SUPERHOT ROCK GEOTHERMAL

Technology Needs for Scaling Geothermal Resources Globally

HERO
Hotrock Energy Research Organization

Authors:
Hotrock Energy Research Organization
Matthew Uddenberg, Geoffrey H. Garrison, Susan Petty, Jill Watz

Contributors:
Carlos Araque (Quaise, Inc.), Daniel Bour (Blade Energy Partners), Trenton Cladouhos (Cyrq Energy), Patrick Dobson (Lawrence Livermore National Laboratory), Wilfred Elders (University of California, Riverside), Takako Hattori (Fuji Power), William Glassley (Earth System Sciences, LLC), Stan Mason (Blade Energy Partners), Michael Moore (AltaRock Energy), Tatiana Pyatina (Brookhaven National Laboratory), Samuel Scott (Reykjavik University).

THE FOLLOWING ORGANIZATION(S), UNDER CONTRACT TO CATF, PREPARED THIS REPORT:

Hotrock Energy Research Organization, Inc. (HERO)

TABLE OF CONTENTS

PART I

INTRODUCTION

This paper explores the advantages of superhot rock (SHR) geothermal, the state of its development, future technology needs, and the technological and economic feasibility of scaling SHR to meet global energy demands.

SHR geothermal is capable of unlocking terawatt-scale renewable energy supplies by sweeping heat from very massive stores of high temperature basement rock (>450°C) in the earth's crust.

Superhot Rock and Its Relevance to Clean Energy

Addressing climate change requires a massive shift away from fossil energy over the next three decades. Solar and wind currently dominate renewable energy development, but even when coupled with battery storage for firming, these intermittent resources pose serious challenges due to their low power density, massive land requirements and the need to invest in large-scale and vulnerable transmission assets. Geothermal energy currently provides clean, baseload, grid-balancing power, but it remains a niche energy source due to limited geographical availability. Enhanced geothermal systems (EGS) technology has opened the possibility of producing geothermal energy everywhere, but a decade of research into EGS below 250°C has found it to be too expensive and without a clear path to large-scale market adoption. Economically competitive geothermal power can be developed if the output per well is radically improved. A promising way to achieve this goal is by creating EGS in hotter and deeper rock (>450°C), thereby increasing power output per well by 5-10x over existing EGS projects. These high temperature systems are referred to as superhot rock geothermal (SHR), and they are poised to disrupt the energy industry.

SHR geothermal is a renewable energy resource capable of unlocking terawatt-scale energy supplies by sweeping heat from massive stores of high temperature basement rock (>450°C) in the earth's crust. These temperatures can be found everywhere at depths between 5–20km. SHR is unique in its potential to replace all existing fossil fuel power generation and meet most of the future global energy demand with a very limited environmental footprint and at costs competitive to US natural gas and other renewables. No other primary energy source is as ubiquitous, clean, and secure as SHR. Production can be located near demand centers and serve as baseload power, eliminating the need for major investment in transmission and energy storage.

SHR resources at depths shallower than 10 km can be reached today using existing mechanical drilling technology and could potentially supply up to 50% of current global electricity demand.

Key technologies needed for the development of SHR resources are underway. Much of this work is funded and supported by the public sector in countries around the world. Currently, the US government does not fund R&D in SHR. Several private companies are also pursuing the development of these resources and the necessary supporting technologies. By leveraging the work done by both the public and private sectors, a near term demonstration can be realized within 3-4 years and the first SHR power plan is achievable within 5-6 years.

Most importantly, SHR resources at depths shallower than 10 km can be reached today using existing mechanical drilling technology and could potentially supply up to 50% of current global electricity demand (Figure 1). With technology investments aimed at economically reaching depths between 10- 20 km, SHR resources can eventually scale to meet a significant portion of global energy demand.

Scaling SHR requires the combined efforts of the global energy industry, to leverage their knowledge and expertise to accelerate the development of critical technologies. Scaling SHR to meet global climate goals can leverage the fossil fuel industry's expertise and global infrastructure distribution, providing the industry a successful economic pivot to clean energy.

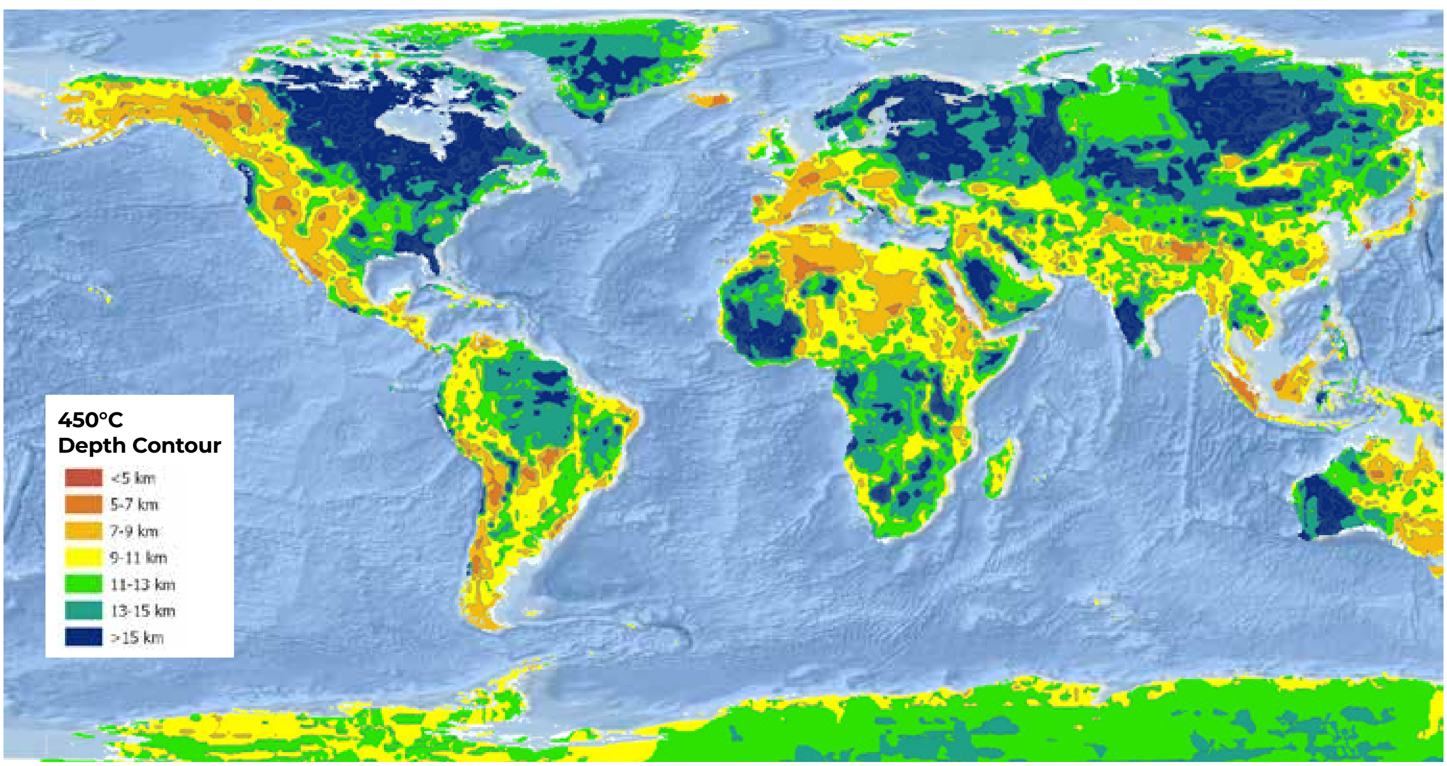


Figure 1. Regions of the world where SHR resources (temperatures exceeding 450°C) are accessible with conventional continental drilling technologies - depths < 10 km. These regions are within 200 km of 50% of the world's population (PNNL, 2022; University of North Dakota, 2022).

