Superhot Rock Energy

A Vision for Firm, Global Zero-Carbon Energy

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CLEAN AIR TASK FORCE

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Executive Summary

Superhot rock energy is poised for a breakthrough as a high-energy-density, zero-carbon, always-available energy source that could be commercialized worldwide in the 2030s. Analyses for Clean Air Task Force (CATF) by Lucid Catalyst and Hotrock Energy Research Organization (HERO) suggest that, with more ambitious geothermal energy funding and public-private partnerships to spur innovation, it could be cost-competitive with most zero-carbon technologies—transforming global energy systems by providing clean, firm, cost-competitive renewable energy while requiring significantly less land than other sources.

Today's conventional geothermal systems have a global capacity of only 16 gigawatts (GW) of power, and are geographically limited to regions where concentrated heat is located near-surface (e.g., volcanic areas or areas where the crust is thin, such as the U.S. Great Basin or East Africa).[1] Compared with today's 2,100 terawatts (TW) of coal capacity in 69 countries, or even today's 1TW of photovoltaic capacity, geothermal energy occupies only a small niche. Superhot rock energy could compete with these energy resources by tapping deep superhot conditions (400°C or hotter) that exist everywhere, deep in the Earth under our feet.

In superhot rock systems, water is injected to depths where the rock temperature exceeds 400°C and then is returned to the surface as supercritical or superheated water to power generators. Several research and development (R&D) projects around the world have already drilled into superhot rock and have begun developing methods for operating in these extreme heat and pressure conditions. While superhot resources have yet to be harnessed for power production, their high energy potential is wildly recognized. Evidence from a test well drilled by the Iceland Deep Drilling Project (IDDP) suggests that an estimated 36 megawatts (MW) of energy could be produced from one well—approximately five to ten times that of a typical 3-5 MW commercial geothermal well today. If this substantial amount of energy can be produced in dry rock at reasonable development costs, based on a preliminary analysis for CATF, superhot rock could be competitive with today's natural gas plants at $20-35 per megawatt-hour (MWh).

Significant engineering innovations will be required to realize the full potential of superhot rock, such as rapid ultra-deep drilling methods, heat-resistant well materials and tools, and deep heat reservoir development in hot dry rock. But these are engineering challenges, not needed scientific breakthroughs. Intensive drilling campaigns can drive rapid learning to address these engineering obstacles and drive further cost reductions. This can be accomplished by geothermal companies or consortia, including highly capitalized oil and gas companies, incorporating innovations from unconventional oil and gas experience. Big tech can also speed the deployment of superhot rock energy by investing in early-stage technology development and providing power purchase commitments. With significant private and public investment, along with protective regulatory policies accompanied by rapid review and continued technological innovation, superhot rock energy can plausibly be commercialized in the 2030s.

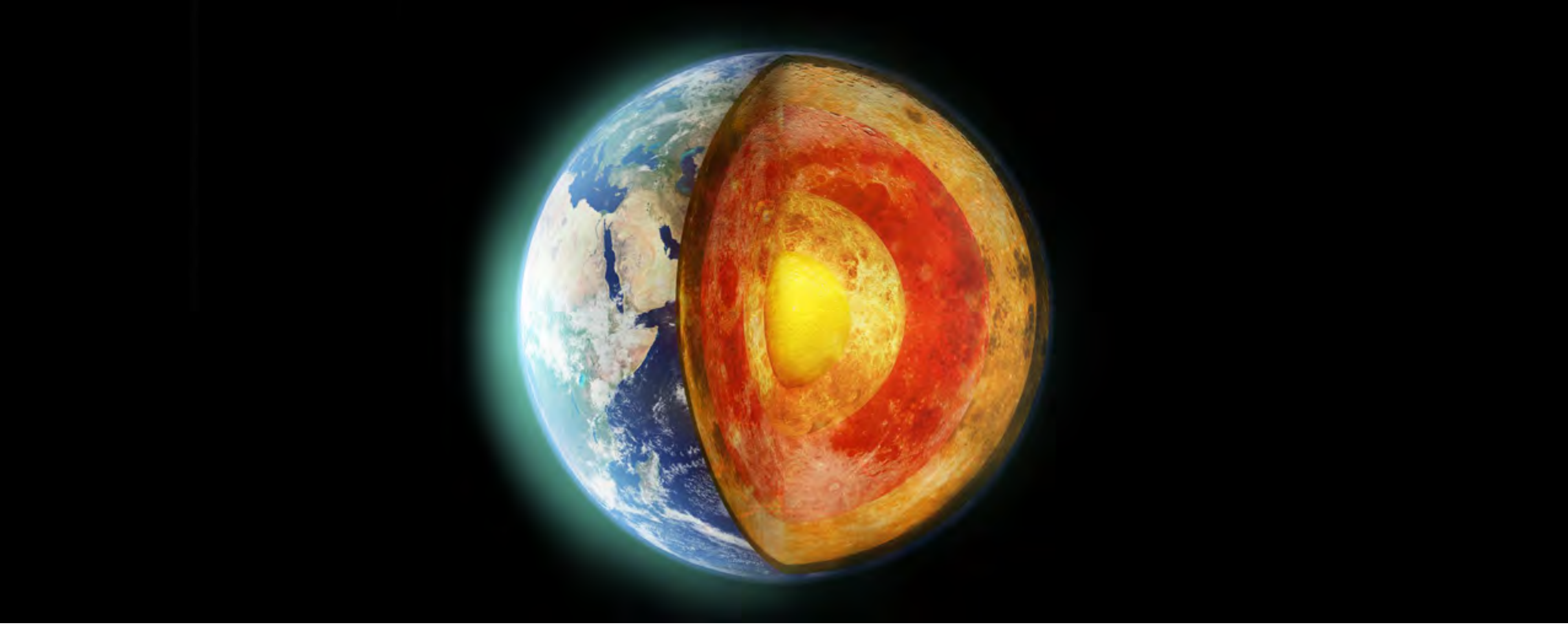
A key first step to commercial superhot rock energy will be moving power demonstrations forward in the 2020s. Several companies are currently preparing for or anticipate projects in this timeframe. These proof-of-concept power production demonstrations will demonstrate the value of superhot rock energy to the energy community and spur investment in large, commercial-scale drilling campaigns. Then, as next-generation superdeep drilling methods are commercialized, superhot rock energy can progress from shallow hot regions to continental interiors where heat is deeper.

The Value of Superhot Rock Energy

- **Cost-competitive** terawatt-scale power and heat
- **Inexhaustible** resource, Earth's heat is everywhere beneath our feet
- **Available 24/7** firm baseload power
- **Energy dense** with minimal surface footprint

- **Zero greenhouse gasses** at point of production
- **Pivots fossil workforce** and technology
- **Potential to repower** fossil power plants
- **Generate zero-carbon fuels** like hydrogen and ammonia

- **Accessible worldwide** with deep drilling innovation
- Significant engineering advancements required but **does not depend on scientific breakthroughs**
- **No fuel cost** associated with geothermal heat
- Ensuring **energy security** by producing firm, zero-carbon power domestically



SECTION 1

Superhot Rock Energy Potential

1.1 Tapping into the Earth's Deep, Endless Heat

The Earth's deep heat is an energy resource everywhere beneath our feet, that can be accessed to provide heat and power at a scale adequate to meet the growth associated with economic development while aligning with the transitioning energy sector—including as a carbon-free energy source for industrial and district heat and transportation. The Earth's deep heat is inexhaustible for energy extraction purposes, and superhot rock technologies are under development to tap into it.[2]

Today's conventional geothermal industry is limited to locations where both heat and groundwater exist near the surface. The rarity of these "hydrothermal" systems—such as Old Faithful[3]—is the primary reason that global installed geothermal electricity capacity only reached 16 GW in 2021—less than 0.2% of total installed global power.[4]

To expand geothermal energy's global reach, engineered systems in hot dry rock seek to emulate conventional hydrothermal energy production by injecting water into hot dry rock and producing steam.[5,6] These hot dry rock systems are typically described as "enhanced" or "engineered" geothermal systems, or "EGS." A 2019 U.S. Department of Energy (DOE) analysis estimated that the U.S. geothermal electricity resource[7] in the United States is more than 5,000 GW of electricity, about five times total U.S. installed utility-scale generation capacity in 2016.[8] And a 2006 Massachusetts Institute of Technology (MIT) report estimated that U.S. engineered geothermal systems could potentially produce over 2,000 times annual U.S. primary energy consumption in 2005.[9] Furthermore, the MIT analyses were limited to a depth of 10 kilometers (6 miles), effectively excluding the huge potential of deep superhot resources. These studies mean that the deep geothermal energy potential is enormous, and far more if superhot rock potential is considered.

