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Gaps, challenges, and pathways forward for superhot rock geothermal: summary report

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ABSTRACT

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Research suggests that 2% of the geothermal energy within 3 to 10 km of Earth's surface could provide the equivalent of 2,000 times the current energy demand of the United States (Petty et al. 2020, Tester et al. 2006, van Oort et al. 2021). This energy is harnessed by circulating water through hot rocks to capture heat energy and bring it to the surface. It is continually regenerating and considered virtually inexhaustible, but for too long has been limited to low-temperature rocks in only a few areas of the world. Superhot rock geothermal energy (SHR) is a new form of geothermal that leverages next-generation geothermal technologies in very hot rocks (374°C or above). With innovation, SHR could have the potential to provide long-term, scalable, renewable baseload power in many more places around the world at a scale and cost equivalent to fossil fuels. However, SHR energy is still developing, and more work is needed to help it reach its full potential at a cost that is competitive with mature energy technologies.

To better understand what's needed to make SHR successful at a commercial scale, Clean Air Task Force commissioned a collection of flagship gap analysis reports from independent international experts. Each report dives into a distinct technology essential for the success of end-to-end superhot rock geothermal projects: drilling, heat extraction, well construction and design, power production, and site characterization. The primary goal of these reports is to evaluate the state of the technology, pinpoint remaining technological gaps, and identify where future research, development, and testing efforts should be concentrated. By doing so, these reports aim to ensure that no critical areas are neglected and to define a clear path forward for each segment of the technology. This report serves as a summary of each flagship report. Each section reviews a category of technologies—drilling, well construction, heat extraction, power production, and siting—for accessing superhot rock geothermal, identifies existing technology gaps within each of these technology areas, and suggests strategies to overcome the technology gaps identified.

The *Bridging the Gaps* reports illuminate two key insights. First, **the technology to enable SHR energy is within reach,** and targeted investments could rapidly accelerate its development. Second, ***the most pressing need is for facilities***—both laboratories and field sites—where equipment and methods can be tested under SHR conditions.

Key Findings: Drilling

To bring superhot geothermal energy to a global scale, boreholes must be drilled into deep (often more than 10 kilometers) and extremely hot (above 374°C) hard, dense bedrock under high pressures (often reaching 40 MPa). Much of the necessary technology to drill in these extreme conditions already exists, thanks to progress in next-generation geothermal and unconventional oil and gas extraction. However, significant innovations are needed to extend deeper, de-risk, and scale up SHR geothermal—specifically innovations that improve rates of penetration and allow downhole drilling tools to operate in ultra-high temperatures. Advancements in drilling rigs, drill bit technology, downhole sensors, and temperature management equipment are essential. Recent improvements in rates of penetration into hard rock and the development of insulated drill pipe demonstrate that the technoeconomic challenges of deep drilling for superhot geothermal are surmountable. ***The primary challenge is the lack of testing in SHR conditions*** (in labs or the field). Thus, further innovation, collaboration, laboratory experimentation, and field testing are crucial for drilling in superhot environments.

Key Findings: Well Design and Construction

Well construction has been the most common point of failure for drilling programs in SHR conditions due to unique challenges posed by high temperatures and pressures, temperature variation, and corrosive hydrothermal environments. Existing equipment and operations from conventional geothermal wells will need to be modified for dry SHR applications. New thermohydraulic modeling tools will need to be developed and validated to account for fluid conditions in SHR wells. Temperature-dependent changes to the material properties of cements, cement alternatives, and cement additives will need to be quantified. The existing casing/liner metallurgies will exhibit changes in mechanical properties following long-term exposures to such high temperatures. This must be accounted for in well design and will require modifications to material selections, modification of existing materials, and identification of newer innovative metallurgies. Well connections experience particularly high stress and are common failure points in conventional geothermal wells, and

impact of material changes must be incorporated into connection designs. ***Facilities designed for small- and full-scale materials testing in SHR conditions should be a priority***, combined with field testing for early demonstration wells.

Key Findings: Heat Extraction

Using injected water to extract heat from superheated rocks, either through fracture enhancement or the creation of closed-loop systems, may be the least mature technological aspect of SHR energy—so significant investments in basic science and technology development will be needed. Existing tools, used in oil and gas and conventional geothermal exploration and production for permeability creation, will need to be adapted for functionality in superhot conditions. Most geothermal projects have been situated and designed to operate at or below 350°C, below the superhot threshold, limiting our knowledge of rock properties in these conditions. In many places in the world, to reach superhot conditions, drilling into the brittle-ductile transition zone (BDTZ)—a layer of the subsurface rock that transitions from brittle rock mechanical properties to properties more plastic in nature—may occur as supercritical temperatures are approached. This means that tools and models will need to be adapted to predict, create, and maintain fractures and borehole pathways in the BDTZ. Moreover, the risks of induced seismicity in the BDTZ are unclear, and more study is required. Better understanding both fracture behavior and seismic risk will require updated models and establishing laboratory and field facilities to test those models. ***Field testing, including in deep non-magmatic reservoir settings, will be critical for improving models, testing tools and hypotheses, and iterating on laboratory-based improvements.***

Key Findings: Power Production

Most of the components needed for a SHR power plant already exist, but an end-to-end SHR power plant is not yet commercially available. Targeted investments in turbine design and associated components could make the fully integrated system suitable for commercial deployment in the near term. The greatest potential for future work in this area lies in R&D aimed at reducing the cost of power plant systems and increasing the longevity of equipment in harsh geochemical environments. ***Thus, recommendations for future R&D include developing lower-cost alternatives to materials that are currently necessary for optimal power plant design and standardizing turbine design for power production from SHR geothermal conditions.***

In all, the findings from the *Bridging the Gaps* reports seek to ensure no technological gaps are left unaddressed and provide key insights for stakeholders to inform and enable strategic decision-making. Furthermore, the reports are designed to guide public and private investment priorities and build momentum for geothermal innovation in SHR geothermal conditions.

Key Findings: Siting and Characterization

Many geophysical methods for SHR exploration are ready to use, but they haven't been thoroughly tested in SHR-specific environments. With approximately two dozen wells reaching supercritical conditions and a limited number of SHR projects conducted to date, there isn't enough existing data to draw strong connections between geophysical signals (like seismic velocity or electrical conductivity) and rock conditions such as temperature, stress, or permeability in superhot rock environments. This lack of data is especially challenging for emerging approaches like machine learning, which could standardize the site selection methods and improve how we analyze and predict subsurface conditions, but require extensive datasets to be effective. To bridge this gap, more real-world testing and lab experiments are needed to better link what we can measure with the conditions we aim to understand. To address this, more **field-validated datasets and laboratory experiments** are needed to establish stronger links between observable data and target conditions.

1. INTRODUCTION

Geothermal energy can offer an inexhaustible, always-available source of clean energy. However, 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 the Earth's surface (e.g., volcanic areas or areas where the crust is thin, such as the U.S. Great Basin or East Africa). Next-generation geothermal technologies like enhanced (or engineered) geothermal systems (EGS) and closed-loop geothermal systems (CLGS) or AGS), aim to make geothermal possible nearly anywhere (Hill 2023). These technologies, when pushed to high-temperature conditions (i.e., superhot rock geothermal), could significantly boost power potential and reduce costs, enabling geothermal energy to compete with fossil fuels (Clean Air Task Force 2023).

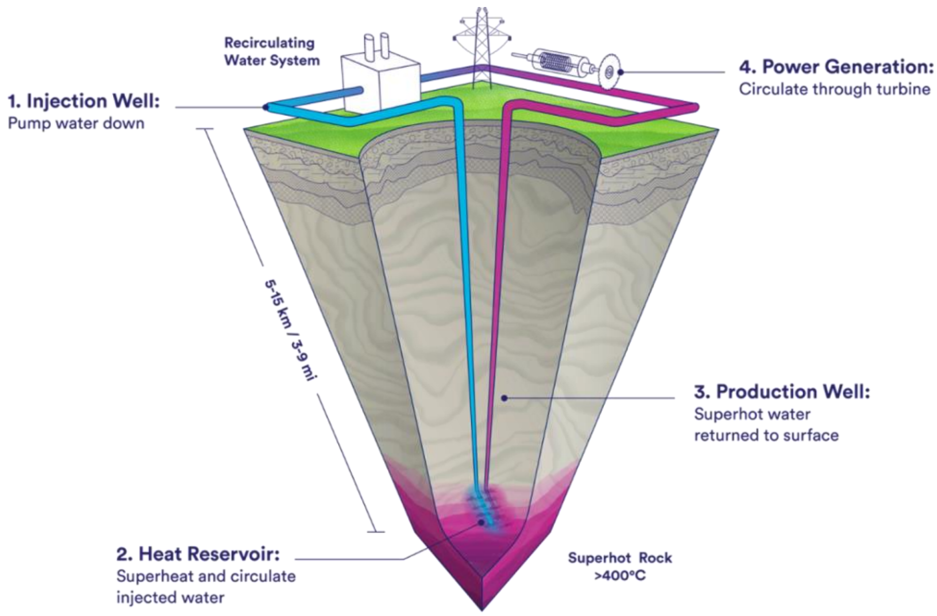

Figure 1: Diagram of a superhot rock geothermal system. Diagram is not to scale.

Superhot rock geothermal energy (SHR) works by circulating water in rock that is heated to 374°C or hotter. When returned to the surface, this water can be used in industrial processes or to power a generator and produce electricity. The 374°C threshold marks the minimum temperature at which water can become superhot and experience a step-change in enthalpy (i.e., its capacity to carry heat energy). This step-change means that SHR power plants will produce significantly more energy per well compared to geothermal energy extracted from lower temperatures, which will simultaneously reduce the capital costs associated with drilling new wells and increase the efficiency of energy production within electricity production equipment.

Next-generation geothermal applications are already harnessing heat from dry rock conditions today, demonstrating the ready potential of this technology. However, the current fleet of commercial projects operates in lower temperatures to leverage off-the-shelf equipment and practices originally developed for oil and gas drilling operations. These efforts are important, and further demonstration of these innovations is fundamental to the liftoff of the geothermal industry. However, operations in these mid-temperature conditions are expected to struggle to compete on cost in unsubsidized electricity markets – the fastest growing electricity markets in the world. We must continue to drive innovation on SHR geothermal energy to enable clean, energy-dense power at a cost point that is competitive in quickly developing markets and at a pace that matters for mitigating climate change.

Reaching superhot temperatures is dependent on not just temperature, but also other variables including water content and pressure. To allow for some flexibility, "superhot" is generally defined as temperatures starting at 374°C, though informal definitions may vary. The authors of the *Bridging the Gaps* reports conducted feasibility analyses on temperatures in the 400°C to 450°C range. Accordingly, labs and test facilities should not aim to address the bare minimum viable superhot temperature (>374°C) but instead provide a buffer of temperature; Clean Air Task Force (CATF) typically advocates for work that targets at least 400°C and above.

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 resources have yet to be harnessed for power production, their high energy potential is widely recognized. Modeling from 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 conventional geothermal well today (Friðleifsson et al. 2017). Models also suggest that if this substantial amount of energy can be produced in dry rock at reasonable development costs, SHR could be competitive with today's natural gas plants at $20-35 per megawatt hour (MWh) (Clean Air Task Force 2023).

Unlocking the full potential of SHR will depend on engineering advancements, such as faster ultradeep drilling techniques, heat-resistant well materials and tools, and the development of deep heat reservoirs in hot dry rock. Equally important are opportunities for testing and iteration to refine these innovations. **The focus, however, is on engineering improvements, not waiting for new scientific breakthroughs.** Broadly, the *Bridging the Gaps* report series finds that SHR energy is within grasp—if the world chooses to reach for it.

Intensive drilling campaigns are a key mechanism to drive rapid learning, overcome engineering obstacles, and continue reducing costs. These campaigns can be undertaken by geothermal companies or consortia, working together with oil and gas companies that are familiar with traditional subsurface energy resources, incorporating innovations from unconventional oil and gas and next-generation geothermal experience. Investors and energy buyers can also speed up the deployment of SHR by investing in early-stage technology development and providing power purchase commitments. Furthermore, government agencies like the Department of Energy and national labs can take on risk, catalyze R&D, establish best practices, enable collaboration, and ultimately catalyze new low-carbon markets through this inexhaustible source of low-cost energy. SHR energy has the potential to build from the existing fossil fuel workforce, infrastructure, and supply chains, which could help to ensure a just transition for energy communities and a rapid scale-up of clean energy once the technology is commercially viable.

Commercializing SHR will require both public and private investment, along with continued technological innovation. End-to-end demonstration and commercialization of SHR energy will require technological advancements across five key areas: site selection, drilling, well construction, heat extraction, and power production. To advance research on these crucial topics, CATF produced the *Bridging the Gaps* report series: reports across each topic area laying out the technological advancements necessary to bring SHR energy to commercial scale. Four of these reports have been published; the site selection report is forthcoming. All will be updated regularly as the state of the technology develops.

