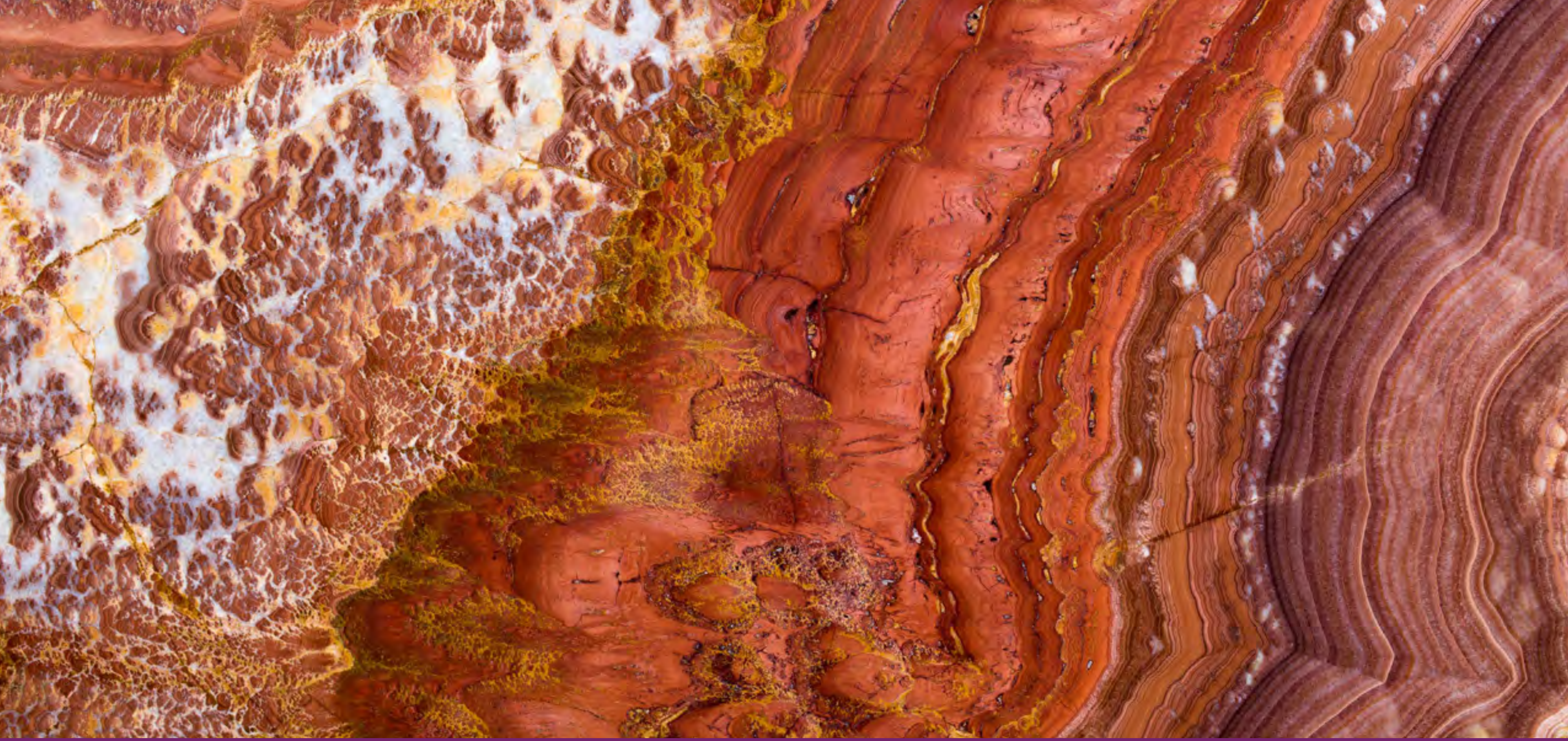

Superhot Rock Geothermal

A Vision for Zero-Carbon Energy "Everywhere"

Published October 2021

CLEAN AIR TASK FORCE

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Executive Summary

Some have called superhot rock (SHR) the “holy grail” of geothermal energy. This is because, in most of the world, SHR could provide competitive, zero-carbon, dispatchable power and could support zero-carbon hydrogen fuel production. It is one of the very few high-energy-density, zero-carbon resources that could replace fossil energy around the globe.

Today’s geothermal systems produce only 15 gigawatts (GW) of power globally and are largely confined to regions where concentrated heat is located near the surface (i.e., volcanic areas or where the crust is thin like the U.S. Great Basin or East Africa). In contrast, SHR will tap superhot conditions (400°C or hotter) at great depths and could potentially be available worldwide.

In SHR systems, water is injected deep underground into a superhot heat reservoir and then is returned to the surface as superhot steam to power steam generators. Several 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 steam has yet to be harnessed for power production, its high energy potential is clear.

A test well drilled by the Iceland Deep Drilling Project (IDDP) demonstrated that an estimated 36 megawatts (MW) of energy could be produced at the surface—approximately 5 times that of a typical 5-7 MW commercial geothermal well today. If this substantial amount of energy can be produced at reasonable development costs, SHR could be competitive at potentially $20-35 per megawatt-hour (MWh).

To realize the full potential of SHR, significant engineering innovations will be required like super-deep drilling, heat resistant well materials and deep heat reservoir development. But these are engineering challenges, not needed scientific breakthroughs. Intensive drilling campaigns, incorporating innovations from unconventional oil and gas experience, could drive rapid learning to address these engineering obstacles and drive further cost reductions. Big tech could also speed SHR by supporting energy drilling ventures or by providing power purchase agreements for successful projects. With significant private and public investment, along with enabling policies and continued technological innovation, SHR could plausibly be commercialized within 10 to 15 years.