Figure 1

Commercial geothermal systems are currently limited to the red or dark orange zones in continental areas on the map below. Superhot rock could extend geothermal to much of the rest of the world. (Davies 2013)[10]

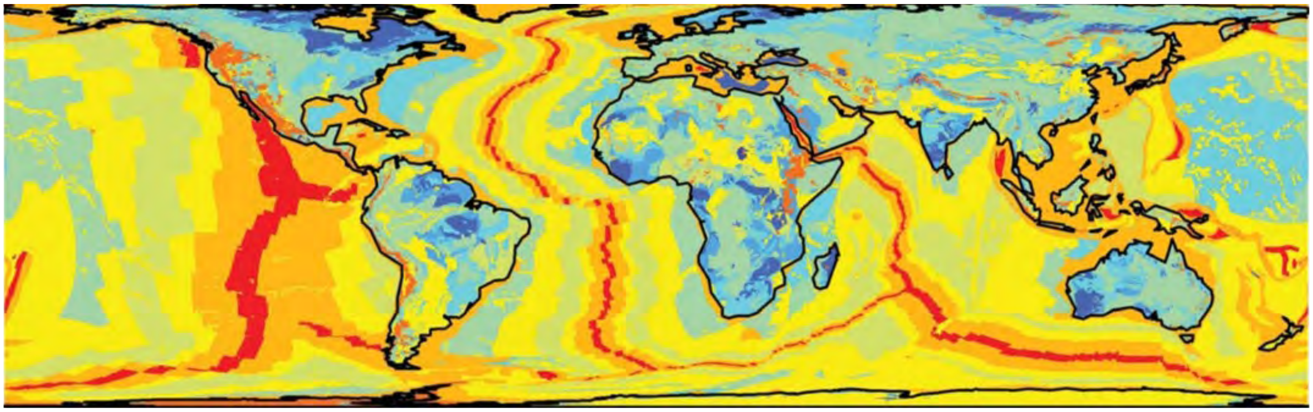
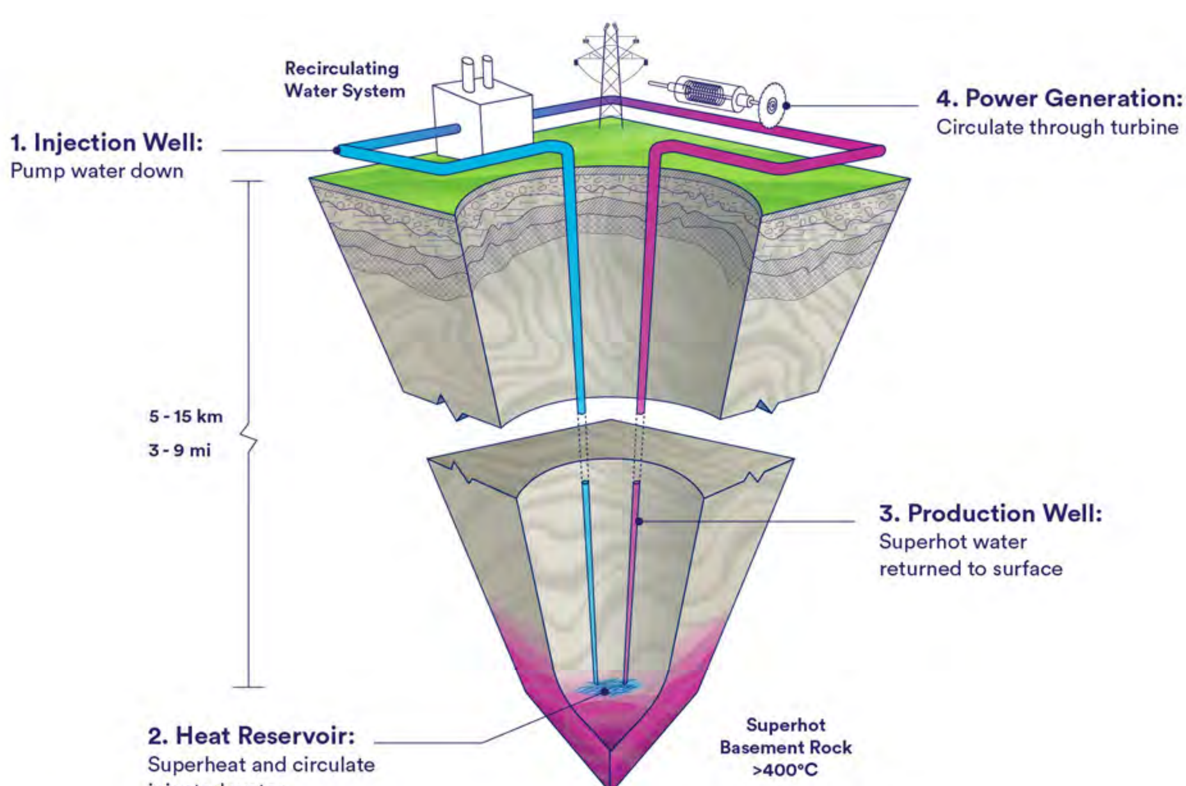


Figure 2

Superhot geothermal energy is mined from natural heat deep within the Earth's crust. Water is injected (through an injection well) into superhot dry rock (rock at temperatures above 400°C) and is circulated through fractures (or drilled conduits) to a production well that provides thermal energy to produce power, heat, or fuels. Accessing affordable superhot resources could transform the power industry but will require innovations in drilling and reservoir engineering.



Note: Not to scale. Underground flow conduits for water may either involve below-ground piping or fracture networks (pictured).

Figure 3

Conventional commercial hydrothermal systems collect steam or hot water from shallow, heated groundwater. Engineered geothermal systems (commonly deemed "EGS") are designed to collect deep heat by circulating water through hot dry rock. Superhot rock systems are deeper, hotter dry rock systems that circulate water through rocks that are above 400°C, bringing far more energy (five to ten times) to the surface per well.

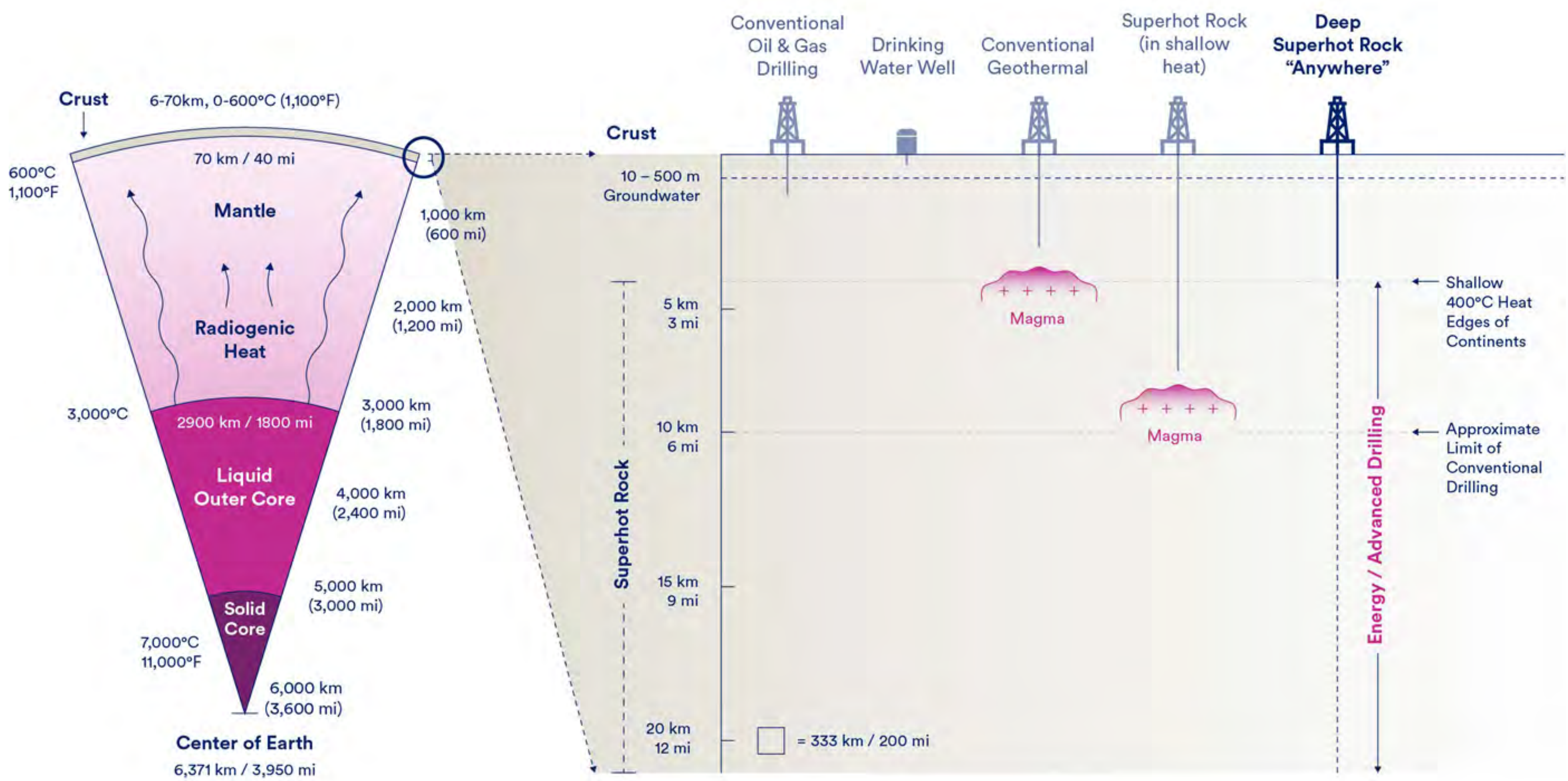


Figure 4

Superhot rock energy will heat water by circulating it through cracks or drilled conduits in rock exceeding 400°C. For example, researchers at FORGE Utah have been testing methods for injecting water through ancient tectonic fractures, like those in the photos, that occur in these 400-million-year-old granites in New Hampshire, USA (left) and half-billion-year-old granites from Maine, USA (right).