1.1 Key global projects

More than two dozen wells have been drilled into superheated conditions around the world (Clean Air Task Force n.d.). These wells have been drilled into hot rocks and geothermal systems that are below or within existing conventional geothermal fields (i.e., locations where heated water naturally exists in the subsurface). By comparison, SHR energy production can circulate water from aboveground and is not limited to locations where water already exists in the subsurface; these conditions are known as "dry rock" And represent next generation heat extraction techniques at higher temperatures. Producing in dry rock conditions is necessary to unlock SHR's full potential.

Hydrothermal systems are typically found at depths of around 3-7 km. While SHR conditions are more ubiquitously found deeper than 10 km worldwide, they can be accessed at depths as shallow as 2 km (Clean Air Task Force n.d.). Although power has yet to be produced from any SHR well in dry rock conditions, due to technological gaps explored in this report, these projects and others in and around hydrothermal fields have provided important learnings and continue to inform the innovations needed to move the commercialization of SHR energy forward.

One such project is the **Japan Beyond-Brittle Project**. Researchers based in Japan have drilled into temperatures above 500°C at a depth of 3.7 km, where the project encountered the brittle-ductile transition zone (BDTZ). How to fracture rock and hold open fractures in the brittle-ductile zone is an area that deserves extensive research. Japan's SHR research continues at Tohoku University and focuses on reservoir development in superhot conditions as well as identifying strategies for minimizing the risk of induced seismicity (Reinsch et al. 2017).

The **Iceland Deep-Drilling Project** is a drilling initiative that has reached superhot conditions in two wells in Iceland. The first well (completed in 2009 near a power plant in Krafla) was terminated when it encountered magma, but it provided an important demonstration of the energy potential of superhot wells. The second well (completed on Reykjanes Peninsula) reached temperatures of 426°C in 2017, but flow was not tested due to a casing failure (Kruszewski and Wittig 2018). A third drilling project in Iceland intended to reach superhot temperatures is likely to occur in the Hengill region of Iceland and is in its early stages of planning (Reinsch et al. 2017).

Italy's DESCRAMBLE project at the Larderello geothermal field drilled the Venelle-2 well, the hottest geothermal well on record, registering 514°C at 2.9 km deep. It made considerable advancements in downhole sensing equipment, but the project stopped when it was discovered that Venelle-2 did not access the targeted hydrothermal resource. The well was shut-in as a dry, unproductive well (Reinsch et al. 2017).

GEMex, in Mexico, is an EU-supported program focused on hot dry rock/enhanced geothermal 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 there in the future (Reinsch et al. 2017).

The **Geothermal: The Next Generation project led by GNS Science 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 superhot rock. Like the Japan Supercritical Geothermal Project, the project hopes to investigate potential systems in the BDTZ (Reinsch et al. 2017).

In the United States, several next-generation geothermal pilot sites have considerably advanced the research frontier of well construction in hot, hard rock—some in superhot conditions. They have progressed R&D on vertical, tangential, and horizontal well construction and completion in hot, crystalline rock, laying the foundation for continued research for SHR geothermal projects. The wells drilled at the

U.S. Department of Energy (DOE)-funded Utah FORGE project have been instrumental in improving conventional drilling technologies for drilling into high-temperature impermeable rocks up to 240°C. The objective for Utah FORGE is to push the frontier on hard-rock drilling and reservoir creation for next-generation geothermal projects (Moore et al. 2019). While not specifically pursuing superhot rock conditions, their achievements are directly transferable to SHR energy projects. Elsewhere in Utah, Fervo Energy's work at its 400MW Cape Station project, where the company has drilled six horizontal wells at significant depths (Fervo 2023, Fervo 2024), is also providing learnings relevant to drilling superhot rock.

At **Newberry Volcano in Oregon,** SHR energy is also being explored. A pilot well was drilled to 3 km in 2008-2011 but the plan is to go deeper, hopefully reaching greater than 425°C at 4.9 km (Hill 2021). Newberry is the first publicly announced global project ready to demonstrate superhot energy production in dry rock that is not associated with an existing geothermal field (Hill 2021). In 2024, the DOE announced funding for an EGS pilot project at Newberry. DOE is also funding EGS pilot projects near an existing geothermal field in Sonoma County, California, and at the FORGE site in Utah (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Geothermal Technologies Office 2024).

See CATF's SHR map (https://www.catf.us/shr-map/) for more information on past and ongoing global projects (Clean Air Task Force n.d.).

1.2 Technology readiness levels

Each of the five reports in the *Bridging the Gaps* series—drilling, well construction, heat extraction, power production, and site selection (forthcoming)—considers the technology readiness level (TRL) of the physical components needed for SHR energy production. The lower the number on the TRL scale (1-9), the less prepared the component is for commercial use (Table 1). A 9, for example, means the system is proven in an operational environment. A 7 means a system prototype has been demonstrated in an operational environment. A 5-6 means the technology is validated or demonstrated in a relevant environment.

Table 1. Technology Readiness Level (TRL)

TRL Level	Meaning
1	Technology is in the basic research stage; transitioning from scientific research to applied research
2	Technology is in the applied research phase; analytical tools are developed for simulation
3	Technology is in the proof-of-concept validation stage; active R&D is initiated in analytical or lab studies
4	Technology prototype is validated in lab experiments; integration of other elements starting
5	Technology prototype is tested in a representative environment; system components integrated
6	System is validated or demonstrated in a relevant environment; engineering feasibility fully demonstrated
7	System prototype has been demonstrated in an operational environment; system is at or near scale of the operational system
8	System completed and mission qualified through tests and operational demonstrations; fully integrated hardware and software systems
9	System is mission proven/commercially ready; fully integrated and proven in an operational environment

Some technologies mentioned in the reports are already at a TRL 9—for example, the cooling condenser required for power production. Others, like direct energy drilling, are at a 2-3. The reports identify the TRLs for the most critical technologies needed to move SHR forward and note the steps needed to advance each technology to TRL 9. This work will culminate in the technology roadmap report (2025 release), which will map out measurable steps to closing the gaps discovered in these reports based on opinions collected from experts. More information can be found on the Superhot Rock Technology Gaps poster on CATF's Bridging the Gaps page (Clean Air Task Force 2024).

2. BRIDGING THE GAPS: DRILLING[1]

The frontier of drilling in superhot geothermal environments is steadily advancing. Recent achievements in polycrystalline diamond carbide (PDC) drill bit design, improved rates of penetration into hard rock, and the development of insulated drill pipe show that deep drilling for SHR geothermal projects is on the not-distant horizon.

[1] This is a Clean Air Task Force and Cascade Institute summary of "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways for Superhot Rock Drilling" by Rebecca Pierce and Tony Pink (2024). https://www.catf.us/superhot-rock/bridging-gaps/.

SHR wells have been drilled in the past; however, the high temperatures, pressures, and depths needed to de-risk drilling and enable it in deeper locations pose significant technical challenges. Technology companies and laboratories must make rapid advances in specialized drilling rigs, bit technology, high-temperature downhole tools, and temperature management equipment to bring down this financial risk. Currently, these drilling systems—and the amount of time required to access deep, hard-rock formations—create significant project costs. To bring SHR to commercial viability, drilling technology companies and laboratories must rapidly develop, test, and deploy new technologies.

Conceptually, a drilling system needs to be able to:

- Drill into hot (>374°C), high-pressure geological domains
- Drill deep (often >10 km) into hard crystalline bedrock, as well as varying rock types
- Drill economically, reducing drilling time and therefore costs by an order of magnitude

Overall, SHR geothermal wells can be drilled by deploying a combination of existing technologies, and current technological challenges to SHR drilling are surmountable. The economic challenges are a function of limited availability and testing of these drilling systems, both of which will decrease as the SHR geothermal industry expands. A first-order gap for drilling is the lack of access to SHR conditions, both in-field and in controlled laboratory conditions. Without open-access experimental facilities and pilot sites, these technologies cannot undergo iterative improvements necessary to de-risk SHR drilling and propel the industry forward.

2.1 Key findings

Technology companies and laboratories must overcome two big-picture technology gaps to make SHR drilling and well construction technically and economically viable:

1. Improve rates of penetration when drilling into hard basement rock
2. Develop ultra-high-temperature electronic downhole tools and temperature management equipment

Although SHR wells have been drilled in the past, their unprecedented temperatures, pressures, and depths present significant technical and financial challenges. Technology companies and laboratories must make advancements in specialized drilling rigs, bit technology, downhole sensors, and temperature management equipment to drill quicker and cheaper—the key hurdle for scaling up and de-risking SHR systems. Recent progress in improving rates of penetration into hard rock and developing insulated drill pipe shows that the technoeconomic challenges of deep drilling for superhot geothermal are surmountable. However, further innovation, collaboration, laboratory experimentation, and field testing are crucial for drilling and constructing wells in superhot environments.

See Table 1 in the Appendix for a list of big-picture technology gaps.

The drilling technologies with the highest potential for innovation include drill bits, direct energy drilling systems, high-temperature downhole tools, insulated drill pipe, low-heat coefficient coatings, supercritical carbon dioxide drilling, drilling muds, mud coolers, and corrosion inhibition (see Table 2 in the Appendix). Surface rigs capable of delivering optimal flow rates and hoisting heavy drill strings will be essential. Current temperature management and rock-destruction technologies face challenges related to rig capacity, flow rates, and the distribution of power downhole. As wells reach greater depths, conventional rotary and hybrid drilling methods, along with surface equipment, will encounter growing difficulties from increased string weight, high frictional resistance, and excessively long trip times.

Much of the necessary technology already exists, thanks to progress in next-generation geothermal and unconventional oil and gas extraction. However, significant innovations are needed to de-risk and scale up SHR by drilling more quickly and cost effectively. Recent improvements in rates of penetration into hard rock and the development of insulated drill pipe demonstrate that the technoeconomic challenges of deep drilling for superhot geothermal are surmountable. However, further innovation, collaboration, laboratory experimentation, and field testing are crucial for drilling and constructing wells in superhot environments.

The unique drilling systems and long drilling timelines for accessing deep hard-rock formations incur exponential project costs. That’s where innovation will help. Getting there will require technological combinations and international collaboration among governments, academia, and industry.

2.2 State of the technology

2.2.1 Rock-destroying techniques

Three drilling techniques are used to cut through rocks: conventional rotary drilling, hybrid conventional drilling, and direct energy drilling.

Conventional rotary drilling—PDC, roller cones, and hybrid PDC/roller cone systems—are the most mature type of drilling technology. Most conventional geothermal and enhanced geothermal wells have been drilled with these techniques.

Hybrid conventional drilling involves drilling with augmented waterjet, percussion, or particle impact drill bits. Hybrid conventional techniques specifically target the brittle state of basement crystalline rocks, unlike conventional techniques, which were developed for soft rock formations. Thus, there may be room for leaps in efficient hybrid drilling that supersede rotary methods.

Direct energy drilling uses plasma or millimeter wave (MMW) drilling techniques to weaken or vaporize rock at depth. Startups working on direct energy drilling are targeting depths greater than 15 km, which makes it an important technology to consider for regions where superhot temperatures are only found at those depths. However, direct energy drilling has the lowest technological maturity, as the techniques are not currently in practice. Advantages to direct energy drilling include minimal downhole equipment, few complications from high temperatures and pressures, and significantly less trip time than rotary or hybrid conventional techniques.

2.2.2 Temperature management techniques

A SHR drilling system must be designed to cool the drill string and the electronic components of the borehole assembly (e.g., drill bits, logging tools) to a temperature that all the equipment can survive. To access geothermal gradients sufficient for power generation, equipment will need to operate in temperatures from 374°C to 450°C or more. Currently, most downhole drilling tools—instruments and devices used in the wellbore to perform operations, gather data, and manage the drilling process—run at 175°C, with a few operating in the range of 200°C to 225°C; some drill fluids can reach 353°C. Models suggest that the drill string, downhole tools, annulus (the space between the borehole wall and the casing), and rock can be cooled down below 175°C with a combination of technologies, but the process is slow.

There are two temperature management options: cool the well and rock or increase the temperature threshold for well equipment. If drillers choose to cool the well and rock, then that lower well temperature will need to be maintained throughout drilling operations. If instead the choice is to increase the temperature threshold for the well equipment, maintaining a cooler well will not be necessary. A third option has more potential: a combination of cooling the well and rock and increasing the temperature threshold for well equipment.

