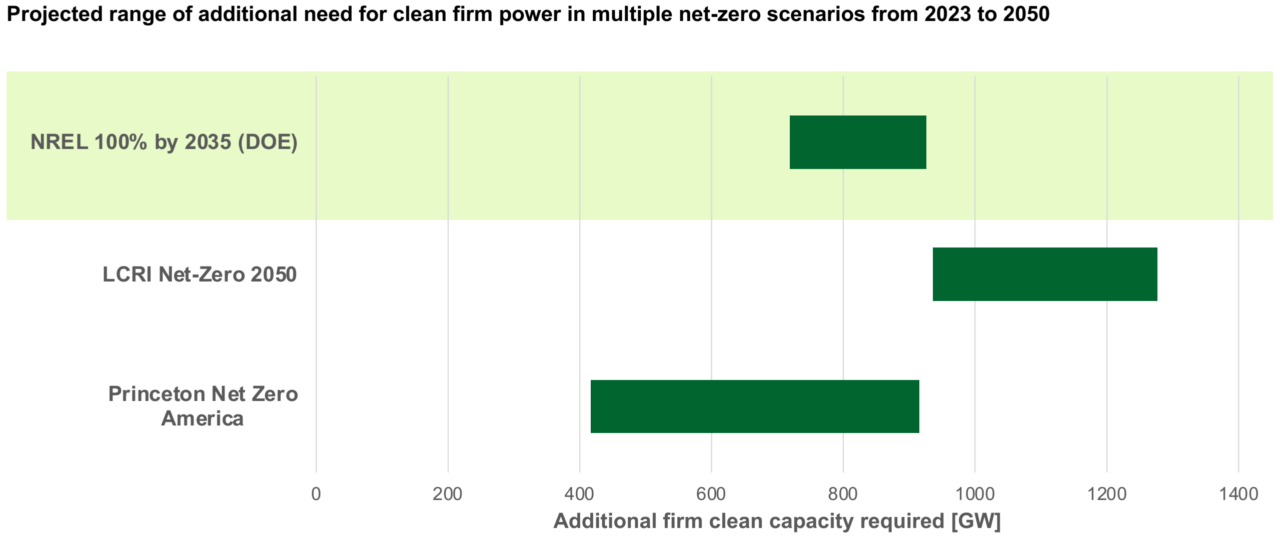


Figure 4: Additional clean firm power needed for the United States to reach grid decarbonization goals by 2035, across three different economy-wide assessments[g]

Simultaneously, projections of electricity demand growth have doubled. The nationwide forecast of electricity demand growth by 2028 increased from a projection of 3.8% in 2022 to 7.8% in 2023,[35] and the projected growth in peak demand estimated, both in winter and in summer, increased from zero to multiple gigawatts in some load-serving entities. Figure 5 shows the planning areas with the largest increases observed in summer, but winter peak demands have been increasing by similarly large amounts.[36] **These increases require utilities to plan for 17 *additional* GW of capacity beyond what was planned for only a year ago.[37]** Increases are being driven by large new consumers that require firm power, such as manufacturing plants and data centers.[38]

The additional cost to develop a balanced, decarbonized electricity system using only commercially available technologies today can be hundreds of billions of dollars. Low-cost, commercially available variable renewable technologies are the backbone of any future decarbonization scenario.[39] However, a broader suite of clean firm generating technologies, some of which have yet to be fully commercialized, are also needed to avoid large system costs and infrastructure buildouts resulting from full decarbonization. The incremental cost of decarbonizing the grid by 2035 is lowest with deployment of a diverse array of technologies, including technologies not yet deployed at scale such as that of next-generation geothermal.[40][41] Independent analysis of California and the Western Interconnection found that the cost of decarbonizing an electricity system with only variable renewables is up to 40 percent more than in a scenario in which currently nascent clean firm technologies are included.[42]

g Notes: Sources: **NREL**: Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035 (nrel.gov); **LCRI**: Executive Summary | LCRI Net-Zero 2050 (epri.com); **Princeton**: Net-Zero America Final Report Summary

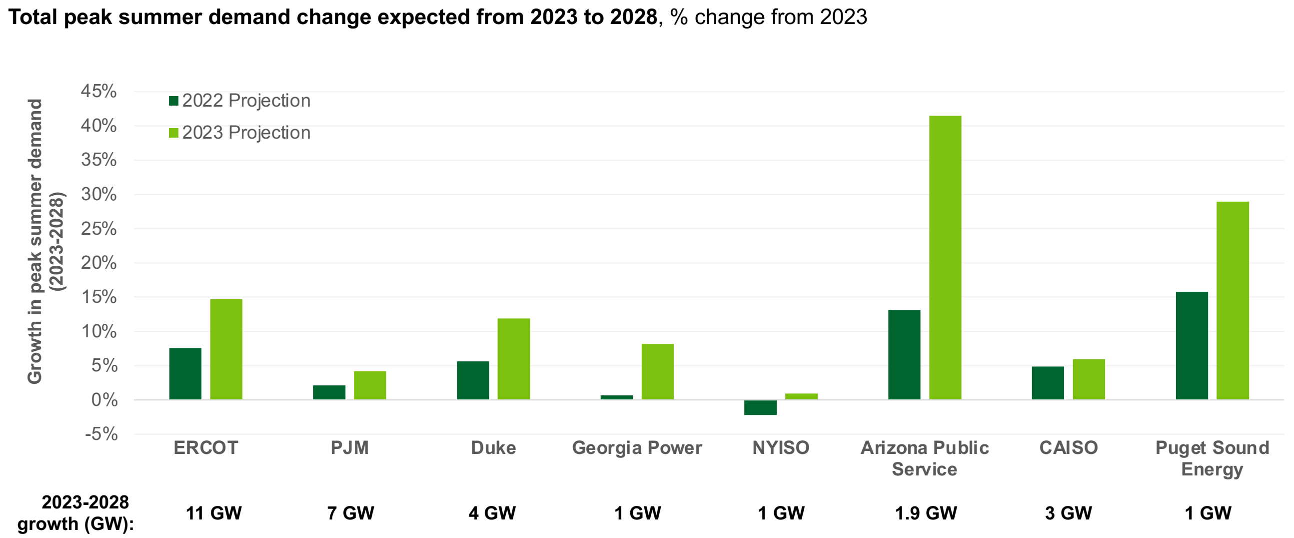


Figure 5: Total peak summer demand increases in areas with the highest projected load growth changes[h]

To fully decarbonize a grid, operators eventually need to add sources of clean firm and dispatchable capacity.[43] As seen in California, once enough variable sources of renewable energy come online, more flexible dispatchable power generation or energy storage is required. For power purchasers or developers looking to compare technologies, levelized cost of electricity (LCOE) can be misleading because it does not capture many dimensions of cost and value, including system-wide cost and plant profitability. Other metrics should also be considered. For instance, "capture price" is a resource's time and generation-weighted price on the grid and may be higher or lower than the simple average wholesale price on a grid depending on a technology's characteristics. Profitability-adjusted LCOE, net value of electricity, and levelized value of electricity are all other metrics that try to comprehensively capture technology costs and benefits.[44 45 46] The Lazard LCOE+ analysis recently proposed another metric called "firming cost" to estimate the additional grid-level costs to accommodate entry of variable capacity on certain grids.[47] A multi-dimensional view of costs, prices, and value can help assess the cost competitiveness of clean firm power sources with higher average costs but no need for supplemental dispatchable power or storage."

The combination of large near-term grid system imbalances and the cost of rectifying these imbalances with existing technologies are driving buyers to pay between $70-$100 per MWh for the procurement of new clean firm geothermal power (Table 1), and geothermal has emerged as a valuable supplier in this market. The market for clean, firm power has two major buyer classes: (1) vertically integrated electric utilities that must satisfy clean electricity mandates while maintaining grid functionality at the least cost; and (2) public and private purchasers of clean energy due to a variety of decarbonization procurement goals. In the utilities market, clean energy standards are creating a market pull for new conventional and next-generation geothermal power today. The best example of this is in California, where a ruling by the California Public Utilities Commission mandating the procurement of 1 GW of clean, firm power by 2026[48] has driven the signing of 262 MW of new conventional and next-generation geothermal power purchase agreements at and exceeding $70/MW.[49] Most of the PPAs listed in Table 1 after 2021 are responsive to this mandate, and this total capacity represents four times the total geothermal capacity contracted nationwide the year before the mandate.[50] However,[51] it should be noted that such a mandate impacts energy development in other states: much of this power is not being developed in California; rather, it is being developed in neighboring Nevada and being sold into markets in California.

h Notes: Figure adapted from 2023 National Load Growth Report; **Puget Sound Energy:** Puget Sound Energy Demand Forecast; **CAISO:** 2022 Integrated Energy Policy Report Update; **Arizona Public Service:** 2023 Integrated Resource Plan; **NYISO:** 2022 and 2023 Load & Capacity Data; **Georgia Power:** Integrated Resource Plan; **Duke:** Carolina Resource Plan; **PJM**: Energy Transition in PJM; **ERCOT:** 2022 and 2023 Long-Term Load Forecast

Table 1: Recent public power purchase agreements for geothermal and next-generation geothermal projects

Purchaser	State	Geothermal Supplier	State	Size [MW]	Pricing [$/MWh]	Term [yrs]	Year Signed
Imperial Irrigation District	CA	Controlled Thermal Resources	CA	40	$75	25	2020
Southern California Public Power Authority	CA	Open Mountain Energy	NV	3	$67	25	2020
Southern California Public Power Authority	CA	Open Mountain Energy	NV	12.5	$70	25	2020
Southern California Public Power Authority	CA	Ormat	CA	16	$68	20	2020
Hawaii Electric Light Company	HI	Puna Geothermal Venture	HI	46	$70	30	2020
University of Utah	UT	Cyrq	NV	20	Undisclosed	25	2020
Monterrey Bay Community Power	CA	Coso	CA	56	Undisclosed	15	2020
Silicon Valley Clean Energy	CA	Coso	CA	33	Undisclosed	15	2020
Nine California Clean Choice Aggregators	CA	Fervo	NV	20	Undisclosed	15	2022
Ava Community Energy	CA	Fervo	NV	40	Undisclosed	40	2022
Clean Power Alliance	CA	Fervo	NV	33	Undisclosed	15	2022
Nevada Energy	NV	Eavor	NV	20	Undisclosed		2022
Sacramento Municipal Utility District	CA	Calpine	CA	100	$99	10	2022
Google	NV	Fervo	NV	3.5	Undisclosed		2022
Port of Oakland	CA	Calpine	CA	2	$70	12	2023
Northern California Power Agency	CA	Calpine	CA	100	Undisclosed	12	2023

Public and private energy purchasers have also driven recent high-value geothermal PPAs. These deals are driven by growing private-sector interest to commit to the procurement of clean firm power sources that match their demand 24/7 without offsets. In May 2023, Google announced a direct power purchase agreement with Fervo Energy, a next-generation geothermal developer, to provide clean firm power to its data centers.[52 53] Microsoft also signed a 10-year power purchase agreement with geothermal developer Contact Energy in New Zealand in 2023.[54] Similarly, multiple public Community Choice Aggregations (CCAs) have driven recent high-value PPAs—Sonoma Clean Power has signed multiple geothermal PPAs recently, with a goal to drive the buildout of 600 MW of incremental local geothermal capacity.[55]

Market for flexible power

Increases to overall demand and increasing variability in supply are also forcing a market for new *flexible* clean electricity sources—sources that can quickly and cost-effectively ramp up and down in response to the diurnal electricity supply patterns created by variable renewable energy sources. Increased variable energy penetration in electricity markets drives greater volatility in electricity prices, including by creating market conditions in which electricity prices are negative.[56] Greater system flexibility is needed to maintain supply-demand balance in the grid; thus, fast-ramping generators with low fixed costs, which can save money by only generating when electricity prices are high, and energy storage devices that shift generation to valuable periods can have a competitive advantage over baseload generators in a grid with significant variables penetration.[57]

Few technologies today can dispatch clean energy flexibly. Commercially available 4-hour batteries can provide electricity during midday summer demand peaks, but the technical readiness of longer-duration storage technologies is still evolving.[58] Pumped storage hydropower is the primary source of longer-duration energy storage needs today; however, future development is limited by land use suitability and climate uncertainty.[59] Nuclear power can ramp up and down; however, long restart times and high fixed operating costs make flexible nuclear generation economically undesirable.[60] Grid operators today rely on fossil fueled "peaker" plants[61] to provide grid flexibility over longer timescales,[62] but reducing the emissions from these plants will be challenging because it is not yet clear how technically viable flexible carbon capture will be when applied to these plants.[63]

Geothermal plants can satisfy market demand for flexible power through changes to operations,[64] potentially doubling their value on the electric grid.[65] [66] While geothermal plants today have been used continuously at maximum capacity, as there has been no market incentive to limit production, geothermal plants have limited costs associated with ramping up or down.[67] An increasing need for flexible generation is driving geothermal operators to investigate operational practices that allow geothermal plants to bank energy in the subsurface during times when electricity supply is plentiful and prices are low, and release that excess energy during times when supply is low and prices are high. This capability can enable geothermal energy to shift generation to respond to diurnal and seasonal fluctuations in demand, with round-trip energy storage efficiencies of 59–93%, effectively allowing operators to capitalize on owning both a power and a long-duration energy storage resource.[68] One study finds that aggressive implementation of flexible geothermal operations can also reduce the cost of fully decarbonizing the Western Interconnection in 2045 by up to 25 percent.[69]

Geothermal value chain & workforce

A workforce of over 300,000 that exists today already possesses skills and expertise necessary for geothermal power development (Figure 6. These workers are largely in the oil & gas and electric power industries,[70] but the robust infrastructure of training and recruitment that creates these skillsets can also be used for geothermal development. The total number of jobs needed for a mature geothermal industry is less than the size of the existing workforce in occupations with adjacent transferrable skills (Figure 6. Furthermore, substantial shares of these jobs are permanent. Geothermal power creates between three to four times the number of long-term jobs per megawatt as solar and wind[71] [72], with potential amplification due to the highly local nature of those jobs. Such opportunities for fossil fuel workers would also provide further options for this workforce to participate in the energy transition as the economy decarbonizes, as well as the corresponding economic benefits.

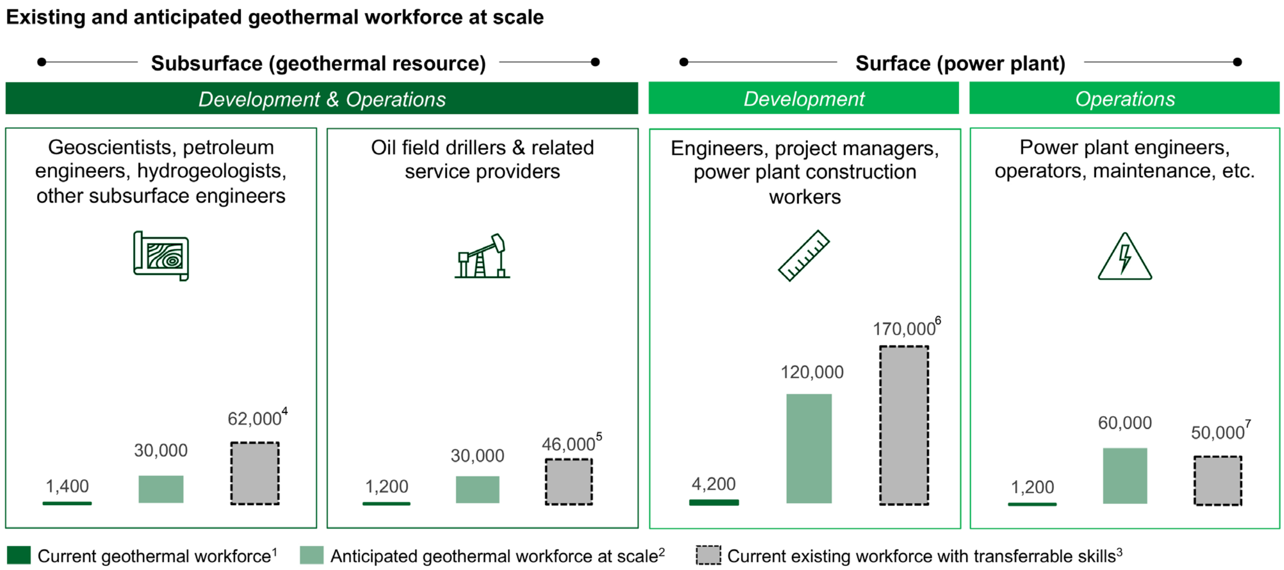


Figure 6: Geothermal workforce along each step of the value chain[i]

Similar skillsets are needed for both the development and the longer-term operations of the subsurface resources driving geothermal power. Developing a geothermal resource requires subsurface characterization to understand rock temperature, permeability, and other suitability features, and drilling and hydraulic fracturing (if necessary) to create the fluid pathways. Operating a geothermal plant requires monitoring to ensure proper flow rates and temperatures are maintained, as well as additional drilling and hydraulic fracturing as needed. About 61% of the total oil & gas workforce available today is involved in those activities and has skills directly transferable to geothermal development and operations right now given appropriate on-the-job retraining.[73] This total is about half the approximately 120,000 workers expected for subsurface activities in a next-generation geothermal workforce at full scale.[74] This could imply a relatively efficient ramp-up of the necessary workforce; however, because workers in the oil & gas industry are among the highest-paid in the energy sector,[75] geothermal developers may need to pay high wages to compete.

