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Geothermal Everywhere: A New Path for American Renewable Energy Leadership

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EXECUTIVE SUMMARY

America's abundant oil and gas reserves have been central to its economic prosperity, but the development of these energy resources have significant negative externalities in terms of their impact on the local environment and contribution to global climate change. In 2021, the Biden administration recommitted the United States to the Paris Climate Accord and began exploring pathways to decarbonize the domestic economy to meet international climate goals.[1] Electricity generation and residential/commercial heating together account for more than a third of the United States' greenhouse gas emissions, which means that energy policy must be a central component of the U.S. climate strategy.[2] This will require both a divestment from existing oil and gas projects as well as substantial investment in new renewable energy resources.

Today, the United States' renewable energy portfolio is dominated by hydropower, wind, and biomass, with a rapidly growing contribution from solar.[3, 4] Electricity derived from geothermal resources is almost non-existent, providing just 17 billion kWh — less than 0.5% of U.S. electricity generation — annually.[5] But this is not for lack of geothermal resources. The United States, and particularly the western United States, is a hotbed of geothermal energy that could meet the electric and thermal energy requirements of the entire country many times over.

In this paper, we identify the technological, economic, and political reasons that the United States has failed to exploit its geothermal resources. We provide actionable policy recommendations to sustainably and economically utilize the vast energy reserves under our feet, namely:

Streamline the federal permitting process for geothermal projects — Federal permitting restrictions on drilling geothermal wells on public land are more burdensome than for otherwise similar oil and gas drilling projects. Extending the same National Environmental Protection Act (NEPA) exclusions that oil and gas projects have to geothermal projects would enable the fledgling industry to quickly scale in the parts of the country with the shallowest heat resources.

Increase the federal budget for large scale geothermal R&D projects, particularly those led by public-private partnerships — Expanding the budget for the Department of Energy's (DOE) flagship FORGE geothermal site would generate valuable data about experimental drilling techniques and provide the private sector additional opportunities for large-scale field demonstrations to attract additional investment.

Create incentives for geothermal generation in state electricity markets — Adjusting the criteria for Renewable Portfolio Standards (RPSs) in states that are unnecessarily restrictive would help put geothermal energy on an even playing field when compared to wind or solar. Further, adding a requirement that some percentage of RPS goals be met by a clean, baseload power source would acknowledge the special importance of geothermal for firming our energy supply.

Establish federal innovation prizes (or related mechanisms) for the development of key geothermal technologies — Drilling deep into bedrock is difficult and time consuming. And identifying the most fruitful subsurface locations to drill for geothermal energy is expensive. Accelerating breakthroughs in these key technological bottlenecks could dramatically impact the pace of geothermal power generation.

Reskill oil and gas workers for geothermal projects through federal jobs programs and private investment — The U.S. has a lot of machinery and a specialized workforce that is well-equipped for oil and gas drilling. There is a high degree of overlap between the skills and equipment necessary to effectively drill for fossil fuels and for geothermal energy. The U.S. should speed the transition away from fossil fuels to geothermal by aiding in worker retraining efforts and/or equipment retrofitting.

We conclude that these policies would greatly accelerate the development of geothermal projects and lay the foundation for energy abundance in the green economy. The United States is uniquely poised to become a leader in geothermal energy due to its abundant hot rock resources and the deep talent pool in the oil and gas sector. A combination of strong leadership and smart policy can and should make geothermal energy a valuable asset in the United States' renewable energy portfolio while laying the groundwork for international geothermal expansion.

INTRODUCTION TO GEOTHERMAL ENERGY

Geothermal energy is the catchall term for heat generated by natural subterranean geological processes. All geothermal wells operate in the crust, a layer of hot, solid rock that extends a few miles beneath the surface. The rock in the crust is heated by the mantle, a region of molten or semi-molten material called magma that extends about 1,800 miles beneath the surface. This magma was created from the intense heat emanating from the Earth's core, where the natural decay of radioactive material releases a tremendous amount of thermal energy.[6] In fact, Earth's internal heat content is enough to meet the entire global energy budget billions of times over.[7] Realistically, only a small fraction of the planet's heat content can be converted into useful energy. But the geothermal energy trapped in the hot rock near the surface is more than enough to meet Earth's energy needs and can effectively be treated as an inexhaustible energy resource.

WHERE IS GEOTHERMAL ENERGY?

Geothermal energy is ubiquitous, but not all geothermal resources can be economically exploited. The cost of a geothermal well increases exponentially with depth. Many pockets of hot rock are simply too deep to profitably access. Others may not be hot enough to produce electricity. Current geothermal systems typically require water heated to at least 200 C to profitably drive the steam turbines that produce electricity. Technological advances may create the opportunity to economically produce electricity from "low-grade" geothermal resources (<100 C, below the boiling point of water), but many of the key technologies are still in their infancy.

The best geothermal resources are hot and shallow. These are typically found around the boundaries of the Earth's tectonic plates where magma near the surface heats pockets of ground water or solid rock.[8] A classic example of a geothermal hotspot is Iceland, which straddles diverging tectonic plates. This is the cause of Iceland's famously vigorous volcanic activity, but it is also the source of a vast network of geothermal hot springs near the surface that can be tapped to produce electricity and direct heat.