Figures 2 and 3 illustrate how superhot rock energy takes advantage of deeper, hotter, and more energy-dense rock. These systems will inject water down a deep injection well and circulate it through hard crystalline "basement" rock, where temperatures are 400°C or higher, via fracture systems (similar to those in Figure 4). Other options being explored include micro-tunnels drilled single or multi-well reservoir systems. The heated water will then be circulated back up production wells to generate electricity at surface power facilities. With the ability to drill, engineer wells, and create deep thermal reservoirs, geothermal energy could be tapped nearly anywhere in the world.

1.2 High Energy Density

Superhot rock energy promises to be vast, but also very energy-dense, generating large amounts of energy beneath a small surface footprint—a key superhot rock advantage (Figure 5). This advantage comes from the potential to harvest concentrated heat from kilometers of subsurface heat resources, combined with modern drilling methods that minimize the land use of drilling pads. Figure 5 illustrates hypothetical comparative land usage for the energy consumption of Italy, showing how the high energy density of superhot rock systems require far less land use than other energy resources.

Why does superhot water carry so much more energy? The injected water transforms into a superhot, superfluid form scientists call "supercritical" water.[11] Supercritical water can penetrate fractures faster and more easily and can speed far more energy per well to the surface—roughly five to ten times the energy produced by today's commercial geothermal wells or predicted for lower-temperature engineered wells.[12] This means that a few superhot rock wells can bring substantial commercial energy to the surface. This high energy potential has been demonstrated in Iceland, where the Iceland Deep Drilling Project's "Krafla" borehole produced natural superhot water at 452°C and an estimated 36 megawatts of energy (MWe) production potential.[13] In comparison, a typical commercial hydrothermal geothermal project produces about 3-5 MW per well.[14] For comparison, the Reykjanes geothermal field in Iceland, one of the hottest producing field in the world at 290-320°C, has 12 wells producing a total of 100 MWe from 2 turbines.[15] Superhot rock energy has the potential to produce the same amount of heat in 2-3 wells. This is why superhot rock is sometimes referred to as the "Holy Grail" of geothermal energy—because more heat energy could be harvested from far fewer wells. Furthermore, this means that the surface area required to feed a very large power plant (hundreds of megawatts or a gigawatt in size) could be relatively small and associated well construction and maintenance costs would be reduced.

1.3 Competitive Dispatchable Power

Clean Air Task Force commissioned Hot Rock Energy Research Organization (HERO) and LucidCatalyst (LC) to estimate the levelized cost of commercial-scale superhot rock electricity. HERO and LC developed a power plant cost model based on anticipated Nth-of-a-kind costs for a superhot rock plant, using known wellfield costs and power generation costs (sourced from cost data from existing geothermal and thermal plants). The model estimated the levelized cost of energy for different technology regimes, from existing technology to future technologies such as the yet-to-be-commercialized high-energy drills. Results suggest mature superhot rock will be competitive at

Figure 5

This illustrative and hypothetical diagram is scaled for the total energy use of Italy and shows that the amount of energy delivered by geothermal systems per unit of surface (land or ocean) area is very high; conversely, the amount of surface utilized is very small per unit of energy delivered. This simple graphic illustrates the relative magnitudes of surface area used for several forms of energy and highlights the potential land use advantage of superhot rock energy. Relative sizes of squares were scaled-up for the total final energy use of Italy for illustration purposes only. The ratios are based on Italy's 2019 IEA Energy Balance and are not based on an independent energy analysis for Italy.[16]

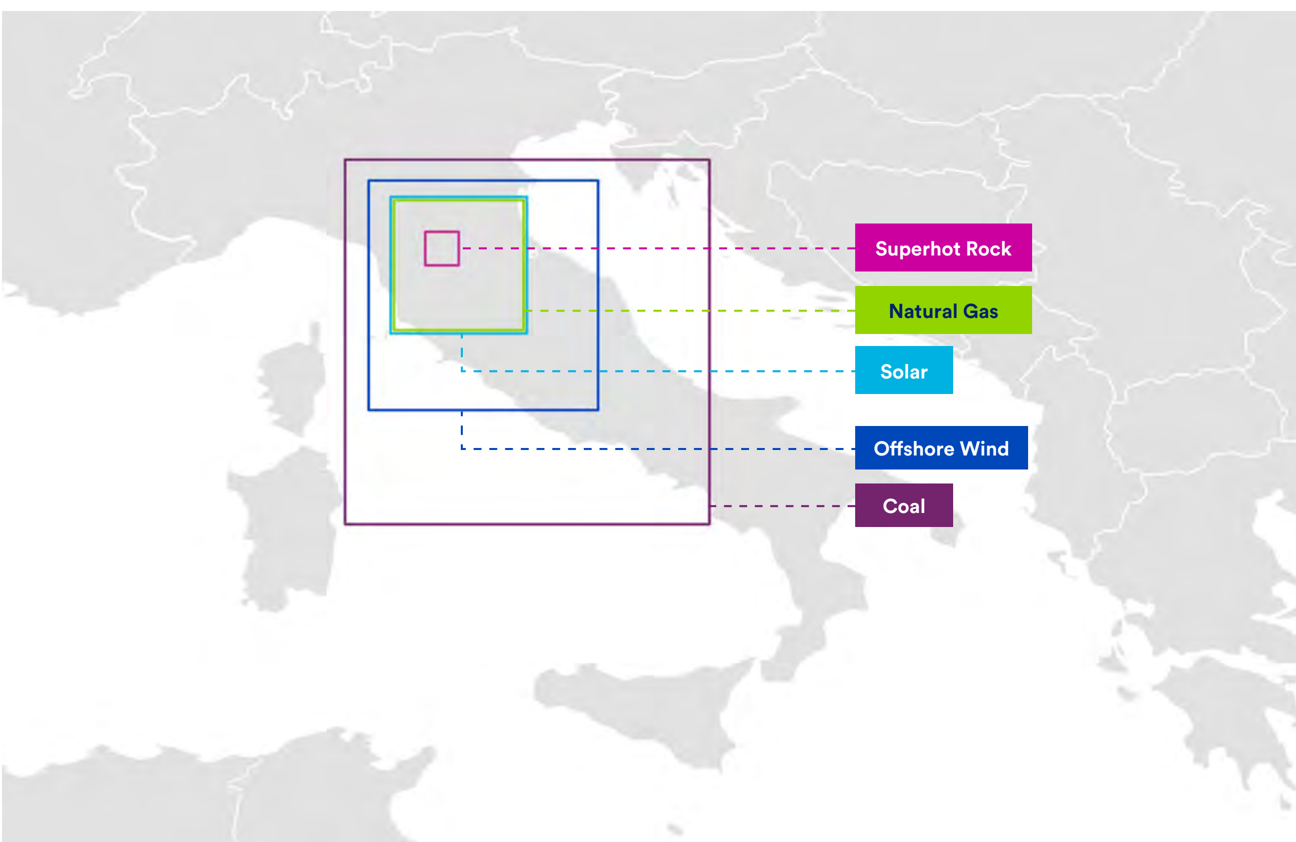
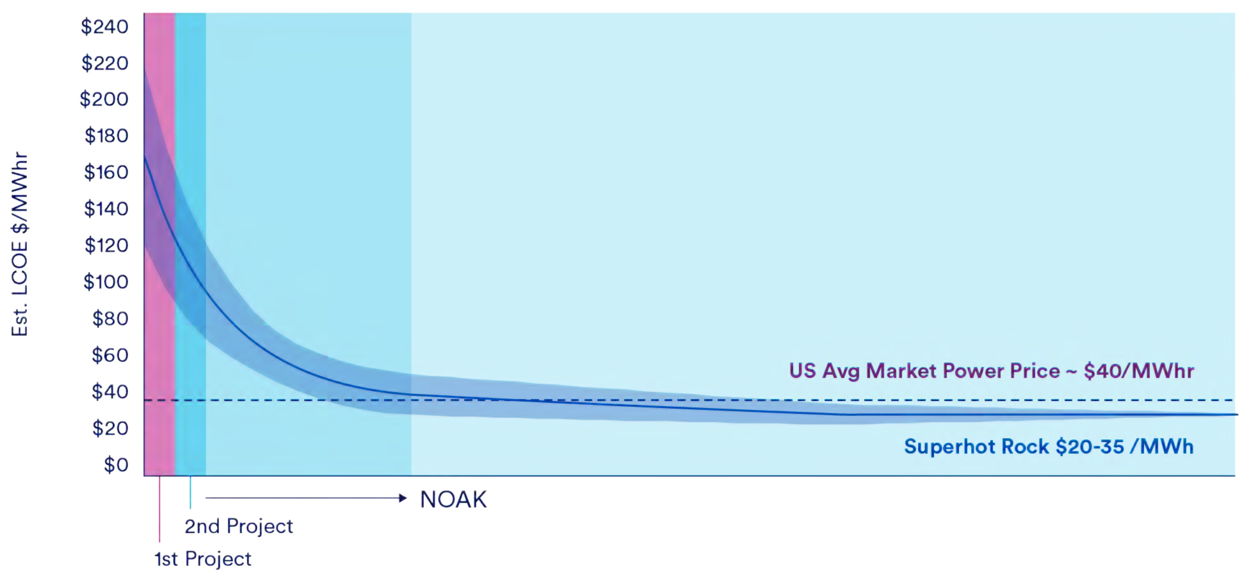


Figure 6

Illustrative graph shows how electricity produced from superhot rock is expected to be competitive for Nth-of-a-kind plants (NOAK) based on estimated levelized cost of electricity after full commercialization. Lucid Catalyst and Hot Rock Energy Research Organization (HERO) have preliminarily estimated that superhot rock geothermal could have an LCOE in the range of $20-$35 / MWh. This would be competitive with other dispatchable and intermittent energy resources.