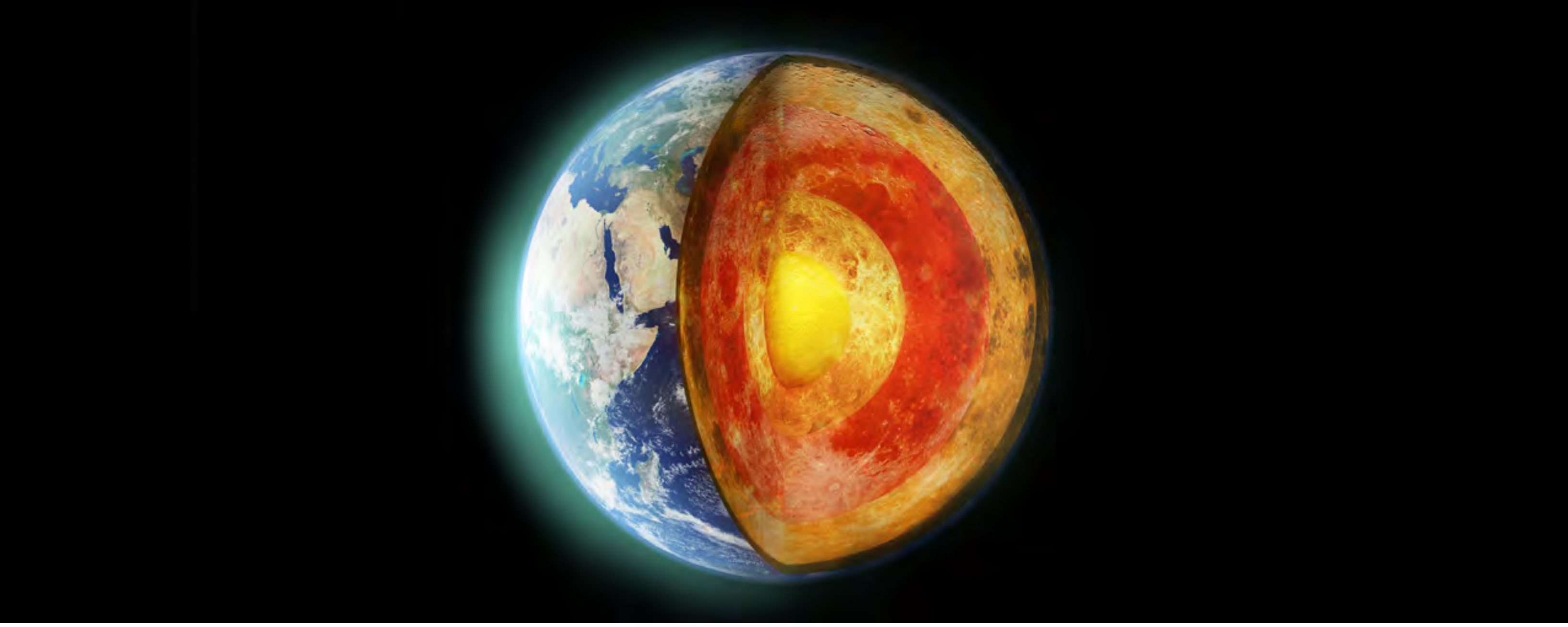
A key first step to commercial SHR will be moving three to five SHR power demonstrations forward in the next five years. Successful proof-of-concept power production demonstrations will "wake up" the energy community and spur investment in commercial demonstrations. To evolve SHR to "geothermal everywhere", initial demonstrations should take place in shallow hot dry rock settings without natural hydrothermal steam resources. One such SHR project (by AltaRock Energy) is being planned in Oregon. Then as next-generation superdeep drilling methods (energy drilling) are commercialized, SHR can progress from shallow hot regions to deep continental areas.

The Value of Superhot Rock Geothermal

- **Competitive** power
- **Endless** Earth energy resource
- **Dispatchable,** meaning always on, baseload power
- **Energy dense,** high energy with a small surface footprint
- **No fuel cost**

- **Zero** greenhouse gases
- **Pivots fossil energy** to geothermal across the globe
- **Potential to repower** fossil power plants
- **Generates carbon-free hydrogen** as a transportation fuel

- **Accessible worldwide** with super deep drilling innovation
- Significant engineering advancements required but **does not depend on scientific breakthroughs**
- **Energy security and modernization**



SECTION 1

Superhot Rock Geothermal's Energy Potential

1.1 Tapping into the Earth's Deep, Endless Heat

The Earth's deep heat is an energy resource that could be accessed to provide power and hydrogen fuel worldwide with minimal environmental impacts. The Earth's deep heat is boundless for energy extraction purposes, and SHR technologies are under development to tap into it.

Today's geothermal industry is limited to locations with very high near-surface temperatures (e.g., near or above volcanic systems) where it is feasible to produce energy from natural steam from circulating groundwater (Figure 1). The rarity of these "hydrothermal" systems—think of Old Faithful[1] or other natural geysers[2]—is primarily why global installed geothermal electricity capacity was only 15 GW in 2018, less than 0.2% of total installed global power capacity.[3]

To expand geothermal energy's global reach, hot dry rock (HDR) systems seek to emulate conventional hydrothermal energy production by injecting water into hot, dry rock and producing steam.[4] [5] These HDR systems are typically described as "enhanced" or "engineered" geothermal systems, or "EGS". A 2019 U.S. Department of Energy (DOE) analysis estimated that the US geothermal electricity resource[6] 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.[7] 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.[8] These analyses make clear that the theoretical HDR/EGS energy potential is very large, and much more if SHR's potential is considered.

Figure 1

Commercial geothermal systems are currently limited to the red or dark orange zones in continental areas on the map above. SHR could extend geothermal to much of the rest of the world. (Davies 2013)[9]

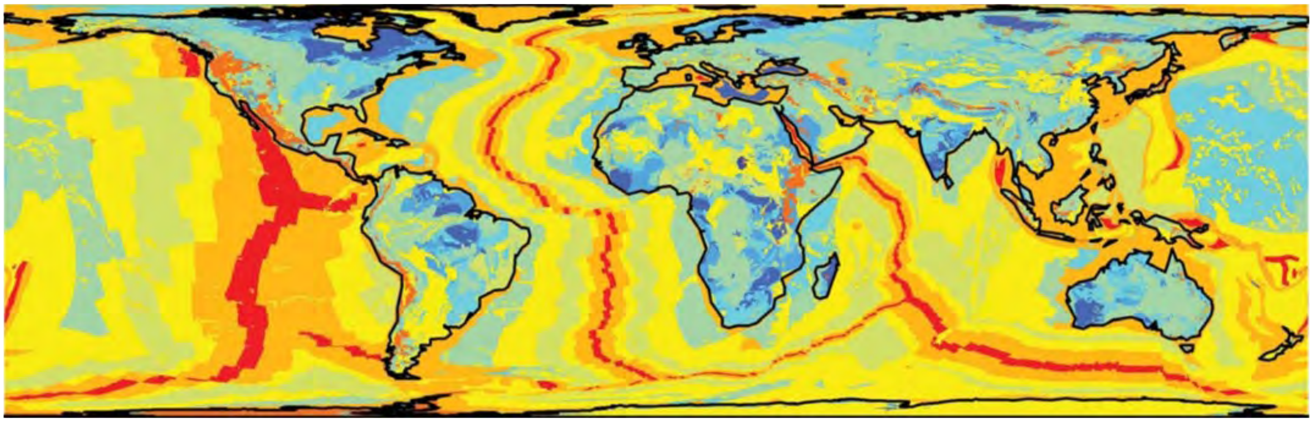


Figure 2

There are four principal kinds of geothermal systems: (1) **commercial hydrothermal systems**, which collect steam from shallow, heated groundwater; (2) **sedimentary systems**, which will collect energy by circulating water or supercritical carbon dioxide through lower temperature sandstones and shales, a natural extension of oil and gas technology; (3) **hot dry rock systems** (commonly deemed "EGS"), which are engineered to collect heat by circulating water through dry rock; and (4) **superhot rock systems**, which 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.