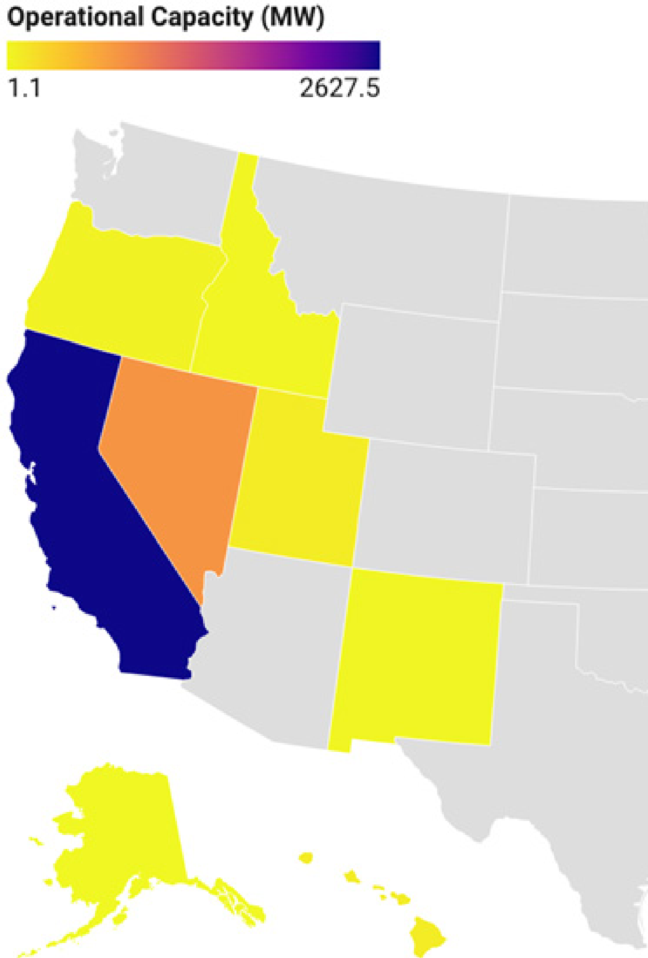
All geothermal energy in the United States is currently produced from conventional hydrothermal resources. The Geysers in California is the largest domestic geothermal field in operation, but conventional geothermal resources, both known and inferred, account for just a fraction of available geothermal energy in the country.[9] (In this paper, we'll refer to a known geothermal resource as one that has been measured and an inferred geothermal resource as one that is believed to exist based on geological conditions or local drilling but has not been measured.) Instead, most of this geothermal energy is trapped in vast fields of relatively shallow hot dry rock that can be exploited with enhanced geothermal systems (EGS). The highest quality geothermal energy resources — both known and inferred — are concentrated west of the Rocky Mountains due to their proximity to the boundary between the North American and Pacific tectonic plates.[10] Technological advances are also creating the possibility of using the comparatively lower quality geothermal resources that are abundant in the Eastern U.S., but in the near term most geothermal development will likely occur in the western United States.

HOW IS ELECTRICITY PRODUCED FROM GEOTHERMAL ENERGY?

Geothermal energy produces electricity by transferring naturally occurring geologic heat to water, pumping it to the surface, and converting the thermal energy into electrical energy. There are many different types of geothermal power station, and their configuration depends on the characteristics of the resource. For example, some subsurface aquifers contain water that is hot enough to drive a steam generator directly, but the heat from cooler aquifers might need to be transferred to another working fluid with a lower boiling point to generate electricity efficiently.

However, geothermal systems are generally split into two broad categories: conventional and enhanced. Conventional geothermal energy, also known as hydrothermal energy, taps into shallow, naturally occurring pockets of hot water below the surface and pumps that water to the surface. Enhanced geothermal systems (EGS) are broadly characterized as systems that inject water into deeper pockets of dry hot rock and then pump it back to the surface, essentially creating artificial hydrothermal reservoirs.[11]

GEOTHERMAL CAPACITY BY STATE



There are variants and overlap between these approaches to geothermal. For example, conventional geothermal systems may inject water back into a natural hot spring to replenish the resource. Some proposed EGS projects use a closed-loop format where water runs through subsurface pipes without ever coming into direct contact with the hot rock. Meanwhile, other EGS projects are attempting to tap into naturally occurring pockets of extremely high-temperature supercritical fluids, which can store vastly more thermal energy in a given volume than water.

In all cases, a geothermal system requires drilling a well. The size and depths of these wells can vary dramatically. A typical well will have a minimum borehole diameter of around 8 inches and a depth of several hundred feet.[12] The deepest commercial well is currently the St1 Deep Heat project in Otaniemi, Finland, which recently completed drilling and testing of its 6 km well and expects to begin producing electricity in the near future.[13] The methods for drilling geothermal wells are essentially the same as the techniques used in the oil and gas industry, but with significantly higher temperatures and lower reservoir pressures than those found in oil and gas wells.[14]

THE ENVIRONMENTAL IMPACT OF GEOTHERMAL ENERGY

Geothermal energy is the only source of carbon-free electricity that is both renewable and capable of delivering variable baseload power at the scale needed for the U.S. energy transition. Wind and solar are ill-suited to providing an always-on solution for the grid due to large fluctuations in production. Large-scale chemical energy storage such as lithium-ion batteries can help offset these fluctuations, but this remains an expensive solution. Perhaps recent advancements in iron-flow batteries will make long-duration energy storage a more realistic solution, but these technologies are still being actively tested and proven.[15] Advanced nuclear systems are an alternative source of energy that can operate in both baseload and load-following configurations, but nuclear is not a renewable resource and may present proliferation concerns if exported widely around the world. Biomass and biofuels are an alternative source of renewable baseload power that is capable of load following configurations, but they are challenging to sustainably scale due to their large land use requirements.[16]

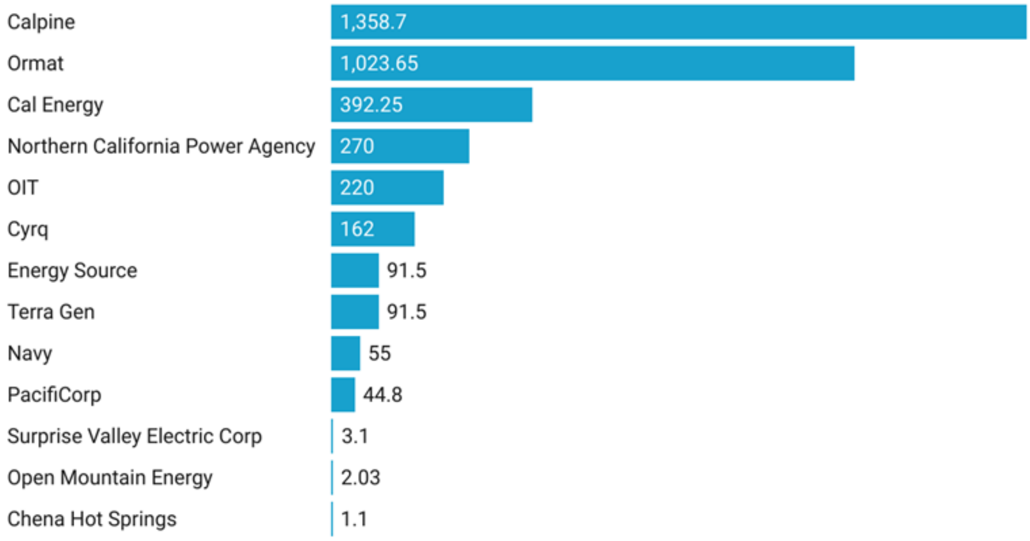
Geothermal energy is a minimally extractive energy source. The primary environmental impacts come from removing rock to create a well, material inputs for well-casings, and pumping water into or out of the well. Once a geothermal well is operating, it may use anywhere from 5 to 720 gallons of water per MWh depending on the type of cooling system used on the surface.[17] Although geothermal power stations use substantially less water compared to other electric generation technologies,[18] it is critical that future geothermal projects in the western United States are optimized for water conservation given the persistence of extreme drought conditions.[19]