$20-35 per MWh (Figure 6).[17] Drilling and reservoir development costs—combining labor, equipment, and materials costs—are expected to be higher for first-of-a-kind projects but to progressively decline through continuous improvement, similar to the deep cost reductions and productivity improvements that occurred in large-scale unconventional shale oil and gas development.

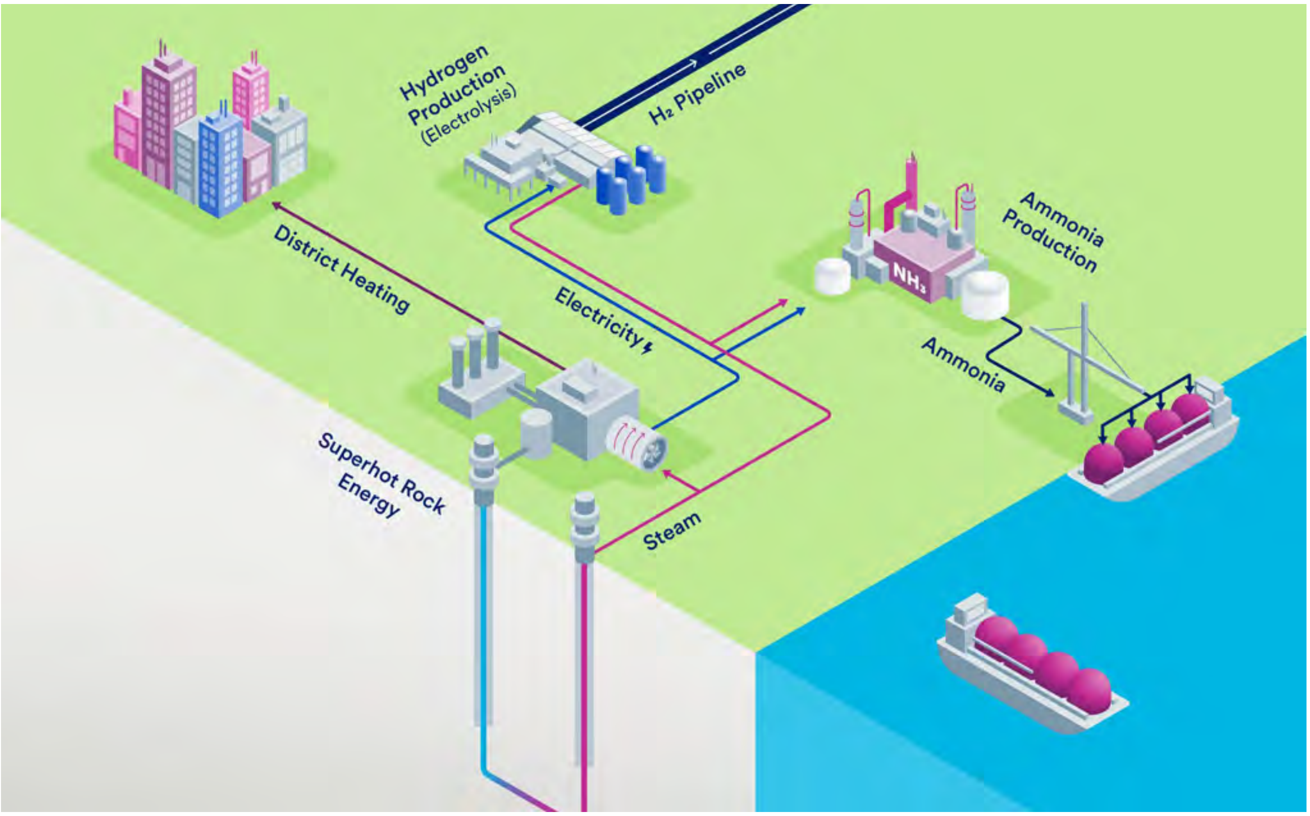
1.4 Superhot Rock Hydrogen Production Potential

Because superhot rock plants promise low-cost electricity and high-quality heat, they could be excellent resources to produce zero-carbon fuels such as hydrogen and ammonia. The techno-economic cost model developed by HERO and LC for CATF estimated production costs for these two fuels, both assuming the use of high temperature steam electrolysis via solid oxide electrolyzer cells (SOEC).[18]

Reliably achieving hydrogen production costs at or below $1.50 would achieve parity with the costs from producing hydrogen in an environment with low natural gas costs. With advanced drilling and casing technologies, the costs begin to approach $1/kg, which would achieve the DOE's 2030 Hydrogen Earthshot Initiative target cost. This would have significant implications for ammonia production, as well as for the production of other synthetic fuels that could play a major role in decarbonizing the global liquid fuels industry.

Figure 7

Superhot rock energy could generate hydrogen using high temperature steam electrolysis from its zero-carbon electricity and heat from the superhot steam, extending its use to transportation.



1.5 Manageable Environmental Footprint

Like all energy sources, superhot rock energy may have environmental impacts requiring mitigation, but these should be modest and much less than comparable resources when considering the magnitude of energy produced.

No direct greenhouse gas emissions

Unlike fossil power, no direct carbon dioxide (CO_2) will be produced in the process of generating power in dry rock. This also represents a small advantage over commercial hydrothermal geothermal systems, some of which can emit low levels of carbon dioxide from the natural water used to produce power.

Minimizing drinking water risk

While superhot rock energy will involve injecting water into existing and new stimulated fractures underground, water utilization is expected to be minimal as the produced steam will be condensed and reused in a largely closed circuit. This will require makeup water for water loss but will not require continual refreshing. Furthermore, non-potable brines may be possible working fluids. Moreover, superhot wells will inject recycled water far deeper (typically 4 kilometers or deeper) than near-surface drinking water aquifers (typically a few hundred meters in depth), leaving several kilometers of impermeable crystalline rock to effectively seal off the superhot rock "reservoir" from near-surface water resources. All U.S. geothermal projects must currently operate under the Safe Drinking Water Act's Underground Injection Control rules (typically termed "UIC") or state program equivalent, to ensure potable water is protected from contamination. Regulatory review of current UIC and related state and international regulations will ensure robust and predictable water protections appropriate for the risk profiles of superhot rock systems.

Small surface footprint

Superhot rock energy does not require thermal generation facilities such as boilers for fossil and nuclear energy. Neither does superhot rock energy have the immense land utilization that solar panels do. Instead, superhot rock surface equipment will be limited to a buried heat gathering system connecting wells to the electricity production facilities comprised of steam turbines, electricity generators, and transmission facilities. Innovations from unconventional oil and gas may further minimize the surface footprint of superhot rock wells through drilling of multiple injection and production wells from a single movable drilling pad, harvesting significant amounts of energy from a single project site.

Minimizing induced seismicity risk

Seismic activity and "felt" earthquakes (and, in a few cases, earthquakes that caused damage) have been recorded in lower temperature engineered projects where water has been injected into hot, dry (but not superhot) rock (e.g., Vendenheim France; Pohang, South Korea; Basel, Switzerland).

There are several strategies that may help ameliorate seismic risk from projects in hot dry rock. First, recent experience suggests advanced site study and selection is primary step that should be required in advance of approval to proceed. For example, pre-project study of natural seismic activity could have identified the active fault zone and might avoided triggering the South Korean Pohang quake. Useful methods could include seismic profiling and baseline seismic and microseismic monitoring to identify and avoid such active fault zones. Second, microseismic monitoring-informed "green light/red light" systems have been pioneered, and found effective, that require temporary shutdowns or slower injection rates if significant earthquake activity risk is elevated during operations.

The U.S. Frontier Observatory for Research in Geothermal Energy (FORGE) has a focused research effort on earthquake avoidance in lower temperature engineered systems,[19] which should help inform regulatory development. Furthermore, in Japan, scientists are studying the possibility that rock at 400°C (700°F)—in the so-called "brittle-ductile transition zone," or "BDT"—may have plastic-like properties which may be less likely to generate seismic activity from injection operations. Further laboratory in field testing is required to test the BDT hypothesis.

SECTION 2

Status of Superhot Rock & Necessary Innovations

2.1 Superhot Rock Initiatives, Past & Present

Engineering concepts for hot rock geothermal energy systems originated in 1970 at Los Alamos National Laboratory.[20] This project continued through 1992, systematically exploring the hot dry rock concept through drilling and related experiments. Other early projects included Rosemanowes in the UK, followed by the operational Soultz-Sous-Forets and Rittershoffen EGS plants in Alsace, France. Later, the EU's Horizon 2020 initiative funded DEEPEN, a superhot research and development initiative including drilling projects in Italy and Iceland and research in Mexico and New Zealand. The EU Geothermica initiative continues these efforts.

Over two dozen wells have been drilled into superhot rock conditions around the world. The map (Figure 8) shows global superhot rock initiatives (blue dots) and numbers of wells that have encountered superhot rock. These wells have generally been in comparatively shallow, high-temperature heat below existing geothermal fields, typically at depths of around 3-7 km (2-5 mi).