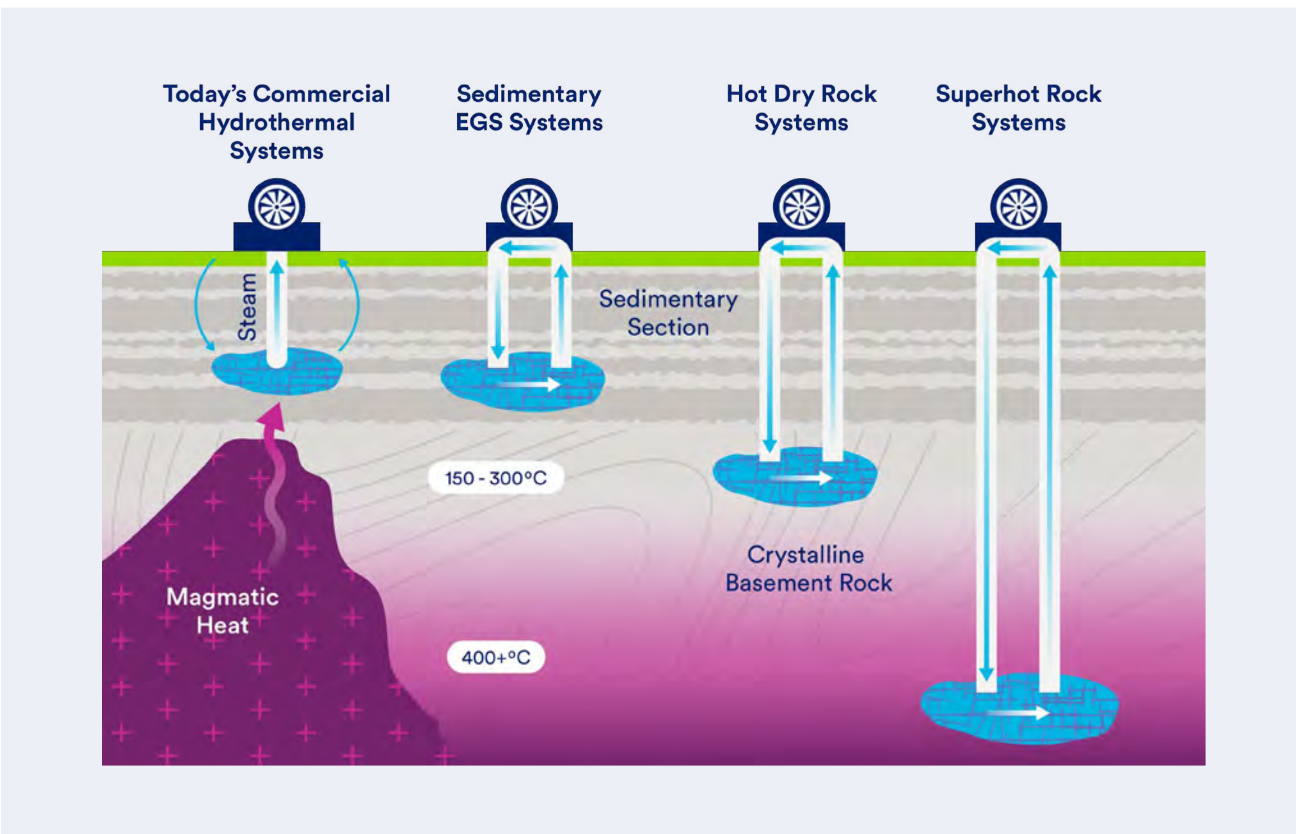


Figure 3

Superhot geothermal energy is mined from natural heat deep within the earth. Water is injected (through an injection well) into superhot dry rock, at temperatures > 400°C, and is circulated through a reservoir of existing fractures to a production well that provides energy to produce power, heat, or fuels. Accessing affordable superhot resources could transform the power industry but will require drilling and reservoir engineering innovations. (Illustration modified from HERO)

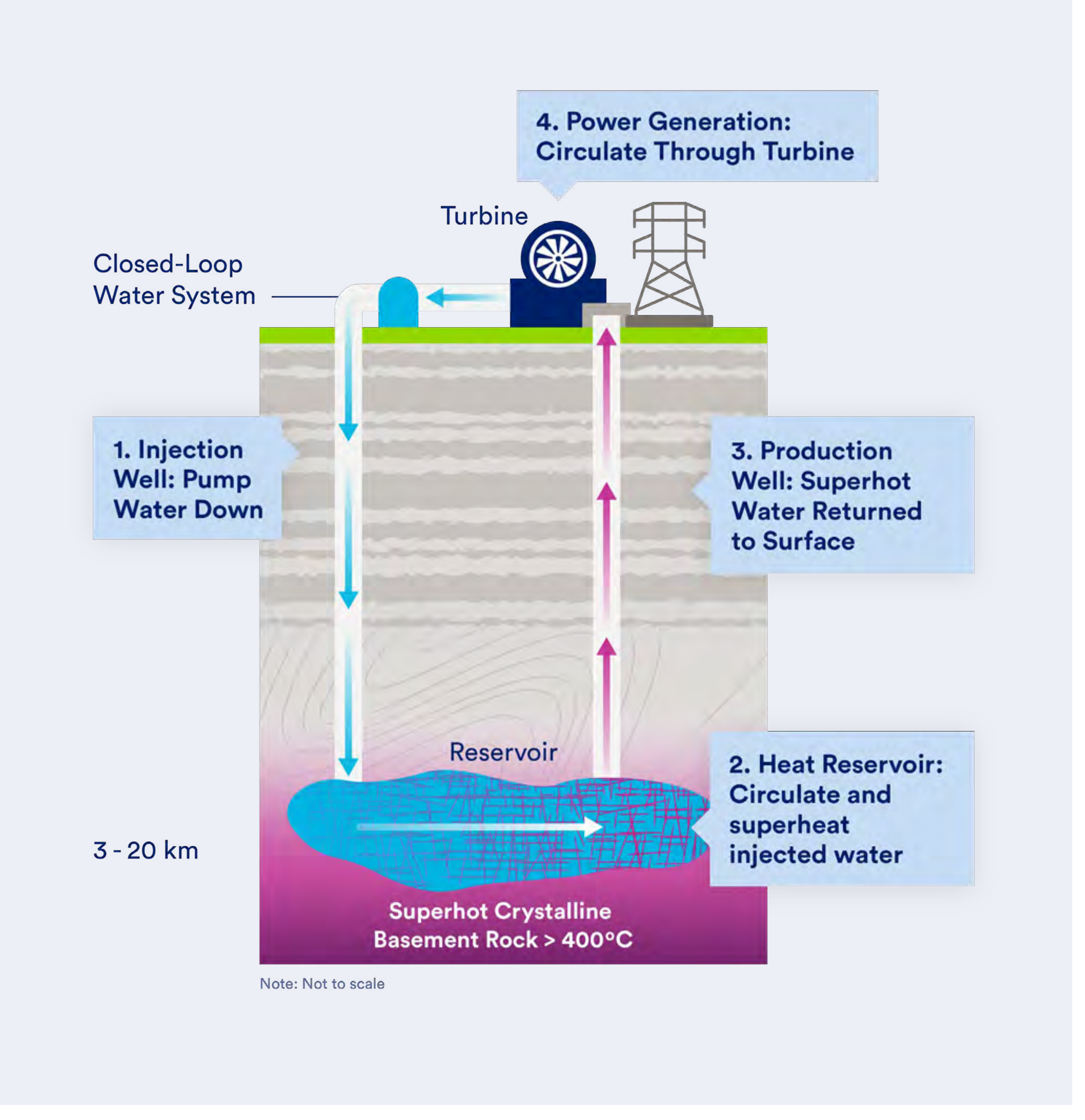


Figure 4

SHR will inject water to be heated by circulating it through deep existing fracture sets, such as illustrated by these fractures that dissect the half-billion-year-old granites in Maine, USA.