Above-ground power plant development and operations skills are also largely transferable from other industries. Geothermal power plants use the same processes (steam turbines) to produce energy as most fossil-powered power plants on the grid today; the only fundamental difference is the heat source.[76] There are about 170,000 workers in the U.S. designing, engineering, managing, and constructing electric power plants, and about 50,000 workers operating power plants (Figure 6). Retraining to handle some of the unique attributes that come from working with geothermal fluids as opposed to fossil fuels, such as managing corrosion of plant components due to geothermal brines[77] may be required, but the core activities remain the same. A mature next-generation geothermal industry would require approximately 120,000 workers for power plant design & construction, and about 50,000 power plant operators (Figure 6)—these totals are within scope of the existing workforces available today, providing important transition opportunities for oil and gas workers.

i Notes: 1. 20% full-time positions -- Green Jobs through Geothermal Development (geo-energy.org); 2 Sum of workforce divisions extracted from USEER 2023 Public Data using 2022 data; 3 Modeled in consultation with Boston Consulting Group based on analysis supporting Geothermal: Policies to Help America Lead – Third Way; scaled from 33 GW to represent 90 GW of capacity; 4 Sum of 2022 workforce size reported to the Bureau of Labor Statistics for the following subsets of Oil & Gas Extraction: 47 (Construction), 49 (Installation), 51 (Production), and 53 (Transportation & material moving); 5 Sum of 2022 workforce size reported to the Bureau of Labor Statistics for the following subsets of Oil & Gas Extraction: 47 (Construction), 49 (Installation), 51 (Production), and 53 (Transportation & material moving); 6 Sum of the current workforce size reported to the Bureau of Labor Statistics for the following subsets of Electric Power Generation, Transmission, and Distribution: Architects, Surveyors, and Cartographers; Engineers; Drafters, Engineering Technicians, and Mapping Technicians; Life Scientists; Physical Scientists; Supervisors of Protective Service Workers; Firefighting and Prevention Workers; Other Protective Service Workers; Construction Trades Workers; Other Construction and Related Workers; Extraction Workers; Electrical and Electronic Equipment Mechanics, Installers, and Repairers; Vehicle and Mobile Equipment Mechanics, Installers, and Repairers; Other Installation, Maintenance, and Repair Occupations; Assemblers and Fabricators; Metal Workers and Plastic Workers; Motor Vehicle Operators; Material Moving Workers; 7 Sum of the current workforce size reported to the Bureau of Labor Statistics for the following subsets of "Electric Power Generation, Transmission, and Distribution": Computer Occupations, Mathematical Science Occupations, Plant and System Operators, Other Production Occupations

Geothermal environmental impacts

Next-generation geothermal applies subsurface engineering technologies leveraged by the oil & gas industry, such as hydraulic fracturing, that have caused environmental harms in the past and can create community trust concerns. Early engagement with communities and thoughtful analysis that delineates differences and proposes mitigations for risks can help ensure these harms do not occur in the next-generation geothermal industry. Because the industry is at the pilot scale and on the cusp of scaled expansion, an opportunity exists to collaboratively develop processes and methods for reservoir creation that eliminate or minimize the use of hazardous materials. Engaging in early, frequent, transparent, and two-way dialogue with communities can provide a strong foundation of community trust.

The most pertinent environmental impacts that next-generation geothermal operators consider are air quality, water quantity, water quality, and induced felt seismicity:

Air quality

All emissions from geothermal plants are regulated under the Clean Air Act.[78] Geothermal plants do not emit the air pollutants typical of fossil generation plants, such as sulfur dioxide, nitrogen oxides, and fine particulate matter.[79] In conventional geothermal systems, hydrogen sulfide can be released by a flash geothermal plant during operation, but next-generation binary geothermal power plants have effectively zero emissions.

Water quantity

Water consumption in geothermal operations ranges widely, but because geothermal power plants are designed to circulate, rather than consume water, most water used in operations is reinjected into the same underground reservoir from which it was drawn. Overall, conventional and EGS plants can consume between 0.3 to 0.73 gallons per kilowatt-hour,[80] meaning that a 30 MW EGS plant may consume between 2 and 6 million gallons of water per year. This is a lesser average water demand than that of coal, natural gas, nuclear, and biomass power.[81] Geothermal power at scale could represent up to 8.5 percent of total electric generation nationwide, but it would represent only 1.1 percent of power-sector water withdrawals.[82]

Most geothermal water use needs can be supported by non-freshwater resources, such as municipal wastewater and brackish water, so freshwater demand is low.[83] For example, the Geysers Geothermal Field in northern California uses secondary treated wastewater for geothermal injection activities.[84] Freshwater consumption for geothermal plants is between 0.4 to 0.5 gallons per kilowatt-hour, which is significantly less than for most fossil generation technologies and on par with that for other renewables such as solar and wind.[85] Geothermal deployment could therefore be supported in areas where freshwater is limited, which is frequently the case for areas with high geothermal potential. There are ongoing research activities to evaluate water scarcity and use in the context of geothermal deployment pursued across academia and industry.

Water quality

Groundwater contamination has never been connected to conventional geothermal development,[86] and despite the technological alignment between oil & gas hydraulic fracturing and EGS, many of the water contamination risks associated with oil & gas hydraulic fracturing do not apply to today's EGS developments. These differences include:

1. **Fluid chemical composition:** Hydraulic fracturing in EGS is a chemically distinct process from hydraulic fracturing for oil & gas. There are fewer additives in EGS hydraulic fracturing; these can include friction reducers (polymers), viscosifiers (such as guar gum), tracers (chemicals used commonly to track groundwater flow), and proppants (sand and ceramic designed to keep fractures open). Because EGS does not occur in hydrocarbon basins, fouling of shallow freshwater reservoirs with hydrocarbons cannot occur. As the next-generation geothermal industry develops, care must be

taken to ensure that chemical compounds used in hydraulic fracturing operations are not harmful to human or environmental health, safely managed in collaboration with surrounding communities, and wherever possible, substitutions for potentially hazardous compounds are sought. Important considerations in evaluating the risks of hydraulic fracturing chemicals on human and environmental health include indications as hazardous by existing laws such as the Clean Water Act and Safe Drinking Water Act, indications as emerging chemicals of concern, or indications as ecotoxic and/or endocrine disruptors.

2. **Well casing:** The wells used to access EGS reservoirs are fully cased with steel casing, and the void space outside the casing is completely cemented from the bottom of the well to the surface. This is fundamentally different from most oil & gas wells. A fully cased and cemented EGS well increases well integrity and prevents EGS reservoir fluids from interacting with shallow water aquifers. Casings can fail[87]—however, best practices in the industry have demonstrated the safety and efficacy of geothermal well casings if they are properly designed and maintained. Proper well design, execution, and monitoring of well integrity is key to ensuring wells do not contaminate water and soil.

3. **Reservoir depth and type:** EGS reservoirs in basement rock formations are generally much deeper than unconventional oil & gas reservoirs, disconnected hydrologically from any groundwater or near-surface drinking water supplies, and drill through much less permeable rock. The average depth of unconventional oil & gas reservoirs hovers between 4,000 and 5,000 feet,[88] whereas planned EGS reservoirs are developing at 8,000 feet or more. Furthermore, EGS reservoirs are most typically deep in crystalline bedrock, where permeabilities are negligible.[89] The separation of thousands of feet from near-surface drinking water supplies, combined with the low permeability of the rock, makes groundwater contamination from reservoirs highly unlikely.

4. **Fluid circulation:** Hydraulically fractured oil & gas wells must dispose excess fluids to operate; in EGS, fluids are self-contained in a loop that is only open at depth. With binary power plants, geothermal fluids are passed through a heat exchanger to transfer heat energy to a secondary working fluid that drives steam turbines. These closed systems ensure that subsurface fluids are not exposed to the atmosphere or drinking water supplies.

Induced seismicity

The subsurface engineering necessary to create next-generation geothermal plants could induce seismicity felt by communities if mismanaged, and such mismanagement has created community felt seismicity in the past.[90] Fluid movement through subsurface environments can change rock stress and temperatures, which can trigger felt seismic activity as can occur in any subsurface energy industry where the state of stress is changed.[91] Induced seismicity risk associated with geothermal development is mitigated because fluid that is introduced into the subsurface is also removed from the subsurface.[92] This differs from unconventional oil & gas development, in which additional fluids are injected into the subsurface without a similar volume being removed.

The risk of induced seismicity can be managed. DOE has developed a mitigation protocol to address induced seismicity from EGS and required that all funded projects follow this procedure.[93] It includes preliminary screening of potential project locations, community outreach and engagement, development of location-specific criteria, establishment of a seismic monitoring system, quantification of natural and project-induced hazards, assessment of risks, and the development of a risk-based mitigation plan. DOE continues to support activities to ensure risks are mitigated through funded R&D efforts and collaboration with the international community. No induced community felt seismicity has occurred at a DOE-funded project.[94]

Geothermal deployment potential

Next-generation geothermal energy can provide 90-132 GW of electric power to a fully decarbonized grid by 2050, with the potential for significantly more. Electricity system modeling performed independently at NREL and Princeton University indicates that, if expected cost reductions are realized and the Energy Earthshot target is reached by 2035, there is an opportunity for 90-100 GW of next-generation geothermal on the grid in 2050 (Appendix A), a 25-times increase in the amount of geothermal on the grid today. In a case in which land available for other renewables is restricted, over 130 GW of next-generation geothermal may be economically deployed. Significant deployment can occur in the next decade—by 2035, 30-35 GW can be online (Figure 7).

Estimated next-generation geothermal deployment potential, GW

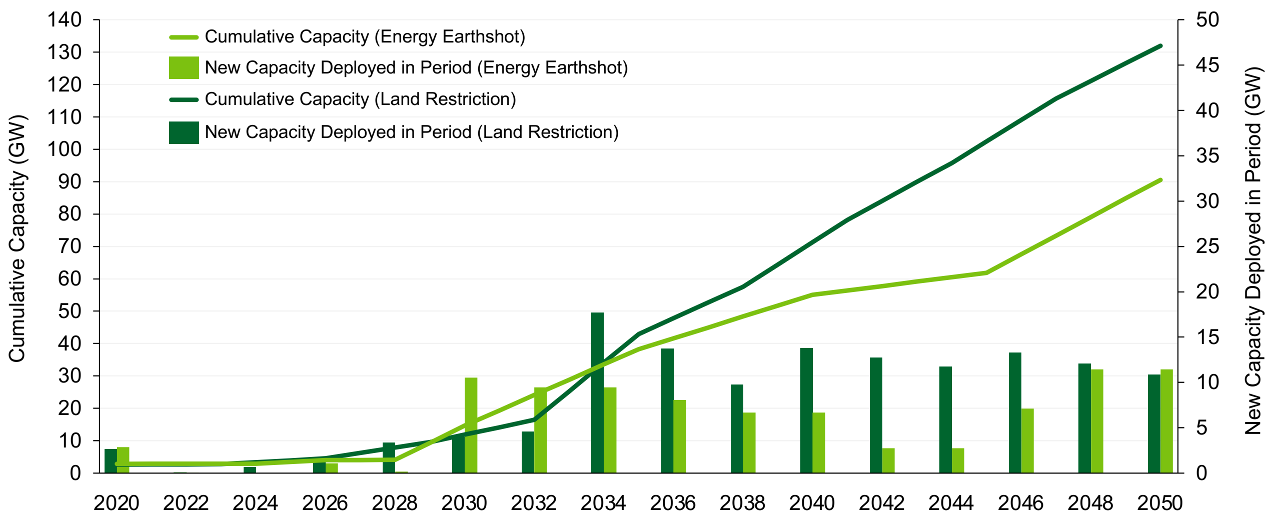


Figure 7: Projected cumulative deployment of next-generation geothermal power until 2050 [left axis] and added capacity in two-year increments [right axis]. Light green scenario represents the projected deployment from the "Energy Earthshot Original" modeling scenario; dark green scenario represents the projected deployment from the "land use restriction" modeling case. See Appendix A for details.

Potential geographic extent of next-generation geothermal deployment over time

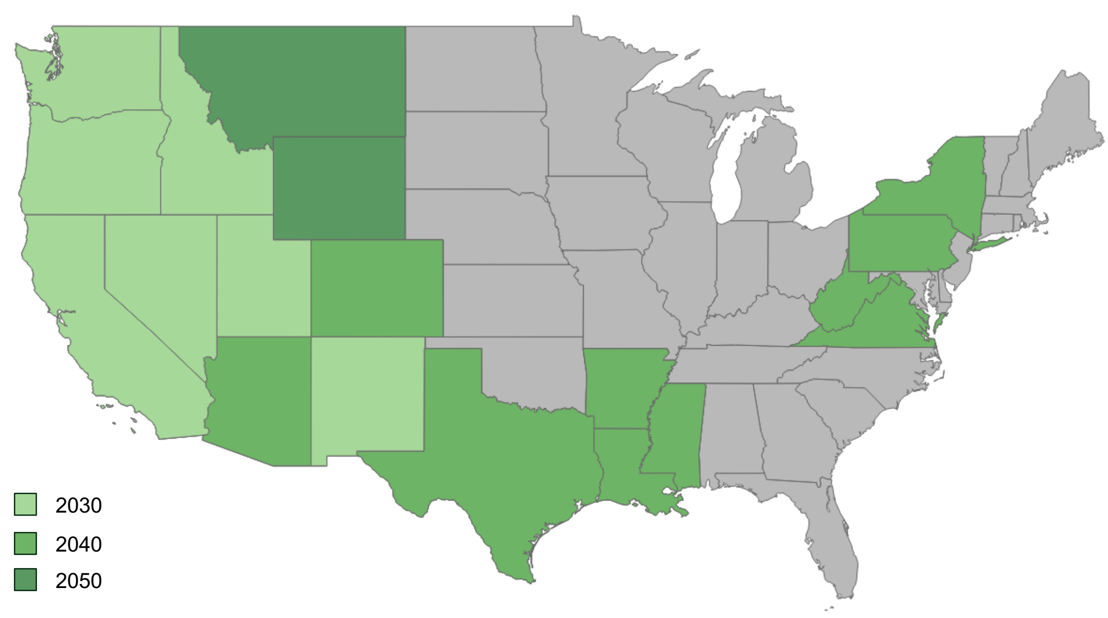


Figure 8: Geothermal deployment over time across the U.S. in 2030 (light green), 2040 (middle green), and 2050 (dark green) based on the "Energy Earthshot Original" modeling scenario. See Appendix A for details.

Geothermal potential doubles if flexible generation is widely adopted (Figure 9). This potential increase is driven by the additional value that can be captured by storing power during low pricing events and discharging it when prices rise. In these cases, next-generation geothermal can represent 171 or more GW on the grid in 2050.

Next-generation geothermal technologies unlock geothermal deployment across the United States. While the bulk of next-generation deployment still occurs in the western U.S., where high subsurface temperatures are more easily accessed, multiple gigawatts could be deployed in Pennsylvania, West Virginia, and Virginia as early as 2035, and Arkansas, Mississippi, Louisiana, and Texas by 2050 (Figure 8). Overall, these modeling results show that by 2050, next-generation geothermal deployment opportunities could exist in at least 18 states, which is three times the number of states that have geothermal online now. Deployment in these states is partially driven by the presence of clean energy standards and renewable power standards, and further adoption or rejection of such standards would likely affect the reach of next-generation geothermal.

Geothermal potential also increases if widespread deployment of variable renewable generation sources faces major deployment challenges, or if other key nascent technologies do not sufficiently commercialize. In scenarios in which renewable energy buildout is constrained by limited availability of land, which could arise due to siting conflicts or other policy or regulatory factors[95] geothermal potential increases by more than 25 percent (Figure 7). In scenarios with limited deployment of hydrogen and direct air capture technologies, geothermal potential triples to nearly 300 gigawatts, as few options are available to provide needed clean firm capacity.

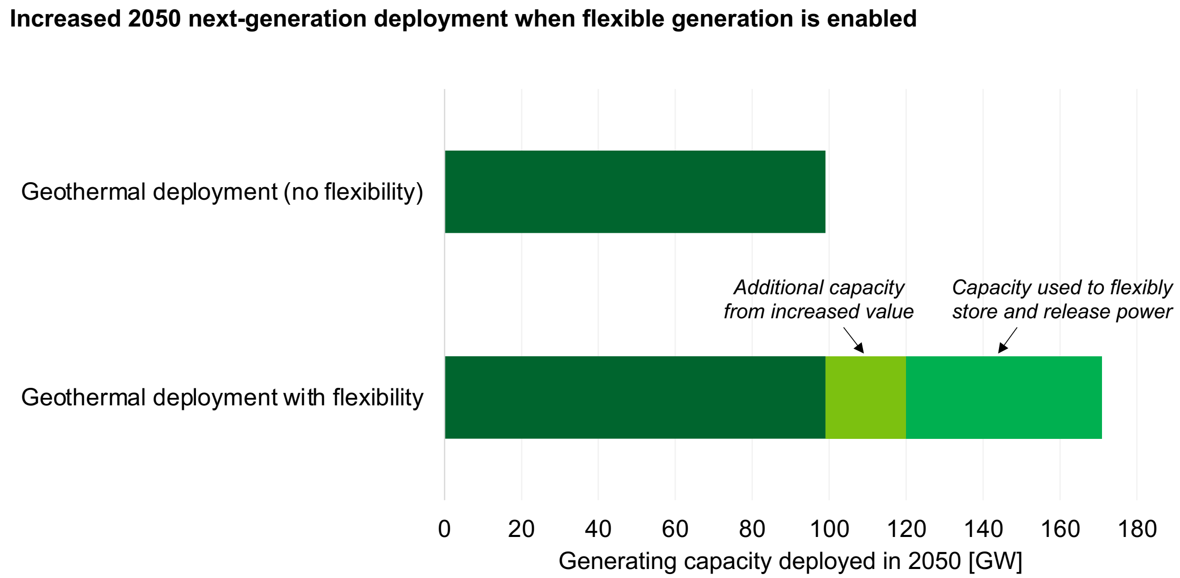


Figure 9: Comparison of deployment with flexible generation. Compares the "Energy Earthshot Update, GenX" model scenario to the "Flexible Generation, GenX" model scenario (see Appendix A for details).