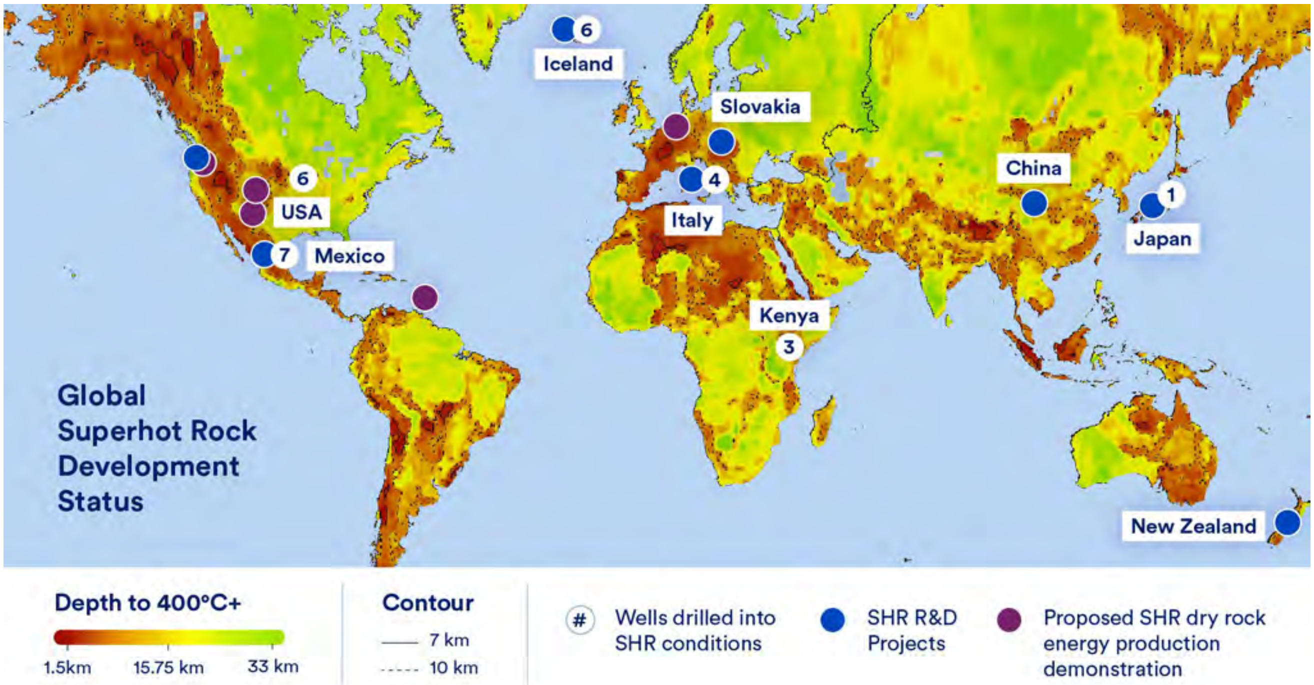
The following initiatives have focused on drilling and superhot rock energy technology development. Although power has yet to be produced from any superhot rock well, these projects and others have provided important learnings and continue to inform the innovations needed to move commercial superhot rock energy forward.

Japan Beyond Brittle Project

Japan's New Energy and Industrial Technology Research and Development Agency (NEDO)'s Kakkonda well in northeast Japan was drilled in 1994-1995 to temperatures above 500°C at a depth of 3.7 km (about 2.3 mi). Further investigation suggested that the well drilled into a zone of low earthquakes known as "brittle-ductile transition zone," where rock is more plastic and possibly less susceptible to brittle failure. JBBP's superhot rock research continues at Tohoku University, focusing on reservoir development in superhot conditions and identifying strategies for minimizing the risk of induced seismicity.[21] JBBP contemplates eventually drilling a second exploration well as a part of the project.

Figure 8

Global superhot drilling and research sites. Dark red indicates areas where superhot rock heat is available less than 10 km below surface, the most viable regions for early superhot rock energy development. (Heat map: Pacific Northwest National Laboratory and HERO).



Iceland Deep Drilling Project

IDDP has been a superhot drilling initiative for over a dozen years as a part of the EU's DEEPEGS program.[22] The first test well, IDDP-1 Krafla, was completed in 2009, after drilling was terminated when it encountered magma. Krafla provided an important demonstration of the energy potential of superhot wells with a projected energy flow of 36 MWe. The second IDDP well, IDDP-2 Reykjanes, reached its objective of supercritical (superhot) conditions at 426°C in 2017. IDDP plans to flow test the well in the future, pending funding. IDDP is anticipating a third superhot well, IDDP-3, in Hengill, Iceland, near the Nesjavellir plant; however, it is currently unfunded.[23]

DESCRAMBLE

Italy's Larderello geothermal field has been a heat resource for two centuries, with electric power production since 1913, and was the site of an intensive EU collaborative effort from 2015-18 (known by the acronym DESCRAMBLE) to drill into superhot rock as a part of the EU DEEPEGS program. Superhot conditions were originally encountered in the early 1980s in Larderello's San Pompeo-2 well.[24,25] Larderello's Venelle-2 is the hottest geothermal well on record, registering 514°C at a depth of 2.9 km (1.8 mi).

GEMex

GEMex is an EU-supported program focused on hot dry rock/EGS development and SHR systems. It drilled several wells at the Acoculco geothermal field, reaching "well above" 300°C in dry wells. GEMex also investigated and modeled the superhot system at the Los Humeros geothermal field in anticipation of drilling the supercritical system in the future.[26]

Hotter and Deeper

The HADES project in New Zealand has been exploring superhot resources in the Taupo Volcanic Zone since 2009 and is planning a scientific drilling project into New Zealand's deep-seated superhot rock.[27] Like JBBP, the project hopes to investigate potential existing reservoir systems in the superhot plastic brittle-ductile transition zone at about 7 km, where geophysics suggests there is little seismic activity. This is another EU-supported project.[28]

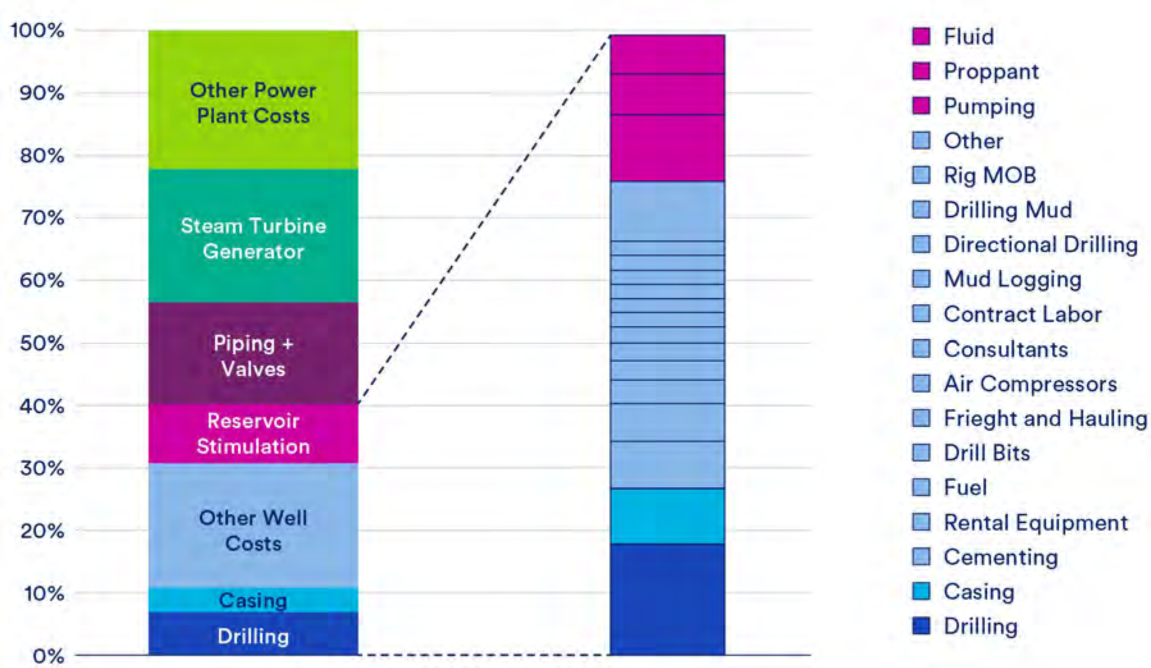
2.2 Innovations Needed for Commercialization of Superhot Rock Energy

Research and development wells used conventional drilling to reach superhot conditions for several decades. Yet new tools and technologies are needed to drill and complete wells to produce energy at these superhot temperatures and at deeper depths than ever.[29] The long-term need to enable successful "geothermal everywhere" is drilling innovation to reach far deeper resources at reasonable cost. But innovations are also needed in such areas as subsurface reservoir creation, well metallurgy and cements, downhole power supply and monitoring, and surface power conversion. All these technologies have been anticipated and are at various stages of development for very hot commercial applications, with some adapted for use in pilot superhot drilling operations like in Iceland.