PART II

TECHNICAL AND ECONOMIC ADVANTAGES OF SHR RESOURCE

Economic Advantages of SHR

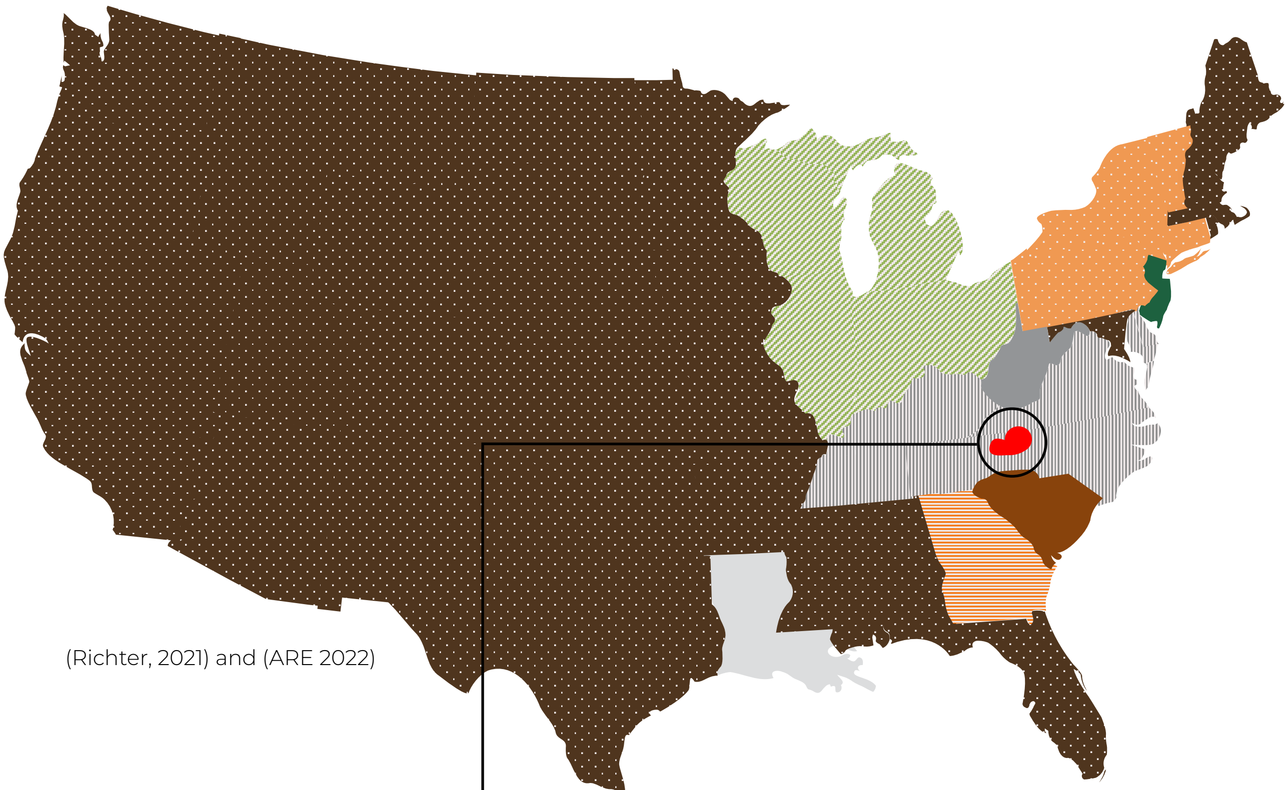
The wholsesale cost of electricty produced from SHR resources is projected to be in the range of \$35-\$50/MWh, which is equal to or far lower than the world's best geothermal resources. For example, geothermal power in Iceland costs around \$40-45/MWh (Richter, 2011). Cost is determined by these factors:

1. **Capacity** – Larger plants can capitalize on economies of scale to lower costs.
2. **Energy per Well** – Producing higher enthalpy (energy) fluids leads to higher heat production per well and allows for the use of more efficient power conversion technologies such as supercritical turbines and power cycles.
3. **Pressure** – Higher pressure reservoirs translates to higher mass flows, and higher turbine efficiency, enabling greater power production.
4. **Small Environmental Footprint** – SHR plants will have a smaller environmental footprint compared to conventional geothermal or EGS because SHR produces far more power per well. SHR plants require less than **one-tenth the land use** and **one-tenth the water** of conventional geothermal[1].
5. **Power Density** – SHR's power density, net MWs of electric power produced per square kilometer, is on the order of 100 MWe/km^2, is similar in range to hydrocarbon fuels, but far exceeds the power density of most other renewable energy resources.

1 Compared to conventional geothermal for example, a SHR plant using steam or supercritical water needs ~500 kg/s of flow to generate 200 MW, a 200 MW binary power plant using 150°C water requires 5000 kg/s of flow. More flow requires larger pipes, larger footprint, and leads to more heat loss.

Figure 2

Comparison of Primary Energy Source Land Use per Terrawatt (TWe) of Electric Power Produced



(Richter, 2021) and (ARE 2022)

RESOURCE	KM²
Biomass	4,756,680
Wind	630,720
Hydro	473,040
Solar PV	323,244
Natural Gas	162,936
Solar Thermal	134,028
Coal	84,972
Geothermal Conv	65,700
Nuclear Power	21,024
SHR Geothermal	10,000

SHR Geothermal uses a fraction of the land compared to all renewables, fossil fuel and nuclear

Scaling carbon-free energy sources to meet climate objectives must take into consideration and minimize environmental impacts. Minimizing land use required to develop these energy resources mitigates the fuel/food trade-off and preserves critical habitat and biodiversity. Figure 2 compares the amount of land use required to generate one terrawatt of electric power. It is notable that SHR utilizes the smallest land footprint, at least an order of magnitude smaller than renewables and several times better than conventional resources.

Newberry Volcano, OR: Site for First SHR Demonstration in the US

Newberry Volcano, in central Oregon, is one of the best locations in the United States for demonstrating a SHR resource. The target temperature of 450°C is accessible at depths as shallow as 4.5 km, and AltaRock Energy (ARE) has continuously improved characterization and modeling of the resource over the past decade. A techno-economic study comparing a conventional EGS to SHR development has been evaluated, and the results are compelling. ARE[2] numerically modeled fracture initiation and propagation in Newberry's high temperature basaltic basement and coupled that fracture analysis with a reservoir model run over a 30-year period to evaluate reservoir production rates over time. These results were used to determine the type of power system required to best utilize the resource. Results indicated that a 100 MWe plant using this SHR resource could provide power at a competitive price of $0.035–$0.05 per kilowatt-hour.

Table 1 compares project design and economics between a 100 MWe SHR resource and conventional 200°C EGS resource.

Table 1

Comparison of project economics between SHR and conventional EGS for a 100 MWe power plant at Newberry Volcano, Oregon.

	SHR	Conventional EGS
Reservoir Temperature	**420°C**	200°C
Number of Wells P:I	**4:2**	24:12
Footprint (acres)	**50-150**	500-800
Fluid flowrate	**240 kg/s**	2160 kg/s
LCOE $/kWh	**$0.035-$0.05**	$0.08-0.12

Source: AltaRock Energy

2 ARE conducted this analysis in collaboration with University of Oklahoma and Baker Hughes. Results will be published in 2022.

SHR reservoirs can produce 5 to 10 times more electricity per well than a conventional EGS well, thus requiring substantially less infrastructure to create the same amount of electricity (Ingason, 2018).

Economics of Scaling SHR

As more SHR projects are built, costs will decline with learning and technical improvements. In a typical geothermal field, the tenth well will cost only 25% of the first due to learning over time (Lukawski, 2016). Current geothermal plants typically exploit unique hydrothermal systems that are rare, small, and chemically and structurally unique. This makes scaling geothermal technologies difficult. The knowledge, and cost-savings gained developing one geothermal field do not often transfer well to another field. However, SHR targets deep basement rock, which is typically more uniform, even from region to region. SHR success will not be dependent on unique collocation of natural features such as permeability, chemistry, and accessibility. Dry wells and fluid chemistry are less of a risk because fluids are added and chemistry can be controlled during the creation of the reservoirs. SHR resource developers will design the inlet conditions, pressure, and temperature of produced fluids by selecting specific depths and conducting specific types of stimulations. This will enable suppliers to standardize tools and operations across multiple fields. Finally, power plant designs do not have to be site specific but can become standardized from project to project, further reducing costs.