Figure 2 and 3 illustrate how SHR takes advantage of deeper, hotter and more energy-dense rock. Engineered hot dry rock SHR systems will inject water down a deep injection well and circulate it through ancient fracture systems (similar to those in Figure 4) in hard crystalline "basement" rock where temperatures are 400°C or higher and then bring the superhot water back up production wells to generate electricity at surface power facilities.

With the ability to drill, engineer wells and create heat reservoirs deep enough, geothermal energy can be tapped nearly anywhere in the world.

1.2 High Energy Density

The superhot rock resource promises to be vast, but also very energy dense—a key SHR advantage. While regions with thin, shallow heat resources used in commercial geothermal projects will provide test beds for early SHR systems, these geographically limited regions are scattered throughout the world and typically found only near continental margins. In contrast, continental crust makes up most of the inhabited areas of the globe and is many tens of kilometers thick. This means the volume of rock that could be mined for heat could be kilometers thick (depending on fractures and ability to develop reservoirs) and could be effectively limitless and produced anywhere drilling can reach deep enough. SHR power facilities will tap into this thick, deep, energy dense resource, yet they will occupy a very small surface footprint relative to the enormous heat resource they sit above.

Why does superhot water carry so much more energy? The injected water transforms into a superhot, superfluid form scientists call "supercritical" water.[10] Supercritical water can penetrate fractures faster and more easily and can carry 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 HDR wells. So a few SHR 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.[11] Similarly, AltaRock Energy projects that 25-45 MWe could be produced from a single production well at its Newberry SHR project.[12] In comparison, a typical commercial hydrothermal geothermal project produces about 7-8 MW per well. Also for comparison, the Reykjanes geothermal field in Iceland—perhaps the hottest producing field in the world at 290-320°C—has 12 wells producing a total of 100 MWe from 2 turbines.[13]

With SHR, more heat energy can be harvested from fewer wells. This means the surface area required for SHR well fields to feed a very large power plant (hundreds of megawatts or a gigawatt in size) could be relatively small. And SHR well construction and maintenance costs could be less than conventional geothermal or HDR wells *per unit of energy produced*.

1.3 Competitive Dispatchable Power

The higher heat energy per well and therefore lower well and reservoir costs per unit of energy produced are expected to drive SHR's cost-competitiveness. Yet, it is unclear whether HDR/EGS projects in crystalline rock below superhot conditions will be competitive without substantial incentives. For example, the sale of electricity from France's Soultz-Sous-Forêts site, the only such operational site, is closely tied to a relatively steep feed-in tariff (0.22 Euros per kilowatt-hour).[14]

Clean Air Task Force commissioned Hot Rock Energy Research Organization and Lucid Catalyst to preliminarily estimate the levelized cost of commercial-scale SHR electricity. Results suggest mature SHR will be competitive at $20-35 per MWh (Figure 5).[15] 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, like the experience that drove deep cost reductions and productivity improvements in large-scale unconventional shale oil and gas development.

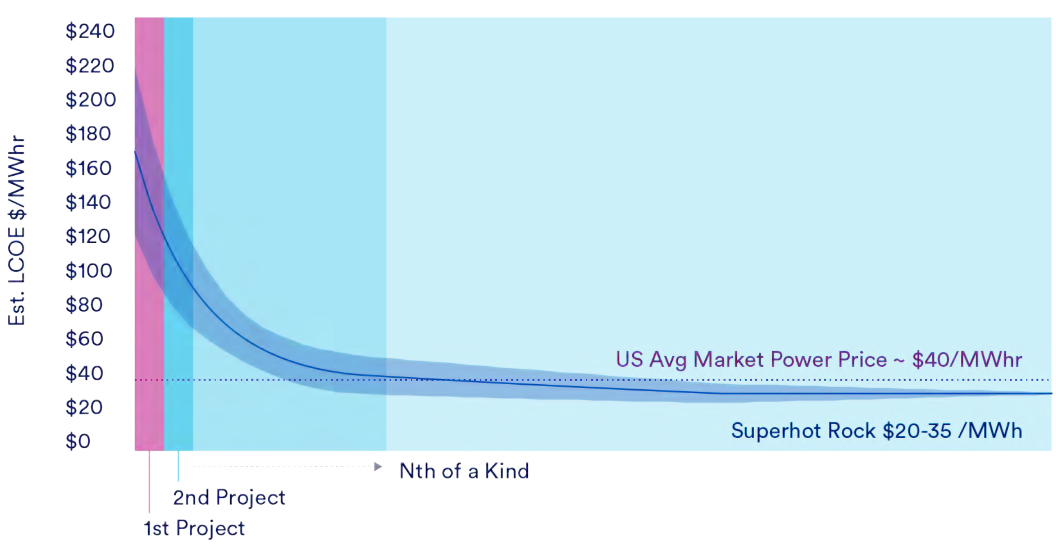
1.4 Manageable Environmental Footprint

Like all energy sources, superhot geothermal power will 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 carbon dioxide (CO_2) will be produced in the process of generating power. Also CO_2 will not be produced by the circulating water, which is a small advantage over some commercial hydrothermal geothermal systems, some of which can emit low levels of carbon dioxide from the natural water used to produce power.
- **Limited water use and minimal drinking water risk.** While SHR will involve injecting water into existing fractures underground, water volumes consumed are expected to be minimal as the produced steam will be condensed and reused. SHR wells will inject recycled water far deeper (several kilometers) than near-surface drinking water aquifers

Figure 5

Illustrative graph shows how electricity produced from superhot rock is expected to be competitive for "Nth of a kind" plants (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 $0.02-$0.035 / kWh. This would be competitive with other dispatchable and intermittent energy resources.



SHR Hydrogen Production Potential

Superhot rock high temperatures could facilitate generating hydrogen, an alternative fuel that could help decarbonize mobility, space heating and some industrial processes. Hydrogen is also a potentially promising feedstock and energy source for producing zero-carbon ammonia—which is emerging as a major global zero-carbon liquid fuel. A Lucid Catalyst analysis produced for Clean Air Task Force estimates that SHR energy could potentially produce hydrogen competitively.