Extrapolated from costs of today's commercial geothermal plants, operations and maintenance in superhot rock systems should have little effect on the levelized cost of electricity (LCOE). As in most renewable energy power plants, the LCOE will be primarily driven by capital expenses (as illustrated below in Figure 9). This means that, once in operation, there will be no resource cost volatility—unlike power from baseload fossil plants, which can swing with the cost of coal, oil, and gas. This figure also illuminates the need for cost reduction innovations throughout the entire cost structure, as no single category or technology consumes more that 30% of the total

Figure 9: Estimated Breakdown in Capital Cost for a Hypothetical 250 MW SHR Plant

Based on costs from today's commercial geothermal plants, operations and maintenance in superhot rock systems will have little leverage on the levelized cost of electricity, which will be driven more by capital expenses. This means that, once in operation, there will be no resource cost volatility—unlike power from baseload fossil plants, which can swing with the cost of coal, oil, and gas. Note that drilling represents a small part of capital cost (Lucid Catalyst for CATF, 2022).



capital cost assumptions. While there are currently significant efforts underway to reduce the cost of drilling, this alone will not push superhot rock energy to a point that it is at grid parity with other producers today. (LucidCatalyst and HERO for CATF, 2022).

Drilling Superhot Rock

The deepest well ever drilled in crystalline hard rock—12.5 km, 40,000 feet, or almost 8 miles deep—was completed in the 1970s in the Kola Peninsula of Russia. However, this was in rock at much lower temperatures. Currently-available large mechanical drilling rigs are being used today to drill to depths of 3-7 km (~2-4 mi) in relatively shallow superhot rock. The challenge of drilling and widely deploying superhot rock will require innovative new technologies that can cost-effectively reach superhot resources in hard crystalline rock at depths of up to or exceeding 15 km (9 mi). When drilling hard crystalline rock, today's rotary drilling requires time-consuming and frequent "trips" to pull the "drill string" (pipe) out of the hole to change out worn drill bits. Emerging hybrid contact-drilling innovations like hammer drills and particle drilling (e.g., those from NOV and Particle Drilling Corporation) have begun to progressively increase penetration rates. Moreover, recent advances in contactless energy drilling methods (e.g., those of Quaise, GADrilling, and Tetra Corporation) should require far fewer trips out of the hole. Such innovations promise to increase the speed of drilling, reducing drilling costs and making deeper and hotter wells more accessible and affordable.

Laboratory tests with emerging contactless drilling demonstrate that such non-mechanical energy drilling methods, which are yet to be tested in the field, can soften or melt rock through energy directed downhole. Two principal energy drilling methods that are currently being designed for superhot temperature drilling are plasma drilling and millimeter wave drilling (see box). GA Drilling (Slovakia) is preparing to test its Plasmabit drill in the field in the coming year, while Quaise (Houston) is developing an MIT- proposed millimeter wave drill at Oak Ridge National Laboratory. ENN, a private company in China, has also evaluated both plasma and millimeter wave energy drilling methods in a recently constructed rock mechanics laboratory. Other methods being developed include Tetra Corporation's pulsed electronic discharge drill, which has been tested in hard sandstone and is expected to do equally well in granite, and NOV/Particle Drilling Corporation's particle drilling bit, which is now being tested in the field.

Thermal Reservoir Creation

Creating thermal reservoirs in fracture systems in dry superhot rock while avoiding seismic risk is a critical challenge that must be addressed to achieve widespread commercial success. Injected water (without the fracking chemicals used in oil and gas) must be able to flow from an injection well through fractures in the deep rock to absorb heat before being pumped back up through production wells. In this process, engineers will dilate existing fractures or create new ones using new technologies such as thermal fracturing or hydroshearing.

As mentioned above, FORGE Utah remains focused on reservoir creation, increased drilling efficiency, and developed methods for seismic avoidance in lower-temperature hard rock engineered systems.[30] Meanwhile, in Japan, the JBBP geophysical research team is investigating the plastic properties of superhot rock, which may allow opening existing fractures while minimizing seismic risk.[31] Similarly, New Zealand has been conducting investigations into the "brittle-ductile transition" (BDT), a region where the rocks become "ductile"—that is, less brittle and more plastic. Modelers and seismologists suggest that the BDT has inherently lower seismic activity and lower risk of induced earthquakes.

In addition to circulating water through fractures, engineered geothermal methods are also being explored to use drilled subsurface conduits for heating water and returning it to the surface, thereby avoiding use of fractured systems and possible seismic risk. These systems are designed to circulate water in a closed loop through the rock and then back to the power production plant at the surface. Two companies, Eavor and Greenfire, are presently testing their closed loop technologies.[32] Eavor, which is developing its Eavor-Loop™ and Rock Pipe™ "underground radiator," has launched demonstration projects in Calgary, Germany, and New Mexico. In New Mexico, the Eavor-Deep well is being directionally drilled (Fall 2022) to target greater than 5 km and 300 C in granite using Eavor's proprietary method to cool the drill string and bottomhole assemblies.

Figure 10

Left: Iceland Deep Drilling Project drill rig at IDDP 2 in Reykjanes Iceland (source: https://iddp.is/); Right: Steam from IDDP-1 Krafla well test which indicates 36 Mw from a single well (Courtesy, Dr. Gudmundur Olaf Fridleifsson).

Well Construction

Well failure is a principal reason that early superhot rock efforts have yet to succeed. The deep, hot conditions required for superhot geothermal require innovations in metallurgy and cements for more robust casing of wells. Casing, the pipe that holds the rock of the outer borehole in place, prevents the loss of fluids into the surrounding rock and maintains pressure in the well. Casing and cements are typically designed for conditions in the range of 150-300°C. Wells drilled into hot and superhot conditions have begun to advance well construction materials engineering, and new alloys and polymers are being developed that can maintain strength at high temperatures and pressures. One such innovation being tested is the Eavor "Rock Pipe", an applied synthetic borehole rock sealant.

Downhole Tools & Power

Critical barriers to hotter and deeper drilling are tools and downhole power that can function at high temperatures. Failure of tools has been a significant issue at the FORGE Utah project and is an immediate need for advancing successful deeper hotter projects. Such monitoring tools will be necessary to identify fracture and permeability zones and to ensure well integrity during well construction and ongoing maintenance. Current sensors and electronics used to monitor wells are limited by high temperatures and downhole power availability. Research and demonstrations are underway on cooling systems for drilling (e.g., Eavor- Deep, mentioned above), packaged electronics (e.g., surrounded by protective polymers), downhole sensor cooling systems, and new electronic materials that can better withstand the high heat and pressures that will be encountered in superhot rock environments. Moreover, the Norwegian energy research organization SINTEF has developed a method for insulating electronics that have a 300°C limit such that they do not exceed 210°C, tested in a specially developed furnace that heats to 450°C.

Successful superhot rock energy will also require transmitting power downhole for several purposes. First, conduction of power downhole will be required for energy drilling. Plasma and millimeter wave drills will require significant amounts of energy to drive the cutting bits at the bottom of the hole. This is a critical challenge for successful energy drilling because the current limit for today's instruments is about 250°C; electronic cables do not function at temperatures above 350°C.[33] Second, power will be needed for operating wireline logs and other tools in superhot wells.

Surface Power Production

At the surface, production of electricity from early superhot rock plants will likely come from utilization of superhot steam (rather than direct use of supercritical water), adapting existing high-pressure, high-temperature steam turbines, with adaptations for corrosion resistance and for managing possible deposition of silica. For future power generation directly from supercritical resources, insulated tubulars will likely be required to maintain the supercritical state from the reservoir to the surface in the production well.

Advanced Rapid Drilling Methods

Methods to drill rapidly and ultra-deep are key to engineered geothermal systems and unlocking geothermal "everywhere." One area of innovation that is key to managing the cost of drilling is "rate of penetration." Several companies are focusing on improving the speed of drilling with new technologies. One promising area of research and development is energy drilling, which will eliminate the need to rotate a drill bit to grind the rock in the deep subsurface. One of the chief advantages of energy drilling is the much reduced need to remove or "trip" the drill pipe string out of the hole to change a drill bit. Reduced tripping combined with a rapid rate of penetration and no rotation of the drill string promises to substantially improve the capacity for, and economics of, super-deep drilling.

GA Drilling's PlasmaBit drilling technology emits a stream of plasma—extreme heat energy formed as electrons are stripped off of atoms using a high-voltage electric current. GA Drilling is currently engineering its drill to operate as a pulsing plasma "hammer." The drill will be powered by a mud-cooled cable, enabling operation in extreme superhot rock temperatures.

Photos: GA Drilling, Slovakia)

Quaise Energy has designed a millimeter wave drill that is being tested at Oak Ridge National Laboratory. If successful, it will be the first demonstration of drilling a borehole through full rock vaporization. Quaise Energy ultimately aims to reach 10-20 km (6-12 mi) in depth with its drill.

Photo: Quaise, Houston, Texas

NOV and Particle Drilling Technology are field testing their particle drilling/polycrystalline diamond compact (PDC) hybrid bit designed to provide faster, deeper drilling in hard crystalline rock. An intense stream of hardened particles removes 80-90% of the rock and then the PDC cutters remove the remaining rock and provide stability and a smooth borehole.