Chapter 2: Next-Generation Geothermal Technology and Market

Key Takeaways:

- Despite cost-competitiveness, conventional geothermal project development is constrained by a limited resource base, risk of incorrect resource characterization, inconsistent repeatability, long project lifecycles, and investment perceptions shaped by select project failures.
- Next-generation geothermal technologies transfer risk from resource identification to engineering capabilities, creating the potential to sidestep issues that have traditionally held back the geothermal industry.
- Iterative improvements enabled by modularity in drilling operations have cut enhanced geothermal system drilling costs in half over the last two years.
- Further drilling improvements and advances in drilling technology and techniques, modularity, and power plant scale suggest that DOE's Enhanced Geothermal Shot target of $45/MWh is achievable, making EGS cost-competitive with other clean firm energy technologies by 2035.
- Observed and potential future cost reductions have catalyzed substantial recent momentum in the next-generation geothermal market, as the first at-scale demonstrations are under construction, and capital raised by developers has increased year over year since 2021.

Current challenges for conventional geothermal project development

Despite cost advantages and a century of development in the U.S., new conventional geothermal project development is primarily limited due to a geographically constrained resource base and rare subsurface conditions suitable for development described in Chapter 1. Development is also limited by the impacts on project development from the risk of incorrect resource identification, inconsistent repeatability, long project lifecycles, and past select project failures leading to large investment losses. Conventional geothermal power is one of the lowest-cost options for baseload power generation, yet it represents only 0.4% of American power generation.[96] With an estimated LCOE of 61-102 $/MWh, conventional geothermal power falls mostly within the same cost range as coal (68-166 $/MWh) and gas combined cycle (39-101 $/MWh).[97]

Resource identification risk in conventional project development has been shown to deter investment.[98] The correct identification of subsurface conditions is critical to project success, but roughly 20% of projects do not find the intended resource.[99] While initial subsurface characterization is possible with techniques that do not require drilling, full confirmation of a resource's characteristics and sustained production can only happen after exploration and confirmation wells are drilled and begin to produce fluid flow. This represents a significant portion of overall drilling cost, which is the largest project cost driver (40% or more of project costs).[100] [101] This large investment is all exposed to risk—if a resource is incorrectly characterized, there is little recourse in a conventional project, and the entire project could fail.

Additionally, the geological uniqueness of each development makes it more difficult to transfer learnings from one site to another. Although conventional geothermal resources have archetypal characteristics, there is enough uniqueness between sites that there are limited opportunities for iterative improvements. Nonetheless, significant effort has led to progress in recent years.[102] [103] [104] [105] As an example, the adoption of play fairway analyses to geothermal resource identification, requiring the synthesis of varied geologic and geophysical information (much of which derived from DOE sponsored research) has aided in the identification of hidden conventional geothermal systems.

All geothermal projects are currently subject to long timelines driven by complex permitting processes and multiple points of contact with permitting and licensing agencies.[106] The total development timeframe for geothermal projects today is 7-10 years.[107] While reforms are being actively deliberated through various channels driven by legislation, rulemaking, and technology changes[108] (see Chapter 4), this long lead time dampens appetite for project development and potential offtake agreements.

Finally, some select project failures have increased the perceived risk levels of new conventional projects for potential investors and lenders. The most critical information needed for project development is the power output estimate, and that number is subject to uncertainty that damages investor confidence. For instance, the power output of multiple major geothermal power developments in the Philippines in the 1990s had to be revised downwards midway through the project lifecycle,[109] with negative effects on project economics. At the Blue Mountain geothermal plant in Nevada, an estimated capacity of 50 MW[110] was also revised downward after operations began,[111] which eroded trust in resource estimates. For institutional banks with very low risk tolerances, the track record of overestimated capacity, or potential failure (albeit with older technology), significantly increases the burden of proof for any low-risk and low-cost debt in a geothermal project.

Investment committees typically require unlevered rates of return of 15-20% on geothermal projects, which are higher than is typically possible.[112] These risks and others discussed in the industrial literature[113] compound to drive up the cost of capital and drive down the expected returns. The risks and challenges discussed, plus difficulties in financing geothermal projects, have contributed to more conventional projects being canceled than have come online in the last 10 years.[114]

Next-generation geothermal: Changing risk profiles

The technical innovations and best practices from the oil & gas industry that underpin next-generation geothermal technologies fundamentally shift the risk profiles of geothermal developments. Across three major risk categories—resource, technology, and environmental—next-generation developments will have different characteristics from those of conventional developments. While the major risks in conventional projects are around resource identification and confirmation, the main risks in next-generation geothermal projects are around technological and engineering capabilities. Further, because the resource itself is engineered, an underperforming resource can be modified to correct insufficient flow conditions.

By shifting the main risk from resource identification to engineering—a category that can demonstrate a new track record and continual improvements—next-generation geothermal has the potential to leverage a new and massive heat resource while sidestepping issues that have traditionally held back the geothermal industry. Both EGS and closed loop geothermal developments require the confluence of fewer subsurface conditions than conventional systems and involve a less complicated characterization process. The key properties next-generation systems need measured are temperature at depth, rock properties, and stress direction, none of which require test wells that produce fluids (a large cost driver in conventional geothermal exploration).[115]

While the technology associated with conventional development is well-established and continually improving, both EGS and closed loop geothermal have evolving technology and environmental risks that will need to be addressed for deployment at scale. EGS, which has an estimated technology readiness level (TRL) of about 7, involves the application of existing technologies developed for unconventional oil & gas recovery in new, high-temperature environments. This successful deployment of EGS technology has not yet been demonstrated in varying conditions, or in greenfield sites without previous subsurface characterization. Closed loop geothermal systems, which have an estimated TRL of about 6, require drilling long well loops at depth and using new casing approaches[116]—many greenfield closed loop geothermal scenarios include drilling over 7 km in depth, with hundreds of kilometers of lateral length.[117] Simultaneously, the environmental risks highlighted in Chapter 1, particularly relating to water use and induced seismicity connected to EGS, must be demonstrated to be manageable or avoidable through using best-available protocols.

Next-generation geothermal: emerging modularity driving cost reductions today

This repeatable, modular design for next-generation geothermal affords a clear path to iterative improvements in processes at each successive well within a project. EGS projects are composed of many individual 2-5 MW or more hydraulically fractured well pairs within a single site, such that one 30 MW EGS facility could comprise about 20 wells. The rate at which costs decline from well to well due to iterative improvements at a single site, "learning rate," is a key input to the oil & gas business model. Oil & gas plays, which also consist of many individual hydraulically fractured wells drilled in a single site, consider anticipated learning rates when considering the profitability of development. Learning rates occur because drillers learn new information about the reservoir as they drill, which allows them to optimize drill bit performance, more efficiently use cement & casing, and optimize rig operation speeds. Oil & gas learning rates average about 15 percent today.[118]

Current EGS demonstrations are doubling average oil & gas learning rates, driving cost reductions of up to 50 percent in the last two years. Early data from the DOE-led FORGE site and private sector deployment have shown rapid decreases in drilling times and drilling cost because of operational drilling improvements. Drilling rates (the rates at which drills penetrate the subsurface) at FORGE have improved by over 500 percent since the first well was drilled in 2017 (Figure 10). The private sector has shown how these drilling rate improvements translate to massive cost reductions: recent reports from Fervo's earliest deployments demonstrated a 300 percent increase in drilling rate in the process resulting in drilling costs decreasing from an initial of $9.5 million to $4.8 million over six wells in 6 months.[119]

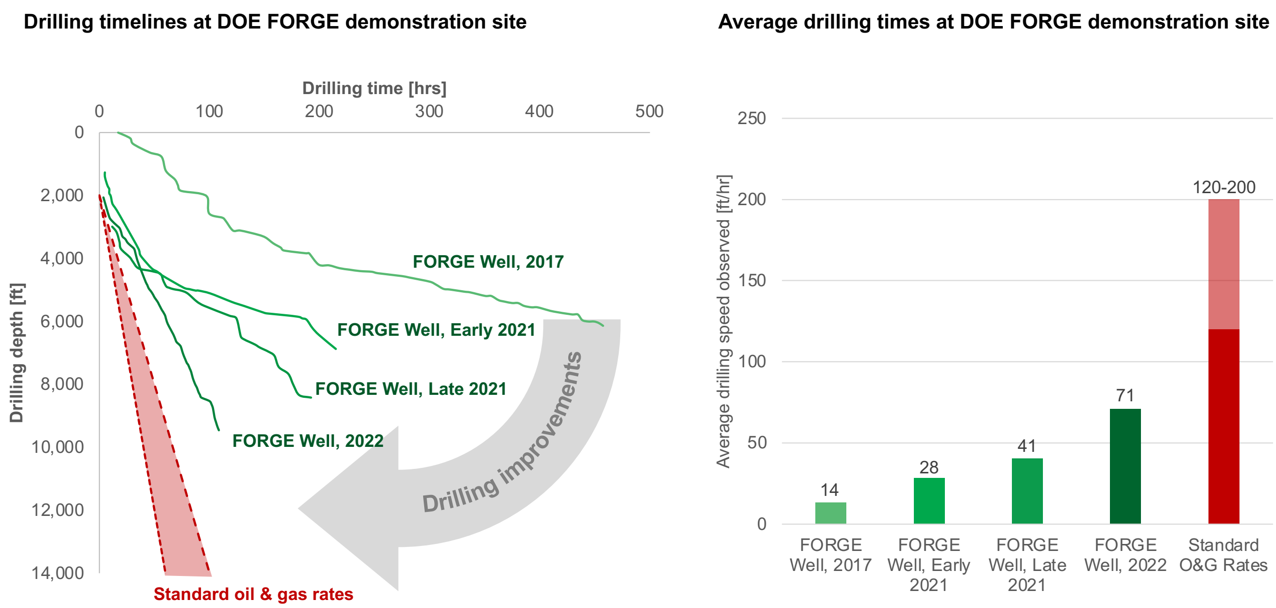


Figure 10: Drilling rate improvements in early next-generation geothermal demonstrations

Closed loop geothermal projects can derive analogous benefits from modularity. A single U-tube closed loop geothermal project leverages multiple "lateral" well loops to increase the surface area needed to conduct heat—these loops can result in up to 90 km of total drilled hole per site.[120] For closed loop geothermal, a 5 km deep well with 20 km of lateral drilling could achieve roughly 1-5 MW capacity, similar to individual EGS wells. The successive development of each individual modular component of a project provides opportunities for cost reductions.

Projected future cost reductions in next-generation geothermal

Iterative operational improvements and new technical advancements can drive next-generation geothermal costs to be competitive with other clean firm sources in the near term. In 2021, DOE launched the Enhanced Geothermal Shot™, part of the Energy Earthshots Initiative™ to promote RD&D to reduce the cost of geothermal power to $45/MWh by 2035.[121] The Enhanced Geothermal Shot[122] targets an aggressive yet plausible path to a 90 percent reduction in the cost of EGS by 2035, to an effective LCOE of $45/MWh. Current cost reductions outpace that estimate (Figure 11). Field evidence resulted in a reduction of the Overnight Capital Cost (OCC) estimate of $27,800 per kW in 2021 to a 2023 estimate of ~$14,700 per kW.[123] The major drivers of this decline are improvements to geothermal drilling, well field stimulation, and economies of scale from potential plant size due to improved flow rates. While these technology improvements were realized for EGS, these drilling improvements drive down costs in both exploration drilling and well drilling across EGS and closed loop geothermal.

Actual next-generation geothermal deployment costs are likely already lower than the 2023 estimate. Beyond drilling rates, flow rates are also a major driver of geothermal productivity and ultimately cost. NREL's "Annual Technology Baseline,"[124] which provides a consistent set of technology cost projections based on industry input, is a commonly used indicator of potential future technology costs. These costs are physically modeled at a base year (2022) and a target year (2035), with a learning curve applied in between. The 2035 Annual Technology Baseline (ATB) estimates reported here assume flow rates of 80 liters per second, and drilling rates of 110 feet per hour in the most aggressive scenario, compared to a 2022 baseline of 40 liters per second and 25 feet per hour. However, recent EGS data published by Fervo reported flow rates of 61-63 liters per second and drilling rates of 40-80 feet per hour, already more than 50% of the way to 2035 estimates and ahead of the 2023 cost estimate inputs.[125]

Capitalizing on the recent improvements to the inputs that drive EGS cost, the industry has an achievable path to further cost reductions that will allow the technology to deliver clean firm power at competitive prices in the near term. With the 47% decrease in cost estimates as a starting point, EGS can reach an OCC of $4,700-5,000 per kW by 2030 with further 33% reductions costs, driven by exploration, well and reservoir construction, and power plant costs. As discussed in further detail in Chapter 3, at this level of OCC, the industry can competitively reach a level of deployment that is sufficient to catalyze self-sufficient and sustained growth.

These cost reductions mainly come from engineering improvements in the subsurface, which interact with process and design to lower overall cost. The reductions in exploration costs flow from a reduction in the number of wells necessary for resource confirmation, in addition to drilling cost reductions realized from both iterative improvements and new technologies. The reduction in well and reservoir construction costs (including materials costs) will flow mainly from iterative and technical drilling cost reductions, including increasing well diameters, and improvements to stimulation capabilities. Power plant cost reductions are derived from economies of scale enabled by higher fluid flow rates from larger-diameter wells and more centralized plant development. This target corresponds to an unsubsidized LCOE of $60-70 per MWh and represents an interim goal to the 2035 Energy Earthshot target of $3,700 per kW with an LCOE of $45 per MWh.

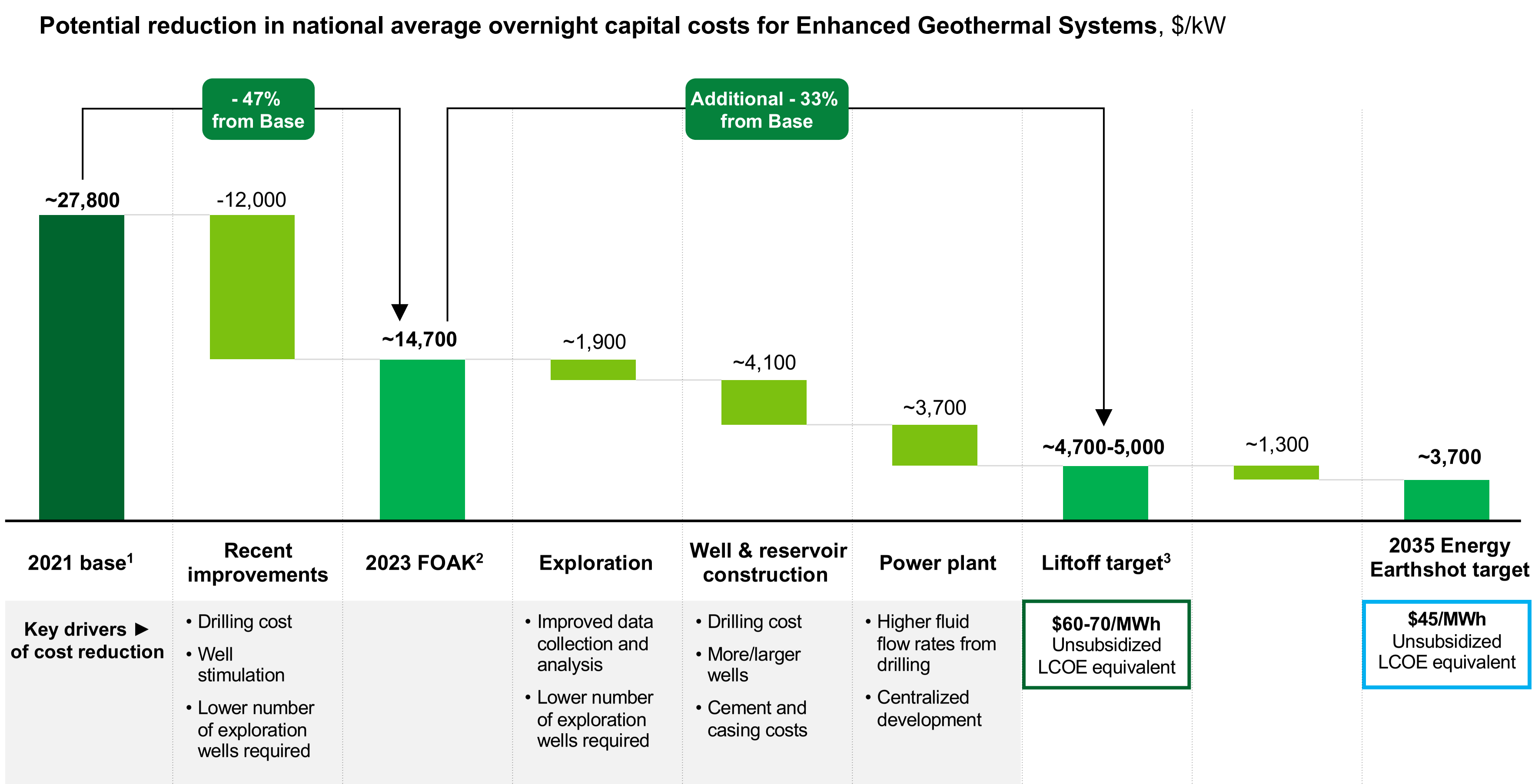


Figure 11: Cost reduction waterfall for EGS[j]

j Notes: 1. NREL ATB 2021 Base Case 2. NREL ATB Advanced Case 3. 2030 target based on trajectory to Energy Earthshot 2035 target

There is also a credible, though ambitious, path for closed loop geothermal systems to achieve cost reductions that allow the technology to deliver clean firm power at competitive prices by 2035 (Figure 12). Taking the same input assumptions as those for the 2035 Energy Earthshot target for EGS, a hypothetical closed loop geothermal system could see its costs fall from an overnight capital cost of roughly $33,000/kw today to roughly $9,000-10,000 per kw by 2035, corresponding to an unsubsidized LCOE of $80-90 per MWh. These reductions would be driven mostly be drilling rate improvements and by the potential to deploy non-steel casing completion techniques—a technical possibility because of the specific design of some closed loop geothermal wells that reduces casing costs significantly by using non-steel casing completion techniques.