2.3 Gaps, challenges, and future work

2.3.1 Gaps and challenges

Rock-Destroying Techniques

Conventional rotary drilling is the most mature technology for geothermal wells and offers the most potential for reaching deeper, hotter SHR zones in the short term. Drill bits can be specialized for extreme temperatures, interbedded formations, or extended bit life, but combinations of all of these features should be tested on drill bits in SHR conditions in various geodynamic settings. Conventional drilling has proven to be successful in SHR conditions in the past, but drill bit improvement can reduce technological risk, increase rates of penetration, and make conventional drilling more efficient for SHR as a whole. **TRL: 9.**

Hybrid conventional drilling systems, which incorporate percussive, waterjet, and particle impact methods, have shown potential for improved rates of penetration and bit longevity at high temperatures. However, they still face issues such as costly bit replacements, long trip times, excessive string weight at greater depths, and fluid losses in fractured rock. These challenges impact both rotary and hybrid drilling methods and require extensive field testing to validate their effectiveness in SHR environments. **TRL: 5-7** (7 for percussive, 5 for waterjet and particle drilling).

Direct energy drilling, such as millimeter wave (MMW) and plasma drilling, is the least mature technology. Key gaps include:

- Acquiring a high-powered (>1 MW) MMW beam for scale-up experiments
- Access to laboratory facilities with SHR conditions for experimentation
- Modeling the absorptive properties of heterogeneous rock
- Ruggedizing gyrotron equipment for field conditions
- Engineering waveguide deployment to cope with downhole conditions such as bends and temperature variations

Fluid management is another crucial factor, particularly for plasma drilling. Access to laboratory and field facilities for larger-scale experimentation is needed to test these challenges. **TRL: 2-4** (2-3 for MMW, 3-4 for plasma).

Ultra-High-Temperature Drilling Tools and Temperature Management

There are two temperature management options: cool the well and rock or increase the temperature threshold of downhole tools. The most promising approach is to combine both strategies. Downhole tools, such as those in the bottom hole assembly (stabilizers, reamers, shock tools, mud motors, and rotary steerable systems), Measurement While Drilling tools, Logging While Drilling tools, and other directional drilling tools operate at temperatures up to 175°C, with some capable of 200-225°C. SHR environments far exceed these limits, which means that temperature management techniques are also needed.

Temperature management options include:

- Low-heat coefficient coatings for drill pipes (**TRL: 6**)
- Insulated drill pipe (externally or internally coated, or vacuum-sealed) (**TRL: 7**)
- High-temperature drilling fluids with water-based additives (**TRL: 8-9** for low-angle holes, **TRL: 4-5** for high-angle/horizontal wells)
- Supercritical CO_2 (sCO_2) as a drilling fluid (**TRL: 3**)

- Mud coolers to lower surface mud temperatures (**TRL: 9**)

Currently, insulated drill pipe technology can maintain well temperatures below 175°C in 400°C SHR environments, but cost and weight remain major challenges. Similarly, titanium drill pipes, while effective at higher temperatures, are prohibitively expensive. Water-based fluids can sufficiently clean boreholes below 20 degrees inclination, but above this angle, further research into high-temperature additives is necessary, particularly for horizontal drilling.

Supercritical CO_2 has been proposed as a potential drilling fluid, but while the individual components of an sCO_2 system exist, integrating them into a fully functional package for field testing remains a challenge. **TRL: 3.**

Electronics and High-Temperature-Resistant Materials

High-temperature-resistant electronics, such as nonorganic seals or high-temperature capsules for tools, require significant improvements to endure SHR conditions. "One run" disposable tools could offer a cost-effective (but potentially wasteful) short-term solution. Engineering SHR-capable tools without cooling remains impractical with current technology.

See Table 2 in the Appendix for a detailed list of gaps.

2.3.2 Future R&D and testing

Rock-Destroying Techniques

Field and laboratory testing of rotary, hybrid, and direct energy drilling methods in SHR conditions are critical for closing the technology gap. Hybrid systems (percussive, waterjet, and particle drilling) should be scaled up from laboratory tests to field trials, particularly in environments that mimic the extreme conditions of SHR. Direct energy drilling technologies like MMW and plasma drilling require experimentation with high-powered beams, waveguide design, and fluid management to progress.

Field testing in various rock types is necessary to refine models and optimize drilling techniques for different geological conditions. This includes improving rates of penetration, managing specific energy, and addressing the unique challenges posed by supercritical conditions.

Ultra-High-Temperature Drilling Tools and Temperature Management

Further research and development are required to improve the performance and cost-effectiveness of insulated drill pipes and high-temperature drilling fluids in SHR wells. Collaboration between project owners and pipe manufacturers, supported by government grants or private investment, could accelerate the development of a complete insulated drill pipe system. Water-based additives for drilling fluids should be tailored to SHR conditions, addressing issues like borehole cooling, lubrication, and fluid losses. Systems need to be designed to handle both impermeable rock and highly fractured zones.

In addition to downhole tools, advancing real-time electronic tools for high-temperature environments is crucial. However, the immediate focus should be on refining temperature management techniques and combining them with the highest-rated electronic tools available today.

Laboratory and Field Testing

There is a lack of laboratory facilities capable of testing drilling technologies at temperatures exceeding 374°C. Following extensive experimentation in a controlled laboratory setting, high-temperature, SHR-rated drill bits should be deployed in active SHR or EGS projects for further optimization of deep, hot rock drilling. Without open-access experimental facilities and pilot sites, these technologies cannot undergo iterative improvements necessary to de-risk SHR drilling and advance the industry. Additionally, continued research in automated and AI-assisted drilling at these sites could yield insights into improving drilling efficiency, safety, and cost management.

2.4 Conclusions

SHR geothermal systems have the potential to provide long-term, scalable, renewable baseload power. Unlocking this potential requires significant innovation in drilling technologies to improve rates of penetration and develop high-temperature downhole tools and temperature management equipment.

Currently, rock-destroying equipment, high-temperature downhole tools, and temperature management equipment share three overarching challenges:

1. Lack of access to SHR in controlled, laboratory settings,
2. Lack of access to SHR in in-field settings, and
3. Lack of incentives for collaboration between major drilling firms.

Collaboration between the public and private research community can help overcome these overarching challenges by first identifying all facilities around the world capable of SHR experimentation (e.g., Utah FORGE, IDDP), then creating the necessary incentives for greater cooperation between major drilling companies and research groups, and finally ramping up experimentation and R&D in SHR conditions.

Across all drilling technology domains, one theme is clear: The technology to complete superhot or ultradeep geothermal boreholes and wells exists—but the overall cost and time on task to drill a deep, superhot geothermal well must be reduced for SHR to reach its full potential.

See *Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Drilling* for more (Pink and Pearce 2024).

3. BRIDGING THE GAPS: WELL DESIGN AND CONSTRUCTION[2]

Well construction has been the most common point of failure for past SHR demonstrations. Exceeding 374°C at depth brings unique challenges, as do temperature fluctuation, high pressures, and corrosive environments in wells. This section discusses challenges and technology gaps in the design and construction of SHR geothermal wells, with a focus on long-term integrity.

3.1 Key findings

Commercialized equipment for both oil and gas and hydrothermal wells can operate in environments as high as 300 to 350°C, but well-construction materials must be tweaked to withstand operation in superhot geothermal environments that may reach or exceed 450°C. Recent developments in cement and casing materials have made these materials more robust in these settings. However, challenges remain in constructing and operating SHR wells that can last more than 25 years, which is the lifetime needed to reflect a realistic geothermal power plant). **Deep, long exposure times to high temperatures and extreme temperature swings in the wells, high downhole pressures, and corrosivity pose the most significant challenges** to well design, construction, and longevity. Past projects that reached superhot and supercritical conditions in Greece, Iceland, Italy, Japan, Kenya, Mexico, and the U.S., all experienced failure in well construction that led to project halt and the inability to move further into project operation (Kruszewski and Wittig 2018).

Current thermohydraulic modeling tools are inadequate for handling water flows at extreme temperatures. Thus, the development and validation of new models to understand and predict fluid behavior in these conditions is important. In addition, a better understanding of material property changes and degradation under long-term exposure to high temperatures, particularly in carbon and other alloy systems, is needed. This includes a better characterization of microstructural changes, creep and creep-like behavior (slow material deformation), multiaxial fatigue under high temperatures and pressures, and the effects of >450°C temperatures on well-construction loads, cement integrity, cement additives, and connection designs. The development of stimulation equipment for directional control, zonal isolation, and perforation for multistage hydraulic fracturing also needs more aggressive R&D. Proper well design, construction, and completion will remain a challenge until these material properties are adequately characterized, and until new stimulation fluids, proppants, and diverters for SHR temperatures are developed and tested. Testing of alternative techniques to enhance well connectivity through fractures, repurposing underbalanced drilling techniques, and improving methods for long-term flow assurance will also be useful.

To address these challenges, specialized facilities and programs should be established to conduct both small- and full-scale laboratory testing of well construction and completion. These programs should focus on characterizing and testing current commercial casing and cementing materials, developing new materials where needed, making modifications to design methodologies that account for behavior beyond its elastic limit, testing connection designs, and developing operational protocols that can ensure well integrity under SHR conditions. Additionally, developing and validating high-temperature modeling tools that integrate geochemistry and thermal shock modeling for fracture creation and flow assurance will be particularly useful when predicting the heat extraction efficiency from an engineered geothermal system. Knowledge-sharing opportunities around connection design should also be pursued while maintaining intellectual property protections. Ultimately, full-scale and field testing will be required to validate these materials and designs in realistic SHR environments.

3.2 State of the technology

Effective well design and construction are critical because well failure prevents both the exploration and extraction of geothermal heat. ***Without a properly functioning well, the resource cannot be accessed, analyzed, or utilized.*** Several earlier attempts to access superhot resources saw rapid well material failure that ended the projects. Current high-temperature geothermal technologies will need to be altered for use in superhot systems. Key elements to consider are tubulars (including casings and liners) and connections, all of which will experience large thermal loads over an extended period and thermal swings. Connections undergo the greatest thermal strain and are the most common failure point in existing thermal wells. Cements and cement alternatives that are durable in superhot, supercritical, corrosive environments are equally important for a well's longevity.

A successful superhot geothermal system will need to use a combination of three approaches to well design—low cycle fatigue (LCF), working stress (WS), and reliability based (RB) design—to withstand the challenging heat, pressure, and geochemical conditions. Each

[2] This is a Clean Air Task Force summary of "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways for Superhot Rock Well Design and Construction" by P. V. (Suri) Suryanarayana and Ravi M. Krishnamurthy (2024). https://www.catf.us/superhot-rock/bridging-gaps/.

of these approaches has been used by the geothermal and oil and gas industry, so operators have a good understanding of their strengths and weaknesses. The SHR wells will need to incorporate material changes from extended exposure to high temperature into the designs.

A key design consideration is whether there will be separate wells for injection and production, or whether a well will serve both purposes. If a system uses dedicated injector and production wells, the design constraints are less restrictive; high-strength tubulars may be used in the injectors, and ductile grades can be used in producers. But if wells for injection and production are combined, there will be a depth at which design requirements will transition from LCF to WS or RB design. Because pressures and temperatures generally increase with depth, the deeper that transition from LCF to WS or RB design, the more feasible the well design. A key goal is to optimize well construction by creating this transition at the deepest point possible, as explored in the well design and construction report (Suryanarayana et al. 2024).

An extreme temperature gradient (from 20°C to 30°C at the surface to 450°C at depth) poses a fundamental design challenge for SHR wells, particularly for casing materials and cements, as they are exposed directly to that gradient. Many materials have not been tested or designed to perform in such conditions.

Tubular casings and liners are made of carbon steel alloys (such as K55, L80, T95, P110, and Q125) graded to perform in different temperature and pressure conditions, with tradeoffs between strength and ductility. There are other stainless steel, nickel, and titanium alloy options; however, the impact of extended exposure to these temperatures must be characterized. Cements used in existing thermal energy projects include Portland cement, which has a theoretical temperature limit of 390°C, and other calcium aluminate blends. Cements are commonly mixed with additives that aid in installation and improve the material's performance.

3.3 Gaps, challenges, and future work

Constructing geothermal wells in SHR conditions is challenging primarily because of high pressures, corrosive fluids, and extreme temperature gradients and swings during hot-cold cycles.

3.3.1 Casing and tubular materials

Gaps and Challenges

Casing materials in SHR wells face long-term degradation due to high temperatures (350°C to 500°C), causing microstructural changes that reduce tensile strength, ductility, and toughness. Common materials like K55, L80, and T95 have historically failed in superhot conditions. Low-carbon steels may exhibit creep (slow deformation) at temperatures from 435°C to 700°C. The extent of these changes remains insufficiently characterized across different alloy types, and there is limited understanding of how steels and corrosion-resistant alloys respond to prolonged exposure to extreme temperatures. This lack of data makes it challenging to select appropriate materials that minimize the risk of casing failure. **TRL: 4-6**.