Photo: Courtesy, Particle Drilling Technologies

SECTION 3

A Path Forward

3.1 Proof-of-Concept Pilot Demonstrations

Successful pilot demonstrations of superhot rock power generation will be key to attracting the large-scale investment needed to move superhot rock to terawatt scale. Successful pilot demonstrations in dry rock must be followed by commercial demonstrations that move superhot rock into the realm of utility-scale power operations. This is not an entirely new endeavor; superhot rock energy research and development has been underway for several decades. Projects in Iceland, Italy, and elsewhere have already contributed to superhot rock proof-of-concept by reaching superhot (supercritical) fluid temperatures and pressures in natural superhot hydrothermal resources at existing geothermal fields —and need to be continued. For example, IDDP's Krafla well (Figure 10) demonstrated an order of magnitude (10x) larger energy production potential for superhot wells as compared to nearby conventional geothermal wells. This project is being extended in the current Krafla Magmatic Test Bed (KMT) project. These projects have also provided important test beds for drilling, well construction and superhot fluid handling. Next steps will include successful well completions, bringing the resource to the surface for power generation in adjacent existing plants or in modular power generators. At the same time, other global superhot rock demonstration efforts must invest in drilling, well completion, and production of energy in dry rock, where there is no superhot hydrothermal resource at depth. The inability of downhole tools to function at higher temperatures has limited the successes of EGS projects such as FORGE. This is an immediate and critical need.

Cracking the superhot rock code will require solving the additional engineering challenges specific to dry rock, particularly aseismic heat reservoir development. These initial pioneering projects can be drilled with today's mechanical drilling technology, targeting regions where shallow heat exists (Figure 12 and red shaded regions in Figure 13). These pilots will provide critical proof-of-concept for “geothermal everywhere.” To speed the process of learning by doing, many wells must be drilled. An ambitious goal would be to move a half dozen pilot power demonstrations forward in the 2020s, transitioning to larger commercial demonstrations (e.g. 50-100 MW) in the late 2020s

Figure 11

A quiet revolution is underway as a result of a confluence of innovations in all aspects of geothermal, informed by unconventional oil and gas technologies (such as directional drilling and drilling multiple wells from a pad) and inspired by the recognition of the vast potential of engineered geothermal systems. Superhot rock can be commercialized and scaled up in several decades if adequate resources are invested in the 2020s (akin to other zero-carbon resources) to drill many wells across the globe, leading to rapid innovation and commercialization in the 2030s followed by scale-up in the 2040s.

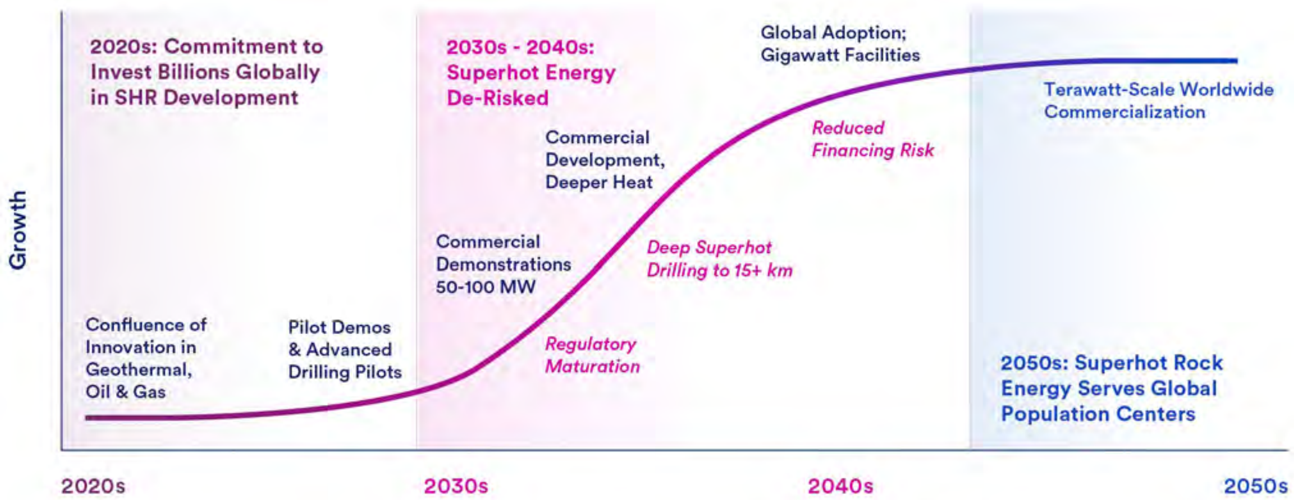


Figure 12

Early power production demonstrations using mechanical drilling in relatively shallow superhot dry rock near magmatic/ volcanic regions should be prioritized by governments for funding and be followed up by intensive drilling campaigns. These demonstrations could initially take advantage of existing steam-power production facilities and transmission lines.

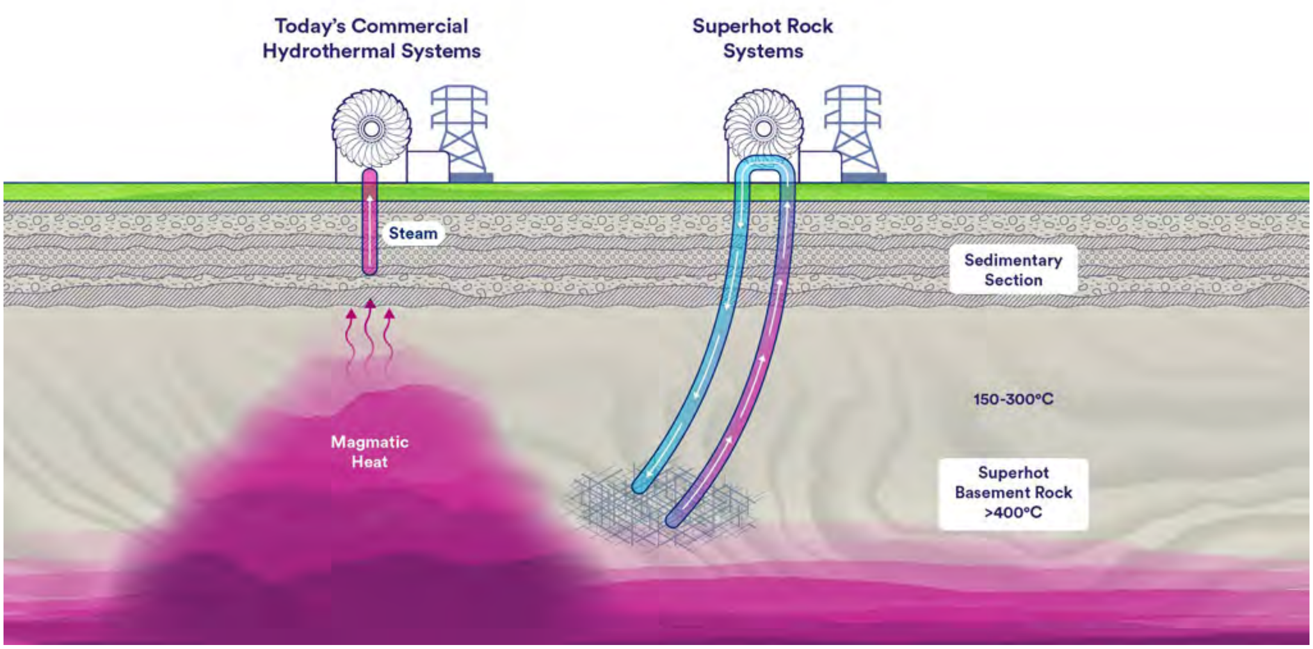
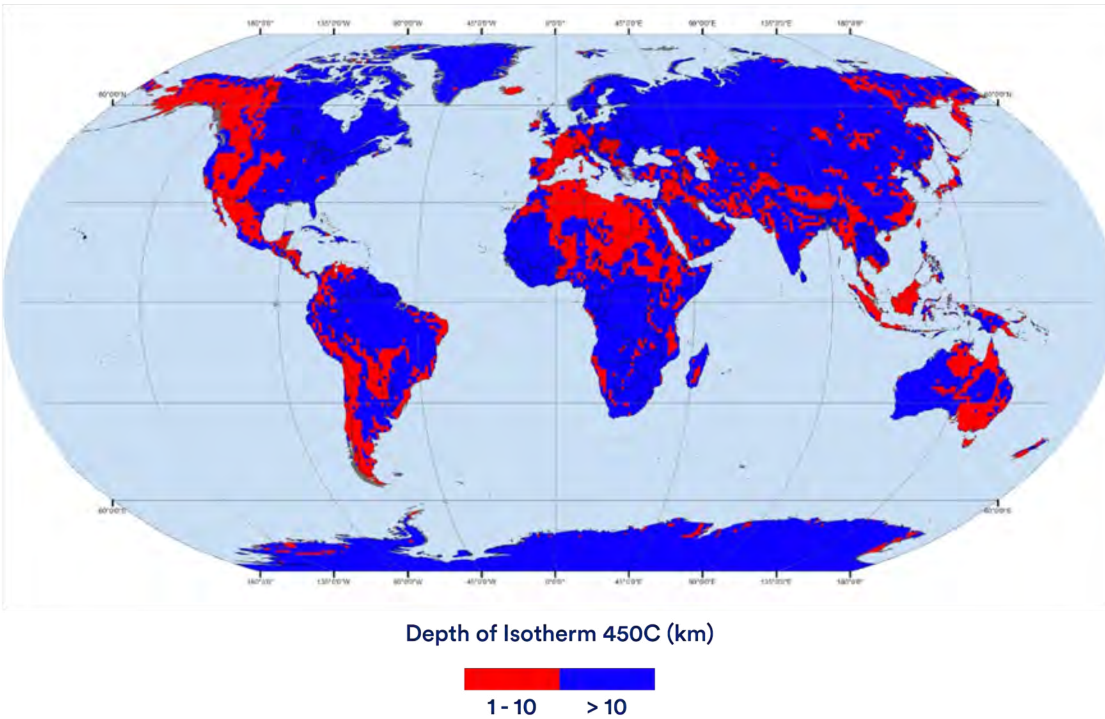


Figure 13

Why superhot rock energy matters: regions in red (roughly depicted) may have accessible superhot rock resources (>450°C) shallower than 10 km in depth that might be accessed with today's enhanced mechanical drilling methods. Advanced drilling methods are being developed and tested that may be able to reach much deeper depths highlighted in the blue regions (Map: Pacific Northwest National Laboratory).[34]



and early 2030s. Potential candidate areas might include, for example, the western United States, Eastern Europe, Africa, Japan, New Zealand, and Oceania, among many other regions.