(typically not much more than one or two hundred meters in depth), leaving several kilometers of impermeable crystalline rock to effectively separate the SHR "reservoir" from near-surface water resources. U.S. SHR projects will operate under Safe Drinking Water Act requirements to ensure potable water is protected from project water. Nonetheless, establishing effective regulatory review to ensure robust water protections are in place prior to commercial SHR deployment is a priority.

- **Small surface footprint.** SHR energy does not require thermal generation facilities. Therefore, geothermal power plants generally require small operations areas with surface equipment essentially limited to steam turbines and electricity generators. As mentioned previously, SHR's surface footprint is expected to be small relative to the very large amount of energy that could be produced at a single site. Innovations from unconventional oil and gas can further minimize the surface footprint of SHR wells through drilling of multiple injection and production wells from a single moveable drilling pad.
- **Careful site selection to minimize induced seismicity risk.** Seismic activity and "felt" or damaging earthquakes have been recorded in association with lower temperature HDR/EGS projects where water has been injected into hot (but not superhot) rock to stimulate or create fractures (e.g., Soultz, France; Pohang, South Korea; Basel, Switzerland). The South Korean experience in particular demonstrates the need for rigorous site selection processes in advance of developing SHR resources to avoid injection into fault zones. Therefore, as a precondition for operations, stringent regulatory protections must be anticipated, developed and adopted in advance of SHR commercialization. These should include rigorous project site investigation and selection using modern methods such as 3-D seismic profiling and microseismic monitoring, to identify and avoid active fault zones. Once operational, monitoring (and real-time reporting) should continue. The U.S. Frontier Observatory for Research in Geothermal Energy (FORGE) has a focused research effort on earthquake avoidance in HDR/EGS systems[16] which should help inform regulatory development.

SECTION 2

Status of SHR & Necessary Innovations

2.1 SHR Initiatives, Past & Present

Engineering concepts for hot rock geothermal energy systems originated in 1970 at Los Alamos National Laboratory.[17] This project continued through 1992, systematically exploring the HDR concept through drilling and related experiments. This work laid the groundwork for understanding and exploring hotter and deeper heat resources.

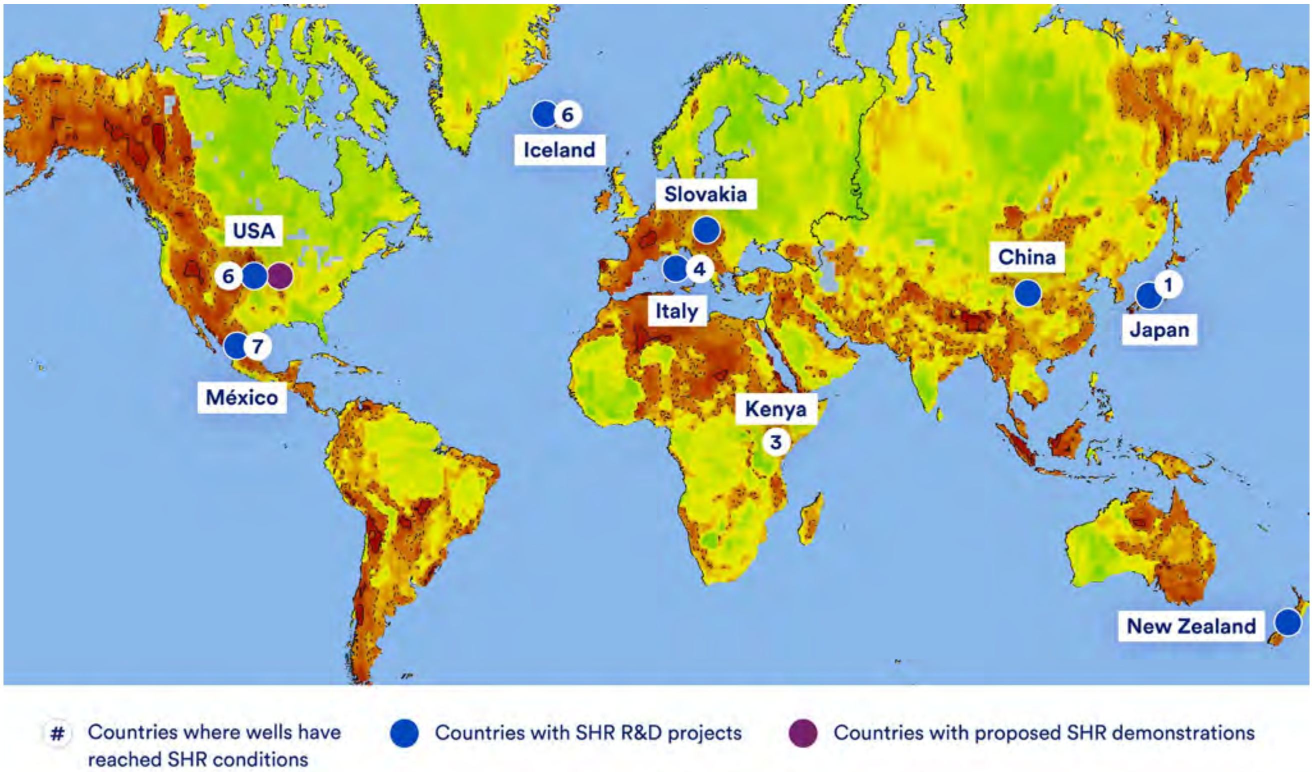
Over two dozen wells have been drilled into SHR conditions around the world. The map (Figure 6) shows global SHR initiatives (blue dots) and numbers of wells that have encountered superhot rock. These wells have generally been in comparatively shallow, high-temperature heat below existing geothermal 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 SHR well, these projects and others have provided important learning and continue to inform the innovations needed to move commercial SHR forward.

- **Japan Beyond Brittle Project.** Japan's NEDO Kakkonda well in northeast Japan was drilled in 1994-1995, reaching to the "brittle-ductile transition zone" where rock is more plastic at temperatures above 500°C at a depth of 3.7 km (about 2.3 mi). JBBP's superhot rock research continues at Tohoku University where its focus is on reservoir development in superhot conditions and identifying strategies for minimizing risk of induced seismicity.[18] JBBP contemplates drilling a second exploration well as a part of the project.
- **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.[19] 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 planned to flow test the well in 2021. IDDP is currently planning a third superhot well.