Future R&D and Testing

To address the issues associated with long-term degradation of casing materials, alternative materials like stainless steel, nickel-based alloys, and titanium alloys must be tested for strength, ductility, and corrosion resistance at temperatures up to 450°C. Laboratory studies should investigate creep behavior and microstructural changes at these high temperatures. Fatigue experiments on tubulars and connections (see Section IV.C.2) will validate models to inform material choices. Full-scale testing combined with finite element modeling is essential to optimize material selection and ensure post-yield design meets the demands of high-temperature operations. ***Well design should favor ductility over strength*** to ensure long-term well integrity, particularly in regions exposed to significant thermal stress.

3.3.2 Casing connections

Gaps and Challenges

Casing connections are often the weakest link in geothermal well systems, subjected to extreme temperature changes and high rates of strain and fatigue from cyclic loading. Testing of thermal service connections has been limited to 350°C. Multiaxial fatigue under high-temperature and pressure conditions remains poorly understood, further complicating the design of reliable connections. Without a comprehensive understanding of how material properties change with temperature, designing robust connections for SHR environments is challenging. **TRL: 6**.

Future R&D and Testing

Testing of thermal service connections must expand to at least 450°C, with cyclic loading and small-scale laboratory testing to characterize microstructural changes in commonly used carbon steel tubulars (e.g., K55, L80, T95) and alternative materials like stainless steel and nickel alloys. Creep behavior and material degradation must also be studied, and connection designs should be revised to reflect the temperature-induced changes. A study of connection strain localization factors is needed, but proprietary concerns regarding connection geometry may hinder information sharing. Solutions to protect intellectual property while advancing research for casing connections should be explored.

3.3.3 Cements and Cement Alternatives

Gaps and Challenges

Cements in SHR wells must withstand extreme thermal swings and high pressures while being exposed to corrosive fluids. Common cements, such as Portland cement (effective up to 390°C) and calcium aluminate blends (tested up to 540°C), have not been adequately tested under superhot conditions. Additionally, cement additives critical to enhancing ductility and preventing lost circulation have not been tested beyond 400°C. The long-term integrity of cement under cyclic thermal loading remains unknown, and failure in cementing operations can lead to gas or liquid migration, posing significant risks to well integrity. **TRL: 6**.

Future R&D and Testing

Laboratory and field testing are essential to assess cement integrity under cyclic loading and corrosive environments. Testing Portland and calcium aluminate cements in SHR environments for longer periods of time will help establish their operational limits. Cement additives, such as retardants and dispersants, must be evaluated for high-temperature performance, and new materials may need to be developed for extreme conditions. Cement modeling tools should be refined for accuracy in SHR environments, and innovative approaches for placing cement along long well segments must be tested to minimize the risk of buckling or other failures.

3.3.4 Flow Assurance and Fluid-Rock Modeling

Gaps and Challenges

Fluids in SHR conditions pose greater risks to equipment (e.g., corrosion, scaling, and mineral precipitation) compared to fluids present in lower-temperature systems. Geochemical compositions vary; thus, the potential for these fluids to negatively affect well materials and flow remains insufficiently understood. The presence of highly corrosive fluids may require the use of corrosion-resistant materials, and proper flow assurance strategies must be integrated into the overall well design to address these challenges.

Fluid-rock behavior and interactions under high-temperature and pressure conditions are not well understood and require more study through fluid-rock modeling. **TRL: 2-4**.

Future R&D and Testing

Water chemistry data from previously drilled SHR wells should be analyzed to inform thermodynamic models that indicate possible corrosion, scaling, and mineral precipitation behaviors. Commercially available corrosion and scaling models must be tested under SHR conditions to assess their effectiveness. New devices to monitor water chemistry in the field, under extreme conditions, will be necessary for real-time data collection and system optimization. This may not be a concern for closed-loop systems.

Additionally, new thermohydraulic modeling tools need to be developed for SHR conditions and validated through both laboratory and field tests. High-temperature rock-fluid interaction experiments should be conducted using core samples from SHR reservoirs. These studies will help refine models of fluid-rock interactions and ensure that wells maintain integrity and efficient flow over time. Core retrieval from SHR boreholes will also help in facilitating a better understanding of fluid-rock interaction in SHR conditions.

3.3.5 Overall Design and Construction

Gaps and Challenges

SHR well designs face numerous challenges, including the need to account for material degradation, multiaxial fatigue, and connection failures due to extreme temperature swings and high pressures. Materials like stainless steel, nickel alloys, and titanium may provide the necessary corrosion resistance with adequate testing, but current design approaches do not sufficiently address the complex demands of SHR wells.

Future R&D and Testing

Existing well construction methods should be modified to minimize thermal stress and improve long-term well integrity. New operational protocols and design solutions must be developed to reduce the temperature swings that wells experience during injection and production. Design that adequately flattens the temperature gradient response in the well design will be important in helping reduce thermal stress and minimizing the potential for material fatigue. Advanced modeling and testing programs are necessary to verify the effectiveness of new designs, particularly for managing high-temperature multiaxial fatigue. **TRL: 2-6**

3.3.6 Well Completion

Gaps and Challenges

High-temperature stimulation tools are lacking for SHR wells, which hampers the ability to enhance well productivity through multistage hydraulic fracturing. Equipment like directional control tools, zonal isolation plugs, sliding sleeves, and perforation techniques are not yet developed to withstand SHR temperatures. Ensuring long-term well connectivity through fractures, while maintaining flow assurance and minimizing proppant erosion, remains a significant challenge, particularly given the 20- to 30-year lifespan required for geothermal operations. **TRL: 4-6**.

Future R&D and Testing

Research should focus on advancing reliable, high-temperature stimulation tools for SHR conditions. Laboratory and field testing of new materials like stimulation fluids, proppants, and diverters that can withstand supercritical conditions will be necessary to ensure their viability. Improved fracture characterization techniques and hydraulic fracturing models must be developed and validated in field conditions. Industry collaboration with research institutions will be crucial in driving the development of effective well completion technologies for SHR geothermal systems. See more information in the Heat Extraction section (Section V) of this report.

See Table 3 in the Appendix for a detailed list of gaps.

Overall, while labs around the world have the capability to perform some of the testing required for SHR well design and construction, more access to laboratory and field-based facilities for validation and long-term testing of well equipment needs to be developed.

3.4 Conclusions

SHR systems will exceed 374°C at depth, higher than temperatures typically encountered in oil and gas and geothermal projects. Exceeding this threshold brings unique challenges, primarily around significant temperature variation, high pressures, and corrosive environments. Materials for well casings and liners, tubulars, connections, and cements have typically not been designed for these conditions, so a range of laboratory and field-based tests will be necessary to define material behaviors and requirements. Cements and connections are of particular importance, as they have been demonstrated as the most likely failure points leading to well shutdown in various geothermal projects to date.

See *Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Well Design and Construction* for more (Suryanarayana et al. 2024).

4. BRIDGING THE GAPS: HEAT EXTRACTION[3]

Extracting heat from SHR reservoirs—whether through fractured or closed-loop systems—remains one of the most underdeveloped aspects of superhot geothermal energy production.

This section reviews existing knowledge, approaches, and technologies related to heat extraction. It identifies knowledge and technology gaps that will require research and development, as well as opportunities where public and private investment is necessary.

4.1 Key findings

Knowledge and tools from oil and gas and existing geothermal systems are directly applicable to permeability creation, but the relevant equipment and operations have limited ability to perform in these high-temperature, corrosive environments. Lab- and field-based R&D of reservoir stimulation equipment will be needed for fracture creation. New models and analog reservoirs are also needed, especially to constrain fracture and fluid dynamics and induced seismicity risks. In parallel, closed-loop systems, which do not rely on permeability, will require advancements in well-construction materials and heat transfer mechanisms to ensure efficient operation in SHR conditions.[4]

One crucial need for fractured systems is SHR reservoir stimulation equipment—including diverters, proppants, tracers, and packers—that allows for multistage fracturing in superhot rock and ensures reservoir longevity. Diverters direct fluid during the fracture process; proppants keep fractures open; tracers are added to injected fluid to track fluid pathways; and packers are downhole equipment used to isolate targeted sections of borehole. Most of these tools and materials were designed with maximum operational temperatures between 200°C and 350°C. Therefore, tool upgrades and lab and field testing of materials will be needed to identify suitable alternatives.

In addition to fracture-based approaches, closed-loop geothermal technologies offer another promising pathway for SHR energy extraction. Unlike fracture creation, these systems do not rely on permeability but instead focus on well construction materials to facilitate efficient heat transfer. A key challenge in closed-loop systems is developing alternative cements that offer superior heat transfer and long-term structural integrity, particularly under SHR conditions. Field and laboratory testing of new materials, fluids, and well completion methods will be necessary to ensure the durability and efficiency of closed-loop systems in superhot environments. More information on well construction is in the Well Construction and Design section (Section IV) of this report.

To reach superhot geothermal conditions in many places of the world, drillers may need to access the brittle-ductile transition zone (BDTZ). In this zone, rock is more ductile than shallower crustal rock and thus responds differently to outside forces. Testing in analog reservoirs, both in the laboratory and in the field, will be needed to validate and constrain stress, strain, and resource decline

[3] This is a Clean Air Task Force summary of "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways for Superhot Rock Heat Extraction" by Trenton T. Cladouhos and Owen A. Callahan (2024). https://www.catf.us/superhot-rock/bridging-gaps/.

[4] Information on closed-loop systems in this section came from closed-loop experts after the first version of the full heat extraction report was published.

assumptions for modeling in the BDTZ. While some rock mechanics testing apparatuses work up to about 800°C, these capabilities are rare and access to 800°C testing facilities needs to be expanded. (See Table 4 for an overview of the gaps and steps needed.)

Additionally, truly making geothermal scalable beyond magmatic regions will require deeper field analogs in midcontinent locations to test conceptual models. Data are needed to better understand the impacts of the BDTZ and supercritical fluids on fracture propagation, arrangement, and longevity, including the potential for induced seismicity. These data will contribute to improved models of reservoirs and fracturing in SHR conditions, which current oil and gas models do not accurately represent. Finally, laboratory experiments on how metal alloys and other materials respond to temperatures above 350°C, coupled with field demonstrations and validation, will be needed to address the potential for well failure in superhot conditions. Field testing will allow for analog reservoirs to be used to improve models, test tools, test hypotheses, and iterate on laboratory improvements.

4.2 State of the technology

4.2.1 Relevant ongoing work in hot dry rock

Several EGS pilot projects have been pursued worldwide, but only a few are operational and producing power today. All currently operational EGS projects were created in rock at or below 200°C. The hottest dry rock attempt to date, which occurred at Newberry Volcano in Oregon, had a maximum temperature of 320°C (Cladouhos et al. 2018). Several dozen wells have encountered temperatures above 374°C—the critical point of water. However, those wells were challenged by the superhot environments and could not extract heat from the heat reservoir.

To achieve global access to SHR through EGS, permeability creation must be possible in diverse lithologies. Previously, volcanic formations have been geothermal targets, but reservoir stimulation and modeling should include other high-temperature crystalline formations that more accurately reflect Earth's surface at large. The native fluids encountered in superhot environments have also been diverse (e.g., with high salinity and varying dissolved elements and gases) and dynamic, introducing more complexity. In some cases, high temperatures and pressures in superhot environments may mean that the BDTZ is encountered. In this zone, rocks become more ductile, creating more complications with permeability creation. For wells that have reached this transition zone, diminished fracturing, reduced permeability, and higher temperatures have been documented.

4.2.2 Approaches to permeability creation

Four main approaches to heat extraction include closed-loop systems (which do not create fractures), shear stimulation, hybrid fracture networks, and planar hydraulic fracturing. The type of stimulation used in EGS depends on the geologic setting, the temperature limits of tools and materials, and whether a new well will be drilled or an existing well will be repurposed. These techniques were designed for lower temperatures and will need to be adapted for SHR conditions. Oil- and gas-inspired hydraulic fracturing approaches may eventually be extended to superhot rock. However, currently available off-the-shelf equipment is not adequate, and relying on drilling longer laterals to increase flow rate and stimulate more stages will increase the system cost with diminishing returns.