Developing SHR within 10 km depth is the near-term target for technology advancement and demonstration. Every continent has regions where SHR resources can be accessed with conventional drilling and could meet the electricity needs of 50% of global population.

Technical Advantages of SHR

SHR does not rely on exploration for in situ geofluids or steam, they are engineered geothermal systems[3] and therefore, dry hole risks of conventional geothermal are eliminated. Figure 3 shows different geothermal resource attributes in terms of depth, geology and temperature for: conventional, hydrothermal, conventional EGS and both shallow (<10 km) and deep (>10 km) SHR.

SHR eliminates the exploration risk associated with conventional geothermal and significantly lowers upfront development costs.

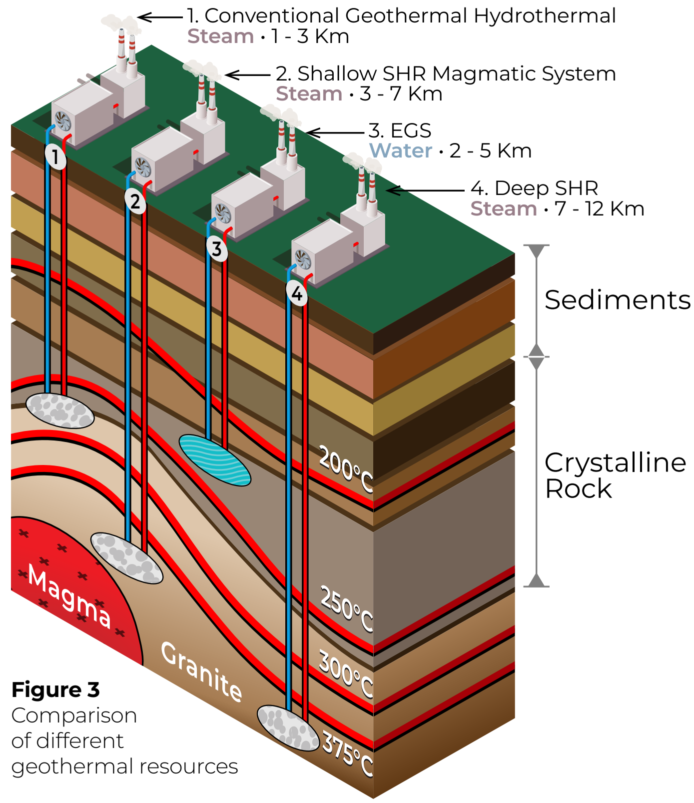


Figure 3
Comparison of different geothermal resources

Enthalpy Boost: More Energy per Well

The energy content, or enthalpy, of water increases as it approaches the critical point, 375°C and 22 MPa (see Figure 4). Above this critical point (where water behaves both like a liquid and a vapor) water becomes supercritical, and has high enthalpy, high energy density, and low viscosity. These physical characteristics improve reservoir fluid flow and energy efficiency and are key to dramatically improving SHR system economics. As a point of comparison, 150°C water at 10 bar, which represents a typical produced fluid from a moderate temperature EGS field, has a fluid enthalpy of 630 KJ/kg, whereas fluids produced from a SHR resource will have fluid enthalpies of > 2000 KJ/kg (Moon, 2012; NIST, 2022)

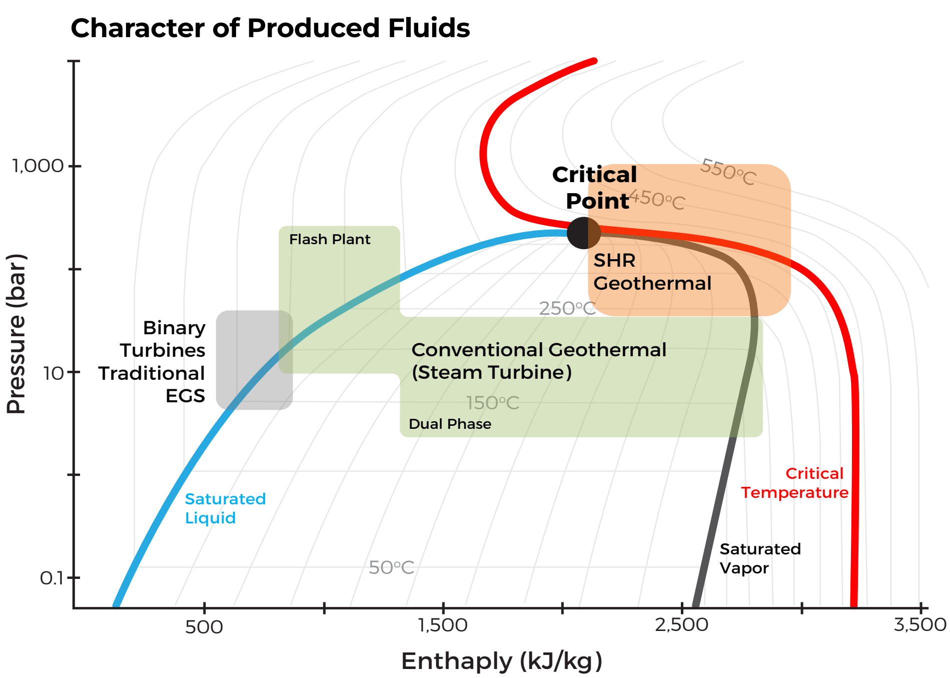


Figure 4
Water phase diagram showing the different conditions (pressure, temperature, and enthalpy) of conventional EGS (200°C) and SHR (450°C).

3 SHR are distinctly EGS and not supercritical hydrothermal systems, where in situ fluids exist in a supercritical state in fractures or porous matrix often located above magmatic systems.

Energy Conversion Efficiency Boost: More Power from the Turbines

Increasing fluid enthalpy enables higher efficiency power plants and improved power production. High temperature conventional geothermal plants (200–350°C input) use a steam turbine with net efficiencies of 13–23%. Lower temperature geothermal plants (125°C–175°C input) use binary organic rankine cycle power generation with net efficiencies of only 6–12%. Supercritical power plants, however, could obtain much higher thermal efficiencies, the theoretical max being about 50% (Moon, 2012). Thus, not only will SHR reservoir geofluids carry more energy per mass, but their high temperatures allow more of that heat to be converted to electricity. The net result is that SHR reservoirs can produce 5 to 10 times more electricity per well than a conventional EGS well, thus requiring substantially fewer wells and less infrastructure to create the same amount of electricity.

Scalability

Meeting aggressive decarbonization of the global economy by mid-century requires that every reasonable option for clean power generation be pursued. An analysis of the technology development pathway for SHR indicates that within 2-4 years, and with appropriate investment, the first SHR resource <10 km depth can be demonstrated, and power production can be attained within 4-6 years. By 2030, advanced drilling (>10 km) will likely be ready for commercial deployment. With these new drilling tools, SHR could easily scale to meet a significant portion of the world's electricity and industrial heat needs by 2050.

Using the historic ramp-up of US unconventional oil & gas resources over the past 25 years, analysis shows that SHR can very conservatively become >20% of worldwide electric generation by 2050. For example, the U.S. Energy Information Administration (EIA, 2020) estimates that global electricity demand will reach 45 trillion kWh by 2050. Assuming an average conservative production of 25 MWe per well, then 40,000 new SHR wells would be needed by 2050 to supply approximately 9 trillion kWh. This field deployment would require an average of 1000 drill rigs globally, completing two wells per year for 20 years. This assumes conventional drilling technology and a rate of penetration of 66 meters per day. By comparison, 2000+ drill rigs were deployed in the US unconventional oil & gas by 2014, a rig count that followed a substantial build-up over a single decade. Drilling capabilities and rigs are already widely available and distributed on every continent, thus scaling SHR well beyond 20% of projected 2050 demand is well within reason. The existing global O&G infrastructure can be utilized to build out SHR resources.

Some current geothermal projects are already tapping into natural supercritical geothermal systems (e.g., Iceland IDDP, Salton Sea, CA, New Zealand CNS) where there are shallow high temperature fluids (Dobson, 2017). While accessible natural supercritical systems are rare, developing these resources will contribute important information and technology toward expanding SHR everywhere. Developing SHR within 10 km depth is the first step toward technology advancement to scale geothermal globally. Every continent has regions where SHR can be accessed using conventional drilling (Figure 1).