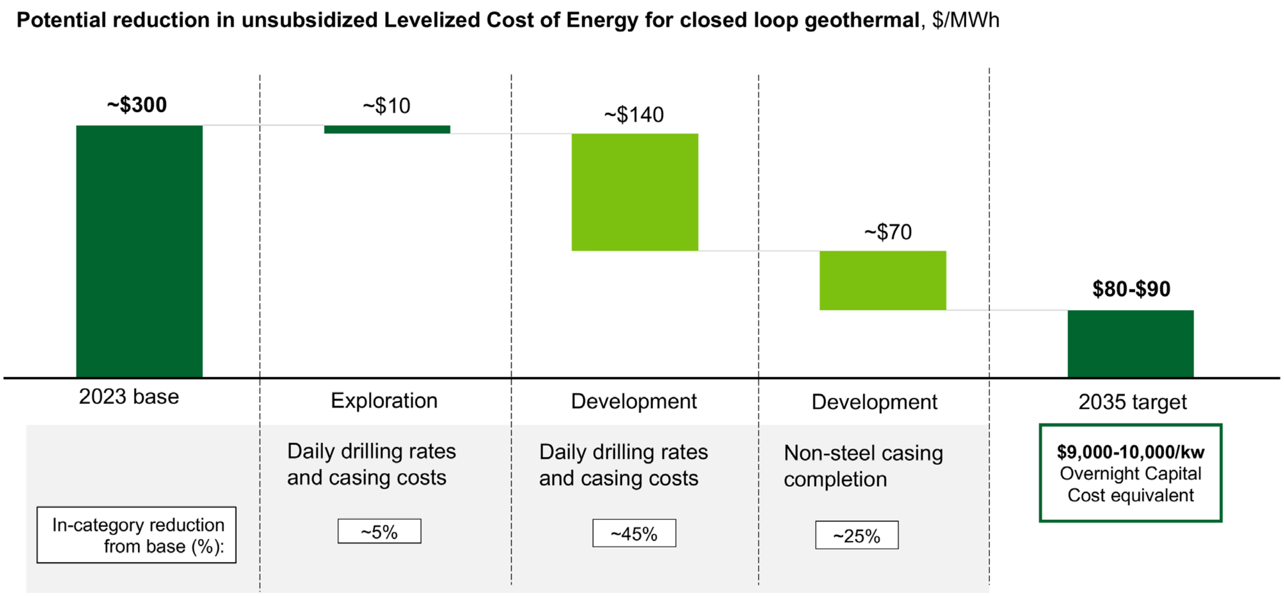


Figure 12: Cost reduction waterfall for closed loop geothermal[k]

The cost improvements described in this section will be driven by further deployment of next-generation geothermal technologies, as well as by key RD&D initiatives. Government-sponsored RD&D has unlocked most of the capabilities that enable next-generation geothermal technologies today. Ultra-durable polycrystalline diamond compact (PDC) drill bits, catalyzed by DOE investments in the 1980s,[126] enable geothermal drillers to achieve drilling rate increases. DOE had an important role to play in the development and testing of hydraulic fracturing technologies in the 2000s, whose recent application to EGS is showing great promise and also unlocked the shale gas revolution.[127] DOE investments in field testing at the EGS Collab site in South Dakota[128] and FORGE, and subsurface engineering RD&D, provided the opportunities to test capabilities that the private sector is now leveraging. DOE's Geothermal Technology Office (GTO) also has a long history of funding micro seismicity research, from collecting and processing said data to understand the subsurface conditions, to developing new downhole sensors that can monitor seismicity in high-temperature environments. Continuing this successful trend of RD&D is essential to further reduce costs. The Enhanced Geothermal Energy Earthshot target set in 2022 not only set the target for where costs could reasonably decline to, but also outlined the key RD&D opportunities needed to achieve those reductions.[129]

Next-generation geothermal costs in 2035

Next-generation geothermal costs are poised to fall below the cost of other clean firm power sources by 2035, according to best-estimate projections. NREL's "Annual Technology Baseline,"[130] which provides a consistent set of technology cost projections based on industry input, is a commonly used indicator of

k Note: Model of U-tube 20,0000 m closed loop system at 5 km depth based on DOE analysis. Drilling rate improvement assumptions applied based on Energy Earthshot analysis. Power plant costs consistent across cases because scale assumed to be the same (unlike EGS case).

potential future technology costs. The 2023 ATB "Advanced Case" cost projections for 2035 places EGS system at $71/MWh in 2035, compared to $50/MWh for conventional, and an estimate of $52/MWh for renewables and 90% matching (from the LDES Council[131]), $66/MWh for nuclear, and $64/MWh for natural gas and CCS (Figure 13). However, the recent reductions in major cost inputs, including a 50% reduction in the current cost, suggest that this is a potentially conservative estimate of the reductions in costs that EGS is poised to make. The Energy Earthshot target of $45/MWh is achievable[l], which suggests that EGS cost will fall below that for other clean firm power.

Projected range of possible 2035 LCOE for clean firm energy technologies, $/MWh

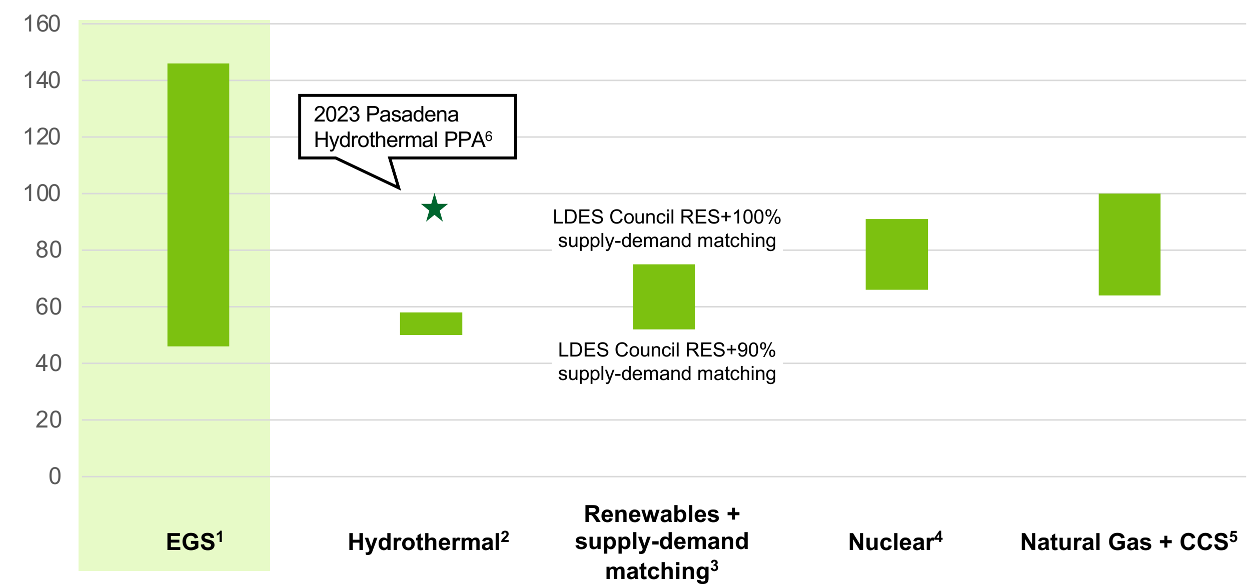


Figure 13: LCOE of comparable energy technologies[m]

Market momentum

Capitalizing on the recent technological improvements and demonstrations, the next-generation geothermal market has shown notable market momentum in the last three years. 2021, 2022, and 2023 saw two, four, and five recorded investments in next-generation geothermal companies, with totals of $68M, $138M, and $190 million invested, respectively (Figure 14).[132] There are currently at least four companies operating in the concept stage, six in the pilot stage, and two companies in the demonstration stage of development worldwide.

Next-generation geothermal companies and startups have reached several major milestones since Fervo Energy signed the first PPA with Google for 24/7 power in 2021.[133] Some notable examples include the completion of Fervo Energy's successful pilot in Nevada,[134] Eavor's 2022 demonstration in New Mexico,[135] the beginning of exploration drilling for the first phase of a 400 MW Fervo Energy project in southwest Utah scheduled to come online by 2028,[136] Sage Energy's completed field test for underground energy storage,[137] Eavor's pilot demonstration in Germany expected to be online in 2028, and its contract to provide power to a U.S. Air Force facility. At least four public PPAs have been announced;[138] this complements the overall geothermal PPAs recently announced and summarized in Table 1.

l LDES Council estimate.

m Notes: 1. High case: NREL ATB moderate for enhanced geothermal binary; low: Enhanced Geothermal Shot cost target for 2035 2. High case: NREL ATB moderate for conventional flash; low: NREL ATB advanced 3. High case: LDES Council, A path towards full grid decarbonization with 24/7 clean Power Purchase Agreements, RES + 100% matching 2035; low case: RES + 90% matching 2035; 4. High case: NREL ATB moderate for advanced nuclear (IEA); low case: DOE, Advanced Nuclear Pathways to Commercial Liftoff NOAK cost target 5. High case: NREL ATB moderate Capex and operating costs in 2035 assuming 34% capacity factor; low case: same inputs, assuming 68% capacity factor 6. $95/MWh, 15-year contract; Pasadena Expands Renewable Electricity Resources with Geothermal Contract | Pasadena Water and Power (cityofpasadena.net)

Capital raised and cumulative deal count in next-generation geothermal, 2021-2024

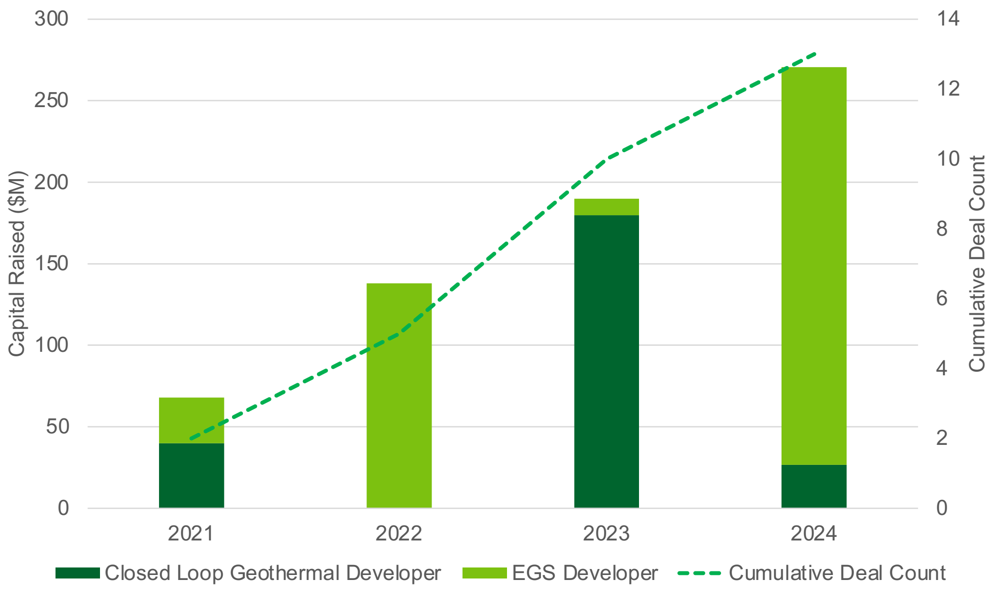


Figure 14: Market momentum. Source: SightLine Climate Geothermal market overview[139]

The current next-generation geothermal market is highly concentrated, and activity is dominated by the activity of a small group of innovative companies. The early-stage capital for these companies has largely come from corporate venture and philanthropy, including Breakthrough Energy, Google, and Microsoft's Climate Innovation Fund,[140] [141] as well as government projects, including DOE,[142] the Canadian Growth Fund[143] and the European Innovation Fund.[144]

However, there are early signs that market entry could increase, especially from entities with transferable skillsets and meaningful balance sheets, such as oil & gas developers, oil field service providers, mining companies, or renewables developers. From 2016 to 2020, the DOE's Geothermal Technology Office hosted two meetings with oil & gas companies regarding geothermal development, whereas from 2020 to 2023, the office held over 40 meetings. The same office also recently announced three projects will receive up to $60 million to support EGS pilot demonstration projects and field research[145], which include partnerships with oil & gas companies Chevron and Oxy[146] in addition to funding for Fervo Energy and Mazama Energy. Increasing market entry will be important for the industry to reach its full potential and commercial scale, as discussed at length in the next chapter.

Tax Credits

The IRA provides a powerful boost to next-generation geothermal power economics, but may not be sufficient to accelerate commitments for deployment at scale. The recent passage of the Inflation Reduction Act (IRA) introduced two technology-neutral clean energy tax credits that have the potential to improve LCOE: the Clean Energy Production Tax Credit (PTC) and the Clean Energy Investment Tax Credit (ITC). The PTC provides an inflation-adjusted $27.5 per MWh in tax credits for every MWh of power produced by a geothermal power plant for the first ten years of operation. The ITC provides 30% of the capital cost for a geothermal plant back in tax credits in year 1 of operation. Meeting prevailing wage and apprenticeship requirements in the construction and maintenance of the facility is required to be eligible for the full value of the PTC and ITC. Both incentives have two possible 10% adders for siting in energy communities and for the use of domestic content. Note the ITC bonus adders are 10 percentage points, so a facility eligible for both adders would have a 50% ITC. Every project developer/owner will have a unique set of considerations when determining how to leverage the IRA tax credits.

Chapter 3: Pathway to Commercial Scale

Key Takeaways:

- The next-generation geothermal industry is characterized by a combination of unusually high up-front costs, plus a maturation timeline that includes not only reductions in key risk, but also a resource base that increases mainly as new projects are developed.
- Demonstration in 5-10 separate geologic settings can reduce risk and verify resource availability, catalyzing commercial liftoff in the U.S. by 2030. This corresponds to 100+ developments, 2-5 GW of overall deployment, and $20-25 billion of investment before 2030.
- To reach scale by 2050, next-generation geothermal will require an additional $225-250 billion in investment, driven by a new ecosystem of developers, investors, utilities, and other offtakers, and leveraging existing workforces and supply chains.
- RD&D and iteration within drilling and hydraulic fracturing will drive cost reductions as was observed in the oil & gas industry throughout market maturation, and breakthroughs in drilling and resource characterization can further expand potential.
- At different market maturities, different development models apply.
  - At low maturity, unique developer classes with strategic motivations will likely fund projects entirely with equity.
  - At medium maturity, most subsurface development will still require up-front equity, which may promulgate higher-risk financing strategies. A broader array of developer classes may leverage debt for plant construction.
  - At high maturity, a wide array of developer classes leveraging project finance could dominate.

Pathway to commercial scale

Full-scale deployment of next-generation geothermal power will proceed in two phases, against a backdrop of continuing RD&D in pursuit of technological breakthroughs (Figure 15). In the first phase, next-generation geothermal developers must prove the market opportunity to reach commercial liftoff. In the second stage, the industry can achieve scale by expanding the viability of resources in early competitive regions, and subsequently expanding the next-generation geothermal footprint across the United States.