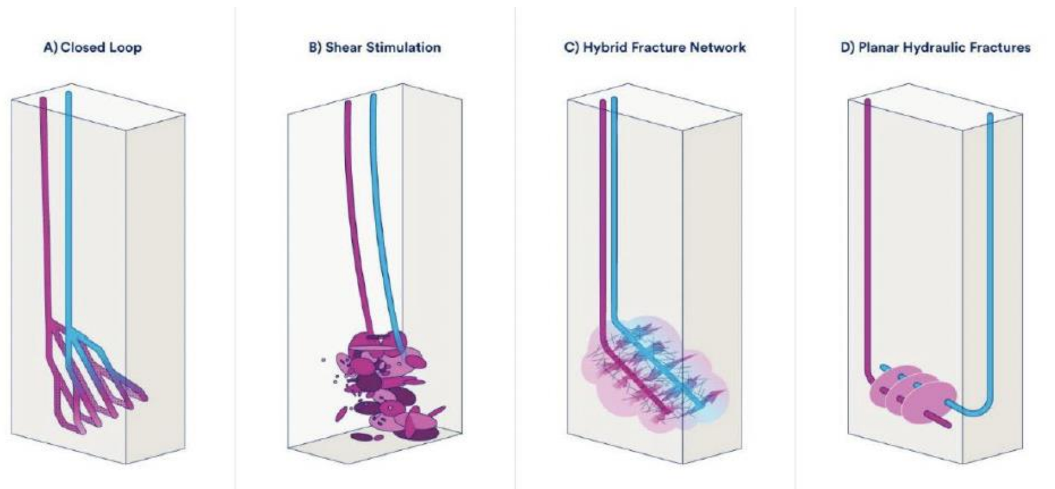

Figure 2: Approaches to permeability creation

Fundamentally, enhanced geothermal comprises injection and production wells, and mining heat from the hot rock between injection and production wells by circulating fluids through them. A closed-loop system (a) does not change permeability, and some may not consider this engineered or enhanced; the others (b-d) change permeability using an engineered fracture network.

4.3 Gaps, challenges, and future work

Because technology has, to date, limited the exploration of the SHR zone in the ground as well as in the lab, critical knowledge gaps exist in almost every aspect of the heat extraction process.

One of the most important unknowns is potential fracture size in superhot geothermal reservoirs. Hydraulic stimulations have not been performed at high or moderate pressures in SHR. Therefore, uncertainty surrounds the geomechanics of rocks near the BDTZ and impact of supercritical fluids on fractures.

See Table 4 in the Appendix for a detailed list of gaps.

4.3.1 Reservoir stimulation equipment

Gaps and Challenges

Low permeability has been found in rocks drilled into deep (>3 km) wells outside of traditional hydrothermal fields, suggesting natural permeability alone may not allow for heat extraction in many deep environments. Existing equipment for oil and gas fracturing will not generally work in these superhot environments, so reservoir stimulation equipment—including diverters, proppants, tracers, and packers—will need to be adapted to allow for multistage fracturing in SHR and ensure reservoir longevity.

Hydraulic stimulations have not been performed at high or moderate pressures in superhot rock, so the geomechanics of rocks near the BDTZ, thermal cracking, and the effects of supercritical fluid properties on SHR heat extraction have not been field tested. Maximum fracture length induced by stimulations in SHR enhanced geothermal represents a critical knowledge gap due to the impact of supercritical fluid, brittle-ductile transition, thermal fracturing, and intragranular fracturing. Most existing tools and materials were designed with maximum operational temperatures between 200 and 350°C; tool upgrades and lab and field testing of materials will be needed to identify suitable alternatives. **TRL: 4-6**.

Future R&D and Testing

Researching and developing fluids, proppants, and tools for fracture creation, as well as those for enhancing and maintaining flow within fractures in superhot conditions, will need to include:

- Proppant placement and chemical, thermal, and mechanical durability
- Nontoxic additives to enhance flow rates
- Tracer fluids
- Predicting how fracture permeability will change with time

If superhot durable proppants cannot be developed, alternative propping mechanisms will need to be developed. Examples include high-density fluids, hydropropping, and chemical treatments.

Testing of a complete SHR EGS will require field testing in superhot wells, experimentation with an extremely large sample (i.e., >1-meter blocks) in a superheated rock mechanics laboratory, or—most likely—a combination of both. Casing materials, zonal isolation inside and outside the casing, fracture initiation and growth, and nontoxic proppant selection and emplacement are key targets for such testing.

Because scale is critical to understanding fracture growth directions and size within a large rock mass in field conditions, fracture initiation methods should be tested in SHR wells and in SHR EGS demonstration projects. Results from laboratory testing and modeling may provide useful predictions for fracture initiation and growth, but performing and documenting field tests will be needed to constrain the potential fracture size and stability.

Vendors and service providers will need to see a clear market opportunity to expand into equipment capable of fracture creation and propping in SHR conditions, as well as equipment to test rock behavior in superhot and supercritical conditions. A comprehensive, ***global survey of SHR-capable equipment is needed***. Collaboration with metamorphic petrologists will be key here.

Equipment exists that can perform experiments for permeability creation and management in superhot conditions. However, since most labs do not have the necessary equipment, many variables relevant for SHR permeability creation have not been tested at superhot conditions and remain unconstrained, thus limiting the accuracy of modeling.

4.3.2 Modeling of Reservoirs and Fractures

Gaps and Challenges

Existing oil and gas models of fracturing, rock and fluid mechanics cannot accurately represent reservoirs in superhot conditions. Basic information is lacking on thermodynamic and kinetic behaviors of fluid-rock interactions in superhot and supercritical conditions, limiting models' constraints. Models are not designed to include dynamic supercritical fluids, and long-term thermal, hydraulic, mechanical, and chemical changes in the reservoir. Similarly, models of fracture propagation and long-term stability in superhot conditions do not exist. Challenges to SHR modeling include dynamic fluid states at supercritical and superhot conditions, fracture behavior in or near the BDTZ, and behavior of diverse host rock lithologies at superhot conditions. **TRL: 7**.

Future R&D and Testing

Traditional oil and gas hydraulic fracturing software was designed to predict hydraulic fracture apertures, dimensions, and propagation direction in a layer-cake stratigraphy of sedimentary rocks. A comprehensive survey is needed to ascertain the capabilities of existing modeling packages in more heterogeneous, and potentially ductile, rock. A set of new, physics-based models will be needed to design, create, and manage SHR EGS projects, including modeling of fractures that create permeability and of the long-term behavior of those fractures in the reservoirs. Some existing fracture models from oil and gas can serve as useful starting points, but lab- and field-based experiments will be needed to constrain and validate the models.

New models will need to:

- Explore fracture creation, with sufficient surface area for heat extraction, in a range of rock types
- Account for phase transitions and geomechanics at and near the BDTZ, and with near-critical point fluids of various compositions
- Represent heat conduction and supercritical thermodynamics in reservoirs
- Address long-term reservoir management and sustainability, including changing geochemical conditions

To build and validate these models, more thermodynamic and kinetic data on rock-fluid interactions in superhot and supercritical conditions will need to be collected.

As more in-field data from reservoir analogs becomes available, models will improve as well. Due to the limited number of wells successfully drilled into superhot conditions, analog systems in magmatic and metamorphic settings will be vital for validating and constraining stress, strain, and resource decline assumptions for modeling in superhot geothermal conditions, particularly near the BDTZ. Current reservoir analogs tend to be too shallow and limited to magmatic settings, and therefore are of limited use for SHR research. Broader and deeper analog systems must be developed to explore SHR's full potential in diverse geological formations.

4.3.3 Induced seismicity

Gaps and Challenges

Regulatory agencies worldwide have established mitigation protocols for induced seismicity for EGS projects. The risk of induced seismicity in SHR geothermal systems remains uncertain, particularly in regions near the BDTZ. While some studies suggest the seismic risk could be lower in superhot conditions near the BDTZ, others suggest an increased likelihood of seismic events. This knowledge gap inhibits forecasting of induced seismicity risk for SHR projects. **TRL: 8**.

Future R&D and Testing

Further research, including laboratory tests, analog studies, and field demonstrations, is needed to quantify and mitigate the risk of induced seismicity, especially in regions with higher seismic activity. More research is needed on the effects, if any, that stimulating reservoirs near the BDTZ has on seismic risk. This will require robust mechanical testing in laboratories, investigations in reservoir analogs, modeling and validation, and field validation at demonstration sites. Experience from previous EGS projects suggests that projects should avoid urban areas until a reliable method to detect unknown critically stressed faults is developed.

Investigations should explore:

- The geomechanics in the BDTZ, including whether their mechanics will change the risk of induced seismicity.
- Whether induced seismicity triggered by cold fluid injection migrates downward, as previous work has suggested. Seismic data from geothermal injection programs could be used to test this hypothesis.

4.3.4 Thermally conductive cement alternatives for closed-loop systems[5]

Gaps and Challenges

Because closed-loop systems do not require proppants or the creation of fractures, the focus for reservoir creation for closed-loop technologies shifts to well construction materials. Efficient heat extraction in these systems depends on finding alternative cements that may offer superior performance in heat transfer and long-term structural integrity. Adequate cement alternatives still need to be fully developed and tested in both laboratory and field settings.

Future R&D and Testing

Many existing materials, fluids, and additives that could be used for well completions with cement alternatives require in-depth study in SHR conditions in lab and field environments. Eavor, a closed-loop geothermal company, has developed its Rock-Pipe™ system, and XGS Energy reports using materials several times more thermally conductive than rock in its closed-loop system.

See the Drilling section of this report (Section III) for information on directional drilling, which is also important for reservoir creation in closed-loop systems.

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[5] This subsection came from data collected from closed-loop experts after the first version of the full heat extraction report was published.

4.3.5 Other future work: landscaping of laboratory facilities at superhot reservoir conditions

A comprehensive, worldwide survey is needed of the capabilities of existing laboratories and upgrade pathways to reach superhot conditions. While existing laboratories have a subset of the tools and equipment needed to research superhot rock conditions, they are geographically distant from each other, and their operators may not know they can help transform geothermal energy. Establishing and strengthening connections between geothermal, oil and gas, and research institutions will accelerate this process.

Laboratories will need to:

- Test equipment, materials, and rock-fluid interactions in superhot and supercritical conditions, including the BDTZ
- Measure fracture toughness, geomechanical behavior, and rock material and thermal properties across a range of superhot and supercritical conditions, including the BDTZ
- Test the effect of thermal shock on rock weakening
- Rigorously test the behavior of rock and fractures at and near the BDTZ; basic research will be needed to first identify how this can be explored in a laboratory setting
- Test materials such as cements, proppants, and additives for their solubility, stability, strength, flow, and thermal properties under superhot and supercritical conditions

4.4 Conclusions

The purpose of the *Heat Extraction* study was to identify knowledge and technology gaps around heat extraction (permeability and reservoir creation) in superhot rock. Existing knowledge, models, and tools from oil and gas have limited applicability to the SHR geothermal environment. Existing EGS, as well as oil and gas systems, provide an engineering basis for permeability creation, but they operate at lower temperatures than SHR systems targeted in this work.

There is limited understanding of rock and fluid behavior in superhot and supercritical conditions, especially when considering the possibility of brittle-ductile rock behavior. This leaves fracture initiation, growth, and long-term stability as critical unknowns that should be targeted in R&D. ***Laboratory facilities in the government, universities, and private industry that can test permeability creation and reservoir management in superhot rock conditions are extremely important for de-risking and scaling up SHR.*** Results from laboratory experiments and field demonstrations are critical for improving predictive models and informing next steps for making long-term permeability creation and fracture management possible in superhot geothermal conditions.

The gaps discussed above are broad and interdisciplinary. Bridging them will require a highly collaborative approach. However, many solutions may already exist; the scientists, engineers, and service providers who possess this knowledge need to be made aware that their knowledge is crucial for transforming geothermal energy and be given opportunities to collaborate in that transformation.

See *Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Heat Extraction* for more (Cladouhos and Callahan 2024).

5. BRIDGING THE GAPS: POWER PRODUCTION[6]

Geothermal power plants share a similar build with other thermoelectric plants, but bringing SHR to a global scale requires some advancements in equipment and design. The *Power Production* study aims to identify future work needed for surface equipment in SHR power plants by breaking down system components and assessing technology gaps in equipment not yet commercially viable for superhot geothermal production.

The evaluation began by examining three primary power plant systems to determine the most efficient pathway for SHR energy production. After identifying this pathway based on the study's assumptions, individual components were assessed for their technology readiness and ability to operate in superhot geothermal conditions. This analysis also highlighted the future targeted work required to commercialize superhot geothermal power.

Given the close link between suggested R&D and cost reductions, the study included an assessment of the cost of a superhot geothermal power plant as it exists today. Additionally, the study included a scenario analysis to assess water use with different cooling systems, as cooling choices significantly impact water consumption and plant efficiency. See *Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Power Production* for these additional analyses (Brown et al. 2024).