Resource analyses conducted by HERO using data from the Pacific Northwest National Laboratory (PNNL) and University of North Dakota,[4] based on heat flux and geologic data, have shown that exploiting SHR in areas shallower than 10 km can supply electricity to 50% of the global market. With the advancement of energy drilling technologies, deeper SHR resources will become accessible and dramatically increase SHR's potential share of global clean energy production.

4 https://engineering.und.edu/research/global-heat-flow-database/heatflowlinks.html

Risks

Any potential energy solution developed to mitigate climate change will carry some inherent risk. However, the geothermal industry has shown that with proper planning, reservoir management, and seismic monitoring, it can control seismic events to levels below physical detection at the surface. The Geysers geothermal field has been producing geothermal energy since the 1960's and the seismic impact on local communities has been minimal (Khan, 2010; Majer 2007). This is despite being located in one of the most tectonically active regions in the United States. The long-term success of this operation can be attributed to the monitoring and mitigation techniques honed over 70 years of operation. Additionally, seismic risk may decrease as hotter and deeper, more ductile, rock is accessed. At elevated temperatures, rocks begin to bend instead of break in response to stress. Studies have corroborated this thesis, showing that the frequency of earthquakes goes down significantly with depth and temperature (Tal, 2015). Furthermore, geothermal operations include both injection and production of fluid from the reservoir, which will partially mitigate the build-up of pressure and reduce the chance of larger seismic events. The largest seismically induced events appear to be related to long-duration wastewater injection into basement faults (Rubinstein, 2015). It is believed that these large earthquakes are the result of pressurizing faults over large areas. By managing the extent of the pressure transient within fault like features, seismic events associated with SHR can be manged and minimized.

Tools, Solutions and Resources: Current State of SHR Development

Many of the technologies needed to create SHR systems currently exist. This is demonstrated by the wells which have been successfully drilled into natural supercritical hydrothermal systems and by the development of high pressure and temperature geothermal power plants at resources such as the Salton Sea Geothermal Field. However, additional technical advancements are needed to enable ubiquitous SHR resources in the following areas: drilling, instrumentation, well completion technologies, and reservoir development in high temperature environments. HERO evaluated the state of technology development with industry experts, and Table 2 provides a summary of the state of play and path to commercialization. While technical challenges remain, much of the technology needed exists but needs to be optimized for SHR. Additionally, where new technology is needed, developments are in-progress throughout the industry and the engineering required is readily achievable with investment. For example, power generation using supercritical water and high-pressure steam turbines is a mature technology already deployed globally in coal and nuclear power plants. Therefore, with slight modifications to accommodate specific geochemistry and inlet conditions, SHR systems could use existing power plant technologies.

Table 2

SHR Technology Development Needs

SHR Technology Needs	Description of Key Technologies	Current State of Commercial Technology	Limitations/Development Requirements	State of Tech Development* R&D – concept under dev LT/P – lab testing/prototype FD/T – field deployment/test	Time to Commercialization (years)
Instrumentation	HT Downhole measurement/monitoring tools	Limited to <250°C	Requires >350°C with cooling. HT electronics, fiber optics technology is in development across multiple suppliers. Temperature and pressure tools from Probe are rated to 370°C[5]. Other tools, like gamma or resistivity, will be more difficult to build for high temperature.	LT/P	1-4
	Downhole Borehole Televiewer		Commercial BHTV are only rated to <200°C Prototypes of an ultrasonic viewing tool have been tested to 300°C but have not been commercialized[6].	LT/P	1-3
	MWD (T, P, flow, etc)		Commercial MWD tools are only rated to <200°C. Prototype versions have shown to be operatable up to 300°C[7].	LT/P	1-3
Well Completion	Robust well engineering design using HT materials capable of long-life thermal cycling				
	HT Cements	<200°C	HT cements under development at National Labs and companies. Robust lab testing completed, many promising candidates[8].	R&D and LT/P	1-2
	HT Couplings	>300°C	It is possible to use existing technology today, however, lifecycle under SHR conditions unclear. Expandable couplings are promising for mitigating thermal expansion of the casing string. High temperature expandable coupling are currently being field tested by ISOR[9] and other companies.	LT/P	1-2
	HT Casings	>300°C	Need lower cost casing capable of thermal cycling with composite materials/lower cost field deployment (in-situ). The metallurgies needed to complete these wells exist, but too costly. Composite materials with novel delivery and well completion design are in development and could drive down completion costs..	R&D	1-5
Reservoir Engineering/HE	Zonal Isolation, stimulation and reservoir integrity methods/technologies				
	Mechanical zonal isolation	>300°C	Mechanical permanent packers developed tested and rated for >500°C[10]. Other removable zonal isolation tools (swellable packers) are in development.	LT/P /FD for MPP LT/O – removable packers	< 1-2
	Chemical zonal isolation	>300°C	HT Diverters have been studied up to 300°C and may be robust for higher temperatures[11]. New materials optimized for higher temperatures are also being explored.	LT/P	<1
	Stimulation methods	<250°C	Hydro-shearing stimulation methods have been tested to >300°C[12], whereas hydraulic fracturing stimulation has not been successfully implemented above 225°C. Hydraulically fracturing high temperature rock requires new methods. Some promising techniques are under development.	R&D	2-5
	HT Proppants	<200°C	Current proppants for O&G are limited to <225°C[13] New materials for development and field testing underway.	LT/P	1-2
Drilling	Conventional Drilling needs HT components for cost reduction/Deep drilling >10 km	>300°C			
	HT Bits	>300°C	Multiple bits have been used to successful drill to temperatures >400°C. The drilling rate can likely be improved with the creation of high temperature PDC bits.	FD/T	<1-3
	HT drilling fluids/mud	>300°C	Water based drilling fluids can be used to drill to >400°C if adequate cooling is available.	FD/T	<1
	Deep drilling >10 km	>300°C	Several options under development by multiple companies	R&D, LT/P	>5
Power Plants	Cycles/Equipment	450-800°C HP Systems	SHR can used low end of existing equipment with decent efficiency and cost. Turbine manufacturers have ability to optimize SHR power plant for specific range of temperatures and pressures from SHR reservoirs.	Engineering/FD	2-3

** refer to figure 5*

5 https://www.probe1.com/solutions/geothermal/
6 https://www.energy.gov/sites/prod/files/2014/02/f7/high_patterson_gufi.pdf
7 https://www.osti.gov/biblio/1496969-high-temperature-measurement-while-drilling-system
8 https://www.bnl.gov/isd/geothermal/cementitious-composite.php
9 https://en.isor.is/geconnect-tight-geothermal-casing-connections-axial-stress-mitigation
10 https://welltec.com/products-landing-page/wabs-packers/magma-packer-for-geothermal/
11 https://patents.google.com/patent/US9090810B2/en
12 Cladouhos, Trenton T. [1]; Petty, Susan [1]; Swyer, Mike W. [1]; Nordin, Yini [1]; Garrison, Geoff [1]; Uddenberg, Matt [1]; Grasso, Kyla [1]; Stern, Paul [2]; Sonnenthal, Eric [3]; Foulger, Gillian [4]; Julian, Bruce [4]. Newberry EGS Demonstration: Phase 2.2 Report, 2015. AltaRock Energy, Seattle WA.
13 Clay G. Jones, Stuart F. Simmons and Joseph N. Moore, 2014. Proppant Behavior Under Simulated Geothermal Reservoir Conditions. PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 24-26 Newberry EGS

Drilling

Drilling tools and methods are the most mature of the technologies for SHR. Conventional drilling has been commercially deployed to reach depths of up to 10km and reach temperatures greater than 450°C. However, these achievements occurred separately. Drilling 10 km and 450°C is currently cost prohibitive. Some refinement of mechanical drilling tools and methods will be needed for SHR, but the drilling technology providers are confident only incremental changes are required to existing technology. The few wells drilled to date into (shallow) supercritical systems were done with conventional technologies adapted for the unique geology, high temperatures, and corrosive fluids at each of these projects (Bertani et al, 2018; Friðleifsson, 2015; Friðleifsson, 2018). In addition, there have been some big improvements in specific technologies, such as mud motors, bits, and mud systems, which enable cheaper, higher efficacy, drilling at SHR conditions. With the introduction of high temperature electronics currently under development by several teams, such as Probe and Ozark OC, drilling SHR wells will become far less challenging and expensive.