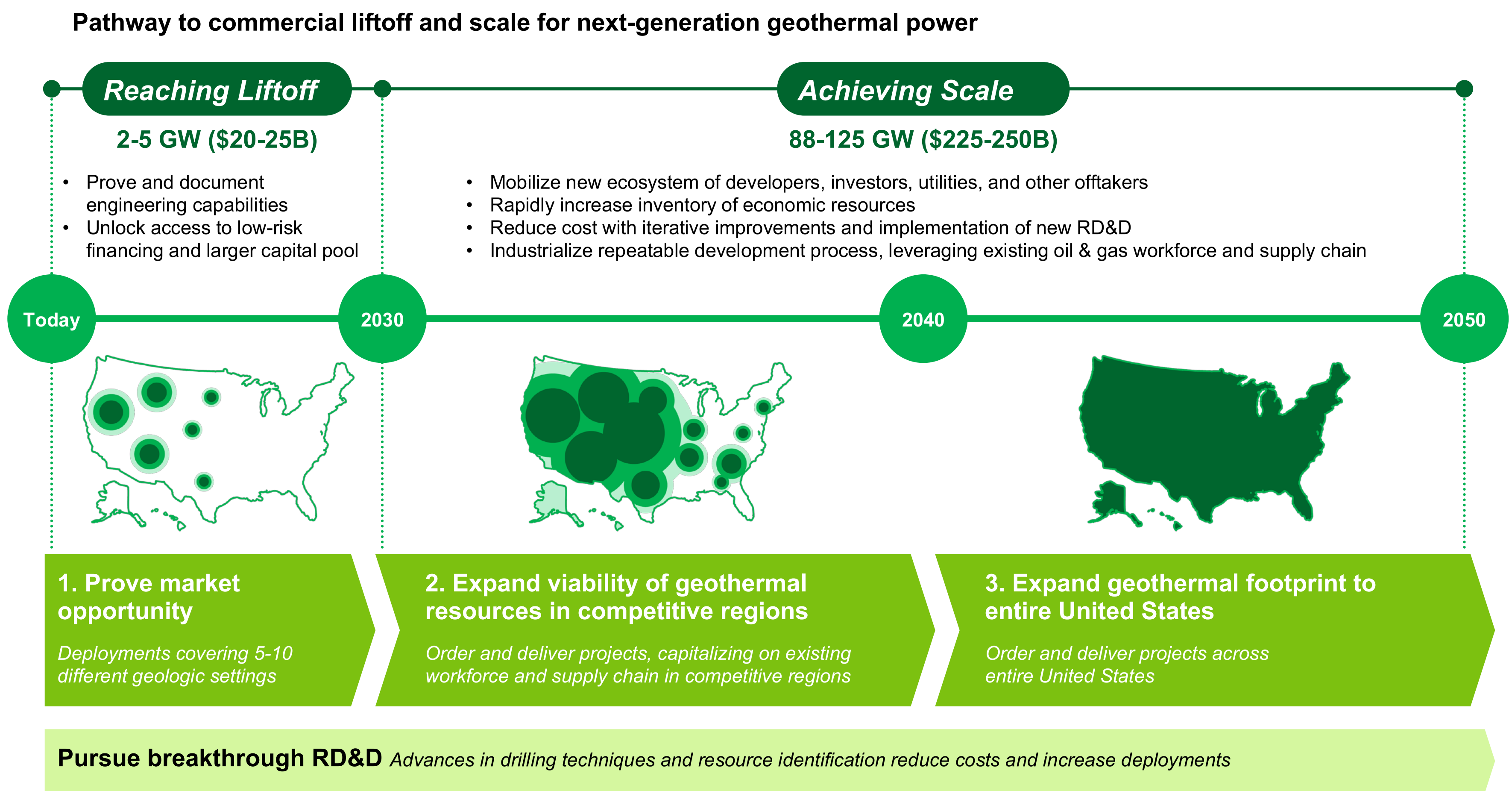


Figure 15: Pathway to commercial liftoff and scale. Green dots correspond to representative geothermal footprint in terms of power use.

Phase 1: Reaching Liftoff

Conditions and key enablers for next-generation geothermal liftoff

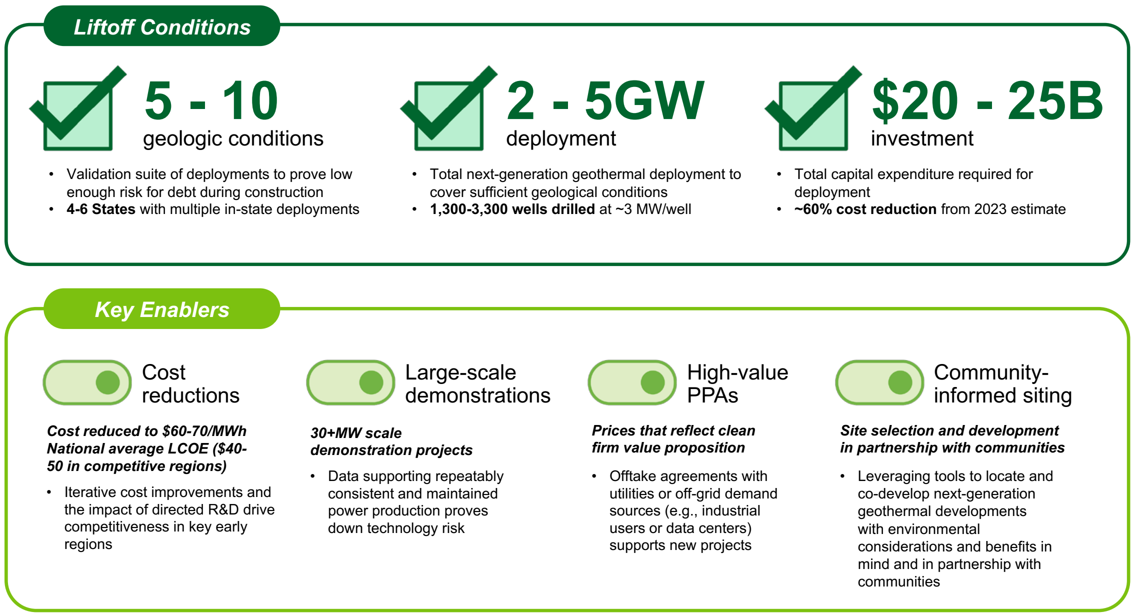


Figure 16: Liftoff conditions & enablers

To reach commercial liftoff, next-generation geothermal must demonstrate that the engineering capabilities can be deployed with reduced risk in greenfield conditions—i.e., locations unrelated to existing geothermal resources (conventional or next-generation). With sufficient technical evidence that these barriers are cleared, institutional investors could issue debt at earlier stages of geothermal developments, and the industry could reach an inflection point of self-sustaining expansion, or liftoff. The next-generation geothermal industry would reap catalytic benefits from access to debt at earlier stages of a project's lifecycle, as this would help address high up-front capital requirements.

Successful deployments in five to ten separate geologic conditions would produce the validation suite of data for institutional banks to feel confident in risk assessments of next-generation geothermal engineering capabilities, according to investors and geothermal developers consulted for this report. Lenders require a comprehensive understanding of reservoir characterization and operations for next-generation geothermal across multiple environments over multiple years, as well as an understanding of avenues of recourse from resources that do not produce the heat and/or flow rates initially estimated.[n] While early deployment of next-generation geothermal will most likely occur as EGS in the Basin and Range Province (a geologic region that covers much of the western United States where the geothermal resource is plentiful and close to the surface), multiple successful deployments of varied technological approaches across this vast region would provide the experience and track record that investors could use to assess project viability in other similar geologic environments across the U.S. Simultaneously, the existing niche ecosystem of third-party technical consultants could also grow to sufficient maturity to support and validate risk assessments for potential investors.

Overall deployment of about two to five GW across four to six states requiring $20-25 billion of capital[o] could assemble the validation suite required to de-risk greenfield geothermal deployment sufficiently for liftoff, as indicated by our modeling of the power system. This level of deployment would be reached at national average prices of $60-70/MWh by 2030, corresponding to $40-50/MWh in the competitive regions where first deployed, which is a ~60% decrease from 2023 prices.

n Key indicators that could comprise this validation suite are highlighted in Chapter 5.

o In two major cases considered–the Earthshot Scenario and the Earthshot with Limited Access Scenario (see Chapter 1 and Appendix A for further discussion)–2-5 GW of deployment and $20-25 billion of total capital expenditure are sufficient to include deployment in 5-10 separate geologies by 2029-2030.

Most early deployment will occur at near-field sites, in the same or similar geologic conditions as those of existing conventional geothermal and next-generation geothermal installations, because the subsurface will already be characterized and transmission infrastructure will already exist—these geothermal development areas may reach scales of 100 MW or more. However, nationwide demand for clean firm power could incentivize the development of new regions and geologic conditions, despite the higher investment and potential risk, eventually reaching this deployment threshold. The first set of next-generation geothermal developments in new locations are likely to be smaller than 30 MW, and may be expanded upon once specific acreage and regions are de-risked.

Key Enablers

To reach its full potential for scale in a decarbonized grid by 2050, next-generation geothermal must stay on track to reach liftoff by 2030. If deployment occurs over a longer period, the ultimate potential of 90+ GW will be difficult to reach, because it would require buildout in later periods that is faster than what the economy can likely support. Instead, rapid and early deployment to this threshold is critical, and can be catalyzed by four key enablers (Figure 16).

1. **National average LCOE of $60-70/MWh by 2030 (60% reduction from today)**. This is realized through continual iterative improvements (Chapter 2) and RD&D (see Chapter 4). Importantly, **next-generation geothermal does not need to reach full national average cost parity with other technologies to reach liftoff**, because of its early advantages in competitive geographies.
2. **Multiple large-scale demonstration for emerging and promising technical approaches.** Projects on the scale of 30 MW will be critical to gather the necessary data to support repeatable construction techniques and consistent production of power in the period after construction. With more data, the period required to demonstrate consistent power production with high confidence should also decrease. These demonstrations, if established across a variety of geological conditions, will drive further deployments and form the early industry track record.
3. **Well-designed power purchase agreements (PPAs) that reflect the value proposition of the clean firm power that next-generation geothermal provides.** Building on recent momentum in the industry, project development can be pursued under the right market signals and with confidence of eventual payouts from creditworthy entities. In addition to competitive prices, PPAs will need to include guarantees of delivery and penalties when timelines are not met. Preemptive agreements and real penalties can create increasing confidence in development timelines and incentivize technical progress, as can a growing track record of delivery.
4. **Early and continued engagement with local stakeholders.** The currently low maturity of the next-generation geothermal industry affords it an opportunity to collaboratively develop processes and methods for reservoir creation that eliminate or minimize the use of hazardous materials. Assessing these considerations, including water quality and induced felt seismicity, through the lens of how different communities or groups will be impacted, how impacts will interact with existing burdens, and how communities can inform decision-making can inform deployment and reduce negative impacts to local areas. Engaging in early, frequent, transparent, and two-way dialogue with communities on siting and potential project development creates the greatest likelihood of project success[p]. For this reason, DOE has committed to mandatory early community engagement on all funded demonstration projects.

Phase 2: Achieving Scale

To achieve scale, the next-generation geothermal industry must first expand the viability of resources in early competitive regions, and then expand the next-generation geothermal footprint to the entire

p Such as the CEJST tool

United States. In this phase, an additional $225-250 billion in investment can help deploy next-generation geothermal technology to its full potential, with an expansion of 88-125 GW.[q] Early competitive regions include states across most of the western U.S. (Figure 8), and eventually cost reductions, new financing, technological improvement, and demand for clean firm power will allow the industry to expand to the east.

Validation of the resource and access to lower-risk financing achieved in Phase 1 expands the capital pool that is available to invest in next-generation geothermal developments in Phase 2. This can serve to incentivize market entry from new developers, investors, and offtakers in the second phase (see Figure 17 and discussion below). While strategic offtakers can continue to procure next-generation power directly behind the meter, as they did in Phase 1, next-generation power can also satisfy expanding utility demand. Utilities should begin participating in demand organization as early as possible, and all offtakers will need to place orders in emerging regions as project delivery continues apace in established regions.

As with the extraction of other subsurface resources, development of new geothermal resources will have a snowballing effect with regards to proving the viability of further resources. In oil & gas exploration, reserves, or the quantities of petroleum anticipated to be commercially recoverable, are classified as proven, probable, and possible. A probable reserve may be converted to a proven reserve after the first higher-risk attempt at extraction. Similarly, geothermal resources will move from lower to higher certainty as developers undertake the first successful deployments in specific regions. The amount of acreage that is low risk for development will rapidly increase with every subsequent greenfield deployment, and a snowballing inventory will enable **further cost reduction towards the ultimate Energy Earthshot goal of $45/MWh.**

Finally, next-generation geothermal at scale will capitalize on workforce and supply chain starting advantages. An existing oil & gas workforce and supply chain that is largely transferable and already at an appropriate scale already exists for full deployment scenario (see Chapter 1). By leveraging this workforce and supply chain, the next-generation geothermal power industry can rapidly build an industrialized and repeatable workflow at large scale, to achieve 10+ GW deployed per year across the entire U.S.

Emerging development models and market ecosystems in next-generation geothermal

As the next-generation geothermal industry matures, new developer classes, sources of investment, and development models that drive deployment may emerge. **Ultimately, a fully mature and de-risked geothermal industry could develop projects using a traditional project finance model, in which combinations of debt and equity are available early in a project lifecycle and leveraged projects release capital for other developments.**

Most emerging technologies must follow a trajectory that involves higher-risk early demonstrations and deployments followed by lower-risk later financing strategies to reach scale. However, **the next-generation geothermal industry is characterized by a combination of unusually high up-front costs, plus a maturation timeline that includes not only reductions in key risk, but also a resource base that increases mainly as new projects are developed.** Specific developer classes with different risk tolerances and skillsets may integrate at different maturation stages to manage this dynamic and achieve scale. Therefore, the path to full maturity may be different for next-generation geothermal than it has been for other renewables technologies due to specific developer classes and investment sources.

Low maturity (now):

Technology risks remain high, although the risk of incorrect resource identification for early deployments is lower than it is for conventional geothermal development. At this stage, all subsurface and surface construction is completed using equity, which is about $450 million for a 30 MW facility at today's costs for EGS.[r] Deployments in this stage are necessary to increase market maturity and prove down risks.

q In two major cases considered–the Earthshot Scenario and the Earthshot with Limited Access Scenario (see Chapter 1 and Appendix A for further discussion)–next-generation geothermal reaches 88-125 GW of additional deployment by 2050, with an additional $225-250 billion in capital cost.

r Assuming an overnight capital cost of $15,000/kw.

Investment for first of a kind (FOAK) deployments can come from multiple sources, including public grants or low-interest loans, early-stage corporate equity, private capital, or strategic investor-offtakers. These entities could be motivated to provide capital for the anticipated strategic value of competitive skill acquisition, capitalizing on a starting advantage, early-stage market entry, national or philanthropic priorities, or satisfying operational needs such as green mandates. This includes well-capitalized conventional geothermal developers, oil & gas developers, oil field service providers, data center owners, direct air capture developers, or industrial users. Partnerships between geothermal companies and these entities have already begun (see Chapter 2) but scaling up their investment is critical to fund this initial validation suite.

Medium maturity:

Technology risk is reduced but the risk of characterizing resources in greenfield developments is not eliminated; most subsurface development will still require up-front equity, while projects may be able to access debt for the surface construction. Higher-risk financing strategies such as a "farm-down" model, in which developers use equity to perform subsurface development, demonstrate de-risked operations, and then sell a stake of the operation to recoup investment, may be a useful business model for project development. In this arrangement, the amount of up-front equity is reduced—but still high—at ~$180 million for a 30 MW project at current cost estimates for EGS, and this estimate may vary depending on technology class, geography, and future cost reductions.[s] [147] [148]

There are several appropriate developer classes for this type of financing structure. Maturing early-stage entities that have built expertise, momentum, and an early track record from the FOAK deployments that they spearheaded may continue to develop projects in this stage. Upstream oil & gas entities (e.g., majors or oil field service providers) or mining companies may also consider market entry given in-house technical expertise and large balance sheets for streamlined equity. However, in partnership with private equity or strategic investor-offtakers (especially those with subsurface expertise), numerous other developer classes with access to capital could step in to push the industry to scale.

High maturity:

With a robust track record of de-risked technology and resource characterization in greenfield sites, next-generation geothermal projects should be able to access institutional debt after early subsurface development at an estimated cost of ~$5-10 million, based on the estimated cost of the first well for an EGS development. With access to low-cost debt, low-risk financing strategies such as project finance could become the main financing model for geothermal project developments. Developers with a lower risk tolerance and lower hurdle rates, like established renewables developers (including matured early-stage entrants), may step in with capital from infrastructure investors alongside banks and use corporate and project equity to develop projects. Mining companies that can leverage similarities in business model or upstream oil & gas players that have tolerance for a new business model (shifting from a commodity market model to a utility model) may also be able to deploy capital and develop projects.

s Assuming an overnight capital cost of $15,000/kw and subsurface development of ~35% of overall cost.

Developer classes, investment sources, and development models available at different levels of industry maturity

Industry Maturity	***FOAK***		***NOAK***
Risks: High / Medium / Low	Technology Resource	Technology Resource	Technology Resource
Appropriate developer class	• Early stage (e.g., start-ups; internal innovation teams)	• Maturing early-stage entities • Upstream oil & gas; mining	• Established renewables developers • Upstream oil & gas; mining
Potential sources of investment	• Corporate equity (early-stage) • Philanthropy and public grants • Strategic investor-offtakers	• Corporate equity • Private equity • High-cost debt • Strategic investor-offtakers	• Infrastructure investors • Corporate equity • Project equity • Low-cost debt
Project stage at debt entry	n/a	Surface construction	Subsurface development (after first well)
Development model *Up-front equity[1]* *(hurdle rate)*	***Unlevered equity*** *~$450M* *(loss leader)*	***High-risk financing strategies*** *~$180M* *(20+%)*	***Low-risk financing strategies*** *~$5-10M* *(5-10%)*
	Demonstration Projects	**“Farm-Down”**	**Project Finance**

Figure 17: Emerging development models[t]

t Note: 1. Estimate of necessary equity required before first access to debt for a 30 MW next-generation geothermal plant

Chapter 4: Challenges & Potential Solutions

Key Takeaways:

- About $5 billion in total up-front capital from various sources is needed to overcome equity-only financing barriers to early demonstration projects that inhibit project development today.
- Transparency of operational data is needed to overcome both perceived resource characterization and technology risks inherited from legacy developments and actual risks inherent in commercializing a new technology using a subsurface resource.
- Federal administrative updates, technology improvements, and centralization could reduce permitting timelines for geothermal projects on public lands by up to three years.
- Premium PPAs that value clean firm, flexible power can drive further adoption of geothermal.
- Environmental and human health risks can be mitigated through early and continued community engagement as well as transparency around seismicity and environmental monitoring. This proactive engagement can reduce the risk of stalled timelines and project opposition.