5.1 Key findings

Modeling, analysis, and conversations with vendors clearly indicate that ***most components needed for an optimal SHR plant already exist***. The TRL for almost all individual system components is 9: ready to commercialize. However, the system itself is not currently available off the shelf—though such a system is close to actualization. Targeted investments in turbine design and associated components will make the fully integrated system suitable for commercial deployment in the near term. **The greatest potential for**

[6] This is a Clean Air Task Force summary of "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways for Superhot Rock Power Production" by Doug Brown, Catherine Roy, Jaclyn Urbank, Jenna Hill, and Terra Rogers (2024). https://www.catf.us/superhot-rock/bridging-gaps/.

future work lies in R&D aimed at reducing the cost of power plant systems and increasing the longevity of equipment in harsh geothermal environments. Thus, recommendations for future R&D include developing lower-cost alternatives to materials like Inconel and duplex stainless steel, and standardizing turbine design for superhot geothermal systems. While most components needed for an optimal SHR power plant already exist, a few key innovations will bring costs down for commercial viability.

5.2 State of the technology

5.2.1 Optimal power plant

This assessment is based on a theoretical 500-MW power plant, assumed to be located in temperate conditions near sea level. Setting a benchmark of 500 MW for energy production represents an approach aligned with industry trends in high-temperature, high-pressure, dry rock geothermal systems. The assumed system relies on five well pads located 500 meters from the plant and two 250-MW condensing steam turbines; 250-MW turbines represent the current industry maximum for steam turbine sizing for standard use. (For more information on the design basis for the study, please reference the full power plant report [Brown et al. 2024].)

Three potential geofluid compositions were evaluated: one representing harsh geofluid conditions, modeled after the IDDP-1 well at Krafla in Iceland; one representing moderate geofluid conditions, modeled after the Fenton Hill project in New Mexico; and one mild geofluid scenario, assuming the use of generic freshwater.

The study evaluated three power plant options: two direct use steam plant options (one using "washed" steam,[7] the other using the dry steam directly) and one binary cycle plant. For each option, high-level process flow diagrams were developed featuring major equipment and flow streams within the surface facilities, and with representative temperatures, pressures, and enthalpy.

The binary and washed dry steam plants require more geofluid, have higher electricity consumption (parasitic load), and require more geofluid per MW of power produced than the unwashed dry steam cycle plant. From a performance standpoint, the direct use configuration with dry steam is the most efficient.

The cooling systems—wet-cooling towers versus air-cooled condensers ("dry" cooling)—also vary in parasitic load and water usage. Water requirements for a wet-cooling system, such as using natural or forced draft cooling towers, are about 20 times higher compared to an air-cooled condensing system. Due to the higher water usage of the wet-cooling towers, the remainder of the study—the total readiness level assessment and the cost estimate—is based on this representative power plant design: direct use with dry steam and dry cooling.

5.3 Gaps, challenges, and future work

5.3.1 Gaps and challenges

An evaluation of individual system components reveals that the TRL is 8 to 9 for most components (see Table 6-1 in the *Power Production* report [Brown et al. 2024]). Among the dry steam unwashed system components, the steam turbine has the lowest TRL at 5-6, primarily due to the specialized turbine design adaptations required to accommodate specific geofluid characteristics. Consequently, the entire system is currently at TRL 5, as a complete prototype design has not yet been constructed or commissioned, nor has it been demonstrated in an operational environment. The SHR geothermal power plant system is on the brink of commercial readiness, requiring investments in turbine design and smaller parts like well valves. The few technological gaps predominantly focus on the need for lowering costs and standardization.

As is common with traditional direct use geothermal plants, the turbine design must be tailored for the specific geofluid characterization. This includes specialized materials for the rotor and stage blades, designing blades to control vibration, optimizing stage condensate removal components, and applying specific blade coatings to manage corrosion. Evaluation of metallurgical options such as ferritic stainless steel, duplex stainless steel, and high-nickel alloys for the turbine design is also essential. The condenser is another component with high potential for cost reduction with improved materials.

Fortunately, these considerations fall within turbine suppliers' expertise, and some have been successfully addressed in other power plant and industrial contexts, either in production turbines or field-tested units. While implementation can be costly, it is feasible—and developing next-generation materials or coatings will help reduce costs further. In the meantime, site-specific analyses will need to consider local geofluid compositions, as the makeup of the fluids—especially silica, sodium, chloride, and hydrogen sulfide, which pose the greatest risk to a plant's integrity and reliability—may affect the choice of construction materials and the corrosion mitigation techniques used. Site-specific analyses may also want to consider local water availability when considering cooling options.

See Table 5 in the Appendix for a detailed list of gaps.

Modeling, analysis, and conversations with vendors revealed that most components needed for a SHR power plant already exist, either in power plant designs or other industries. Nearly every component has a maturity of TRL 8-9 (commercial-ready), except for turbines,

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[7] Geothermal steam is often "washed" to reduce undesirable components in the steam. This requires injecting clean water into the steam to condense a small portion of the steam. The condensate, containing much of the targeted components; is then separated from the steam flow and the remaining steam contains a much lower concentration of the undesirable components.

which are at TRL 5-6 due to the lack of production for this specific purpose. Custom turbine development is currently necessary, but it is not economically sustainable.

5.3.2 Future work

Given the high technology readiness of each of the components, future R&D for SHR power plants should focus on cost reductions and transitioning from specialized equipment to off-the-shelf materials. This means that an end-to-end power plant demonstration in a relevant environment is required. Furthermore, any new materials would need to be vigorously tested in the field prior to use, due to the challenges of the subsurface environment.

5.4 Conclusions

Most components needed for a SHR geothermal power plant already exist but need to be adapted for the resource-specific geofluid and high-pressure/high-temperature environment that is novel for superhot geothermal steam turbines. Future R&D should focus on reducing costs and increasing scalability by developing off-the-shelf turbine designs. Strategic investments in turbine technology and components will accelerate the commercial readiness of SHR geothermal energy, positioning it as a viable option in global energy markets.

See *Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Power Production* for more (Brown et al. 2024).

6. BRIDGING THE GAPS: SITING AND CHARACTERIZATION[8]

Ideal locations for superhot rock (SHR) geothermal reservoirs depend on various factors. Identifying potential well sites, determining drilling depths, and anticipating challenges are critical to minimizing the financial and technical risks of SHR geothermal projects. Subsurface conditions vary widely, with rock behavior influenced by lithology, structures, stress, strain, permeability, and geochemistry. Understanding these characteristics in heterogenous and deeply buried bedrock is essential for project success.

A comprehensive assessment of potential SHR reservoirs requires integrating geophysical and geological investigations. Geophysical methods for detecting heat transfer, structural features, faults, stress, strain, and permeability exist but remain undertested in SHR conditions. Bridging data gaps involves using complementary geophysical techniques across multiple scales. Field-validated datasets, including borehole well logging and laboratory analysis of cores, also provide critical insights into deep bedrock conditions and site viability.

Once regional, local, and laboratory data are collected, machine learning (ML) can refine targeting of potential productive SHR sites. Larger geothermal datasets enhance these predictions. For geothermal development to expand, improved global-scale data-sharing platforms are needed, culminating in an open-source repository to support the “geothermal everywhere” goal.

6.1 Key findings

Many current geophysical methods that can be used in SHR exploration are proven approaches, but remain largely untested in SHR-specific environments. With only a few SHR wells drilled to date, existing data are insufficient to establish strong correlations between geophysical signals and rock conditions, such as temperature, stress, or permeability, in these extreme environments.

While several geophysical techniques can currently support SHR reservoir characterization, challenges persist, especially at the depths of typical SHR systems. Collecting additional field data from complementary geophysical surveys at each potential SHR reservoir is essential to strengthen the interpretation of site conditions.

At the exploration scale, leveraging the existing geophysical techniques for mapping heat, stress regimes, and hazards is an important first step in identifying preferable locations for further SHR exploration. Improving data and modeling resolution for global temperatures and regional stress regimes is necessary to advance SHR siting.

At the reservoir scale, better interpretations of deep SHR can be made by combining geophysical techniques and incorporating direct measurements from boreholes and core rock in the lab. Many characteristics such as high temperatures and pressures, stress fields, and pore pressures can affect both the drilling exploration activities and the operation of future SHR reservoirs. Overlapping geophysical techniques can improve interpretation and thus prevent drilling complications and failures.

While machine learning (ML) offers a lot of potential to improve data interpolation, interpretation, and prediction, there remains a severe lack of data to sufficiently inform these techniques. Collecting more data and maintaining excellent metadata on new sites can move the possibility of ML forward.

[8] This is a Clean Air Task Force summary of “Bridging the Gaps: A Survey of Methods, Challenges, and Pathways for Superhot Rock Siting and Characterization” by Chanmaly Chhun, Rebecca Pearce, Pascal Caraccioli Salinas, Seth Saltiel, and Carolina Munoz Saez (2024). https://www.catf.us/superhot-rock/bridging-gaps/.

Once a SHR reservoir is active, continued monitoring needs to take place to ensure the reservoir continues to produce effectively. Long-term analyses should be developed to track heat depletion, mass balance changes, and fluid-rock interactions within the reservoir. Additionally, seismic monitoring can aid in reducing hazards while in the drilling, permeability enhancement, and production phases but more work is needed to validate the interpretation of seismicity data for SHR environments.

6.2 State of the technology

The primary information needed before siting any geothermal reservoir includes the geothermal gradient, stress, structures, and permeability of the basement rock. Geophysical, geologic, and laboratory techniques can be used at different scales to narrow down siting and characterization of SHR reservoirs.

6.2.1 Expertise and measurement techniques

Exploration Scale

The exploration stage of identifying SHR reservoirs requires surveying, or compiling existing data from, large swaths of prospective geothermal regions with various proven geophysical techniques. Geophysical surveys can be a cost-effective way to collect data to reveal the heat at depth and the deformational regime of the area.

Gravimetric, magnetic susceptibility, and geodetic surveys can be collected by satellites, fixed-wing aircraft, or land-based methods. Mapping geophysical properties like magnetic susceptibility and electrical conductivity can help narrow down the locations of deep, high-temperature rocks with potential for heat flow, while borehole measurements can confirm temperatures and thermal conductivity. Current techniques like the use of the LithoRef18 model and Curie Depth Point mapping can produce large-scaletemperature isotherms.

While gravimetry methods are useful for geothermal investigations, SHR systems are likely to be located at greater depths than conventional geothermal projects. Similarly, magnetic susceptibility surveys can reveal heat and structural trends, but the technique struggles with increasing depth. Geodetic surveys can further refine the stress regimes of a region and are useful as a first pass in identifying deformation trends and geothermal activity in an area. Despite their limitations at depth, these geophysical methods help narrow down where reservoir-scale investigations should occur.

Stress fields directly impact drilling design and permeability-enhancing work in SHR projects. Over the last 40 years, researchers have added and refined stress orientations and tectonic regimes around the globe, creating a world stress map. While an important tool, the map has variable geographic data coverage, leading to knowledge gaps in some regions.

Reservoir and Validation Scale

Reservoir-scale geophysical investigations will further refine the potential of SHR geothermal sites. Using seismic tools, the (an)elasticity regime of a potential reservoir can be mapped, identifying variations in permeability, temperature, and regional stresses. However, the technique has uncertainties—for example, while mapping a geothermal site in Larderello, Italy, the reflection seismic data suggested a horizon of supercritical fluids, but when the borehole itself was deepened, the project team was unable to confirm the presence of these fluids (Bertani et al. 2019, De Franco 2019, Piana Agostinetti et al. 2017). More work is needed to refine and enhance seismic data processing for hard rock environments.

Additionally, more detailed estimates of temperatures, geologic structures, and supercritical fluids within a reservoir can be better defined by incorporating electrical conductivity methods. Employing joint inversion techniques can also help narrow down the interpretations of geophysical data. By combining data from two or more geophysical methods—like electrical resistivity with seismic data—developers can better constrain variables of interest for SHR reservoirs. For validation of these methods, analyses of rock cores are one of the most direct ways to test the interpretations from geophysical data.

For borehole logging, within the deeper levels of hydrothermal systems, temperatures and pressures can surpass the critical point of pure water (374°C and 22 MPa) (Scott et al. 2016). There are few studies with samples of supercritical fluids, and the chemical reactions that control fluid compositions are still poorly understood. But a better understanding of fluid geochemistry is needed for SHR development, because geochemistry effects drill string fatigue and corrosion issues—two conditions associated with high pressures, temperatures, and acidity in supercritical fluids (Gunnlaugsson et al. 2014, Sanada 2000, Miller 1980).

Monitoring

Ongoing characterization throughout the project life cycle is key for ongoing decision-making. These activities are important for managing conventional geothermal reservoirs, but to this point there is limited relevant experience with long-term management of enhanced geothermal reservoirs and none in SHR reservoirs.

Measuring induced seismicity is another important part of monitoring. Seismicity, especially induced seismicity, is an important factor in the operation of the reservoir system. Changes in the stress field or seismicity of the area can affect pore fluid pressures, permeability, fractures, and the operation of the reservoir system. It is important to monitor and mitigate seismic events above a predetermined threshold to avoid infrastructure damage or alarming nearby communities.