Geothermal energy has one of the smallest land use footprints of all clean energy sources. A typical geothermal project occupies around 400 m^2 per GWh_e, which is far below coal (~3600m^2), wind (~1300 m^2), and solar (~3200 m^2).[20] Depending on the location of the geothermal generation station, connecting it to the grid will require significant development of transmission infrastructure and the footprint of these power lines will vary based on the location and size of the geothermal resource.[21]

An important question is whether it increases seismic activity in the surrounding area. Like the hydraulic fracturing or "fracking" techniques used in the oil and gas sector, geothermal wells displace tons of rock and inject fluids down hole, which can create instabilities in the rock formation. Several seismic events have been attributed to geothermal drilling. Perhaps the most notable instance was a 5.5 magnitude earthquake in Pohang, Korea in 2017, which coincided with an experimental EGS well being drilled nearby.[22]

Although seismic activity will always be a concern for geothermal projects, technological advances in the past few decades, particularly improvements in drilling techniques and subsurface mapping tools, have limited the risks of geothermal drilling causing a dangerous seismic event. A prime example of the effects of these technologies was recently demonstrated at

U.S. GEOTHERMAL CAPACITY BY OPERATOR (MW)



the Larderello-Travale geothermal field in Italy, the first to produce electricity with geothermal energy, which recently completed drilling on the hottest geothermal borehole ever created. To address concerns that the pioneering project would trigger earthquakes in the region, an international team of engineers created a local network of seismometers to measure the seismic activity caused by the geothermal well. Over the course of the six-month study, no unusual or dangerous seismic activity was reported.[23]

THE CURRENT STATUS OF GEOTHERMAL ENERGY R&D IN THE UNITED STATES

PRIVATE SECTOR / COMMERCIAL GEOTHERMAL ACTIVITY

The first American geothermal well to generate electricity was connected to the grid in 1960. Today, there are over 60 geothermal power stations in six Western states plus Hawaii and Alaska, and 58 new geothermal projects in various stages of development.[24, 25] Almost all existing geothermal stations are located in California and Nevada, which produce 95% of geothermal electricity in the U.S.[26] California accounts for 70% of U.S. geothermal generation alone. Although American geothermal generation produces just 17 billion kWh annually, representing just 0.4% of electricity generation in the country, this accounts for roughly 20% of global geothermal production.[27] Today, the U.S. produces more geothermal energy than any other country, but may soon be surpassed by Indonesia.[28]

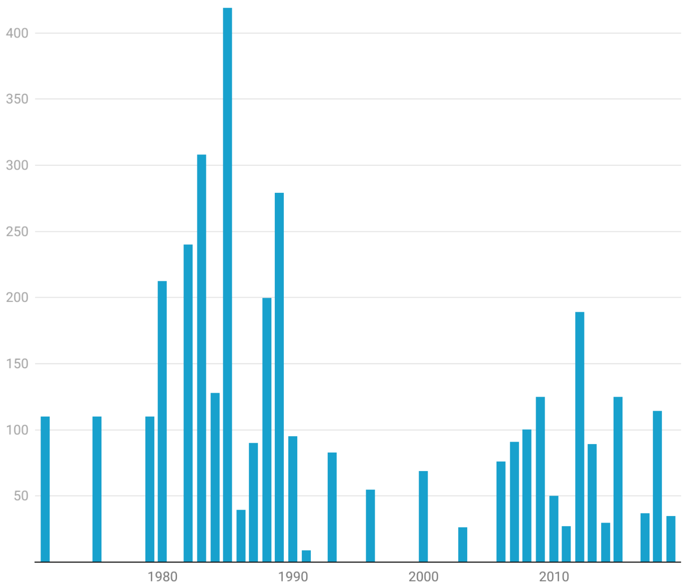
Today, the majority of American geothermal power stations are operated by Ormat, an international energy company headquartered in Reno, Nevada. All existing American geothermal power plants use conventional hydrothermal resources, but in the past decade, several enhanced geothermal startups have been founded in the U.S., but none have completed a commercial EGS project. In recent years, there has been a surge of interest in geothermal projects in the private markets. The most well-capitalized American EGS startup is California-based Fervo Energy, which has raised $39 million to date to fund its EGS project.[29] In May, Fervo announced a partnership to supply geothermal energy to power Google's expansive data centers in Nevada.[30] Several prominent equity finance firms, including Bill Gates' Breakthrough Energy Ventures[31] and Vinod Khosla's venture firm,[32] have invested tens of millions into EGS startups. The venture arms of major oil and gas firms, including BP and Chevron, have also made substantial investments in geothermal startups. In the first half of 2020 alone, an estimated $675 million in private investment flowed to geothermal projects globally — a nearly 600% increase over the previous year.[33]

FEDERAL FUNDING FOR GEOTHERMAL

But the large capital outlays associated with geothermal projects means that startups are still highly dependent on the largesse of federal programs.[34] Federal funding for geothermal R&D in the United States has gone through several boom-and-bust periods. The 1970s and 1980s were something of a golden age for geothermal technology driven by concerns about energy security spurred by the oil crisis. During these two decades, the U.S. Geological Service produced a detailed map of known hydrothermal resources in the U.S., American oil and gas companies prospected hundreds of geothermal wells around the world, and most of the domestic geothermal power stations that are still active today were built.[35, 36, 37] But as the energy crisis subsided, government and private sector enthusiasm for geothermal energy waned. In the 1990s, many oil and gas majors shuttered their unprofitable geothermal units and Unocal, an oil and gas company that established itself as the largest geothermal producer in the world, sold the majority of its geothermal assets.[38] In 2008, the DOE budget proposed entirely defunding the U.S. Geothermal Technologies Office because of the substantial challenges involved with making geothermal energy cost-effective.[39, 40]

Although enthusiasm for geothermal energy had cooled by the new millennium, advancements in drilling technology and prospecting techniques driven by the fracking boom created more opportunities to profitably develop geothermal resources. At the same time, growing concerns about climate change sparked demand for renewable energy and led to more funding for clean energy tech from the federal government.