While unconventional oil and gas development has relied heavily on horizontal drilling to increase output per well, SHR wells will vertical or angled and not horizontal. Oil and gas wells turn horizontal to follow the resource they pursue. Heat, however, increases with depth, and so verticals well reach those resources with the shortest path. It is also a benefit to connect with as many fractures as possible, and induced fractures tend to grow vertically. Thus, an angled well path serves to connect with the most fractures while reaching heat as soon as possible. Horizontal wells also prevent use of many logging and well completion tools. Well paths can be angled in shallow cool rock, and the directional tool then removed when temperatures exceed tool limit, currently ~200 °C (Baker Hughes, 2022). The trajectory can be maintained using mechanical devices such as stabilizers.

Instrumentation

High temperature instrumentation is needed for drilling, well completion, and wellfield operations. For example, most wells are directionally drilled with steering tools to achieve a specific angle and orientation which targets reservoir permeability and enhances well productivity. Targeting is done by controlling the angle and orientation of the bottom hole assembly (BHA), which contains the mud motor, drill bit, and any other tools located at the end of the drill string. Logging while drilling allows drillers to determine downhole conditions, such as rock fractures and temperature. All these systems require high temperature electronics and robust mud cooling to operate in SHR conditions. Tools and techniques developed for SHR conditions have been tried and tested at the Drilling in Deep, Supercritical Ambient of Continental Europe (DESCRAMBLE) project in Italy and the Iceland Deep Drilling Project (IDDP) in Iceland (Bertani, 2018; Friðleifsson, 2018). The only physical attributes measured in these wells were temperature and pressure. Instruments (both Kuster and synthetic fluid inclusion probes) could not directly measure temperatures over 400°C. However, the SINTEF TP tool was able to directly measure temperatures over 400°C (Bertani, 2018).

Well Completion

The three primary areas in need of advancement are: casing, cement and casing couplings. Casing materials must be compatible with the temperatures and chemistry of produced fluids. High temperature metallurgy is a mature discipline, but casing material selection is weighed against material cost and availability. Titanium, is used commercially in current geothermal wellfields, but has limited use due to high costs. The corrosivity of natural supercritical geofluids is a challenge for casing metallurgy. For example, Iceland's supercritical IDDP-1 well is famous for having the highest recorded temperature for a flowing geothermal well, but hydrogen chloride and dissolved silica both corroded, eroded and ultimately led to casing and surface equipment failure. As discussed previously, SHR wells may avoid corrosive fluids by managing the fluids being injected into the reservoir. However, there is still some risk that fluid interaction with the reservoir rock will result in corrosive fluids which must be managed. In such cases, more corrosion resistant metallurgies, such as titanium or high chrome steel, may be needed for the casing exposed to produced fluids.

The cement used during well completion places a barrier between the casing and the rock that protects that casing from corrosion, provides strength to maintain casing integrity and supports the well structure. The most common cement used in well completion is ordinary portland cement (OPC), but OPC doesn't set correctly at high temperatures. Poor cementing jobs and weak cement lead to poor well flow, casing corrosion, compromised well integrity and, in the worst-case scenarios, well collapse. Alternate cement formulations include silica-lime, high alumina, and calcium- aluminate-phosphate, each an improvement over OPC in thermal wells.

Lastly, thermal expansion of well casings may severely weaken the integrity of SHR wells. Wellbore temperature changes of 200+°C can lead to a build-up of strain in concentrated sections of the wellbore which may exceed casing yield strength, and result in casing failure. For example, flexible couplings designed to prevent failure have been developed and tested in the EU-funded GeoWell H2020 project (Ragnarsson A, et al, 2018). These innovative couplings and similar designs could become a standard for SHR well completions in the future.

Reservoir Engineering/Heat Extraction

Moving SHR beyond natural supercritical systems requires methods to extract heat from impermeable hot rock. Rock has a very high heat capacity that enables it to store large amounts of heat, but it has poor thermal conductivity. In order to generate significant power from the SHR reservoir, working fluid used must be exposed to a large amount of surface area within the hot rock volume. A typical EGS design creates a reservoir comprised of many interconnected fractures to achieve a reservoir with a large surface area. Water is cycled through these interconnected fractures to withdraw large amounts of power from the rock. Other designs to maximize heat exchange area at depth have included coaxial downhole heat exchangers, multiple long reach horizontal well legs, and multiple down hole microholes, though none are yet commercial.

Stimulation of impermeable rock needed to create significant permeability at high temperatures is a significant technical challenge for SHR. Deeper SHR will not have much natural permeability, and the mechanical properties of rocks above 400°C have not been sufficiently studied and are not well understood. Numerical modeling and empirical testing of rock behavior at these conditions are needed. There are several academic and government funded projects working on this foundational understanding. For example, published studies from Universities in Japan and China show promising results and indicate that reservoir stimulation may be substantially easier above 400°C (Changbing, 2018; Watanabe, 2019), but more work is required. In addition to better understanding rock properties at these temperatures, other technologies will be needed to create and maintain the reservoir permeability over time, including high temperature electronics, mechanical isolation tools, and proppants.

Energy Conversion/Power Generation

Power generation cycles using supercritical water common to coal-fired and nuclear power plants could be adapted for SHR resources, but they would be challenged by fluid chemistry management. The chemical interaction of supercritical water and rock at SHR conditions can create corrosive and metal-rich fluids that would be damaging to conventional turbine systems. Corrosive fluids can be treated, but the cost to do so may favor producing high pressure steam from SHR wells instead. In that case, conventional geothermal power generation technologies could be used. Reducing wellhead pressure to allow supercritical fluid to convert to steam would reduce the enthalpy of the flow, but it would also allow a higher mass flow rate and still achieve a high energy extraction rate per well.

In order to achieve SHR everywhere, technical advancements are needed in the following areas:

Instrumentation

Technologies to measure and image well and reservoir development in high temperature environments.

Well Design and Completion

Technologies capable of withstanding temperatures above 450°C and long-term thermal cycling.

Reservoir Engineering

Technologies and methods to create and sustain permeable reservoirs within basement rock with pressures and temperatures exceeding 50 MPa and 450°C.

Deep Drilling

Drilling technologies to reach depths >10 km and temperatures > 450°C.

PART III

SHR Development: Current Projects and Development Pathways

Newberry EGS Demonstration, Oregon

Current SHR Projects

Nine research groups are conducting research and development of natural supercritical and SHR resources (Table 3). Six of the projects are funded by the EU and are largely consortia of universities, government research organizations and private developers. EU countries engaged in this research include the Netherlands, Germany, France, Italy, Spain, Norway, Switzerland, and Iceland. Active supercritical field projects are taking place in Iceland as part of the IDDP and DEEPEGS projects, and Italy as part of the DESCRAMBLE project. GNS Science, New Zealand's leading provider of geoscience research, is studying development of supercritical resources and has recently launched Geothermal: The Next Generation resource program as a joint public private partnership. The Japanese government has funded the Beyond Brittle Project which has built a world class laboratory facility for experimental study of rock mechanics at very high temperatures and pressures. In the US, there is currently no direct government support of SHR development. ARE, a leader in EGS technology, is leading a research consortium to demonstrate the first SHR resource energy extraction at the Newberry Volcano in Oregon.