Challenges	Potential Solutions
High up-front costs & risks constraining development capital and limiting geographic reach	About $5 billion out of the $20-25 billion of capital formation in the liftoff phase to finance the validation suite of first-of-a-kind (FOAK) developments in varied geologies, sourced from governments, equity investments, corporate venture or strategic investor-offtakers, or oil & gas Market signals, such as high-valued PPAs, to motivate investment in initial deployments In-field testing and innovation at active geothermal developments through RD&D spending New financial products to reduce drilling costs, such as public/private cost-share agreements and drilling insurance programs
Perceived & actual operability risk for deployments	Strategic demonstration siting and data dissemination from 10+ early deployments to show sustained power production
Long and unpredictable development lifecycles driven by permitting and interconnection	Allowing for combining and streamlining of specific steps in permitting process, where authorized. Technology changes that allow certain steps to occur in tandem Centralization of geothermal-specific permitting expertise, where authorized
Existing business models undervaluing the potential of next-generation geothermal	Planning policies that incentivize higher-cost, higher-value power Leverage flexible geothermal operations to capture highest-value power New offtake models, e.g., subsurface developers providing heat for multiple purposes
Community opposition in some instances	Adherence to long-established induced seismicity and environmental monitoring best practices Early, frequent, and transparent community engagement

Table 2: Challenges confronting the pathway to commercial scale for next-generation geothermal liftoff and potential solutions as determined from analysis and interviews.

Challenge: High up-front costs & risks constraining development capital and limiting geographic reach

High costs and high risks at the start of new projects limit available capital, slow the pipeline of new demonstrations, and reduce opportunities for cost reduction. The riskiest and most difficult-to-raise capital for next-generation geothermal projects is the earliest capital. It costs about $450 million to initially characterize new next-generation developments and yield a reasonable amount of power (assuming a 30 MW plant at current cost estimates of ~$15,000/kw). However, until it is proven otherwise, most capital providers will find the resource or technology risk too high to engage at this early stage, so developers today are limited to a small pool of capital provided by highly strategic investors and venture providers. Raising the $450 million needed for a new development with equity alone dramatically slows the pace at which new projects come online, presenting the single largest barrier to next-generation geothermal scale-up. Developers estimate that project timelines can be elongated by about 5 years if equity raises are required, which would put liftoff by 2030 out of reach.

Because the major driver of cost reductions in next-generation geothermal is iteration, limited project pipelines limit the rate at which costs can decrease. Only 25 geothermal wells were drilled in the U.S. in 2022, compared to an average of 24,000 wells per year drilled by oil & gas developers between 1990 and 2000, when unconventional oil & gas extraction was being first demonstrated.[149] Although the learning rates industry is demonstrating are in line with cost reduction projections shown in Chapter 2, the frequency with which geothermal developers can drill new wells is limited by the rate at which they can raise large amounts of up-front equity.

Furthermore, developers are incentivized to expand development at proven sites, rather than expand. By the time a developer can commence power production at a site, the most serious risks are lowered, and developers may have an easier time finding capital. There is therefore a financial incentive for developers to continue to develop at a proven site, rather than expand to a new one and face high risks again. The ultimate validation of next-generation geothermal technologies, however, is contingent on expansion to a wide array of geologies. Developers do not yet have an incentive to engage in the expansion the market needs to establish itself.

Solutions to high up-front costs

Early up-front capital

The fastest path to enable next-generation scale-up is early capital to finance new demonstration projects.[150] This will reduce developer time spent raising equity and increase the asset base, triggering a positive feedback loop in which future projects benefit from the drilling improvements demonstrated from past projects, have lower costs, and require less equity. It will also increase the incentive for developers to expand to new sites. A 10-demonstration portfolio would cost about $4.5 billion, commensurate with other nascent technologies with similar opportunity spaces funded through recent appropriations in the Bipartisan Infrastructure Law and the Inflation Reduction Act (Figure 18).

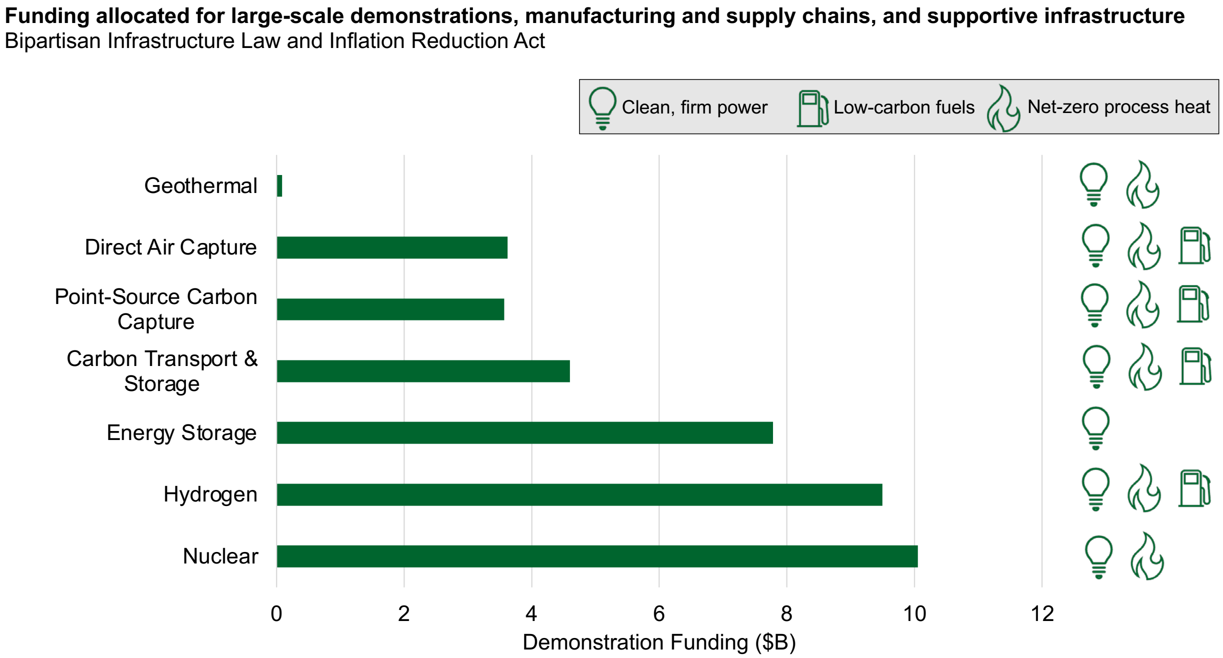


Figure 18: Comparison in government funding availability for large demonstrations, manufacturing and supply chains, and supportive infrastructure across key clean energy technologies

The capital required to fund these requisite demonstration projects can come from a variety of sources, each with different motivations:

- **Governments** are well-equipped to provide capital for nascent technologies to help new industries develop. DOE has a 50-year history of fulfilling this mission through actions such as the development and management of FORGE. The approximately $140 million budget annually appropriated to DOE's GTO currently represents the largest source of capital available for geothermal in the world, but other governmental entities such as those in Canada and Europe have also provided tens of millions of dollars in capital recently.[151 152] DOE's Loan Programs Office is authorized to provide attractive debt financing for high-impact, large-scale commercial deployment of innovative energy projects that reduce carbon emissions. As of January 2024, the Loan Programs Office had a total estimated remaining loan authority of $132 billion that is applicable to next-generation geothermal.[153] Additionally, the tech-agnostic Office of Clean Energy Demonstrations, which manages a $27 billion portfolio of clean energy demonstrations funds, could provide future capital, as authorized. Similarly, state energy offices could manage grant programs in geothermal energy.[154]
- **Equity investments** in early-stage developers can be used to finance first deployments. Investors motivated by the potential growth of an innovative developer may provide capital in the form of equity investments that can be deployed at the project level while technology and capabilities are being proven. Because these are higher risk investments, the expected rates of return are also higher, and the capital is by nature more expensive.
- **Strategic investors or investor-offtakers** may be motivated to provide project capital at this early stage for the strategic value the technology provides. Corporate entities with large balance sheets, large power demands, and/or ambitious clean power commitments, such as large tech companies, could be appropriately motivated to develop this technology to have a corporate advantage in later-stage deployments.
- **Oil & gas integrated majors and service providers** have the most robust starting advantage, as they already have the equipment, technical capability, workforce, and subsurface data needed to rapidly

develop this technology. The business case for developing next-generation geothermal energy has not been strong enough to motivate major investment in this space to this point; however, recent upticks in oil & gas engagement with GTO suggests that this may change.

Demand-side market signals

Demand-side signals that incentivize the procurement of clean firm power can have a major impact on the geothermal project development pipeline. These mechanisms provide a robust incentive by assuring developers a high-value offtaker that they can use to motivate capital raises. There are two primary pathways that have already moved the market on geothermal deployment:

- **Procurement mandates from public utility commissions, particularly in states with clean energy standards:** PUCs operating in states with high penetration of intermittent renewable generation may require firm, load-balancing generation sources to keep the grid operational, and this demand will increase as more large loads come online (discussed in Chapter 1).
- **High-value power purchase agreements for large, well-capitalized private providers:** In 2021, Google signed an agreement to directly purchase geothermal electricity from a next-generation geothermal project developed by Fervo.[155] This agreement was critical to allowing Fervo to continue raising funds for the first commercially operable greenfield EGS plant in the world. Similar agreements with heavy power users, such as data centers and industrial operators, could accelerate capital formation. Potential future loads, such as hydrogen production plants and direct air capture plants, would further accelerate this demand.

RD&D advancements

RD&D complements operational improvements in driving expected cost reductions. Most RD&D areas are focused on reducing the number of wells required to drill, improving the precision of the measurements collected during drilling, and decreasing the amount of time and materials that each well requires. Many of these advancements are transferable across both EGS and closed loop geothermal. Each of these RD&D areas is a current, prior, or anticipated future focus area of DOE's GTO, and details on each area can be found in GTO's Multi-Year Program Plan[156] and the GeoVision Report:[157]

- **Resource characterization improvements** that allow developers to more quickly and precisely identify new resources. These include the development of new technologies to monitor subsurface activity, the integration of computational tools to process large data streams, and field tests to demonstrate viability (see Figure 19).

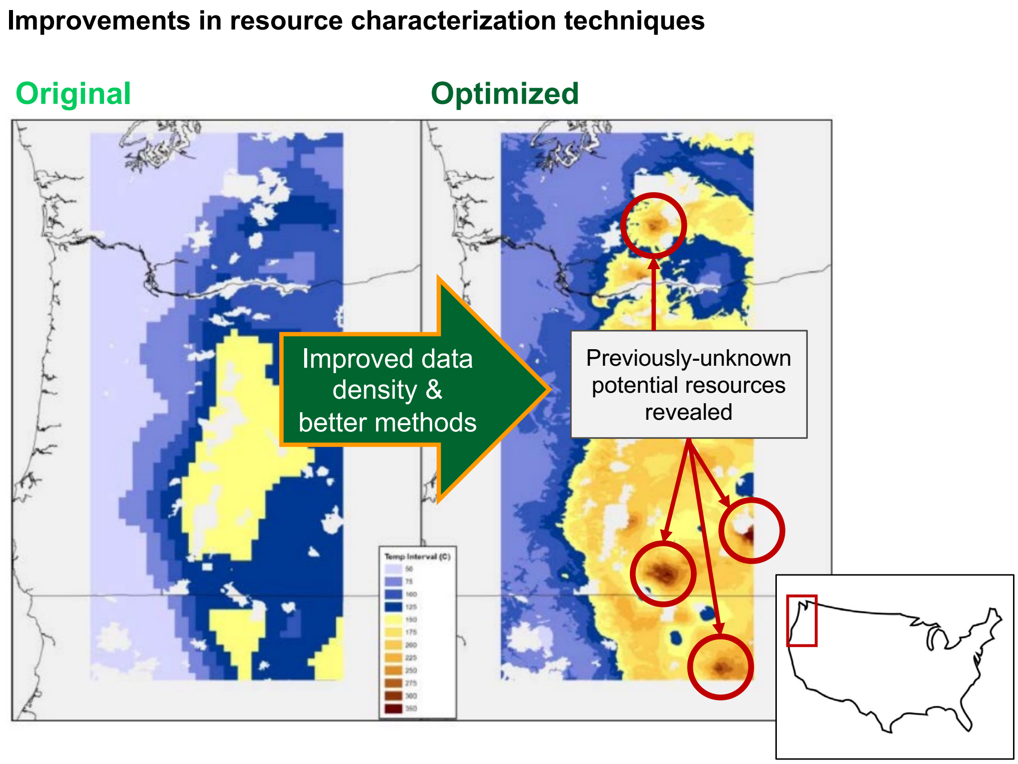


Figure 19: Improved data access leads to more targeted resource estimates.[158]

- **Reservoir production improvements** that reduce the cost to develop the reservoir. For EGS, this includes field testing of new hydraulic fracturing procedures that optimize fracture orientations to maximize the reservoir's ability to conduct heat, zonal isolation of reservoirs, and real-time monitoring of hydraulic fracturing activities to enable fast corrections and reduce drilling times. For closed loop geothermal, this may include flow control demonstrations and developments of well configurations that can better exploit the relatively small surface area for heat conduction.

- **Drilling & well construction improvements** that reduce the number of wells needed to produce power, the time it takes to drill a well, and the materials required to drill and complete a well. This includes demonstrations of new well configurations that optimize reservoir control and iterative improvements to drilling methods, as well as potential step-changes to the drilling industry that leverage new methods entirely.[159]

- **Hardened materials**, including monitoring equipment, that can better withstand the high-pressure, hot, and caustic environments in which the above activities must occur.

The Enhanced Geothermal Shot™ (EGS), part of the Energy Earthshots Initiative™, was launched in 2021 to promote RD&D to reduce the cost of geothermal power to $45/MWh by 2035. The Enhanced Geothermal Shot harmonizes programs across DOE that can drive geothermal development in areas outlined above, and provides periodic, accurate assessments of technical and economic progress. This continuous assessment ensures that RD&D programs remain on the pathway to successful achievement of the decadal goal and resources are allocated to areas that yield the greatest benefits and provides external stakeholders with needed data to motivate investment. Rapid increases in drilling rates observed over the last three years (see Figure 10) are a clear example of RD&D that couples federally funded work with private sector advances. The results presented above for the FORGE project have been replicated and advanced by private sector developers, as evidenced by the Project Cape drilling results recently published.[160]

Specific financial products to reduce financial burden and risk of drilling

In the past, unique financial products have been deployed to effectively replace the role of early-stage debt for geothermal projects. These products have traditionally provided funds to share the cost of drilling or insurance to shelter capital providers or developers from resource development risk. By injecting funds early in development, such programs can drive a pipeline of resource characterization and confirmation that underpins further development for decades.

A prior cost-shared drilling program run by DOE identified much of the geothermal capacity that is currently online in the U.S.[161] The program, called "Geothermal Resource Exploration and Definition" (GRED), was active for most of the last half century (1982–2012). Similar programs have spurred development in other nations, such as Japan, Kenya, Switzerland, France, and Germany.[162]

Both developers and capital providers benefit from cost-shared drilling and insurance programs. Capital providers get access to valuable information, such as subsurface properties, that can be leveraged for public or private means. Developers benefit in that the later-stage project equity is further de-risked, making the opportunity more appealing. At early and middle market maturities, where equity will need to be raised for resource characterization and confirmation, cost-shared drilling and insurance programs can alleviate high equity thresholds. The mechanisms for these financial products can be highly varied.[163] Some options include the following:

- **Grants for resource characterization drilling**, in which funds are provided for some percentage of the drilling and development costs with no expectation of repayment. These grants are best used to assist developers in confirming temperatures and other key geologic properties in a fundamentally new environment.
- **Loans to finance drilling**, in which drilling activities are financed at an advanced rate likely higher than traditional capital markets can provide. This model would be most applicable after FOAK technologies have demonstrated next-generation drilling success and could be provided by either public entities interested broadly in resource expansion or private entities interested in drilling-related intellectual property.
- **Assurance for overages**, in which funds are provided if a development exceeds a certain previously established cost threshold. These assurances attract developer capital otherwise concerned with cost overruns and may be particularly useful to help combat perceived technology risk, described further below.

Challenge: Perceived and actual operability risk constraining demand and investor appetite

Conventional geothermal plays have struggled to raise capital due, in part because of the elevated, site-specific resource characterization risks outlined in Chapters 1 and 2. Investors want to see evidence that next-generation geothermal technologies have eliminated this resource risk. They must see new projects created and engineered in a variety of environments, operating over long timescales, and overcoming development failures. Investors must see how future next-generation geothermal projects overcome resource underestimates using engineering.

In addition to addressing perceived risks, **next-generation geothermal operators must demonstrate to investors that the promise of repeated, modular operations in multiple environments is being realized.**[164] These challenges arise from operating established technologies, such as directional drilling and hydraulic fracturing, in new environments with elevated temperatures and harder rock,[165] as well as operating these established technologies in new configurations (maintaining continued circulation of fluid, rather than a one-time extraction of gas).

Solutions: Strategic demonstration siting and data dissemination from a small asset base

Strategic siting is critical for reducing perceived resource characterization risk. Developers must demonstrate that next-generation geothermal projects can be developed in truly new environments without any prior geothermal activity. Demonstrations in greenfield settings near, but not attached to, prior geothermal activity undertaken by the public and private sector have relatively quickly mobilized hundreds of millions in capital (Figure 14). Further demonstrations in more new environments, particularly areas not widely known as having geothermal potential such as the eastern and central U.S., are critical to convincing a skeptical investor pool that resource conditions can be reliably engineered. The Energy Act of 2020 authorizes, and the Bipartisan Infrastructure Law provides some funding for, four new EGS demonstrations, and mandates that one be east of the Mississippi River.[166] [167] [168] Demonstrations in eastern states with high resource potential (Figure 2) but no historical or active geothermal development, such as Pennsylvania, West Virginia, South Carolina, Louisiana, and Texas, could have an outsized impact on investor confidence.