U.S. NEW GEOTHERMAL CAPACITY BY YEAR (MW)



Since 2006, the Department of Energy has allocated just under $1 billion to geothermal R&D, but only about half of that was allocated to enhanced geothermal projects.[41] A substantial portion of this budget came from the 2009 American Recovery and Reinvestment Act, which distributed $368 million to geothermal projects around the U.S.[42] While federal funding has fallen short of what experts agree will be necessary to commercialize enhanced geothermal technologies, it has rekindled interest in the resource, boosted investor confidence, and laid the foundation for a revolution in EGS technologies. Most recently, Congress passed the Infrastructure Investment and Jobs Act, which allocated $84 million to geothermal energy R&D through 2025. For the sake of context, the U.S. Geothermal Technologies Office budget request for 2022 was $160 million, a 54% increase over the enacted 2021 budget. Notably, the budget proposal includes an 8% increase for EGS research and near-field demonstration projects and a 96% increase in the office's hydrothermal program, which is meant to advance new drilling technologies adapted from the oil and gas sector.

FORGE

The crown jewel of the DOE's investments is the Frontier Observatory for Research in Geothermal Energy (FORGE) initiative, a $200 million underground geothermal research laboratory in Utah that is a critical proving ground for next generation geothermal technologies. The DOE initiated the FORGE program in 2014 to establish field sites to be used as proving grounds for EGS and provide a pathway to large-scale commercialization of next-generation geothermal technologies.[43] FORGE is essentially a first of its kind, large-scale underground geothermal laboratory.

The first few years of the FORGE program were dedicated to selecting and characterizing a field site. The program began with five possible sites and eventually selected a site in Milford, Utah, in 2018.[44, 45] Although running the FORGE program across multiple field sites holds potential benefits such as the ability to test EGS in different subsurface environments, the program's modest funding and limited number of geothermal researchers would make it difficult to achieve the initiative's ambitious aims unless resources were concentrated on a single field site. The Utah FORGE site has several advantages, including relatively shallow hot rock (~6500 feet), minimal environmental risks, low risk of seismic activity, an extensively characterized subsurface environment, and access to transmission infrastructure.[46]

The FORGE field site occupies 15.5 mi^2 and will host two research wells drilled to approximately 8,500 feet.[47] Drilling of the first well began in late 2020 and drilling of the second well is expected to commence in 2022.[48] In addition to the main research wells, several smaller wells outfitted with instruments are distributed throughout the site to study the effects of drilling and energy extraction techniques.

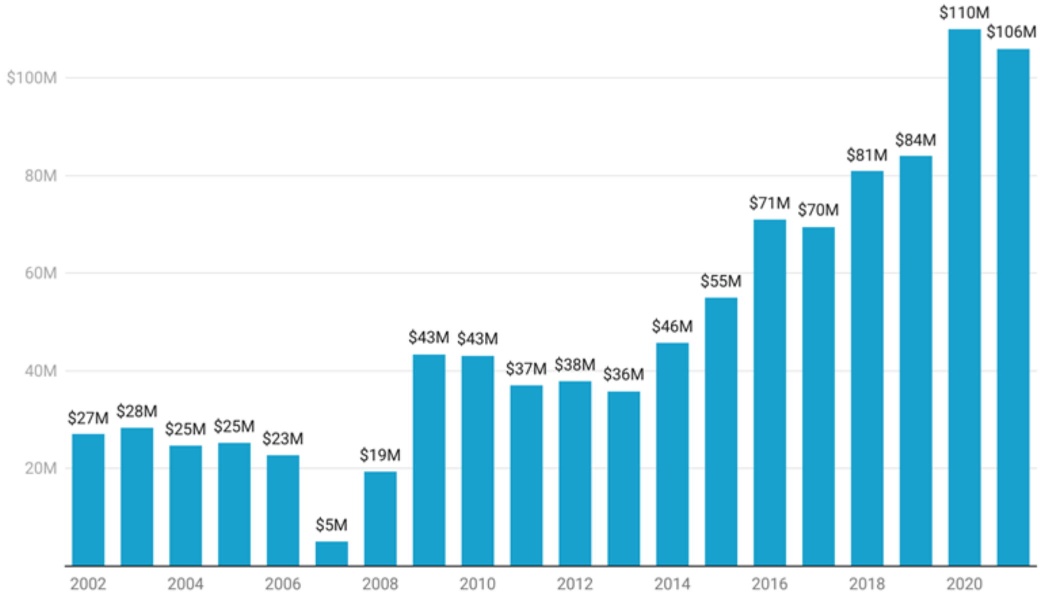
The DOE has earmarked approximately $200 million for the FORGE project through 2024. In 2018, the DOE announced it would distribute $140 million in funding to the University of Utah to support FORGE projects.[49] In early 2021, the FORGE initiative awarded $46 million in funding to be distributed over three years to 17 EGS projects at FORGE.[50] Most of these awards were given to university research groups and federal research organizations, but it also included two grants for commercial geothermal operators.[51]

The most recent FORGE research funding will address a wide variety of key technologies and processes considered essential to the commercialization of EGS. These include well design/completions, stimulation methods, monitoring studies, reservoir modeling, data science, fracture control, detailed stress determinations, and down hole tool design and construction among others.[52]

OTHER FEDERAL GEOTHERMAL INITIATIVES

While FORGE is the primary recipient of federal geothermal funding, there are several other government projects that are also advancing geothermal R&D. The EGS Collab Project is a DOE initiative involving eight national labs and six universities that is focused on understanding the fundamental dynamics of EGS, such as the relationship between well stimulation, seismic activity, and heat production. The EGS Collab project is conducting field experiments on wells at the Sanford Underground Research Facility in South Dakota to validate computer models of well behavior that will provide a foundation for the development of commercial EGS.[53]

FEDERAL FUNDING FOR U.S. GEOTHERMAL TECHNOLOGIES 2002-2021



SOURCE: U.S. DEPARTMENT OF ENERGY OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY

The Geothermal Technologies Office is also supporting targeted research and development of key EGS technologies and techniques through EGS funding opportunities. In 2018, for example, the GTO distributed more than $20 million to projects working on command-and-control technologies for EGS fracturing, machine learning techniques for geothermal energy, waterless stimulation technologies, and advanced drilling technologies.[54, 55, 56] Other DOE offices, including the Office of Fossil Energy and ARPA-E, have also supported EGS projects.[57]

THE ECONOMICS OF ENHANCED GEOTHERMAL ENERGY

The economics of geothermal energy has both a technological and political dimension. On the technological side, the cost-efficiency of geothermal energy production depends on exploration and drilling processes, but there is also room for improvement in converting heat energy to electricity at the surface.