Table 3

Status of Current and Recent SHR Projects Globally

Project	Country/Organization	Description	Research Focus	Key Discoveries	Status and Future Plans
Japan Beyond Brittle Project (JBBP)	Japanese Government	Rock mechanics, induced seismicity, exploration, drilling and logging technologies for geothermal development in and below the brittle-ductile transition.	Shallow magmatic systems. Specialized HT/HP lab for evaluating rocks and stimulation methods and instrumentation.	Cloud fracture formation from thermal shock and overpressure that increased permeability of natural fractures.	Uncertain. https://www.aist.go.jp/fukushima/en/unit/GET_e.html
Iceland Deep Drilling Project (IDDP), and DEEPEGS	Iceland/EU	Wells IDDP–1 and –2 were completed in magmatic-heated supercritical hydrothermal resources.	Drilling, casing and stimulation methods and systems for managing HT, corrosive geothermal fluids; well stimulation using thermally induced fracturing.	Casing failures in well IDDP–1; Diverter challenges and blockage at 777 m have prevented flow test of IDDP–2; study of new materials, compatibility, well designs.	New well (IDDP–3) has been proposed; Power plant development is considered. https://iddp.is/ https://deepegs.eu/
Aotearoa Hotter and Deeper Exploration Systems (HADES)	New Zealand Government and GNS Science	Supercritical geothermal fluid resource development in northern New Zealand.	Supercritical geothermal fluid resource development in northern New Zealand Fracture characterization, deep resource exploration, fluid-rock chemistry.	Characterization and delineation of the supercritical geothermal reservoir in the Taupō Volcanic Zone.	Development of the Taupo Volcanic Zone SHR for long-term electricity production of up to 10 GWe. https://www.geothermalnextgeneration.com/
Integrated Methods for Advanced Geothermal Exploration (IMAGE)	European Union/19 participants from nine member countries	Perform testing and validation of new methods at existing geothermal sites in high temperature magmatic, including supercritical, and in basement/deep sedimentary systems.	Process and properties of high temperature geothermal systems, new exploration techniques and integrating findings into operating geothermal projects.	Developed catalogue of rock properties at high temperatures and pressures, and a world stress map; new active seismic techniques were developed and tested.	Completed. https://vbpr.no/research/ext-research-collaboration/image/
Drilling in dEep, Super-CRitical AMBient of continentaL Europe (DESCRAMBLE)	Italy/EU	Develop and test new and innovative drilling technologies able to withstand SHR resources at Larderello, Italy.	Venelle–2 well (Larderello Geothermal Field) was deepened to 3–4 km with a bottomhole temperature of 450–500°C.	Deep and high temperature drilling methods, advanced drilling muds, mud cooling systems, drill bits, casing cementing, logging tools and wellhead design.	Completed. http://www.descramble-h2020.eu/
GEOWELL	EU funded Iceland GeoSurvey IRIS, Norway TNO-Netherlands BRGM-France GFZ-Germany	2016–2019, evaluated development of new technology for the design and operation of high-temperature geothermal wells.	Cement slurry design, casing selection, couplings, downhole temperature and strain measurements using fiber optics.	Fabrication of expandable couplings for HT wells capable of handling thermal expansion and cycling.	Completed. https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/geothermal/geowell
GEMEX	EU/Mexico	2015 – 2020, focused on exploration and development of two SHR resources at Los Humeros and Acoculco Fields in Mexico.	Focus on characterizing the BDT zone below existing reservoirs using stress measurements and geologic data.	Very high temperature wells have been drilled to 380+°C but, casing material failures due to HT shutdown the project.	Completed. http://www.gemex-h2020.eu/index.php?lang=en
Newberry SHR Demo	Newberry Volcano (OR), AltaRock Energy, Pacific Northwest Labs, Oregon State U., U. of Oklahoma, et al.	AltaRock Energy–led consortium to evaluate development of Newberry as a first SHR demonstration site; Newberry site has two 3.5 km wells with BHT of 350°C.	Stimulation methods at 450+°C, reservoir mechanics, well completion techniques, and power plant design.	In development.	Under development, ARE is executing on a 5-year demonstration program to flow the first SHR-EGS resource in the world by 2025.

Roadmap to a Future with SHR

There is skepticism about moving to SHR geothermal without having fully demonstrated technically viable conventional EGS at scale. However, this research team's analysis suggests otherwise. As explained above, while technical challenges remain for developing SHR resources, the dramatically improved economics, smaller environmental footprint and infrastructure requirements conclude that moving to SHR is an imperative to meet scalability goals necessary to address climate change. Additionally, the technical conditions for developing a SHR reservoir are potentially more favorable at these higher temperatures than with lower temperature conventional EGS. Technical appendices to follow this paper will present a thorough analysis of the current state and advancements needed to achieve SHR across the key technology areas. The figure below summarizes the development pathway for each area and expected timeline for achievement with adequate investment.

We break the critical technologies into four stages of development:

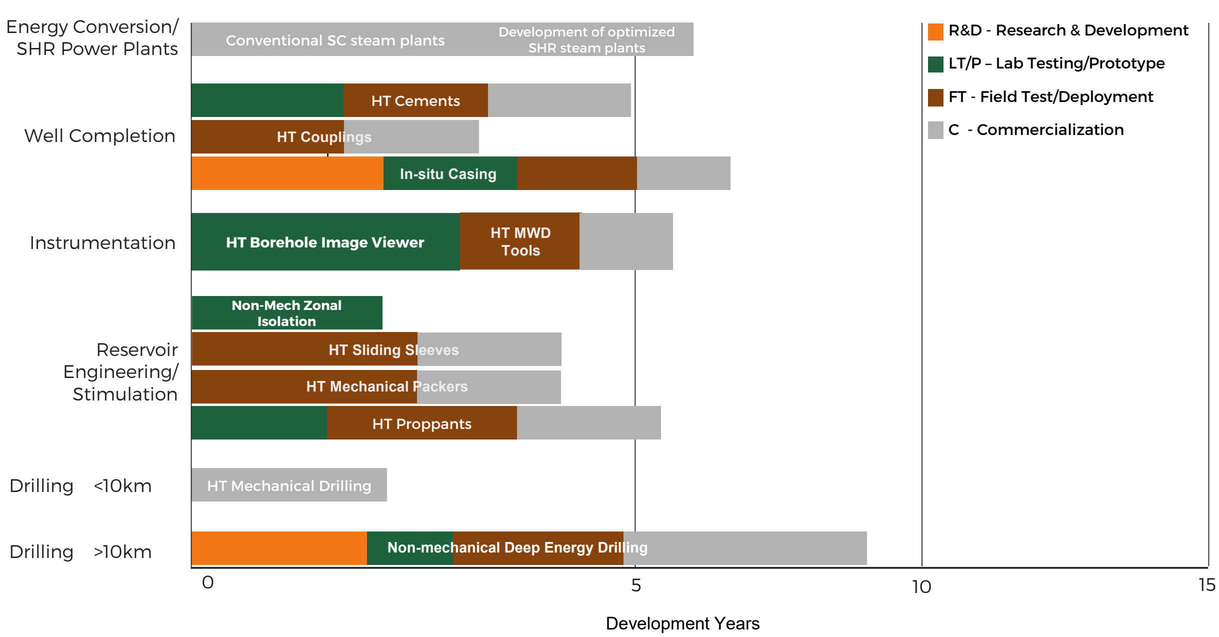
- Research & Development
- Lab Testing/Prototype
- Filed Test/Demonstration
- Commercialization

Figure 5 maps out expected timelines toward commercialization. The majority of the technology development is already in progress. It is expected that with adequate funding the majority of technologies can be demonstrated and proven within the next five years and the entire slate of technologies within ten years.

On the heels of the COP 26 global UN Climate Change Conference in Glasgow, and the dire predictions for a warming climate's adverse impacts on civilization, the world needs scalable, carbon-free energy resources like SHR to come online at massive scale over the next 25 years. This paper argues why and how SHR can be a disruptive energy resource to meet that need in the pivotal timeframe. The US is lagging the international efforts to develop SHR resources, and it is time for both the public and private sector to come together and invest in SHR resource development. As described in this report, a SHR resource demonstration is viable within four years and the first commercial power generation can come online within five to six years. Global shallow SHR resource development can currently meet the electricity needs of over 50% of the world's needs, but its reach will expand with advancements. There is no other energy resource that can match the potential of SHR.

Figure 5

Development Status and Path Forward for Critical SHR Technologies



Source: HERO, 2021

REFERENCES

Baker Hughes, 2022. Drilling Services: A Quick Reference Guide. Website: https://www.bakerhughes.com/sites/bakerhughes/files/2020-09/baker-hughes-drilling-services-quick-reference-guide.pdf

Bertani, R., Busing, H., Buske, S., Dini, A., Hjelstuen, M., Luchini, M., Manzella, A., Nybo, R., Rabbel, W., Serniotti, L.,: The First Results of the DESCRAMBLE Project, PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, (February 2018)

Bonneville, 2021, Personal communication, A. Bonneville, September 2021.