Investors will be further assured that next-generation geothermal technologies are de-risked through transparent, public operational and environmental data. The fastest path to validating project success considering this relatively small asset base is through data dissemination that affirms the value propositions central to next-generation geothermal. This is a departure from the development model of oil & gas, which relied on large amounts of easily accessible internal corporate funding rather than external infrastructure investment to prove down the risks for unconventional oil & gas extraction. Privileged access to corporate debt eliminated the motivation for key operational data to be shared. However, in the absence of such internal capital, operational data are necessary to show that projects are achieving the technical capabilities required of them. Examples of such key operational data is described in *Chapter 5: Metrics to Track Progress*. The disclosure of operational and environmental data will also help uncover new viable resources that can be developed, which enables a wider developer class to emerge.

Operators must also demonstrate that they can minimize potential environmental risks. Next-generation geothermal operators are adapting best practices to ensure projects successfully operate with minimal impacts; this includes management of potential induced seismicity, wellbore integrity, water use, and voluntary reporting of drilling-related chemicals. Operators should demonstrate how they are implementing best practices for such risks, such as DOE's *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems*.[169]

Challenge: Long and unpredictable development lifecycles driven by federal permitting

Historically, geothermal project development timelines typically have been 7-10 years for projects on public land,[170] as described in Figure 20. This long timeline is often cited in conjunction with other risks as a major barrier to geothermal project development (see Chapter 2). More than just long timelines, there is also major uncertainty and lack of predictability, which can deliver a double blow by delaying payback on investments and increasing the cost of capital for project financing, making projects less appealing and ultimately harder to fund. Furthermore, developers frequently point to a "tail risk" of rare permitting delays that can be substantially longer. This uncertainty is frequently invoked as one of the top reasons geothermal projects have been historically difficult to fund and implement.

The project delays and lack of predictability stem from the potential for litigation and a complex and interconnected permitting and licensing process for projects on federally managed land—where most geothermal projects occur. These permitting and licensing processes are a mechanism for protecting natural and cultural resources and ensuring safety but could be more efficient. Multiple state and local agencies also have important permitting and regulatory roles in geothermal project developments on federal land, requiring coordination, for instance when states also permit wells on federally managed land.[171] [172] The review cycles for permitting and licensing can be duplicative in cases in which coordination is insufficient, and review can be opaque. This can present chicken-and-egg issues regarding resource exploration and permitting applications, with funding for activities, including application preparation, held up by the uncertainty in review and timelines. Like all other power projects, these timelines interact with grid interconnection queues and the average delays in different regions; general solutions in that space are applicable to geothermal project development as well.[173]

The process as described in Figure 20 involves one permitting or licensing activity for each step in development of a next-generation geothermal project on federal lands where BLM regulations apply[u]. The top row in Figure 20 represents one end of the spectrum of approval processes. The number of steps required depends on factors such as the project application and proposed location. The main categories in BLM regulations are Exploration (Title 43, Subpart 3250), Resource drilling (Title 43, Subpart 3260), and Utilization (Title 43, Subpart 3270).[174] Around the sale[v] of a geothermal lease,[175] which itself can take significant pre-project resources, the following steps can currently occur in series for geothermal developers:

I. **Exploration**

1. **Categorical Exclusion: Exploration**

   To undertake exploration activities, such as site surveys and initial characterization—but importantly no physical subsurface exploration with the potential to intersect with a natural geothermal resource— an operator must file a Notice of Intent to Conduct Oil and Gas Exploration Operations, and the Bureau of Land Management (BLM) must comply with NEPA before it can approve the exploration activities, which takes on average 2-4 months if there is an applicable categorical exclusion.[w]

2. **Exploration Operations**

   Exploration operations (defined at 43 CFR 3200.1) are activities that may be undertaken to characterize a potential site. Initial exploration activities can include surface and site characterization.

3. **Environmental assessment: Exploration Drilling**

   When access roads and well pads are needed to conduct exploration, an environmental assessment may be necessary and takes on average 6-12 months. If the environmental assessment identifies the potential for significant environmental impacts that cannot be mitigated, BLM may decide to prepare an environmental impact statement, which could lengthen the process.

4. **Exploration drilling**

   At this stage, developers may deploy inexpensive, small-diameter core drilling and temperature gradient wells, so long as the well does not intersect with a natural geothermal resource and may also perform associated surface-disturbing activities.[x] This drilling is required to confirm reservoir temperatures and other key subsurface characteristics to confirm the suitability of a specific site for geothermal or next-generation geothermal development.

II. **Resource drilling**

5. **Environmental assessment: Resource confirmation**

   To perform any subsurface drilling with the potential to intersect a natural geothermal resource requires submission and approval of an operations plan (43 CFR subparts 3260- 3267) and each

u BLM's regulations apply on BLM-administered public land and on "lands whose surface is managed by another Federal agency, where BLM has leased the subsurface geothermal resources." BLM regulations do not apply to unleased land administered by another Federal agency, unleased geothermal resources whose surface land is managed by another Federal agency, privately owned land, or casual use activities.

v Note: Any producing oil & gas lease may qualify for a noncompetitive geothermal lease for purposes of coproduction under section 3105 of the Division Z of the Consolidated Appropriations Act of 2021: https://www.congress.gov/116/plaws/publ260/PLAW-116publ260.pdf.

w Existing BLM Categorical Exclusion (516 DM 11.9B (6)) provides for approval of Notices of Intent to conduct geophysical exploration of oil, gas, or geothermal, pursuant to 43 CFR 3150 or 3250, when no temporary or new road construction is proposed.

x No contact, direct testing, or production of geothermal resources is allowed from wells permitted via a notice of intent for exploration. A lease is not required for these types of activities and notice of intent permits may be applied for on any federal lands open to geothermal development.

well requires approval of a Geothermal Drilling Permit[y]. In some cases, this step may be combined with step 3. To comply with NEPA, BLM prepares an environmental assessment before deciding whether to approve an operations plan together with its subsequent Geothermal Drilling Permits, which has taken on average 1-1.5 years to complete. Current practices allow but do not require a separate environmental assessment to drill "full-diameter" production and injection wells to confirm a geothermal resource. These wells are larger than thermal gradient wells or slim hole wells and involve a larger amount of engineering and machinery.

6. **Drill production and injection wells**

   At any point after proposing an operations plan, once the environmental assessment in Step 5 is completed, the developer may begin to submit applications to drill production and injection wells to confirm and delineate the extent and size of the resource, or to establish the infrastructure necessary to harness heat and power from the subsurface resource.

III. Utilization

7. **Environmental assessment: Power plant and transmission**

   To build surface infrastructure at the site, including a power plant and transmission lines, current BLM regulations and practices recommend, but do not require, a separate environmental assessment to be filed. An operator may submit a proposed utilization plan for utilization facilities and operations under the regulations at 43 CFR Subparts 3270-3277, approval of which can take an additional 1-1.5 years. Facility construction may begin following issuance of a facility construction permit and site license together with approval of the utilization plan as a whole.[z]

8. **Complete power plant, facilities, and transmission lines**

   After the final NEPA review and approval of the utilization plan for construction of facilities and remaining wells in Step 7, the power plant may be constructed and the transmission lines may be completed at the site.[aa] Transmission lines will usually be included in the utilization proposal with the facility and considered in the same NEPA analysis.

Any of these steps may be affected by unforeseen administrative or litigation delays, which adds risk to projects.

y Resource wells are any well designed to contact and directly test the geothermal resource; the operator may choose inexpensive slim hole wells (~6-9" in diameter) initially to limit drilling costs, but there is no BLM requirement to limit the diameter or potential use of wells permitted via an operations plan.

z If the facility is located off-lease on lands managed by another agency, then that agency issues the site license. No site license is required on private lands or split estate lands where the BLM does not manage the surface.

aa Once the plant and facilities are approved, the operator applies for a Commercial Use Permit to commence energy generation, also called utilization or actual production of geothermal resources (NEPA for all stage III activities are combined in the Utilization Plan NEPA).

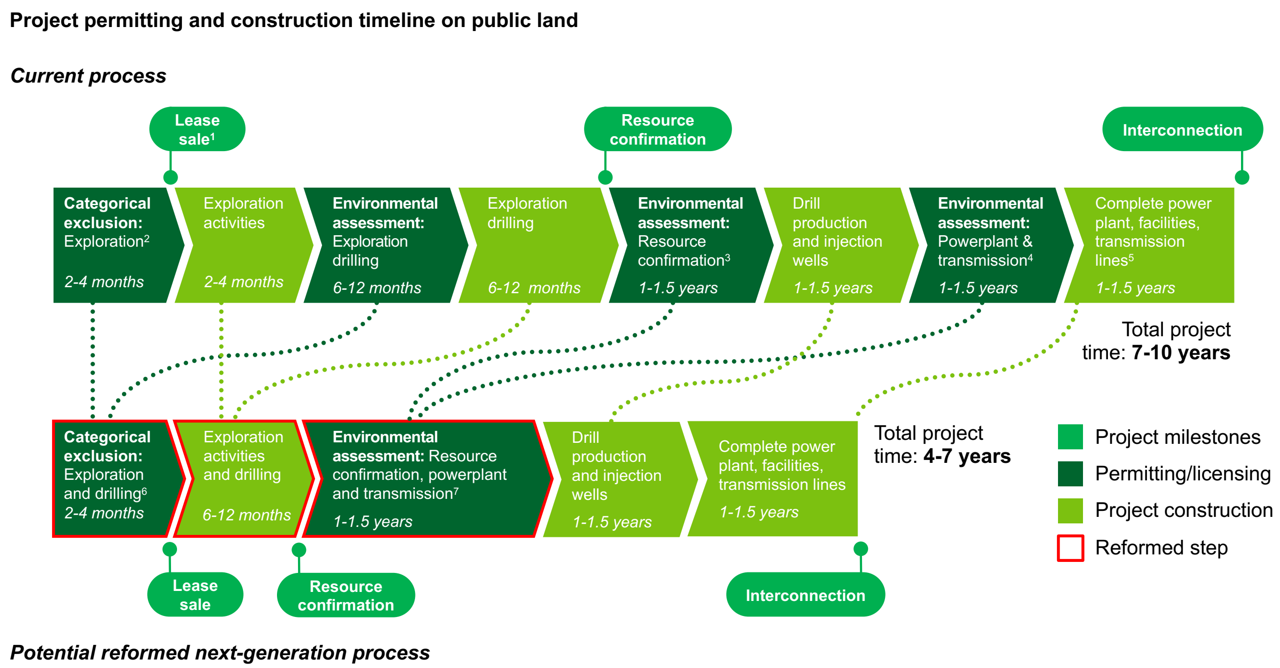


Figure 20: Illustrative depiction of permitting timelines for geothermal projects today [top row] and in a potential streamlined future scenario [bottom row][ab]

Potential solution: streamlined permitting, where authorized

New Federal government administrative tools and differences in the technical capabilities between conventional and next-generation geothermal could enable reductions in project timelines on public lands by up to 3 years, assuming key parallel work (e.g., Endangered Species Act Section 7 review and technical and design work undertaken by the developer) can be properly managed and sequenced. Actions that could streamline the process include:

1. **Allow the initial categorical exclusion[ac] (steps 1 and 3 above) to include both exploration and exploration drilling with surface disturbance.** This could be done in several ways. For example, by developing a new categorical exclusion.[ad] Alternatively, the Fiscal Responsibility Act [176] amended NEPA to enable Federal agencies to adopt each other's existing categorical exclusions, including those that may be more efficient for NEPA reviews of next-generation geothermal. Other approaches could also achieve similar results, as highlighted in recent NREL Task Force recommendations.[177] By combining exploration with exploration drilling and surface disturbance, timelines could potentially be reduced by 6-12 months in permitting and another 2-4 months in project execution.

ab Notes: 1. Noncompetitive geothermal lease may be secured using an existing oil & gas lease 2. Lessee submits exploration permit application (43 CFR 3250), no contact with resource or major surface disturbance 3. Lessee submits operations plan (43 CFR 3260) 4. Lessee submits utilization plan (43 CFR 3270) beforehand. May require **Environmental Impact Statement** (2-3 years). May occur in parallel with previous step 5. This step may occur in parallel with previous steps. Projects may file for interconnection as early as lease sale, which can take over 4 years 6. Proposals to combine exploration activities and drilling into one categorical exclusion by adopting other agency categorical exclusions pursuant to section 109 of NEPA, or internal development of new categorical exclusion 7. Predictability of power plant location with EGS will allow combination of resource confirmation and powerplant environmental assessment.

ac A "categorical exclusion" is a category of actions that Federal agencies have determined normally do not have a significant effect on the quality of the human environment (individually or cumulatively) and for which neither an EA nor an EIS is required to comply with NEPA (40 CFR 1508.4). Although eligible actions may not require an EA or EIS, a categorical exclusion is not an exemption from NEPA requirements.

ad On December 12, 2023, BLM provided a Statement on the Record for H.R. 5482, the Energy Poverty Prevention and Accountability Act; H.R. 6474, regarding Sec. 390 categorical exclusions for geothermal development to the House Committee on Natural Resources. BLM stated: "Currently, the BLM is working on administratively establishing CXs specifically for geothermal development, and these CXs will be more applicable to the geothermal process than the oil and gas-focused Section 390 CXs, which the bill would amend. Additionally, the BLM generally believes that new CXs are better developed through the traditional administrative process than through legislation." https://www.blm.gov/sites/default/files/docs/2023-12/BLM%20Statement%20Statement%20for%20the%20Record%20on%20H.R.%205482%2C%20 H.R.%206474%2C%20and%20H.R.%206481.pdf

2. **Technology changes that allow resource confirmation and power plant siting to occur in tandem for next-generation geothermal**, allowing projects to apply for those separate environmental assessments at the same time, or combining application phase submissions in a comprehensive exploration and development program. Because next-generation geothermal power is less sensitive to the exact location of a resource, developers may be able to predict the power plant location and characteristics before the resource is engineered. This would allow steps 5 and 7 to be combined, reducing project timelines by another 1 – 1.5 years. This may require further categorical exclusions, if authorized, such as a categorical exclusion related to operations plans for resource confirmation drilling and testing.

3. **Increased centralization of permitting expertise.** Centralizing renewable energy subject matter experts from across the Federal government to provide technical review, advice, and assistance could result in shorter and more predictable permitting timelines for each step of the process.[178] The Energy Act of 2020[179] established such a program through BLM to create a national Renewable Energy Coordination Office (RECO). BLM plans to coordinate activities across the Department of the Interior, Agriculture, Energy, Defense, and the Environmental Protection Agency to support RECO development for improving renewable energy project permit coordination on public lands.[180] The establishment of a dedicated geothermal permitting support structure staffed with geothermal experts, set within the RECO and leveraging experts at DOE, National Laboratories, and other Federal organizations, could enable acceleration of project timelines.

These actions together could reduce project timelines by up to three years (Figure 20).

Challenge: Existing business models rarely consider joint value proposition of clean firm power

Next-generation geothermal technologies provide power that is both clean and firm, giving them a unique value proposition that commands a price premium. Currently, however, utilities consider clean electricity sources and firm electricity sources as separate products with separate markets. The most cost-effective clean power option is either wind or solar power, and the most cost-effective firm power option is natural gas. These sources have LCOE values between $25/MWh and 35/MWh[181 182], which is below expected LCOEs for next-generation geothermal for the foreseeable future (Figure 13).

To fully decarbonize the grid, firm power must also be clean, and the cost of that joint value proposition is higher. As demonstrated in Chapter 1, these clean firm sources are in high demand by mid-century; however, clean firm energy sources today have high costs that prevent them from being deployed. **There are relatively few demand signals today for power that is simultaneously clean and firm that would drive deployment of these systems today.** Without market structures that value generation systems that can simultaneously provide firm, clean, flexible power, geothermal power will struggle to be cost-competitive against portfolios of natural gas, wind, and solar.

Solution: Planning policies that incentivize higher-cost, higher-value power

Public utility commissions can reproduce the successful model demonstrated in California to mandate the procurement of clean firm power to enhance the reliability of the electric grid. Such mandates are likely premature for most of the nation at this point, as multiple grid operators interviewed expressed a desire to procure geothermal power but were unable to identify any near-term opportunities. However, in the western U.S., procurement mandates today can help spur next-generation geothermal investments sooner.

Solution: Leveraging flexible geothermal operations to capture highest-value power

Geothermal plants can create their own value by choosing to only sell power when prices are high. The flexible nature of geothermal generation can allow operators to capitalize on diurnal and seasonal trends in the power market by recharging the reservoir when prices are low, and discharging an over-pressurized reservoir when prices are high. In this process, reservoirs that are "recharging" build up excess pressure, ensuring that when discharge occurs, power outputs can exceed the average plant capacity. This flexible operation practice can double the value of geothermal power, leading to approximately twice the economic deployment on the grid (Figure 9). This design capability has not yet been tested at EGS demonstrations. Operators could capture increased value by validating this capability in the field and designing new plants that maximize it; operators should also work with local grid operators to build the appropriate flexible power purchase agreement structures that will enable this style of operation on the grid.