The exploration costs associated with developing new hydrothermal and hot dry rock resources are similar. Unknown hydrothermal resources are those without any surface manifestations such as geysers, hot springs, or fumaroles. Thus, discovery of new hydrothermal resources requires drilling exploration wells, which frequently yield nothing.[58] The same is true for EGS.

The costs associated with both conventional and hot rock geothermal resources increase exponentially with the depth of the well.[59] A primary exploration challenge for geothermal developers is locating resources that are close to the surface and hot enough to efficiently generate electricity (i.e., at least 150 C).[60] In general, the wells required for hot rock resources will be deeper than those required for conventional hydrothermal projects. Although this increases the cost of drilling, these wells are usually significantly hotter than conventional hydrothermal reservoirs, which increases the efficiency of converting heat to electricity at the surface.

Once a developer has identified a promising geothermal resource, secured permits, and drilled exploratory wells, it will be ready to begin drilling a production well. A typical hydrothermal well is about 8-inches wide at the bottom, but requires a bore hole several times larger near the surface to accommodate the telescoping well casing that contains the geothermal fluids. This incurs significant additional drilling costs that don't increase the flowrate and ultimate productivity of the well.

Another significant cost associated with drilling an enhanced geothermal well is known as lost circulation. This is a phenomenon where fluids injected into or extracted from the well leak into geological fissures around the borehole. This both reduces the efficiency of the well and can create instabilities that ultimately lead to the collapse of the well. Research suggests that lost circulation accounts for up to 10% of the cost of productive geothermal wells and 20% of the cost of exploratory wells.[61]

Finally, the advent of EGS will also require outfitting drills with bits that can withstand the intense heats and pressures encountered at depth. Whereas hydrothermal wells can generally rely on the same equipment used to drill oil and gas wells, EGS mostly operates in environments where these tools break down. This requires the development of sophisticated new drilling techniques and technologies.[62]

While there is clearly potential to drive down the cost of geothermal energy with technological advances, the policy side is where the most substantial gains in the cost efficiency of this energy resource are found. First, there is the issue of permitting a new geothermal project, which generally takes several years.[63] Research shows that streamlining the permitting process could substantially reduce the cost and timeline for geothermal development.[64]

Federal tax credits have been key to the explosive growth of renewable energy in the United States over the past two decades, and will be critical to geothermal expansion in the coming years. In 1992, the 10% investment tax credits (ITC) for new solar and geothermal projects were made permanent, but the Energy Policy Act of 2005 temporarily increased the ITC to 30%.[65] In addition to a 10% ITC for new geothermal projects, operators also are eligible for production tax credits (PTC) based on the amount of electricity they produce. Through 2020, geothermal's PTC was 2.5 cents/kWh, which is on par with wind and closed-loop biomass PTC and roughly twice the credits for electricity generated from landfill gas, open-loop biomass, and some hydroelectric projects.[66] In December of 2020, U.S. Congress granted a one-year extension to the PTC for renewables with geothermal keeping its full credit (2.5 cents/kWh) and wind stepping down to 60% credits (1.8 cents/kWh).

The big question for geothermal energy is whether it is competitive with alternative renewable energy sources and under what set assumptions. Today, the levelized cost of energy (LCOE) — the average net present cost of generating electricity over the lifetime of an energy asset — for geothermal plants ranges between $0.04 and $0.14 / kWhe globally depending on the nature of the geothermal resource.[67] In 2019, the global LCOE of new geothermal plants was $0.073 /kWh.[68] In general, high temperature geothermal resources (i.e., flash plants that use high pressure steam to drive a generator) are able to produce cheaper electricity than low-temperature resources (i.e., binary plants that transfer heat from hot water to a working fluid before converting it to electricity).[69] As geothermal technologies advance and make it easier to access high temperature resources, geothermal will become increasingly cost-competitive with other sources of renewable energy.[70] When the unique advantages that geothermal energy adds to the grid are factored into the cost of its energy, such as its ability to operate in both baseload and load-following configurations, the U.S. Energy Information Administration forecasted the LCOE for new geothermal projects entering service in 2026 will be the second cheapest form of renewable energy (slightly more expensive than standalone solar and slightly less expensive than onshore wind).[71]

RETHINKING GEOTHERMAL REGULATIONS

More than 90% of geothermal resources are located on federal land, which means that proposed projects on public land are subject to intense regulatory oversight under the National Environmental Policy Act (NEPA).[72] Indeed, NEPA-related roadblocks are arguably the primary reason that geothermal energy has languished compared to other renewable energy resources and it is substantially more challenging for a new geothermal project to be permitted on federal land than a new oil or gas well. Although any development on federal land that may impact the human or natural environment is subject to NEPA review, geothermal energy is unique in that each phase of the development of a new project may trigger a separate NEPA review. That means that a single geothermal location could potentially trigger up to six separate NEPA reviews whose median review timelines range from a few months to two years.[73]

Overhauling the permitting process for geothermal energy is a multifaceted problem, but the solutions are clear. It is also one of the most cost-effective ways to increase the amount of geothermal energy on the American grid. In fact, the DOE's recent Geovision study concluded that it is possible to double the amount of geothermal energy produced in the U.S. by 2050 through permitting improvements alone.

The regulatory challenges for a new geothermal project on federal land starts at conception. When a developer has identified a promising resource, it will contact the local Bureau of Land Management (BLM) office to initiate the permitting process. The BLM is a federal agency that operates under the Department of Interior and it manages all subsurface geothermal resources on federal lands, regardless of whether another agency such as the U.S. Forest Service manages the land on the surface. BLM is divided into 12 state offices that operate as a loose federation under the federal BLM headquarters. A balkanized BLM creates challenges for geothermal developers because of the variable human resources available to handle geothermal permitting at each office and subjects projects to the whims of a particular office.

Geothermal developers often wait weeks, sometimes months, just to get a reply from a local BLM office to initiate the permitting process. Once a geothermal developer submits an application, BLM officials review it to determine the type(s) of NEPA analysis required for the project. There are five general types of NEPA analysis, which subject proposals to varying levels of scrutiny based on the presumed levels of environmental impact. The ascending order of NEPA analysis type is: casual use, categorical exclusion, determination of NEPA adequacy, environmental assessment, and environmental impact statement.