Figure 6

Global superhot drilling and research sites. Brown areas are where SHR heat is less than 10 km and therefore the most viable regions for earlier SHR development (see Figure 8, later). (Heat map: Pacific Northwest National Laboratory and HERO)



- **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 (also as a part of the EU DEEPEGS program). Superhot conditions were originally encountered in the early 1980s in Larderello's San Pompeo-2 well.[20] [21] 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 HDR/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 Los Humeros geothermal field.[22]
- **Hotter and Deeper.** The Hotter and Deeper Exploration Science (HADES) project in New Zealand has been exploring superhot resources in the Taupo Volcanic Zone since 2009 and has been planning a scientific drilling project into New Zealand's deep-seated superhot rock.[23] Like JBBP, the project hopes to investigate potential 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.[24]

2.2 Innovations Needed for Commercialization of SHR

While research projects and individual wells have reached into superhot conditions for several decades with conventional drilling technology, new tools and technologies are needed to produce energy from challenging depths at superhot temperatures and high pressures.[25] Clearly, the long-term SHR need for successful “geothermal everywhere” is drilling innovation to reach far deeper 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 SHR drilling operations like in Iceland.

Drilling Superhot Rock

Deploying SHR and “geothermal everywhere” globally will require innovative new technologies that can improve drilling rates and cost-effectively reach superhot resources in hard crystalline rock at depths of 7-15 km (~4-9 mi). Currently available mechanical drilling methods can and are being used to drill to depths of 3-7 km (~2-4 mi) to access relatively shallow superhot rock. While emerging contact-drilling innovations like hammer drills should increase penetration rates, limits exist to the depths and temperatures that mechanical drilling can reach. Moreover, today’s rotary drilling requires the time-consuming and frequent removal of the drill pipe to change out worn drill bits. In contrast, energy drilling should require far fewer of these “trips” out of the hole. Therefore energy drilling should significantly improve drilling speed and economics, thus further enabling economic access to greater depths. Laboratory tests demonstrate that such non-mechanical energy drilling methods can soften or melt rock through energy directed downhole. Two principal energy drilling methods are currently being tested: *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 (USA) is developing a millimeter wave drill. ENN (China) has evaluated both plasma and millimeter wave energy drilling methods in its SHR laboratory.

Heat Reservoir Creation

Creation of heat reservoirs in fracture systems in dry superhot rock while avoiding seismic risk is a critical challenge that must be addressed to achieve widespread commercial SHR success. Injected fresh 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 aim to dilate (open) *existing* fractures rather than generate new ones. As mentioned above, FORGE Utah remains focused on reservoir creation and seismic avoidance in lower temperature HDR/EGS systems.[26] 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.[27] Similarly, New Zealand has been conducting investigations into this so-called "brittle-ductile transition" plastic rock zone where geophysics suggests lower seismic activity and risk. In China, ENN has established experimental “rock squeezing” facilities capable of testing large samples in hot conditions to better understand rock mechanics (fracture and heat reservoir development) in superhot conditions.

In addition to circulating water through fractures, engineered methods are also being explored to use subsurface conduits, thereby avoiding use of fractured systems and seismic risk. These systems are designed using directional drilling combined with micro-tunneling and casing to pipe water through a closed loop through the subsurface. For example, the Canadian company Eavor is testing its “Loop” technology at an existing EGS site in Bavaria Germany supported by a feed-in tariff and, if successful, a heat and power purchase agreement.[28] Sage Geosystems in Texas plans to produce energy from sedimentary rock from a single-well, closed-loop system.[29]

Well Construction

Well failure is one principal reason that early SHR efforts have yet to be successful. The deep, hot conditions required for superhot geothermal require innovations in metallurgy and cements for more robust casing of wells. Casing is made up of pipe that lines the outer borehole diameter and is held in place by cementing the casing to the surrounding rock. This prevents loss of fluids into the surrounding rock during water injection and production and can also maintain pressure inside the borehole. 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 interesting but yet-to-be-tested hypothesis is that energy drilling could effectively melt the wellbore walls into an impermeable "glass". If successful, this process of "vitrification" would reduce casing installation materials, time, and costs.

Downhole Power & Remote Sensing Tools

Successful SHR will require transmitting power downhole for several purposes. First, conduction of power downhole will be required for energy drilling. This is a critical challenge for successful energy drilling. Plasma and millimeter wave drills will require significant amounts of energy to drive the cutting bits at the bottom of the hole. Second, power will be needed for downhole remote sensing. Such monitoring tools will be necessary to identify fracture and permeability zones and for routinely ensuring 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 is underway on 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 SHR environments.

Surface Power Production

At the surface, production of electricity from superhot steam will likely require developing new high-pressure, high-temperature power steam turbines and other related equipment. Several companies are investigating how turbines and other power generation technologies can be adapted for superhot conditions.[30] Other innovations that may be required include methods and materials for corrosion resistance.

IDDP drill rig (source: https://iddp.is/)

Energy Drilling

GA Drilling's PlasmaBit drilling technology emits a stream of plasma—extreme heat energy formed as electrons are stripped off 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 operating in extreme superhot rock temperatures. The PlasmaBit drill has been tested in GA Drilling's Slovakia laboratories, which can simulate high temperature and pressure environments. GA Drilling's plan over the next two years is to progress towards drilling a 5 km (3 mi) deep well in crystalline rock in several steps to prove the technology, before moving on to greater depths.

(Photos: GA Drilling, Slovakia)

Quaise is leveraging technology originally developed for nuclear fusion research to develop millimeter wave (MMW) drilling. Following successful experiments at MIT, Quaise is about to begin MMW drilling tests within a DOE-funded project at Oak Ridge National Laboratory. This testing will be the first demonstration of drilling a borehole through full rock vaporization. Quaise plans to subsequently move a prototype MMW drilling rig into the field for increasingly deeper drilling demonstrations. Quaise ultimately aims to reach 10-20 km (~6-12 mi) in depth.

(Photo: Quaise, Houston, Texas)

SECTION 3

A Path Forward

3.1 Pilot Demonstrations in Superhot Dry Rock

Successful pilot demonstrations of SHR power generation will be key to attracting the large-scale investment needed to move SHR to "geothermal everywhere". Successful pilot demonstrations must be followed by commercial demonstrations that move SHR into the realm of utility-scale power operations (Table 1). Projects in Iceland, Italy, and elsewhere have already contributed to SHR proof-of-concept by reaching superhot (supercritical) fluid temperatures and pressures using natural superhot hydrothermal resources in existing geothermal fields. And IDDP's Krafla well demonstrated SHR's significant energy production potential. These projects provided test beds for drilling, well construction and superhot fluid handling. The IDDP project in Iceland could be the first demonstration of power production using its superhot resources.

Table 1

Potential commercialization pathway for SHR in three general phases: (1) widespread demonstration and innovation; (2) initial commercial deployment, particularly in shallow SHR areas; and (3) widespread SHR deployment enabled by access to deeper resources.

Phase 1 →	Phase 2 →	Phase 3
SHR Demonstration and Innovation SHR power production pilot projects using mechanical drilling methods in volcanic regions at depths of 3-7 km; development of methods, tools, and technologies for extreme heat and pressure conditions; energy drilling field demonstrations; parallel successes and learning in hot dry rock and sedimentary geothermal projects; possible high-temperature hydrogen cogeneration tests.	**Initial Commercial SHR Deployment** Commercial demonstrations; expansion of SHR in hot crustal regions (e.g., the western US, Pacific Rim, Sub-Saharan Africa); development of mid-depth systems (e.g. up to 10 km), commercialization of energy drilling.	**Widespread Deployment** Energy drilling unlocks super-deep geothermal across the globe at depths of 10-20 km.