Solution: New offtake models, e.g., subsurface developers providing heat for multiple purposes

Geothermal developments yield heat, which in it of itself is a valuable commodity. Geothermal heat can be directly used in several currently hard-to-decarbonize applications, including process heat for industrial applications.[183] Process heat represents over half the emissions from the industrial sector, and geothermal energy is well-suited to help mitigate the half of those emissions caused by low- and mid-temperature applications[184]. Direct-use industrial applications of geothermal heat include greenhouses, food processing, cement drying, and paper processing. Geothermal direct use heat can also be directly leveraged for hydrogen production at temperatures above 150C.[185]

The value of clean firm power behind the meter can be particularly useful for new clean energy applications that are nascent today. Geothermal energy can provide the zero-carbon, on-demand power needed to keep hydrogen electrolysis[186] or direct air capture net-zero. The world's first direct air capture facility is powered by geothermal energy,[187] and studies are investigating expanded feasibility of these opportunities.[188] Geothermal energy can potentially capture unique value streams in these industries.

The materials dissolved within geothermal fluids can also provide a potentially substantial value stream. Geothermal brines can provide a large domestic supply of lithium if economically extracted.[189] Substantial investment in developments in California's Salton Sea are geared towards the profitable extraction of these metals, which could provide a substantial additional value stream to geothermal developments.[190] [191] [192]

Challenge: Community opposition in some instances

Technical similarities between EGS and oil & gas hydraulic fracturing could prompt environmental health concerns like those pertaining to hydraulic fracturing to affect the next-generation geothermal industry.[193] While key differences in the environments and designs of unconventional oil & gas wells and next-generation geothermal wells reduce many of the environmental risks associated with drilling and hydraulic fracturing (see Chapter 1), lack of public awareness of these differences could create substantial public opposition. Hydraulic fracturing bans that exist in California and New York are specific to oil & gas wells; however, substantial public opposition could extend the scope of these bans, to the detriment of a nascent industry.

Solution: Adherence to long-established induced seismicity and environmental monitoring best practices

Next-generation geothermal developers can benefit from transparent and robust environmental monitoring to help ensure environmental impacts are minimized and the technology develops a strong social license to operate. Monitoring is the best bulwark against potential felt induced. DOE has a decade-plus history of successfully managing seismic activity at its EGS sites through the *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems*.[194] This protocol includes developing a seismicity risk model for each site and provides thresholds on where and when to operate or stop operation. Additionally, advances in high-performance computing are improving predictive capabilities, which is further reducing risk.[195] DOE anticipates releasing updated induced seismicity protocols to reflect technological advances soon. All next-generation projects should employ and adhere to established induced seismicity protocols to ensure this risk is managed.

Transparent monitoring and disclosure of any chemicals leveraged in next-generation geothermal developments also can improve operator license to operate. The next-generation geothermal industry is at the cusp of scaled expansion; an opportunity therefore exists to collaboratively develop processes and methods for reservoir creation that eliminate or minimize the use of hazardous materials. As the technology develops, future work to assess these considerations, including the composition of injected fluids and their impacts on environments and communities, and the differences between geothermal hydraulic fracturing and oil & gas hydraulic fracturing, can inform communities, increase social license to operate, and lead to more effective deployment. Operators will also experience a greater license to operate if hydraulic fracturing fluids deploy non-hazardous substitutes within hydraulic fracturing fluids wherever possible, and to develop such substitutes when not yet available, regardless of the actual likelihood of groundwater contamination.

Solution: Early, frequent, and transparent community engagement

Environmental and human health harm from past and current oil & gas operators has created distrust between oil & gas operators and citizens in some communities.[196] [197] Geothermal operators can proactively mitigate these concerns through local trust-building and engagement. Effective outreach could include collaboration with local partners to leverage next-generation geothermal's ability to flexibly site projects in the most optimal locations for local communities. The expansion of outreach efforts across current and future markets of next-generation geothermal, and initiating behind-the-scenes coordination and research efforts to supply needed information for outreach activities, can also increase awareness and improve community perception.

Transparency also increases trust. Operators can take additional steps to ensure local communities understand and accept the project and its impacts. For example, at the DOE-run Utah FORGE site, seismicity monitors are on display in the public library to transparently show drilling impact in real time.[198] Operators could voluntarily disclose the chemicals that are used in hydraulic fracturing operations via open databases, and in many cases, operators are required by state and local law to disclose this information. For example, FORGE is required to report its water quality data to the Utah Department of Natural Resources.[199]

Chapter 5: Metrics to Track Progress

Progress towards next-generation geothermal liftoff and full commercial scale should be tracked at the regional, state, and national level. Three categories of metrics—outcomes, lagging indicators, and leading indicators—can track the progress and impact of next-generation geothermal sector growth.

Outcomes track the benefits of next-generation geothermal to the grid, economy, and communities:

- **Total clean firm capacity nationwide and by ISO/RTO (MW)**

  Updated estimates on total clean firm capacity can help determine whether the nation's grid and individual ISO/RTO entities are staying on track to an efficient and decarbonized grid.

- **Clean capacity (MW) and clean energy generation (MWh and percentage of overall consumption)**

  MWh of clean generation deployed will indicate progress towards a decarbonized grid, and the average capacity factors, or percentage of overall consumption, will indicate to what extent load serving entities are balancing clean supply and demand for electricity.

- **Transmission buildout**

  The rate of transmission buildout, and ratio of total load to transmission, will indicate the balance between overall grid infrastructure cost and new clean power generation.

- **Consumer prices ($/kWh)**

  Average consumer electricity prices ($/kWh) nationwide and by region will track the efficiency of new generation additions.

- **Workforce transition and specialized education**

  As the next-generation geothermal industry scales, the number of workers entering the industry, either by transitioning from transferable sectors or by training through new programs, will indicate the economic impact of the growth in this sector. An additional proxy may be enrollment in geothermal-specific engineering and management courses at universities that traditionally serve other subsurface workforces (e.g., oil & gas and mining).

Lagging indicators track observed progress towards next-generation geothermal liftoff:

- **Next-generation geothermal capacity (MW), total wells (#), and total plants (#)**

  The total amount of power production capacity from next-generation geothermal will be the clearest indicator of progress towards the full potential. The number of wells and plants is a driver of overall capacity, and a close proxy for industry growth and maturation.

- **Number of regions with deployed next-generation geothermal**

  The number of states and differing geologic conditions in which next-generation geothermal is successfully deployed will indicate the success of the validation suite of early deployments in terms of realizing the technology's applicability beyond early competitive regions that are already well-characterized.

- **Demonstration projects**

  The number of demonstration projects utilizing new technologies or exploring new regions will indicate the health of the innovation ecosystem and diversified growth of the industry overall.

- **Number of active developers pursuing deployment**

  Updates on the number of separate developers pursuing next-generation geothermal deployments will indicate overall market health. Next-generation geothermal will benefit from market entry, in terms of skillsets, competition, and access to capital.

- **Orderbook and signed PPAs**

  As offtakers begin long-term planning processes, the number of signed PPAs (and their terms, including price) will indicate both future demand and overall power sector confidence in the trajectory of next-generation geothermal technology and its potential to provide significant amounts of clean firm power.

Leading indicators track key capabilities and technological progress for next-generation geothermal development:

- **Well cost ($M/well)**

  The cost of drilling a single well in different geologic settings, differentiated between greenfield sites and pre-developed fields, will indicate the trajectory of all key cost inputs into geothermal subsurface development and progress along the industrywide learning curve.

- **Drilling cost ($/ft or ft/day)**

  Drilling cost is the major input into well creation. With drilling time corresponding very well with drilling cost, this can either be measured in $/ft or in ft/day, but progress in this input will correspond to progress in overall cost of development.

- **LCOE ($/MWh)**

  A proxy for overall cost of production, the LCOE of next-generation geothermal developments should continue to be estimated to track overall industry progress.

- **Technical well parameters**

  A suit of technical parameters should be tracked to prove the track record of next-generation geothermal developments in different locations as the industry grows and matures.

  - **Operational data and well capacity (flow rate, temperature, and enthalpy)**
    Flow rate, temperatures, and enthalpy are key technical parameters in well capacity to produce power, and maintenance of these parameters at expected levels is critical to project success.

  - **Resource drawdown (MW/yr)**
    As the heat resource is harnessed from the subsurface, correct thermodynamic characterization of the decay and maintenance is critical to continue to deliver power at the volume intended and ultimately project success.

  - **Resource rebound (MW/yr)**
    A producing well that is shut in can cause the surrounding resource temperature to rebound to its prior-development level. This metric is helpful in determining the thermal efficiency of the reservoir.

  - **Capacity factor (%)**
    A metric of operational success and correct resource use, a track record of meeting expected capacity factors may prove next-generation geothermal engineering and operation capabilities, and their ability to deliver on the clean firm power value proposition.

  - **Resource characterization data**
    Correctly identifying subsurface temperature, rock properties, fracture patterns, and stress states is critical to technical improvements and ongoing development in new sites. Tracking these capabilities will indicate overall industry health.

- **Drilling and stimulation data**
  The collection and sharing of drilling data such as penetration rates, grain size distributions, and core samples, as well as stimulation data such as fracture orientation and overpressure thresholds, will facilitate further development and technical improvements.

- **Lease nominations from the Bureau of Land Management (BLM) (#)**

  To accommodate rapid growth in this industry, the number of lease nominations must stay apace or ahead of developments. Updated views on leases and NEPA reviews will indicate capacity to serve the industry as a whole.

- **Water quality indicators**

  Water quality at geothermal development locations will be important to track continued environmental safety.

Appendix A: Modeling Appendix

Part 1: Methodologies and Assumptions

Economy-wide capacity expansion modeling sensitivity analysis

Analysis objective: Estimate the impact of different market and policy drivers on the economic deployment of geothermal power as a component of the total domestic electricity system.

Description of analysis:

This report leveraged two independent modeling frameworks to estimate economic deployment of geothermal power on the grid by 2050: the Regional Energy Deployment System (ReEDS) Capacity Expansion Model, constructed and managed by NREL,[201] and the GenX Least-Cost Optimization Model constructed and managed jointly by Princeton University and the Massachusetts Institute of Technology.[202] Both models use least-cost optimization algorithms to develop an optimized mix of energy generation given assumptions assigned by the user. This report primarily used ReEDS to estimate deployment of geothermal power between now and 2050, and GenX to estimate the impact of adding flexibility in geothermal generation to deployment.

This report uses the modeling performed for the Enhanced Geothermal Shot[203] in 2022 as the basis upon which all other scenarios are built. The construction of this analysis, which is referred to as the "Energy Earthshot Original" in this report, is described in detail in the *Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office.*[204]

DOE commissioned a series of updated modeling scenarios that built on the "Energy Earthshot Original" scenario to assess how different market and technical factors may impact the estimated deployment of geothermal power through 2050. These updated assumptions are:

1. **Consideration of Inflation Reduction Act Incentives:** Updated scenarios include representation of most provisions from the Inflation Reduction Act of 2022 (IRA). The representation of IRA's provisions is discussed in detail in Section A.3 of the *2023 Standard Scenarios Report*.[205] A notable omission from the IRA provisions is the 45V clean hydrogen production tax credit, which is not represented in this modeling because the Treasury Department has not released final guidance on how the determination of clean hydrogen will be conducted, and alternative potential implementations have significant impact on the provision's impact on the power sector.

2. **Increased overall power demand:** Updated scenarios include new modeled projections of end-use electricity demand growth that incorporate estimates of the potential impacts of IRA's provisions on overall electricity demand. See Section A.1 of the *2023 Standard Scenarios Report*[206] for more discussion of demand assessments.

3. **Updates to generation costs:** Updated scenarios include the most recent representation of the cost for clean energy technologies. Input costs for solar power, wind power, hydropower, battery storage, pumped storage hydropower, and all fossil energy technologies are represented using the 2023 Mid-Case estimate from the *NREL Annual Technology Baseline.*[207] Biopower and nuclear power (conventional and small modular reactors) are represented using estimates from the U.S. Energy Information Administration's (EIA's) Annual Energy Outlook 2023 (AEO2023) projections,[208] and biomass fuel availability was projected based on the "Billion Ton Report" released by DOE in 2016.[209] Current direct air capture (DAC) costs are estimated based on the findings of a DAC Case Study commissioned by the National Energy Technologies Laboratory,[210] and cost reductions over time were based on a solvent-based capture system with a cost improvement trajectory applied based on that case study.

Hydrogen costs used in this report are consistent with the mid-point cost estimate for a proton exchange membrane electrolysis system in the *Pathways to Commercial Liftoff: Clean Hydrogen* report.[211]

Scenario definitions

This report investigated the impact of three main technical and market drivers that have measurable impact on the deployment of geothermal power:

1. **Restriction of land use availability for wind and solar power:** To represent this driver, the total deployment of wind and solar power allowed by the simulation was capped at 1,100 GW. This total deployment cap is the sum of total of wind and solar resources deployed in the land use-constrained scenario within the *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035* study.[212] In the constrained scenario, by 2035, the model output has 600 TW of solar and 500 GW of onshore wind. This scenario was also leveraged to represent a land use availability restriction in the *Pathways to Commercial Liftoff: Advanced Nuclear*[213] report.

2. **Restriction of hydrogen and DAC (nascent technologies):** Certain nascent technologies are critical for late-stage decarbonization, but their future adoption is relatively uncertain. In scenarios in which nascent technologies are restricted, hydrogen-fueled combustion turbines and DAC are removed from the model.

3. **Enabling of flexible next-generation geothermal operations:** The GenX model was used exclusively to represent the impact of flexible generation on next-generation geothermal deployment. Construction of GenX such that generation flexibility is enabled is described in *Ricks et al. (2022)*[214] and *Ricks et al. (2024)*.[215] The generation flexibility scenarios included all original assumptions from the "Energy Earthshot Original" base case, as well as all updates listed in the previous section. Because of the model construction differences between GenX and ReEDS, this report does not compare the impact of flexibility between simulations using different models. Rather, the impact of flexibility was determined by comparing a "control" scenario, using identical assumptions to "Energy Earthshot Original," to a scenario that, aside from enabling flexibility, was otherwise identical.

   On the basis of the attributes highlighted above, eight scenarios were performed in total across the two different models by overlaying restrictions in a controlled manner. The table below summarizes the scenarios analyzed.

Table 3: Description of key inputs for modeling scenarios performed as a part of this work

Scenario	Model	Geo power cost	H2 cost	DAC cost	Other gen costs	Gener. restric.	Flexible generation capability	Decarb scenario		Policies	
Energy Earthshot Original	ReEDS	Energy Earthshot	Excluded	Included	ATB 2021 – moderate	None	None	95% by 2035	100% by 2050	State & regional clean energy standards (CES)	
Land Use Restriction, ReEDS	ReEDS	Energy Earthshot	Hydrogen Liftoff	NETL/ Exxon Case Study	ATB 2023 – moderate	1.1 TW max for solar & wind	None	95% by 2035	100% by 2050	IRA	State & regional CES
Nascent Technology Restriction, ReEDS	ReEDS	Energy Earthshot	Excluded	Excluded	ATB 2023 – moderate	None	None	95% by 2035	100% by 2050	IRA	State & regional CES
Land Use & Nascent Technology Restriction, ReEDS	ReEDS	Energy Earthshot	Excluded	Excluded	ATB 2023 – moderate	1.1 TW max for solar & wind	None	95% by 2035	100% by 2050	IRA	State & regional CES
Energy Earthshot Update, GenX	GenX	Energy Earthshot	Hydrogen Liftoff	NETL/ Exxon Case Study	ATB 2023 – moderate	None	None	95% by 2035	100% by 2050	IRA	State & regional CES
Flexible Generation, GenX	GenX	Energy Earthshot	Hydrogen Liftoff	NETL/ Exxon Case Study	ATB 2023 – moderate	None	Enabled	95% by 2035	100% by 2050	IRA	State & regional CES
Hydrogen Restriction, GenX	GenX	Energy Earthshot	Excluded	NETL/ Exxon Case Study	ATB 2023 – moderate	None	None	95% by 2035	100% by 2050	IRA	State & regional CES
Flexible Generation & Hydrogen Restriction, GenX	GenX	Energy Earthshot	Excluded	NETL/ Exxon Case Study	ATB 2023 – moderate	None	Enabled	95% by 2035	100% by 2050	IRA	State & regional CES

Part 2: Nationwide Deployment Results

Table 4: Projected geothermal deployment in 2050 as corresponding to the modeled scenarios stated in Table 1

Scenario	Deployment in 2050 [GW]
Energy Earthshot Original	**90**
Land Use Restriction, ReEDS	132
Nascent Technology Restriction, ReEDS	287
Land Use & Nascent Technology Restriction, ReEDS	327
Energy Earthshot Update, GenX	99
Hydrogen Restriction, GenX	117
Flexible Generation, GenX	177
Flexible Generation & Hydrogen Restriction, GenX	213

Geothermal deployment absent any additional considerations was projected to be either 90 GW (ReEDS, Energy Earthshot Original) or 99 GW (GenX, Energy Earthshot Update). The largest impact on geothermal deployment of the three factors considered is the restriction of nascent technologies—if hydrogen and DAC are excluded from the model, geothermal deployment increases to 287 GW. If land use restrictions are overlain on a nascent technology restriction, another 40 GW of geothermal deployment was observed.

Land use restrictions alone are impactful, resulting in about 50% more deployment from the original Energy Earthshot scenario.

Flexibility also has a large impact—the inclusion of flexibility nearly doubles expected geothermal deployment, from 99 GW (Energy Earthshot Update, GenX) to 177 GW (Flexible Generation, GenX). Restricting hydrogen from a flexible scenario has a relatively smaller impact, adding 36 GW when flexibility is considered and half that (18 GW) when flexibility is not considered.

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