A typical geothermal project will go through several development phases and each phase may require one or several types of NEPA analysis. Although no permits are needed to lease land for a well field, BLM usually conducts an environmental assessment (EA) or environmental impact statement (EIS) prior to leasing the land. Once the lease is approved, the geothermal project begins its exploration phase, which typically involves water sampling, seismic surveys, and drilling temperature gradient holes to understand the subsurface environment. These exploration activities may also be subject to categorical exclusion, EA, and/or EIS analysis. Next, a project begins drilling slim or full-size wells to confirm the presence of a geothermal resource, which may also be subject to EA or EIS analysis. If the geothermal developer confirms the resource, the next step is to construct the power plant, transmission lines, and production and injection wells. This step is also subject to EA or EIS.[74]

Not every geothermal project will require a NEPA review at each stage of the process, but generally speaking the permitting process is much more stringent for geothermal developers compared to other energy projects. The different types of NEPA analysis have varying levels of approval time, ranging from a median of about three weeks for permits approved through casual use analysis versus more than two years for the median permitting time for EIS analyses.[75] Altogether, the average geothermal permitting process from initiation to operation takes five and a half years. That is substantially longer than the average for new solar and wind projects (18 months) and the average for oil and gas projects (three and a half years).[76]

In many respects, the permitting process for geothermal projects on federal lands is analogous to the permitting process for drilling new oil and gas wells. The key difference is that many new oil and gas wells are subject to NEPA exemptions, and many BLM offices have staff dedicated to appraising oil and gas development applications. For example, if a new oil and gas well is drilled on a field that has already passed NEPA review and has a substantially similar profile to existing wells, it may be excluded from an EA or EIS under a determination of NEPA adequacy analysis or categorical exclusion. Indeed, BLM staff are instructed to look for exemptions for environmental impact analyses when appraising new oil and gas project applications to streamline the permitting process.[77] This can lower permitting times to a matter of weeks or months compared to the years it takes to receive approval for a new geothermal well.

There are no scientific reasons why a geothermal well should be subject to stricter environmental permitting processes than oil and gas wells. Both must demonstrate a low risk of inducing seismic activity, minimal damage to the local surface and subsurface environment, and so on. In fact, in many ways geothermal wells are inherently safer than oil and gas wells insofar as they don't use toxic fracking fluids, don't operate at higher pressures, and don't have the negative externalities associated with burning fossil fuels. If geothermal energy is to become a substantial part of the U.S. energy ecosystem, it is imperative that barriers to permitting are reduced.[78]

TECHNOLOGICAL PATHWAYS TO ENHANCED GEOTHERMAL SYSTEMS

Enhanced geothermal systems (EGS) include all geothermal projects that don't depend on natural low temperature (<400 C) hydrothermal reservoirs. This includes artificial reservoirs, supercritical reservoirs, and closed loop systems. The biggest gains in energy efficiency, as well as the ability to decouple geothermal energy from geography, depends on the development of EGS. Although many EGS technologies are still in their infancy, they are already being deployed at field sites and have demonstrated the massive potential of next-generation geothermal. In this section, we will consider viable pathways from conventional hydrothermal projects to the scalable EGS systems that will truly enable "geothermal everywhere."

There is approximately 3 GW of operational energy capacity in the US today, all of which is derived from tapping natural hydrothermal resources.[79] The U.S. Geological Survey has identified a total of 9 GW of known hydrothermal resources that have yet to be exploited and an estimated 30 GW of undiscovered hydrothermal resources.[80] The expansion of geothermal energy in the U.S. will begin with hydrothermal resources because they are comparatively easy to access and are well characterized from decades of research. But the expansion of conventional geothermal also establishes a foundation for testing and scaling EGS.

The first commercial EGS systems in the U.S. will be so-called "near-field" wells. These are EGS projects that exist in close proximity to conventional hydrothermal resources. This creatinges several advantages for an EGS project. First, the existence of a productive hydrothermal well nearby increases the likelihood that an EGS well will also be productive because the underground environment is better understood and proves that it is possible to efficiently extract thermal energy from the site. Second, near-field sites can take advantage of existing surface infrastructure, and including transmission lines in particular, to convert thermal energy into electricity and deliver it to consumers. Pre-existing generation and transmission infrastructure dramatically lowers the capital required to start a new EGS project.

The first near-field commercial EGS will produce geothermal energy with artificial reservoirs. This process involves pumping water into existing fractures or stimulating the rock bed to create new fracturesones. As the water flows through the fractures in the hot dry rock, it is heated to temperatures in excess of 150 C and pumped back to the surface through a second well. Once the thermal energy from the water is converted into electricity on the surface, the water can be reinjected into the ground again to create a renewable geothermal cycle. The reservoir creation process is effectively the same for greenfield wells, with the primary difference being they are not located near known hydrothermal reservoirs and thus carry a higher degree of uncertainty about the productivity of a given well.

Artificial geothermal reservoirs are conceptually simple and but challenging in practice. The ideal conditions needed to heat water to productive temperatures are typically found at depths greater than 3 km and often consist of hard rock that is difficult to penetrate.[81] Moreover, it can be difficult to locate a suitably large agglomeration of hot dry rock without drilling several expensive exploration wells. But arguably the hardest part of establishing an artificial reservoir is creating the fracture networks that allow water to flow from one well to another. This requires precise horizontal drilling methods, sophisticated sensors that can work in extreme environments, and a non-negligible amount of luck. Even the best laid plans for an artificial reservoir can be stymied by unanticipated geological activity that leads to a well or reservoir collapse.

The higher temperatures associated with hot rock EGS translates into greater energy efficiency compared to conventional hydrothermal resources, but pale in comparison to the energy efficiency of supercritical geothermal wells.[82] This class of EGS consists of geothermal projects that tap into naturally occurring reservoirs of supercritical fluids, a phase of matter that has characteristics of both a gas and a liquid. Supercritical fluids, mostly water with some other elemental compounds, are formed in environments with temperatures above 400 C and pressures more than 200 times greater than at the surface sea level.[83] These fluids are highly energy efficient because they can store more heat energy in a given volume of fluid. In the U.S., the best locations to develop supercritical EGS are found in Alaska and Hawaii.[84]

But the same conditions that make supercritical geothermal wells desirable also make them incredibly hard to access. Normal geothermal drill bits and sensors succumb to high temperatures and pressures well before they reach a supercritical reservoir, which makes it hard to locate existing pockets of supercritical fluids and identify the failure mechanisms down hole. Exploiting America's supercritical reservoirs will require breakthroughs in materials science to develop robust drill bits, high temperature sensors, and well casings that can withstand the corrosive supercritical fluid.