One particular project of interest is the AltaRock Energy project at the Newberry Volcano in the Cascade Mountains of central Oregon, U.S. It is the only such project that we are aware of globally that intends to demonstrate the production of superhot energy at the surface from dry rock. The Newberry project expects to drill and complete its first superhot rock well couplet (an injection and production well combination) with target well depths of 4.5 km and temperatures above 450°C by 2025. The project will test reservoir enhancement methods to demonstrate flowing the first supercritical reservoir. Newberry's heat resource is significant, and with successful demonstration it could be scaled to gigawatts of extractable power in the future. GeoX Energy, another emerging contender in superhot rock, has acquired licenses in Utah, Idaho, and Washington state in the U.S. Its goal is to produce energy from the supercritical resource by drilling deviated (horizontal) wells using a subsurface heat exchanger.

3.2 Commercial Demonstrations and Deeper Drilling Toward Geothermal Everywhere

Following successful pilot demonstrations, *commercial* demonstrations must begin producing power at grid scale (e.g., 100+ MW). These projects must also move to progressively deeper resources to realize the promise of geothermal everywhere. Drilling campaigns can drive innovation, build confidence and investment risk reduction, and evolve superhot rock energy from shallower heat resources and magmatic areas to progressively deeper resources toward continental interiors. One approach may also be to explore whether superhot rock conditions exist and could be targeted at mid-depths in "hot granites" that generate heat by radiogenic decay. Hard rock drilling projects that do not reach superhot rock conditions could nonetheless produce some return on investment as EGS projects.

Moreover, for superhot rock energy to successfully scale, it must be economically competitive. This will require continuous drilling, problem solving, investment, and best practices evolution to overcome technology challenges and achieve cost reductions. This broad programmatic approach to superhot rock energy drilling and project development should reduce project risks and costs over time through "learning-by-doing." Some innovations needed for superhot rock are underway or planned by small venture capital-supported and collaborative efforts like Alta Rock Energy, Eavor, Greenfire, GeoX, Fervo Energy, and Sage Geosystems.[35,36,37] Big tech can also play an important role in demonstration and commercialization of superhot rock energy by offering power purchase agreements or venture capital for successful projects that could provide carbon-free energy for rapidly expanding energy-intensive operations like data centers.

3.3 The Role of Unconventional Oil and Gas Expertise

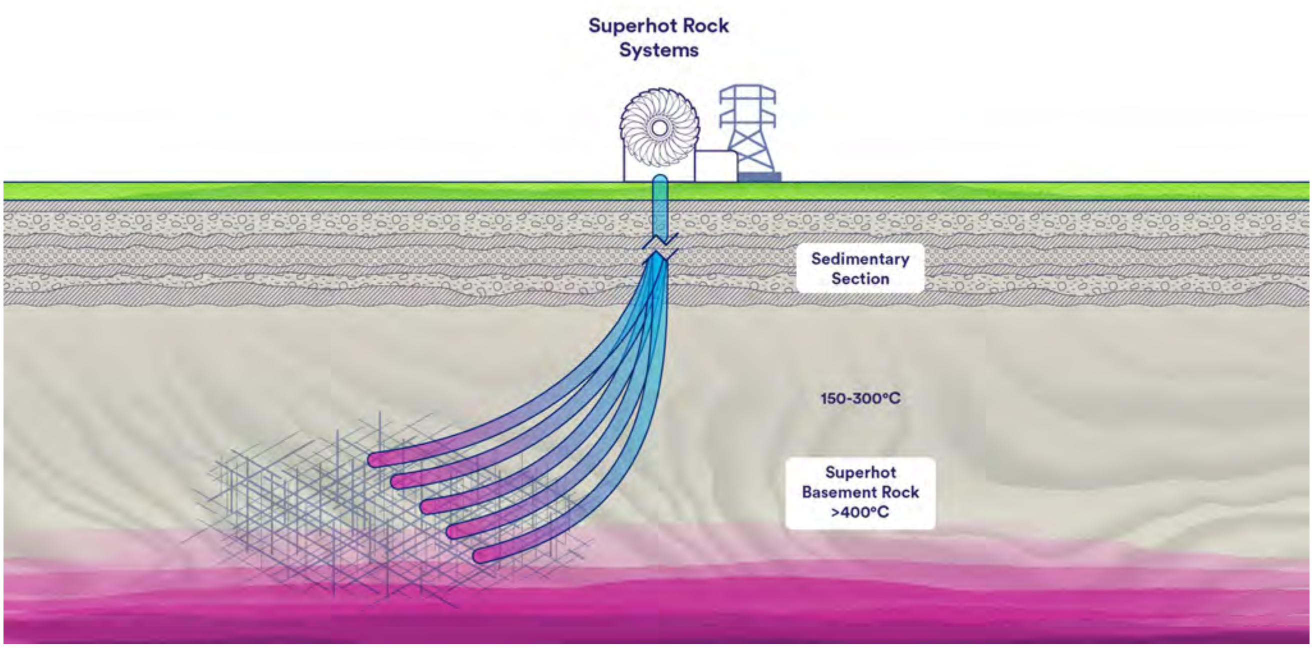
The geothermal industry is striving to incorporate learning from oil and gas into its exploration methods. As far back as the 1990s, Chevron utilized drilling campaigns to drive learning and improve rates of penetration by drilling 90-100 wells at its 375 MW Salak Geothermal Plant in Indonesia. The project eventually achieved 50% cost reduction.[38]

This illustrates how oil and gas industry "know-how" and resources can play an important role in evolving superhot rock energy from proof-of-concept to commercial scale over the next 10-15 years. Superhot rock energy could provide a pivot opportunity that fossil energy companies may need to transition to a decarbonized energy future. Drilling deep into the Earth to produce energy is the oil and gas industry's core expertise, which provided innovations that drove a rapid transformation of shale fossil energy resources previously considered impossible. Some of these innovations included drilling mechanization by mounting a drill rig on rails and systematically moving the rig forward a short distance (e.g., 10 meters) to speed multiple-well project operations and reduce drilling costs and new drill bits to drill faster and minimize trips out of the hole. Directional drilling allowed precise targeting of energy resources and will prove useful to maximize superhot rock energy reservoir energy flows by the ability to optimally orient wells relative to fractures (Figure 14).

Superhot rock energy may also benefit from well-known oil and gas industry strategies for drilling horizontal wells, patterning production wells (e.g., for enhanced oil recovery) to take advantage of multidirectional flow from an injector well surrounded by multiple production wells.

Figure 14

Directional drilling may be a key tool, as it would allow a superhot rock project to: (a) drill from a small surface pad, minimizing impacts and maximizing efficiency; (b) access fractures at angles that allow for better water circulation; and (c) mine heat from progressively deeper heat resources.



SECTION 4

Conclusion: Cracking the Code

Commercial superhot rock geothermal energy could make a transformational contribution to global energy system decarbonization.

Superhot rock energy is poised to be a competitive, high-energy-density, zero-carbon, always-available energy source that could be accessed worldwide in the 2030s with adequate global investment. Key innovations are needed to deploy superhot rock energy widely, including deep drilling, well construction, downhole tool adaptation, and reservoir development in extreme conditions. While technically challenging, these are achievable innovations underway today that could be developed relatively quickly with ambitious public and private investment.

Realizing the promise of superhot rock energy will require the combined resources of the geothermal industry, government laboratories, academic institutions, and the oil and gas industry. Indeed, an intensive drilling and resource development program by well-funded consortia that include oil and gas industry players could provide the knowledge and innovation needed to develop and rapidly commercialize superhot rock energy across the world. Substantial early government investments can jump start the process of commercializing superhot rock energy by providing drilling campaign incentives in promising superhot rock energy locations that differ in depth and geology, as well as by enhancing information sharing and cross-pollination among international projects. The goal should be to learn as much as possible through actual well and reservoir development activities in different subsurface conditions. Such efforts would be enhanced by far more ambitious government support, akin to global support for wind, solar, nuclear power, and zero carbon fuels like hydrogen, and initially spurred by governmental incentives such as write-offs and other meaningful tax breaks.

Moreover, recognizing that permitting can result in long delays, anticipating global regulatory needs and agency staffing early on (such as permitting for groundwater and protecting against induced seismicity) will provide certainty for developers while engendering confidence for policymakers and the public that projects will be safe and will not endanger the environment. Some countries will lack the resources or know-how to independently develop regulations, so one option may be to initiate a global process through the International Standards Organization (ISO), similar to the ISO Technical Committee 265 for carbon capture and storage.

By combining the resources of many countries to underwrite global drilling campaigns in the 2020s, we could crack the code of superhot rock energy such that it could provide terawatts of energy globally in the 2030s—transcending fossil energy and intermittent power, transforming global energy supplies, and providing energy equity and global energy security.

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