Changbing, Z., Zhijun, W., Yuan, Z., Ban, G.,: Experimental study on hydraulic fracturing of granite under thermal shock, Geothermics, v. 71, pgs 146-155, (2018)

Cladouhos, Trenton, William L. Osborn, Susan Petty, Daniel Bour, Joe Iovenitti, Owen Callahan, Yini Nordin,

Dobson, Patrick, Hiroshi Asanuma, Ernst Huenges, Flavio Poletto, Thomas Reinsch, and Bernard Sanjuan. 2017. Supercritical Geothermal Systems - A Review of Past Studies and Ongoing Research Activities. 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, California, February 2017.

Doug Perry, and Paul L. Stern. 2012. Newberry Volcano EGS Demonstration—Phase I Results. 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 2012.

EIA, Annual Energy Outlook with Projections to 2050, https://www.eia.gov/aeo, (January 2020)

Ernest L. Majer and John E. Peterson, 2007. The Impact of Injection on Seismicity at The Geysers, California Geothermal Field. International Journal of Rock Mechanics and Mining Sciences. Volume 44, Issue 8, December 2007, Pages 1079-1090.

Friðleifsson, G, Pálsson, B., Albertsson,A., Stefánsson, B., Gunnlaugsson, E., Ketilsson, J., Gíslason, Þ.. 2015. IDDP-1 Drilled into Magma – World's First Magma-EGS System Created, Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015.

Friðleifsson, G., Albertsson , A., Borolfsson, G., Sigurosson, O., Zeirenberg, R., Elders, W., Johannesson, B., Oskarsson, F., The IDDP-2 DEEPEGS Demonstration at Reykjanes, HS ORKA, Presentation, Georg Geothermal Workshop, (2018)

GEMEX, GEMex: Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems (EGS) and Superhot Geothermal Systems (SHGS), Presentation, (2020)

Gupta, A.V., Rajulu, K., Second Law Analysis of Super Critical Cycle, International Journal of Engineering (IJE), V. 4, Issue 1, (2010)

Ingason, K., Saether, S., 2018. Geothermal Comparison study. Presentation for GRC, GRC 2018. Completed by Mannvit and Equinor.

Lukawski, M., Silverman, R., Tester, J., Uncertainty Analysis of Geothermal Well Drilling and Completion Costs, Geothermics, v. 64, pg. 382-391, (2016)

M. Ali Khan, 2010. The Geysers Geothermal Field, an Injection Success Story. Proceedings World Geothermal Congress 2010. Bali, Indonesia, 25-29 April 2010

Moon, H., and S. J. Zarrouk. 2012. Efficiency of Geothermal Power Plants: A Worldwide Review. New Zealand Geothermal Workshop 2012 Proceedings. 19 - 21 November 2012. Auckland, New Zealand.

NIST, 2022. Thermophysical Properties of Fluid Systems. Website: https://webbook.nist.gov/chemistry/fluid/.

Ragnarsson, A., Durst, P., Randeberg, E., Reinsch, T., Thorbjornsson, I., Wollenweber, J., De Jong, W., Kampfer, G., Sigurdsson, O., Vercauteren, F., GeoWell – Innovatoin Materials and Design for Long-life High-temperature Geothermal Wells, Oil Gas European Magazine, (2018)

Richter, A., Iceland offers geothermal power at $4.3 cents per KWh, Think GeoEnergy, https://www.thinkgeoenergy.com/iceland-offers-geothermal-power-at-43-cents-per-kwh/, (November 2011)

Richter, A. Land-Use Intensity of electricity production methods. Think GeoEnergy https://www.thinkgeoenergy.com/geothermal-energy-is-least-land-use-intense-source-of-the-renewable-energy-technologies/ (January 2021)

Tal, Y., and Hager, B. H. (2015), An empirical study of the distribution of earthquakes with respect to rock type and depth, Geophys. Res. Lett., 42, 7406– 7413, doi:10.1002/2015GL064934.

GLOSSARY

Active Seismic: Active seismic is the analysis of reflected seismic waves derived from an active source. Active in this case means seismic energy generated by humans. Seismic waves can be generated from varying sources, such surface and subsurface explosions, or Vibroseis trucks designed to impart seismic waves with a specific frequency into the subsurface. An array of sensors either on the surface, or in shallow boreholes, record movement in the X, Y and Z directions. Typically, these arrays are set up to record the backscatter reflected seismic waves, which are the waves reflected in the direction of the active source.

Availability Factor: Availability factor is how often a powerplant operates within the course of a year. For example, a solar farm often has an availability factor of 25% because it only generates power when the sun is shining, while a geothermal powerplant has an availability factor 90-95%. Availability factor is different than a capacity factor, which measures the ratio between energy produced over the course of a year and the maximum amount of energy which could have been produced by the powerplant.

Baseload: The minimum level of demand on an electric grid over a span of time. Baseload is also sometimes used as descriptor of power generation. For example, a baseload power plant is a power plant which is run continuously and used to meet baseload demand. Example of Baseload power plants are Nuclear, Coal and Natural Gas Combined Cycle power plants.

Basement Rock: Rock underling young sedimentary rocks within a geological basin. Basement rocks are often igneous or metamorphic in nature. And located fairly deep in the subsurface.

BHA: Bottom hole assembly is the set of tools found at the bottom of a drill string used to assist in drilling. Such tools can include a mud-motor, drill bit, directional tools, logging equipment and others equipment.

Capacity: The maximum amount of power a powerplant is designed to produce.

Casing: Is a metal tubular, often a steel alloy, which is used to line a well in to prevent formation damage, contamination, and hole collapse. Casing is often cemented into place to improve well stability and casing resilience to changes in operating conditions. A well will often contain many pieces of casing, with larger diameter pipe installed at shallow depths and thinner diameter pipe installed to deeper depths within the larger diameter pipe in a telescoping fashion.

Cement: Cement is the material used to seal the hole and bind the casing to the wellbore wall. Conventional cements can be used but, more exotic cement chemistries will be used for Super Hot.

Cooling System: All the systems required to condense the exhaust from the turbine into liquid water. Cooling system is often comprised of heat exchangers, pumps, cooling towers and pipelines to transport cooling water and condensate.

Conceptual Model: Integrates exploration data such as gravity surveys, InSAR, magnetic surveys, geodetic surveys, magnetotelluric surveys, passive and active seismic surveys, geochemical analysis, field geology and downhole measurements into 3D model which describes, lithology, structure, and the dynamics of the hydrothermal system.

Couplings: Couplings are small pieces of casing, 1-3 ft in length, with threads on the inside used to connect two larger pieces of casing known as joints. Joints are larger tubulars which are 10-30 ft long and have threads on outside located at either end of the pipe. Couplings always have a slightly diameter than joints, allowing joints to fit inside the coupling.

Directional Tool: A directional tool is part of the Bottom Hole Assembly which directs the position of the drill bit in order to control the trajectory of the well. There are many mechanisms enable this functionality but the most common is the through the controlling the angle of the mud-motor relative to the drill string through an actuator controlled by mud pulsed communication.

Diverter: A material which temporarily blocks flow into a porous media or fracture. Often used in stimulation.

Down Hole Survey Tools: These tools measure specific characteristics of the rocks down hole. The most common tools are, temperature, pressure and gamma ray. These measure the temperature of the reservoir, pressure of the water column and the radioactivity of the rock as a function of depth. There are many other characteristics which can be measured, including neutron density, resistivity and other downhole geophysical systems.

Drill Bit: A drill bit is a tool used to cut/drill rock. The rotation of a drill bit on the surface of rock causes abrasion and brittle failure, allowing for removal of the rock through a mud circulation system. The two most commonly bits used in geothermal wells are roller cones and poly diamond crystalline (PDC) bits.

Drill Pipe: Drill pipe is engineered pieces of steel pipe that is connect together by threads and is used to transport pressurized fluid to the cutting face within the well and confer torque to the cutting blades or teeth of the drill bit.