There are several experimental geothermal projects around the world that are working to exploit supercritical reservoirs. The Iceland Deep Drilling Project has been attempting to extract commercially viable amounts of energy from a supercritical well for more than three years. It was the first to demonstrate that it is possible to drill into active supercritical conditions, but has so far been unsuccessful at extracting commercially meaningful amounts of energy from the well.[85] The Venelle-2 well at the Larderello-Travale geothermal fields in Italy recently drilled the world's hottest borehole in an attempt to reach an inferred supercritical reservoir, but their equipment wasn't able to successfully penetrate the "K horizon," the poorly understood boundary between the hard, brittle rock near the surface and the more malleable rock that is home to supercritical fluids.[86] The results from the Iceland Deep Drilling Project suggest that expanding geothermal generation in the United States will require investments in both technology development and basic research to better understand the geological environment that will be encountered in these advanced geothermal wells.

The knowledge gained from drilling hot rock wells will advance the geothermal industry's ability to handle the still more extreme conditions faced in a supercritical well. They will also improve the outlook for the third class of EGS, known as closed-loop systems. Artificial geothermal reservoirs and closed-loop systems are conceptually similar in that both involve pumping water into the surface, using geological heat to bring it to temperature, and then pumping it back to the surface. The key difference is that in closed-loop systems the fluids never interact with the rock directly; they are always contained in the well casing.

The primary advantages of closed-loop systems are their ability to use passive pumping systems and avoid circulation loss. Closed-loop systems have cooler water "falling" to depth on one side of the loop and hot water rising on the other side of the loop that creates a natural siphoning effect. This avoids the need to pump the fluid through the system, which allows for the economic extraction of lower temperature resources. But closed-loop systems are also fraught with challenges. Perhaps the biggest hurdle is exposing the water to enough hot rock to bring it to temperature. An average geothermal well is only 8-inches in diameter, which means that the well has relatively little surface area in contact with the hot rock beneath the surface compared to an artificial reservoir. Some geothermal experts consider the challenges associated with efficiently transferring heat from the rock to the water loop to be an insurmountable obstacle for the adoption of closed-loop systems.[87] Nevertheless, researchers continue to explore the potential of closed-loop systems and Eavor, a

Canadian geothermal startup, has raised nearly $70 million in equity financing, including from oil and gas majors BP and Chevron, to develop a closed-loop geothermal system.[88]

POLICY RECOMMENDATIONS FOR AMERICAN GEOTHERMAL LEADERSHIP

The foregoing analysis of the current geothermal energy landscape in the U.S. reveals that the industry faces significant political, economic, and technological headwinds. But it is also clear that the United States is uniquely well poised to leverage geothermal energy, especially EGS, to rapidly decarbonize its energy supply. Importantly, geothermal energy is more than just a tool for the U.S. to meet its climate obligations in the energy sector. It is also a pathway toward energy abundance, which will have cascading effects for reviving the domestic manufacturing and raising the standard of living for all Americans. Considering these goals, we have identified five key policy recommendations to foster geothermal energy in the United States.

(1) Streamline the permitting process for geothermal projects on federal land

The geothermal industry faces significant hurdles in the permitting process for new projects on federal lands. This is one of the biggest impediments to the growth of geothermal energy in the U.S., but the one with the most straightforward solutions.

First, it is imperative for BLM offices to have a dedicated staff for reviewing permit applications for new geothermal projects. This has long been the case for the oil and gas industry and will ensure that applications are handled in a timely manner. Furthermore, the BLM should implement time limits on permit processing. This will give the geothermal industry the certainty it needs to make large, long-term investments in geothermal energy. Many geothermal applications never result in a productive well, but it is critical for geothermal producers to receive rapid feedback on their proposed projects to prevent wasted resources.

Second, it is critical for the BLM to craft a unified strategy for geothermal energy and treat it as a natural resource comparable to oil and gas in terms of the permitting process. This should be a top-down effort led by the Secretary of the Interior. This is critical for creating a regulatory environment that geothermal developers need to bring new projects online. The balkanized structure of the BLM and lack of a coherent framework for evaluating new geothermal projects means that developers are often subject to the whims of the local BLM office, which is especially challenging when a proposed geothermal project requires approval from multiple BLM jurisdictions. To improve these processes, we recommend that BLM tracks permitting for new geothermal applications to identify steps or specific field offices that are creating delays for new developments.

Third, it is imperative that the National Environmental Protection Act (NEPA) be amended so that it is more conducive to new geothermal projects. Fortunately, a framework for these amendments already exists. We propose modeling the geothermal NEPA regulations on those already applied to the oil and gas sector, which has proven to expedite the permitting process.[89] In short, this would require the development of geothermal-specific categorical exclusions, which have far shorter analysis timelines than environmental assessments or environmental impact statements and would dramatically accelerate geothermal development.

(2) Increase the federal budget for large-scale public-private geothermal projects

The DOE's FORGE initiative has demonstrated the immense potential of using federal dollars to accelerate the timeline for commercialization of next-generation geothermal technologies. Moreover, it has shown what can be accomplished on a relatively modest budget. Approximately $140 million was appropriated for FORGE, by far the most ever allocated for an EGS R&D initiative, but it falls far short of the investment needed for geothermal to become a significant energy source in the United States. A 2006 MIT study found that the federal government would have to spend at least $300 million on geothermal R&D over 15 years to make EGS cost competitive.[90]

These are modest sums compared to the government outlay to develop other energy resources. For example, the Office of Fossil Energy and Carbon Management has submitted a 2022 budget request for $890 million that will go toward R&D on technologies such as hydrogen, natural gas, and carbon capture. But so far the requisite funding to make ESG cost competitive hasn't materialized. The Geothermal Technology Office's budget has gone through several boom-and-bust cycles over the past two decades and was nearly eliminated in 2008. Stable, predictable federal R&D funding will be key to ensuring geothermal's growth given the long timelines associated with project development. We recommend a substantial increase in funding for the GTO on the condition that a substantial share of this funding is allocated for field demonstrations meant to advance commercial EGS projects. Results from large-scale field demonstrations are necessary to attract private investment in geothermal, which will be key to the long-term growth of this energy resource.

These field initiatives would be best organized through public-private partnerships where the cost of developing the project is shared equally. This will allow federal dollars to support more geothermal projects and foster a competitive marketplace for geothermal technologies. Furthermore, these projects should largely be based around existing geothermal research infrastructure such as FORGE to lower the fixed costs of development. At present, FORGE only supports two research wells, but is capable of hosting many more. The primary constraint is the initiative's budget, which was largely spent on creating the infrastructure for this underground laboratory. Roughly a quarter of FORGE's total budget was allocated for R&D projects.