The regulatory protocol to reduce induced seismicity (termed adaptative traffic light system, ATLS) exists today and continues to advance. Seismicity reduction methods include continuous seismic monitoring, limiting the frequency and magnitude of events by controlling water injection rates and pressures for reservoir fracture enhancement. However, these methods and advanced traffic light systems are developed for brittle reservoirs, not necessarily in the brittle-ductile transition zone, where rock may behave differently, and which may be encountered in SHR systems.

Related to seismicity, monitoring fluid flows and compositions are important parts of geothermal operations. Electromagnetic methods can be used to help monitor small fractures and permeability changes within a reservoir. Monitoring the chemistry of supercritical fluids can reveal changes in the reservoir rock that can affect long-term reservoir performance, including permeability, flow rate, and recharge zone locations. In addition, geothermal fluids can cause corrosion and scaling within geothermal power plant systems.

6.2.1 Data Availability

Developers in geothermal energy use Play Fairway Analysis (PFA), originally developed in the oil and gas industry, to identify hydrothermal reservoirs. However, the requirements for dry heat reservoirs, where enhanced geothermal and advanced geothermal methods can be employed, may differ. Temperature and ease of access are more common needs whereas a natural source of permeability is not needed for enhanced geothermal and closed loop geothermal systems.

As geothermal advances in its geographic scope and viable depths, the geothermal community should develop a standardized approach to data collection and curation. Right now, the largest centralized data repository for geothermal is the Geothermal Data Repository, but that repository only contains data from projects funded by the U.S. Department of Energy, and the navigability of those data are limited. The leading SHR projects exist in multiple countries, led by a diverse set of technology leaders. A centralized open access data platform should be available to those technology leaders to share their data as well.

A centralized data repository with standardized data collection approaches can pave the way for ML methodology. Since 2018, there has been a trend in using ML for geothermal research and reservoir characterization (Chhun et al. 2024). ML can be used in conjunction with expert-driven assessments to identify SHR reservoirs.

6.3 Gaps, challenges, and future work

Many of the geophysical and geological methodologies for siting and characterizing potential SHR reservoirs have been developed and proven in oil and gas and conventional geothermal prospecting investigations. However, these technologies have specific limitations, including data coverage and resolution, uncertainties in modeling, and the ability of downhole equipment to withstand the temperatures, pressures, and corrosivity of SHR reservoirs. Table 7 highlights the technological advancements needed for exploration, siting, and monitoring of SHR reservoir systems.

See Table 6 in the Appendix for a detailed list of gaps.

6.3.1 Exploration scale: modeling geothermal heat flow

Gaps and Challenges

Today, surface heat flow measurements describe the thermal conductivity of the shallowest strata. The Stanford Thermal Model, a robust and valuable heat mapping tool for the contiguous United States, is limited to the top 7 km of the crust; SHR prospecting needs a tool for depths up to 20 km. Using more surficial heat flow data can lead to misestimations of the geothermal gradient at depth—in some cases on the order of 40% (Batir and Richards 2022).

Current techniques like use of the LithoRef18 model and Curie Depth Point mapping, which can produce large-scale temperature isotherms, have coarse resolution and limitations for smaller-scale reservoir heat mapping.

When mapping heat flow, surface heat mapping and the Stanford Thermal Model techniques have been used. However, because of the variability of geologic rocks and features at depth, there are precision and depth limitations when using these methods.

TRL: 7

Future R&D and Testing

Increasing the global coverage and precision of heat estimates should include:

- Complete global audit of missing data required by thermal modeling
- Incorporate convective heat transfer regimes into existing thermal mapping techniques (e.g. Stanford Thermal Model or LithoRef18).
- Increase coverage of high-quality, high-spatial-resolution surface heat flow and thermal conductivity data from well logs for modeling efforts, including the intensive acquisition of global-scale geophysical datasets to improve exploration scale thermal mapping results
- Complete high-density sampling with improved downhole tools that can handle SHR temperatures and conditions within boreholes to improve heat flow models

6.3.2 Exploration scale: modeling stress at depth

Gaps and Challenges

Related to stress fields, large-scale fault mapping and monitoring does not have the same completeness in all areas of the world. Despite the widespread, global efforts of geoscientists to map and monitor seismicity, unmapped faults routinely produce earthquakes. **TRL: 9**

Future R&D and Testing

Improving the identification of stress states and stress regimes should include:

- Limiting large-scale extrapolation over regions with no or low data coverage
- Incorporating constraints on stress regimes from anisotropy and geodesy measurements
- Investing in accurate prediction of pore-pressure distribution and in situ 3D rock stress models to ensure safe and efficient drilling
- Installing seismometers and other seismic monitoring systems to help map large-scale fault zones

6.3.3 Reservoir scale: geophysical survey methods

Gaps and Challenges

Some geophysical methods can identify an anomaly but cannot definitively denote what is causing it. For instance, electrical conductivity methods can detect fluid migration or the presence of a certain geological unit, but not the geological conditions that are causing the anomaly. **TRL: 6-9**

Future R&D and Testing

Some of the uncertainties in interpreting geophysical methods can be reduced by either coupling multiple geophysical methodologies and/or using borehole and laboratory data to refine modeling. Data from geophysical technologies could be improved by:

- Increasing density of sensors to fill in gaps in coverage
- Using multiple geophysical methodologies to decrease uncertainty, such as combining seismic data and electrical conductivity data
- Developing advanced data processing, noise filtering, or new algorithms and methods for geophysical data to increase model resolution and granularity
- Improving borehole tools to withstand temperatures of about 250°C for field verification investigations
- Creating standardized metadata structure, hosting an open-source data platform of geophysical information
- Employing ML to help forecast SHR reservoirs, once the required threshold of data is met

6.3.4 Monitoring

Gaps and Challenges

Characterization and modeling efforts must continue throughout the lifecycle of the geothermal system. Monitoring activities can identify any reservoir changes and help guide decision-making.

Future R&D and Testing

Monitoring the behavior of a geothermal reservoir throughout citing and operation should include:

- Monitoring seismicity with an array of seismometers, arrays, and/or DAS systems
- Incorporating fluid migration methods described by Theil (2017) for future electromagnetic monitoring of reservoirs
- Increasing borehole sensor temperature ratings to >150°C
- Improving sensor durability and accuracy of downhole equipment in high-temperature/high-pressure conditions
- Developing advanced data processing, noise filtering, or new algorithms/methods to remove amplitude artifacts and enhance signals for velocity or seismic analysis.
- Validating reservoir models using analog sites, and including further testing to improve monitoring techniques
- Creating geochemical tools for areas of active volcanic-geothermal activity or supercritical fluid zones
- Conducting geochemical studies during reservoir development, production, and environmental assessment for use in predicting scaling or corrosion issues

6.3.5 Data interpretation

Gaps and Challenges

Using oil and gas-derived approaches like PFA can be useful in siting and characterizing geothermal systems. However, the methodology has limitations for SHR, including data availability, differences in geologic setting, and different validation techniques.

An array of global datasets can be useful for SHR siting, but these datasets can be difficult to combine, can lack key information, or are unavailable for certain areas. There are also a limited number of SHR-specific datasets to use as benchmarks. These limitations are difficult for interpretations and also prevent the use of technologies like ML.

Future R&D and Testing

Data interpretations can be improved by:

- Modifying the oil and gas PFA to target SHR reservoirs
- Improving global data coverage
- Creating a standard metadata format to improve quality, searchability, and improve the likelihood of using ML
- Creating a centralized open-source repository of data available for all who are interested in geothermal energy resources; the centralized platform should build from publicly accessible databases that already exist

6.4 Conclusions

Although SHR site characterization is relatively young, geothermal development can leverage proven methods from conventional geothermal and the oil and gas sector. Many geophysical and geological techniques used in petroleum exploration can be adapted to identify geothermal plays.

Key factors for viable SHR sites include heat, stress, subsurface structures, and permeability. As such, SHR characterization requires multiple investigative steps, from large-scale regional investigations to site-specific testing. While geophysical technologies can map much of the subsurface, pinpointing regions with high geothermal gradients remains challenging. Geophysical methods have already been developed, but limited examples exist of these approaches being interpreted for SHR characterization. As such, the lack of data on SHR reservoirs hampers the use of helpful technologies such as machine learning.

At the exploration scale, heat mapping is a critical first step to identifying promising locations. The regional stress regime and seismic hazard identification should also be done at this lower-resolution stage—tasks primarily handled through geophysical methods and modeling. At the reservoir scale, geophysical tools can estimate temperatures, stress, and pore pressures at depth, structural features, and permeability, though these require further refinement. Once an SHR site becomes operational, monitoring for induced seismicity, fluid flow, and reservoir changes will be crucial to managing system performance and addressing operational challenges.

No single geophysical or geological approach will fully capture the characteristics of a potential SHR reservoir, due to limitations like increased uncertainty with depth, non-unique rock signatures, and noisy data. Combining geophysical methods with borehole surveys and laboratory analyses enhances modeling accuracy. Expanding field-verified datasets and conducting experiments on cores from boreholes of potential SHR reservoirs will improve the interpretations and identification of geothermal areas of interest. Improvements to data collection—including broader geographic coverage, standardized metadata, and global data sharing—will be an important step to de-risking projects, validating new models, and enabling the advancement of superhot rock geothermal globally.

7. CONCLUSION

The *Bridging the Gaps* reports aim to identify the necessary steps to commercialize SHR geothermal energy, with a breakdown of system components and an assessment of targeted work needed for equipment and other advancements that are not yet commercially available.

Superhot rock geothermal requires site selection, drilling, well construction and completion, and power production from deep subsurface environments, often more than 10 kilometers deep and hotter than 374°C, under high pressures. These harsh conditions pose significant technical challenges. Although much of the technology is already available, thanks to advances in next-generation geothermal and unconventional oil and gas extraction, further innovations are crucial for proving out these systems end-to-end, making these systems more robust, enabling deeper drilling, bringing down technological risk, and bringing SHR geothermal to a global scale. The good news is that the innovations required are engineering challenges, not fundamental scientific breakthroughs. Therefore, targeted investment in R&D, testing, and demonstration will build on years of innovation and progress.

The most pressing technological gap across SHR energy generation is the need for facilities—both laboratories and field sites—where equipment and methods can be tested in SHR conditions. Innovations in drilling are needed to improve rates of penetration and enable downhole drilling tools to operate in ultra-high temperatures. For well design and construction, the focus should be on developing casing materials, connections, and cement that can withstand extreme conditions to reduce failure rates and increase longevity. The biggest challenges for heat extraction are creating and maintaining safe fractures in heterogeneous rocks and extending them into the BDTZ. Testing in analog reservoirs, both in labs and in the field, will be essential to constrain fracture behavior and manage seismic risk. For power production, reducing costs and increasing the durability of equipment in harsh geochemical environments is crucial. Strategic investments in turbine design and related components will make fully integrated power plant systems commercially viable in the near term.

Harnessing just 1% of the world's SHR geothermal energy potential could generate eight times the current global electricity supply (Clean Air Task Force n.d.). SHR geothermal energy offers a small land footprint, 24/7 availability, compatibility with existing power plant infrastructure, and zero-carbon employment opportunities for workers transitioning from the oil and gas sector. Advancements in heat extraction and drilling laid out in this report could make superhot rock geothermal energy accessible in many more parts of the world. Investing in this work today will support the clean energy needs of tomorrow.