To realize SHR geothermal everywhere, pilot demonstration projects must successfully move from these superhot hydrothermal resources to dry rock. This will mean 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 as conceptually illustrated in Figure 7, targeting regions where shallow SHR heat exists (red shaded regions in Figure 8). These SHR dry rock pilots will provide critical proof-of-concept for "geothermal everywhere." An ambitious goal would be to move three to five SHR pilot power demonstrations forward in the next five years. Potential SHR candidate areas may include the western United States, Eastern Europe, Africa, Japan, New Zealand and Oceania.

The AltaRock Energy project at Newberry volcano in the central Oregon Cascades is the only such project that we are aware of globally that is ready to demonstrate superhot energy production in dry rock not associated with an existing geothermal field. With adequate funding, the Newberry "Newgen" project will deepen an existing 3 km (~1.9 mi) well (drilled in 2008) to 4.5 km (~2.8 mi) to reach superhot conditions over 400°C.[31] If Newgen is successful, it is estimated that the resource could be as large as 10 GW. Partners are lined up to demonstrate power at this site if the well project is successful.

In addition to SHR-specific pilot demonstration projects, the learning-by-doing that is occuring in relevant ongoing non-SHR projects—for example by companies seeking to produce marketable energy at lower temperatures (150-300°C) in hot dry rock or in sedimentary basins—will provide SHR-relevant innovations. Current examples include enhanced drilling and well construction methods in hot conditions, injection

Figure 7

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.

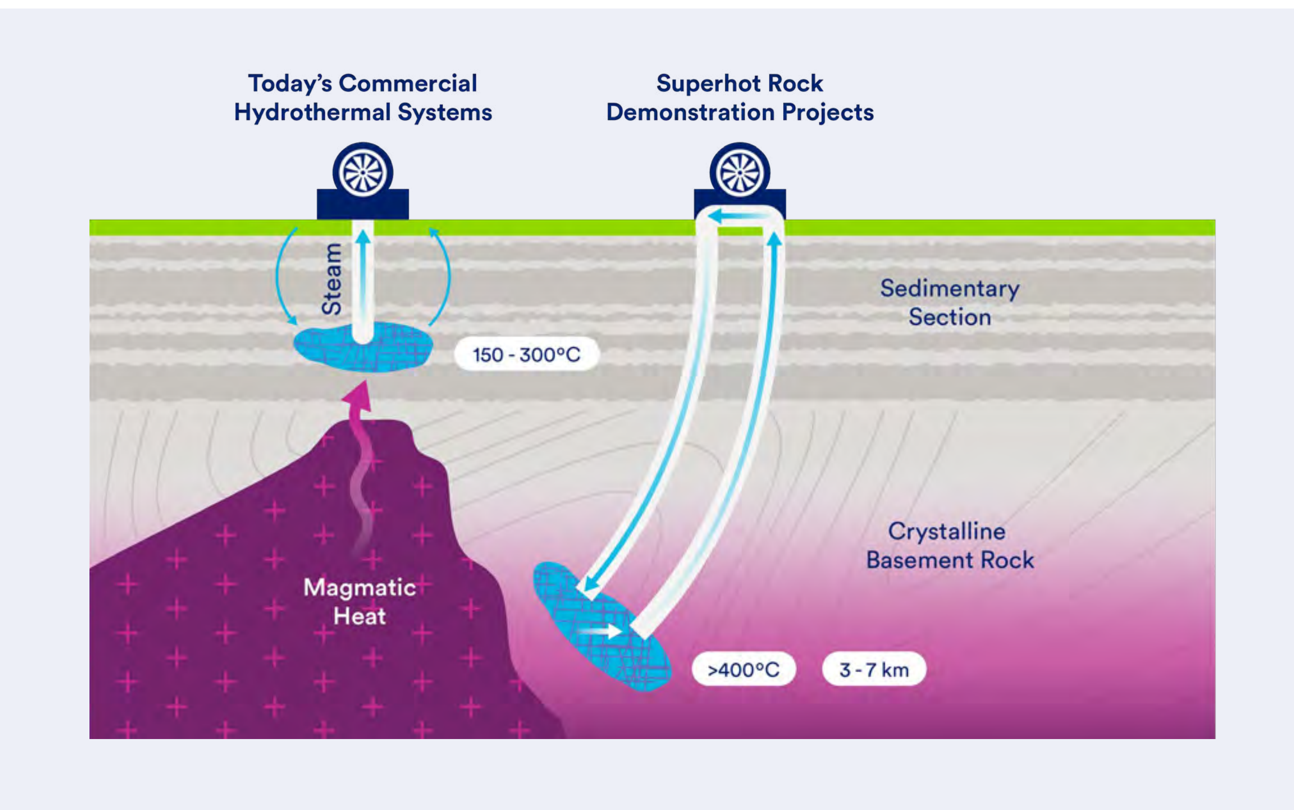
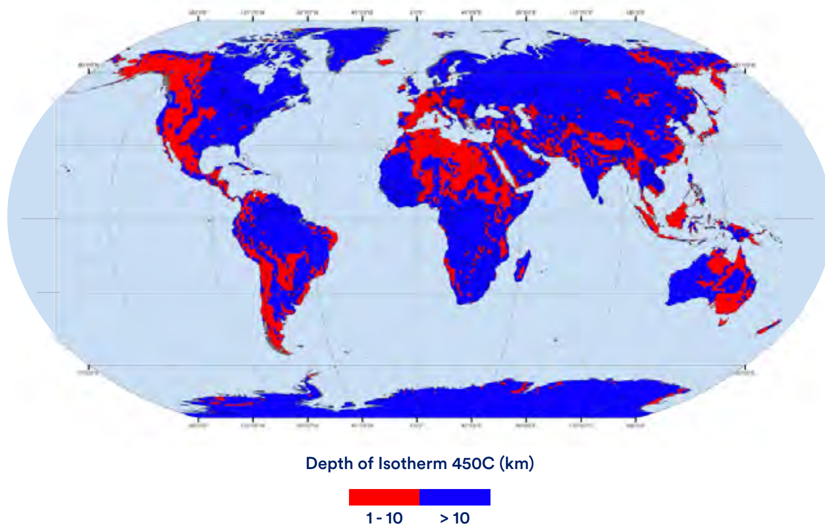


Figure 8

Why superhot geothermal matters: areas shaded red are superhot rock resources >450°C that are less than 10 km in depth and may be accessible with enhanced mechanical drilling methods. Energy drilling could reach depths beyond 10 km in the blue regions.