(3) Incentivize geothermal generation in state electricity markets

The cost of renewable energy on the state electricity markets, particularly from solar and wind, has fallen dramatically in recent years due to a combination of technological improvements and market regulation. One component of this approach has been the development of Renewable Portfolio Standards (RPSs) and Clean Energy Standards (CESs) in most state electricity markets which require that a certain percentage of electricity sold by utilities come from renewable or clean energy sources by a particular date. This naturally boosts the demand for renewable electricity production while providing a coordinating timeframe for utility operators.

Geothermal energy counts towards RPS goals in most states that have them. However, there are states like Missouri, New Hampshire, Minnesota, Illinois, and others which do not.[91] Geothermal energy production will be unnecessarily penalized in these states until the RPS criteria are modified.

Secondarily, even where these RPS allow geothermal, they may not be adequately conveying the relative value of baseload energy that geothermal provides that wind and solar energy lack. In states like Iowa and Texas, this looks like an RPS that targets electricity capacity instead of electricity generation or actual energy sales.[92] A wind turbine which runs for only a few hours a day will have higher electricity capacity, which captures the amount of energy produced at a theoretical peak, instead of a generation target, which measures the amount of electricity actually produced over a longer period of time. [93] RPSs which target capacity over generation or sales are effectively penalizing renewable energy sources which provide baseload power like geothermal.

If anything, a case could be made to proactively favor geothermal energy both in RPS/CESs and in power purchase agreements because the baseload power provided is more reliable than variable energy sources which peak based on weather patterns irrespective of underlying consumer demand. One technology neutral way of doing this would be to specify that some percentage of RPS/CES goals be met by a baseload power source such as nuclear, geothermal, or long-duration electricity storage. This would both encourage the development of clean, baseload energy while also giving state electricity regulators a higher degree of certainty that the electricity grid will be able to meet demand at all hours of the day.[94]

(4) Establish innovation prizes or other incentive mechanisms for the development of key geothermal technologies in national labs and the private sector

Federal support of ESG R&D has been critical to the advancement of low systems with low technology readiness levels and collecting the field data necessary to commercialize next-generation geothermal technologies. Still, many important technologies have stalled out at laboratory-scale demonstrations or have yet to move beyond a prototype stage. We recommend establishing federal innovation prizes or other incentive mechanisms to fast track these technologies from the lab to the commercial applications.

Innovation prizes have been successfully used to drive high-risk fundamental R&D in energy and many other domains.[95] Some of these initiatives have been led by NGOs such as the X-Prize Foundation, which was instrumental in technological breakthroughs in human spaceflight, climate tech, AI, health, and many other fields. The power of innovation prizes could be harnessed to help push progress on key technical challenges such as drilling more deeply, reliably, and cheaply in a variety of geologic environments.

We have also similar incentivize mechanisms lead to breakthroughs in government labs. A notable example was set by Argonne National Laboratory in the field of chemical energy storage. ANL adopted a model where researchers were able to partake in patent royalties from new battery chemistries they developed at the lab. These patents were licensed to private companies, creating a lucrative revenue stream both for the laboratory and its scientists while spurring the development of the commercial battery sector. A similar model could be a major driver of geothermal innovation in America's national laboratories and expedite the commercialization of this EGS.

An alternative model would be the development of a Focused Research Organization (FRO) for advanced geothermal techniques like the model proposed by Samuel Rodriques, the founder of the Applied Biotechnology Laboratory at the Francis Crick Institute, and Adam Marblestone, the CEO of Convergent Research,in a recent paper.[96] Essentially, the government would fund an independent organization that operates at the intersection of basic and applied research with the sole goal of making progress on specific technical benchmarks. The FRO's flexible organization model would be difficult to replicate in traditional federal agencies or national labs. In this case, an FRO focused on developing (and demonstrating) new drilling techniques and/or creating a database of subsurface conditions could help accelerate the pace of geothermal deployment.[97]

(5) Create a federal jobs program to reskill oil and gas workers for geothermal projects

The U.S. oil and gas industry employs approximately 1.5 million workers, but divestment from these energy resources is imperative to meet the nation's climate goals.[98] As the U.S. moves away from an energy mix dominated by fossil fuels, it will create downward pressure on the oil and gas demand and result in substantial industry downsizing. We saw a vision of the future during the global pandemic when plummeting oil prices resulted in more than 100,000 lost jobs in the oil and gas sectors.[99] But the industry expertise in geophysics, exploration, and drilling accumulated over more than a century needn't be squandered.

The U.S. oil and gas workforce is highly skilled and many of these skills are directly transferable to geothermal projects. In fact, nearly all of the major American oil and gas companies already have a geothermal division, but have invested comparatively little in these departments. We recommend establishing a federal jobs program aimed at reskilling the U.S. oil and gas workforce for the geothermal industry. This can be accomplished through a mixture of incentives for private industry to reskill their own labor and government-led programs.

CONCLUSION

If forward-thinking policymakers implement these recommendations, we believe that it is feasible for geothermal energy to produce at least 60 GW of electricity in the United States by 2050. But the true opportunity presented by geothermal energy is even larger. At 60 GW, geothermal would represent approximately 8.5% of electricity generation in 2050.[100] A significant majority of this geothermal energy production will be concentrated in the western United States, but advances in geothermal energy technologies stand to benefit the entire country.

The promise of EGS is decoupling geothermal energy from geography. The first geothermal wells will be concentrated around the best resources (i.e., those that are hot and relatively shallow), but this "learning by doing" approach will also drive technological advances that will make it economic to access deeper and cooler geothermal resources in other areas of the U.S. Indeed, we see these advances as laying the foundation for "geothermal everywhere" and energy abundance in the U.S. Its unique ability to operate in both baseload and load-following configurations, its minimal impact on the local environment while providing effectively limitless electrical energy make geothermal well-suited to the energy and climate challenges of the 21st century. But it also points to a future where Americans have access to effectively limitless energy and the incredible opportunities that entails, such as higher standards of living and the revival of domestic manufacturing.

Finally, the development of EGS creates an opportunity for the United States to be a leader in renewable energy technologies that can reduce global emissions. Not only would these EGS technologies be useful domestically, but they can also be an important export for the United States in ways that other technologies, such as nuclear, cannot due to export controls. Geothermal energy is a resource that is theoretically available to every nation, but not all nations have the technology and skills to access their geothermal resources. By prioritizing the development of EGS in the U.S., it also provides a pathway to geothermal energy and sustainable development for the entire planet.

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