Drill Rig: A drill rig is a collection of equipment which is assembled at a drill site and used to drill a well. A drill rig is comprised of a derrick, where drill pipe is stored in a vertical fashion and where new pieces of drill pipe are connected to the drill string within the well, a rig floor, where personnel connect new pieces of drill pipe and a the driller operates the drill rig, a mud system, where mud is mixed in large metal containers called pits, pumps, which pump mud down the well, and generators which power the drilling equipment.

EGS: Enhanced Geothermal System is geothermal resource where stimulation is used to create permeable pathways, or improve existing permeable pathways, between one or more wells. These systems are built to last at least 20 years or the minimum required lifetime of a geothermal power plant.

EIA: Energy Information Administration is a federal organization which collects and publishes data regarding the energy industry within the United States.

Energy Drilling: Energy Drilling technologies break rock without use of a drill bit, and do not require a mud system to remove cuttings. These systems promise to reduce mechanical ware of the bottomhole assembly (BHA) considerably, increasing OROP and reducing downhole risk. Examples of Energy drilling technologies include millimeter wave drilling and plasma drilling.

Fracture Network: A network of fractures that are connected hydraulically within the subsurface. Is usually used to describe a type of fluid pathway between two wells. Network is comprised of more than one stimulated natural fracture and/or tensile fractures which allow fluid flow.

Geochemistry: the study of the chemical composition of the earth and its rocks, minerals, and groundwater.

Heat Exchanger: A system used to transfer heat between two or more fluids. Heat exchangers are used in both cooling and heating processes. The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact.

Heat Flow: The amount of heat that is transferred to a volume of material as a function of time, usually measured in watt (joules per second).

Hydraulic Fracturing: A stimulation technique which pressurizes a section of wellbore to high enough pressure to induce tensile failure in the rock, causing open mode fracture propagation. Resultant fractures are filled with proppant, usually sand, to keep fracture open once pressure within the well is released.

kW: Kilowatt is a unit measure of power and is 1000 times smaller than a MW. It also the typical electricity demand for a household in the United States.

LCOE: Levelized Cost of Energy is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. LCOE is often represented in terms of dollars per unit energy produced, $/kWh or $/MWh. The LCOE is commonly used to compare fossil fuel energy production with renewable energy production. It is used for this comparison because LCOE accounts for the upfront capital cost, the cost of fuel and the cost of operation and maintenance. Upfront capital cost for renewable energy projects are often higher than fossil-fuel-based generation, however, the largest cost associated with fossil-fuel-generation is fuel consumption. Most renewable energy sources do not require fuel, meaning the traditional method of comparing generating technologies in terms of upfront capital cost is inadequate.

Logging Tool: A downhole tool run down the length of a well, either on a cable or drill string, that measures some quality of the rocks encountered by the well. Common logging tools used in geothermal exploration measure temperature, pressure and resistivity, however, tools can measure many different qualities.

Magma: Molten rock found in the subsurface.

Magma Chamber: A large pool of molten rock contained in the subsurface which is under extreme pressure. Magma chambers are often responsible for feeding volcanic systems.

Minimum Horizontal Stress: The fracture closing pressure. Usually measured in the field through a mini-frac analysis. Orientation is usually perpendicular to the direction of fracture propagation.

MMW Drilling: Millimeter wave drilling technology uses electromagnetic waves in the 30 to 300 gigahertz (GHz) frequency range, with wavelength between 1-mm to 10mm, to melt or vaporize rock at the cutting surface. The MMW is generated using a gyrotron, which is a device originally designed to heat plasma for fusion reactors. MMW are directed to the cutting face through uses of a waveguide, which is an internally ribbed pipe engineered to minimize energy loss of the wave as it travels toward its destination.

Mud: Also referred to drilling fluid, mud, is used during drilling operations to transport cuttings, maintain downhole pressure, reduce leak-off, and reduce friction between the drill pipe and the wellbore wall.

Mud Motor: A device which makes use of the differential pressure between drilling mud in the drill pipe and the open well bore to add torque to the cutting face to the bit. The mud motor is part of the bottomhole assembly and is located at the end of the drill string just above the drill bit. Mud motoe is often used to aid in directional drilling.

MW: Megawatt is a unit measure of power.

MWh: Megawatt-hour is a unit measure of energy.

NGCC: Natural Gas Combined Cycle powerplant is a generating technology where the hot exhaust from a gas turbine is used to heat a working fluid which powers another turbine. This secondary cycle is often water based and uses a steam turbine. These powerplants have high efficiencies, ~64%, and are currently the cheapest form of dispatchable power. However, because they use a secondary steam cycle, they are not well suited for fast ramping. This means that they have a similar use case as geothermal powerplants.

Numerical Modeling: Uses the conceptual model to create a finite element model comprised of grid cells. Each grid cell is given certain characteristics and a starting set of temperature and pressure conditions. These models are then used to predict future performance of the geothermal field as a function of resource development strategies.

Open Mode Fracturing: Also known as tensile fractures, open mode fractures are defined as fractures where tensile stress is perpendicular to the fracture surface. Also characterized as mode 1 opening. Can be thought of as fractures formed when a material is being pulled apart.

Packer: Devices used to seal, isolate and pressurize specific sections of the wellbore. They are often used for stimulation, cementing and during the production phase of a well.

Parasitic Load: Electricity required to run a power plant. Considerable electricity is required to run cooling tower fans, condenser pumps and other essential equipment. Parasitic load usually represents ~10% of the generation.

Passive Seismic: Passive seismic is the capturing of natural or induced seismic events from an array located above the area of investigation. Earthquakes are caused by the brittle failure of rocks in the subsurface. They have a P-wave (compressional) and S-wave (shear) component and come in a variety of sizes. The size of an earthquake correlates to the energy released by the failure event. Typically, the size of an earthquake is recorded in Moment Magnitude (Mo).

PDC: Polycrystalline diamond compact drill bit is a bit with small diamond circular plates impregnated in a tough matrix. The matrix is made from a brittle composite material comprising tungsten carbide grains metallurgically bonded with a softer, tougher, metallic binder. The rotating motion of the bit causes the diamond plates to scrape away material or chip at the rock to generate fast drilling rates. PDC bits were originally designed for drilling in hard shales.

Permeability: A quantifiable quality of a medium which allows liquid or gas to pass through it, usually shown in terms of darcies.

Plasma Drilling: Generating Plasma and directing it toward the cutting face of a well. The interaction of the plasma with the rock will cause spallation, melting or volatilization. The result of this reaction is a function of the energy of the plasma being imposed on the rocks surface. Low energy plasma will cause spallation, high energy plasma will cause spallation. Current plasma drilling technology uses plasma, created through an electrical arc, to melt or vaporize the rock.

Power Plant: A power plant are all the pieces of equipment and facilities necessary to convert steam from the wellfield into electricity. Most power plants have, turbines, generators, cooling towers, pumps, control rooms and substations.

Reservoir: A rock volume which contains interconnected porosity filled with hot water. Porosity in the rock can be comprised of pore spaces or fractures within sediments or hard rock.

ROP/OROP: Rate of Penetration (ROP), is the instantaneous rate at which a drill rig deepens the well. This rate is only calculates when the drill bit is in contact with the cutting surface. OROP, which is the average ROP, is rate at which a drill rig deepens the well over a specified time interval. Included in this calculation is repair time, cementing and other rig operations. For example, if a rig drills 50 ft in 2 hours, but then has to fix a pump for the rest of the day, then the OROP would be 50ft/day or 2ft/hr.

Shear Stimulation: Increasing pressure within the wellbore to initiate shear failure along critical stressed natural fractures. In the context of stimulation, shear failure occurs when the frictional forces preventing slip along a fracture plane are overcome by this increased pressure, allowing the fractures to slip and accommodate strain.

Stimulation: Stimulation is the enhancement of existing permeable features in the subsurface or the creation of new permeable features. The most commonly used form of stimulation used today is hydraulic fracturing, however, chemical stimulation, shear stimulation and other methods can also be used to create or enhance permeability in the subsurface.

HERO
Hotrock Energy
Research Organization