8. APPENDIX

Table 1: Big-Picture Technology Gaps for SHR Drilling

Gap	Why	Current Capability
Stronger, faster rock-destroying technology, including stronger drill bits	To increase the rate of penetration into crystalline basement rock	Drilling systems can penetrate crystalline rock, but too slowly to be economical in deep boreholes; high pressures up to 40 MPa and temperatures >374°C exceed the pressure-temperature capabilities of most drill bits
Ultra-high-temperature downhole tools and temperature management equipment	To access geothermal gradients sufficient for power generation (374°C to 450°C or more)	Most downhole drilling tools run at 175°C, with a few operating in the range of 200-225°C; some drill fluids can reach to 353°C

**See Gaps and Challenges and Table 2, below, for more specific information on technological needs and gaps.*

Table 2. Drilling Technology Gaps Overview

Equipment	TRL	Gaps
Drill bits	Conventional (PDC, roller cone): 9 Hybrid (percussive, water jet): 3-8 Energy (plasma, millimeter wave): 2-4	**Conventional drilling** needs improvement to increase depth and reduce risk, including repeated drilling in various rock lithologies and interbedded formations with large differences in hardness. **Hybrid conventional drilling** should be combined with techniques like thermal spallation, particle impact, plasma and water jet. **Direct energy drilling** needs power supply systems that don't interfere with drilling operations **Overall**: Improvement of materials for increased durability, stability and faster rates of penetration
Temperature management: drill pipe coatings	6	Test low-heat coefficient coatings on conventional drill pipes in SHR temperatures
Temperature management: insulated drill pipe	7	Form partnership between SHR project owner and pipe manufacturer Model, manufacture, test, and field-run a complete system Demonstrate viability in an operational environment
Temperature management: mud coolers	9	No advancement needed
Downhole tools	7 If encapsulated; 8 if used with other cooling methods; 3 if stand-alone	Model, manufacture, test, and field-run a complete system using either exotic materials or in combination with other temperature management methods Iterate complete system to reduce cost and improve performance
Drill rigs	9 for <15 km; 7 for > 15 km	Need an increase in load and draw works capacity to hold the additional/heavier tools needed for ultradeep operations

Table 3. Well Design Technology Gaps Overview

Equipment	TRL	Gaps
Casing material properties and response at temperatures above 350°C under monotonic and cyclic loading (laboratory	4-5	Develop an understanding of how the mechanical and microstructural properties of steels and other materials respond to temperatures in excess of 350°C, since these conditions essentially heat-treat the

testing)		materials Run lab experiments on a range of materials at high temperatures
Connections for SHR well tubulars	6	Design and conduct lab experiments on connections under high-temperature cyclic loading, develop finite element analysis models, expand to range of available connections. This method can be used to shorten time for development.
Cement integrity under cyclic loading	6	Develop a cement integrity model that takes into account fatigue Develop and test high-temperature cements that can withstand swings of 400°C
Fatigue failure of tubulars and connections	6	Run fatigue experiments at 450°C (previous experiments ran only up to 350°C) and validate fundamental theory using experimental results
Flow assurance and materials selection for corrosion, scaling, and precipitation	2	Test corrosion and scaling models and define methods to mitigate corrosion by managing the circulating working fluid
Modeling geochemical interactions between supercritical water and rock	3-4	Develop an experimental procedure to test water-rock interactions under supercritical conditions in SHR cores and run tests

Table 4. Heat Extraction Technology Gaps Overview

Equipment	TRL	Gaps
Reservoir stimulation equipment	4-6	Identify materials (for diverters, proppants, tracers, packers) that can operate in superhot conditions Develop necessary equipment Field test reservoir creation equipment
Reservoir analogs	6	Identify deep, nonmagmatic reservoir analogs to test models Collect data on fracturing and induced seismicity risk in/near BDTZ Expand existing facilities for additional lab and field testing
Improved reservoir and fracture models	7	Develop coupled model with rock/fracture mechanics, fracture propagation, flow, and reactions at SH conditions Develop coupled reservoir models with supercritical fluids, BDTZ mechanics, and dynamic changes over time Collect thermodynamic and kinetic data for modeling fluid-rock interaction within SHR EGS conditions
Induced Seismicity Protocol	8	U.S. DOE and EU need to establish mitigation protocols for SHR wells Mechanical testing, analog investigations, coupled THMC modeling and validation, demonstration sites Field test and validate

Table 5. Power Production Technology Gaps Overview

Equipment	TRL	Gaps
Steam turbine generator – 2 x 250MW	5-6	Technology development: Full system prototype design and demonstration in an operational environment. Bringing down cost: Material cost for a custom steam turbine package was evaluated at $3.8 million USD and therefore likely holds the

		second-highest potential for cost reduction in the power plant.
Wellhead unit/valves	8	Wellhead valves are a common failure point for geothermal, especially superhot conditions. Long-term testing is required to understand comparable long-term viability of current options for wellhead valves.
Air-cooled condenser	9	No technology gaps. R&D for cost reduction recommended; highest potential for cost reduction with improvements.

***Additional equipment was evaluated and determined to not require significant further work; thus, it was left out of this gap table. See Table 6-1 in the full* Power Production *report for more (Brown et al. 2024).*

Table 6: Siting and Characterization Gaps Overview

Subsurface property or analysis technique	TRL	Gaps
Exploration scale: Heat at depth	7	Conduct a global audit of missing data required by thermal models Improve modeling of nonsteady state thermal diffusion regimes Improve constraints of radiogenic heat flow
Exploration scale: Deformation regime	9	Check network completeness Incorporate constraints from anisotropy and geodesy
Reservoir scale: (An)elasticity (seismic)	9	Conduct field validation at depth Create ambient noise methods for 4D monitoring
Reservoir scale: Electrical conductivity	8	Refine electromagnetic and microseismic data in joint inversion methods High resistivity signatures require more study Reservoir monitoring requires further testing
Borehole logging: Temperature	9	Field testing and full-scale operation
Borehole logging: Stress	7	Real-time testing Fluid and temperature effects on final tensor strain
Borehole logging: Permeability	6	Conduct pilot projects Lab-based SHR rheology studies Predictive flow models using numerics or ML
Data interpretation: Resource assessment	6	Identify the key components for SHR play types (components and benchmarks)
Data interpretation: Joint inversion	7	Develop effective methods of joint inversion with differing resolutions of different methods Commercialize academic joint inversion codes and improve usability
Data interpretation: Rock physics and core analysis	7	Develop geophysically constrained constitutive laws across brittle-ductile transition Validation with downhole geophysics and temperature sensing
Data interpretation: Open-source repositories	7	Open-source data, metadata, and ease of access required for funding and permitting
Monitoring: Induced seismicity mitigation	8	Demonstrate real-time feedback control and communication

Monitoring: Permeability enhancement monitoring	2	Lab experiments with geophysical monitoring Site testing and validation EM to resolve permeability change at depth
Monitoring: Heat depletion and water loss	2	Optimized deep well drilling, fluids, casing Continuous geophysical monitoring Use probabilistic or ML forecasting

REFERENCES

Batir, J., and Richards, M.: "Determining geothermal resources in three Texas counties," Texas Water Journal (2022).

Bertani, R., Büsing, H., Buske, S., Dini, A., Hjelstuen, M., Luchini, M., Manzella, A., Nybo, R., Rabbel, W., and Serniotti, L.: "The first results of the Descramble project," Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2018).

Brown, D., Roy, C., Urbank, J., Hill, J., Rogers, T.: "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Power Production," Clean Air Task Force (2024). https://cdn.catf.us/wp-content/uploads/2024/05/20144617/shr-bridging-gaps-power-production.pdf

Chhun, C., Pearce, R., Caraccioli Salinas, P., Saltiel, S., and Munoz Saez, C.: "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Siting and Characterization," Clean Air Task Force (2024). https://cdn.catf.us/wp-content/uploads/2025/01/17155902/shr-bridging-gaps-siting.pdf.

Cladouhos, T.T., and Callahan, O.A.: "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Heat Extraction," Clean Air Task Force (2024). https://cdn.catf.us/wp-content/uploads/2024/05/20145717/shr-bridging-gaps-heat-extraction.pdf

Cladouhos, T.T., Petty, S., Bonneville, A., Schultz, A., and Sorlie, C.F.: "Super Hot EGS and the Newberry Deep Drilling Project," Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2018). https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2018/Cladouhos.pdf.

Clean Air Task Force: "Mapping the Potential of Superhot Rock Energy" (n.d.). https://www.catf.us/superhot-rock/heat-mapping/.

Clean Air Task Force: "Superhot Rock Technology Gaps" (2024). https://cdn.catf.us/wp-content/uploads/2024/05/17165059/shr-gap-analysis-poster.pdf.

Clean Air Task Force: "A Preliminary Techno-Economic Model of Superhot Rock Energy" (2023). https://www.catf.us/resource/preliminary-techno-economic-model-superhot-rock-energy/.

De Franco, R., Petracchini, L., Scrocca, D., Caielli, G., Montegrossi, G., Santilano, A., and Manzella, A.: "Synthetic seismic reflection modelling in a supercritical geothermal system: An image of the K-horizon in the Larderello Field (Italy)," Geofluids, 2019(1), 8492453 (2019).

Fervo Energy: "Fervo Energy Drilling Results Show Rapid Advancement of Geothermal Performance" (2024). https://fervoenergy.com/fervo-energy-drilling-results-show-rapid-advancement-of-geothermal-performance/.

Fervo Energy: "Fervo Energy Breaks Ground on the World's Largest Next-Gen Geothermal Project" (2023). https://fervoenergy.com/fervo-energy-breaks-ground-on-the-worlds-largest-next-gen-geothermal-project/.

Friðleifsson, G.O., Elders, W.A., Zierenberg, R.A., Stefánsson, A., Fowler, A.P.G., Weisenberger, T.B., Harðarson, B.S., and Mesfin, K.G.: "The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the Seawater-Recharged Reykjanes Geothermal Field in SW Iceland Has Successfully Reached Its Supercritical Target," *Scientific Drilling* 23 (2017). https://doi.org/10.5194/sd-23-1-2017.

Gunnlaugsson, E., Ármannsson, H., Thorhallsson, S., and Steingrímsson, B.: "Problems in geothermal operation–scaling and corrosion," Geothermal Training Program, United Nations University, 1–18 (2014).

Hill, B.: "Superhot Rock Geothermal: A Vision for Zero-Carbon Energy 'Everywhere,'" Clean Air Task Force (2021). https://cdn.catf.us/wp-content/uploads/2021/09/21091759/CATF_SuperhotRockGeothermal_Report.pdf.

Hill, J.: *Focus on geothermal innovation heats up with DOE's new liftoff report.* Clean Air Task Force (2023). https://www.catf.us/2024/03/focus-geothermal-innovation-heats-up-does-new-liftoff-report/.

Kruszewski, M., and Wittig, V.: "Review of Failure Modes in Supercritical Geothermal Drilling Projects," *Geothermal Energy* 6:28 (2018). https://doi.org/10.1186/s40517-018-0113-4.

Miller, J. D. A.: "Principles of microbial corrosion," British Corrosion Journal, 15(2), 92–94 (1980).

Moore, J., McLennan, J., Allis, R., Pankow, K., Simmons, S., Podgorney, R., Wannamaker, P., Bartley, J., Jones, C., and Rickard, W.: "The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): An International Laboratory for Enhanced Geothermal System Technology Development," Proceedings, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2019). https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2019/Moore.pdf.

Petty, S., Uddenberg, M., Garrison, G. H., Watz, J., and Hill, B.: Path to Superhot Geothermal Energy Development, Geothermal Rising Conference (2020).

Piana Agostinetti, N., Licciardi, A., Piccinini, D., Mazzarini, F., Musumeci, G., Saccorotti, G., and Chiarabba, C.: "Discovering geothermal supercritical fluids: a new frontier for seismic exploration," Scientific Reports, 7(1), 14592 (2017).

Pink, T., and Pearce, R.: "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Drilling," Clean Air Task Force (2024). https://cdn.catf.us/wp-content/uploads/2024/05/10102719/shr-bridging-gaps-drilling.pdf

Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., and Sanjuan, B.: "Utilizing Supercritical Geothermal Systems: A Review of Past Ventures and Ongoing Research Activities," *Geothermal Energy* 5:16 (2017). https://doi.org/10.1186/s40517-017-0075-y.

Sanada, N., Kurata, Y., Nanjo, H., Kim, H., Ikeuchi, J., and Lichti, K. A.: "IEA deep geothermal resources subtask C: materials, progress with a database for materials performance in deep and acidic geothermal wells," Proceedings, World Geothermal Congress, Kyushu, Tohoku, Japan, 2411–2416 (2000).

Scott, S., Driesner, T., and Weis, P.: "The thermal structure and temporal evolution of high-enthalpy geothermal systems," *Geothermics* 62 (2016): 33-47 (2016).

Suryanarayana, P.V., Krishnamurthy, R.M., and Bour, D.: "Bridging the Gaps: A Survey of Methods, Challenges, and Pathways for Superhot Rock Well Design and Construction," Clean Air Task Force (2024). https://cdn.catf.us/wp-content/uploads/2024/10/01162900/shr-well-design-construction.pdf.

Tester, J. W., Anderson, B. J., Batchelor, A. S., Blackwell, D. D., DiPippo, R., Drake, E. M., Garnish, J., Livesay, B., Moore, M., and Nichols, K.: "The Future of Geothermal Energy," prepared for the U.S. Department of Energy by the Idaho National Laboratory (2006).

Thiel, S.: "Electromagnetic monitoring of hydraulic fracturing: Relationship to permeability, seismicity, and stress," *Surveys in Geophysics*, 38(5), 1133–1169 (2017).

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Geothermal Technologies Office: "Enhanced Geothermal Systems Pilot Demonstrations" (2024). https://www.energy.gov/eere/geothermal/enhanced-geothermal-systems-egs-pilot-demonstrations.

van Oort, E., Chen, D., Ashok, P., and Fallah, A.: "Constructing Deep Closed-Loop Geothermal Wells for Globally Scalable Energy Production by Leveraging Oil and Gas ERD and HPHT Well Construction Expertise," presented at the SPE/IADC Drilling Conference and Exhibition (2021). https://doi.org/10.2118/204097-MS.