(Map: Pacific Northwest National Laboratory)[32]



and production from a single well, closed-loop systems that circulate working fluids through pipes rather than fractures, and potential use of supercritical CO_2 which could advance engineering toward systems with superhot water.

3.2 Commercial Demonstrations and Deeper Drilling Toward Geothermal Everywhere

Following successful pilot demonstrations, *commercial demonstrations* must then 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. The innovations needed to achieve deeper resource extraction may be accelerated by intensive drilling campaigns designed to catalyze rapid learning-by-doing. Drilling projects that do not reach SHR conditions could nonetheless produce some return on investment as HDR projects. Drilling campaigns could drive innovation, build confidence and investment risk reduction, and evolve SHR from shallower heat resources to progressively deeper resources away from magmatic areas toward the continental interiors. One approach may also be to explore whether SHR conditions exist and could be targeted at mid-depths in "hot granites", crystalline rock that generates heat by radiogenic decay in trace minerals.

Superhot rock energy must also 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 SHR drilling and project development should reduce project risks and costs over time through "learning-by-doing", as has been demonstrated by a drilling campaign at Chevron's Salak Plant in Indonesia. This project rapidly drilled nearly 100 wells and achieved significant cost reductions (Figure 9).

Figure 9

Learning-by-doing: At the 375 MW Salak Geothermal Plant in Indonesia, which came online in 1994, Chevron drilled 90-100 wells and eventually achieved 50% cost reduction.[33]

To be sure, innovations will come not just from majors but also from smaller venture capital-supported efforts like Eavor, the company field testing closed loop, cased geothermal systems created by directional drilling.[34] Other companies like Fervo Energy[35] and Sage Geosystems[36] are also working towards projects that incorporate unconventional oil and gas innovations.

Big tech can also play an important role in demonstration and commercialization of SHR by offering power purchase agreements for successful SHR projects that could provide carbon-free energy for rapidly expanding operations like data centers, or by providing venture capital to support emerging energy drilling technologies.

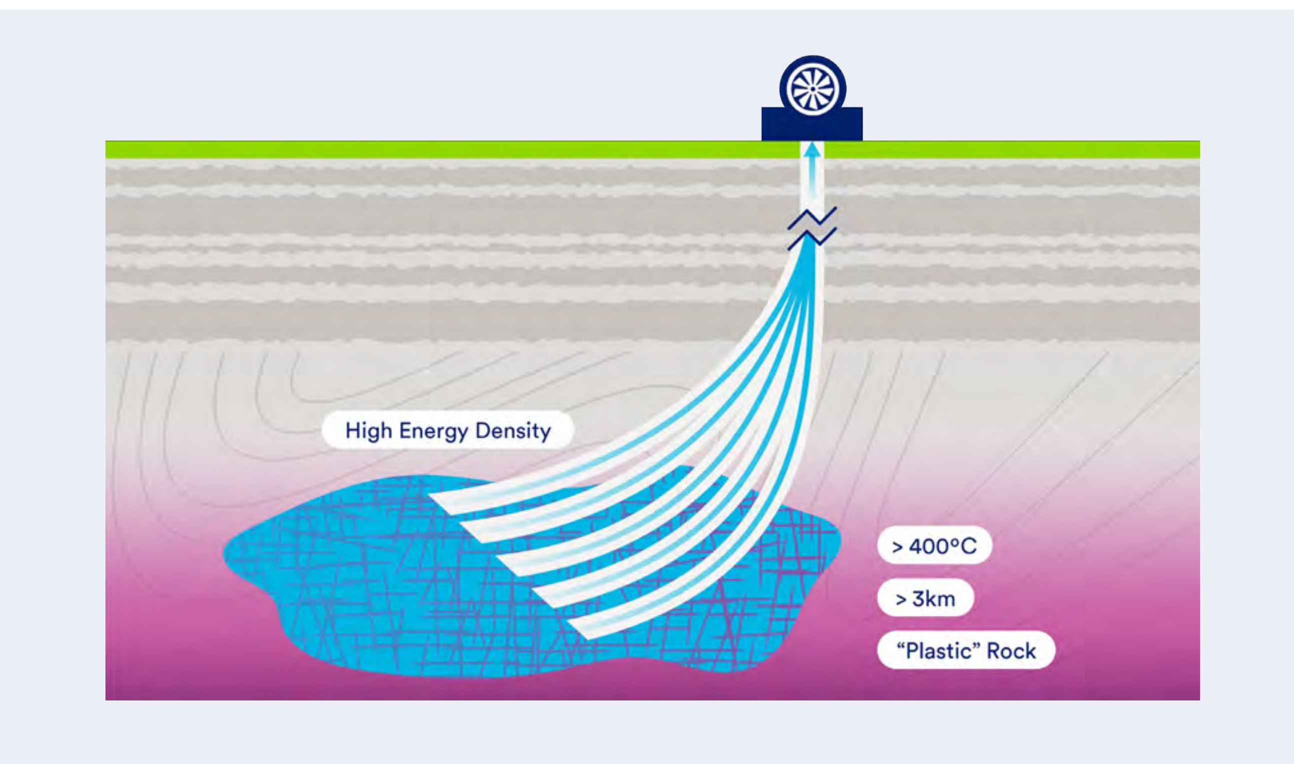
3.3 The Role of Unconventional Oil and Gas Expertise

Oil and gas industry “know-how” and resources can play an important role in evolving SHR from proof-of-concept to commercial scale over the next 10-15 years. SHR energy could provide a “pivot opportunity” fossil energy companies will 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 an unimaginably 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. Directional drilling allowed precise targeting of energy resources and may be useful to maximize SHR reservoir energy flows (Figure 10).

SHR may also benefit from well-known oil and gas industry strategies for patterning production wells (e.g., for enhanced oil recovery) to take advantage of multidirectional flow from an injector well, with multiple surrounding production wells.

Figure 10

Directional drilling may be a key tool, as it would allow an SHR 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

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

SHR is a high-energy-density, zero-carbon, always-available energy source that could potentially be accessed worldwide for baseload power, heat, hydrogen production and industrial process energy. SHR could be economically competitive with most zero-carbon technologies and capable of being deployed rapidly in much of the world. SHR promises a small environmental footprint and could potentially repower or replace many existing fossil fuel energy facilities.

Commercializing SHR will require the resources of the geothermal industry, government laboratories, academic institutions and the oil and gas industry. Substantial early government investments can "jumpstart" the process of commercializing SHR energy by providing drilling campaign incentives in promising SHR locations that differ in depth and geology, as well as by enhancing 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 as soon as is practical.

Key innovations are needed to deploy superhot rock energy widely, including deep drilling and reservoir development in very high temperature and pressure conditions. While technically challenging, these are achievable innovations that could be developed relatively quickly with adequate funding—as was the case with unconventional fossil resource development. Indeed, oil and gas expertise should play a major role in commercializing and rapidly deploying SHR. 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 SHR across the world.

SECTION 5

Endnotes

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