Chapter 1

Geothermal and Electricity Production:
Scalable Geothermal Concepts

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> ***With the size of the resource and the potential for global scale in view, researchers are exploring and developing novel and scalable geothermal technologies at an accelerating rate, with a focus on enabling "geothermal anywhere."***

I. The Geothermal Resource

There is an abundant source of naturally occurring, ubiquitous, and clean energy beneath us. Heat emanating from the core of the earth, which reaches temperatures of 6,000 °C (10,832 °F), exists residually as a result of the formation of our planet, and finds its way to the surface most typically around plate boundaries and in earth's volcanic regions. Geothermal energy for power production exists today in many regions of the world where core heat finds such a conduit to the surface, including locales like Iceland, Hawaii, and areas within the Ring of Fire. When magma flows toward the surface, it heats groundwater trapped in porous rock, or water running along natural fractures and faults.

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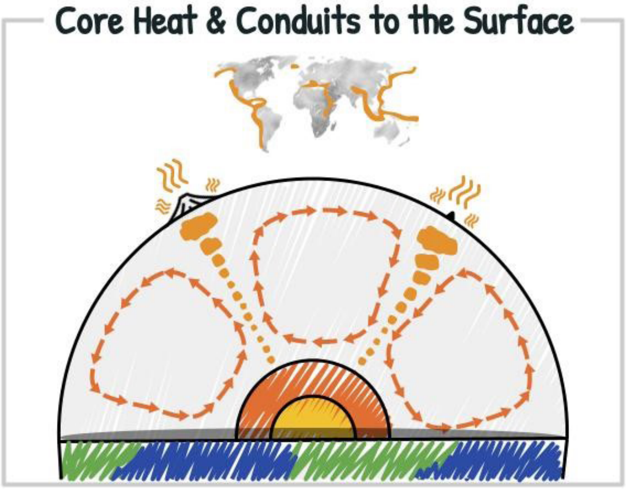

Figure. 1.1. An artist's illustration of global heat flow to the surface and convective currents, with plate boundaries and the Ring of Fire highlighted above. *Source: Future of Geothermal Energy in Texas, 2023.*

Radioactive decay of elements in earth's crust is another abundant source of subsurface heat. This frequently overlooked but significant heat source, estimated to be present near the surface in the range of 40 terawatts, is the target of many geothermal concepts that seek to harvest geothermal "anywhere," as opposed to in volcanic and boundary regions as discussed above.

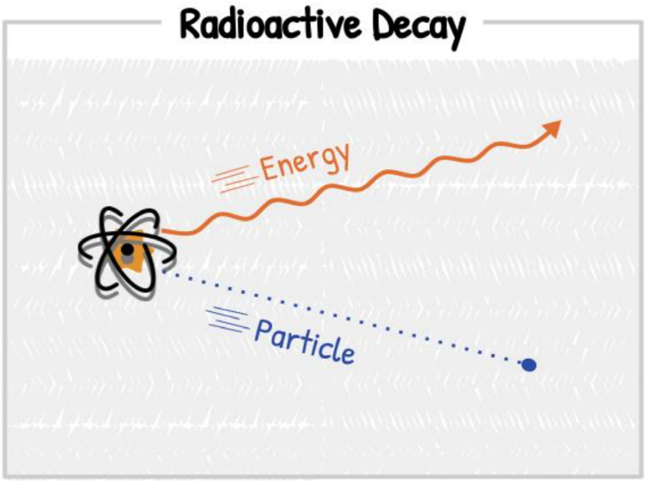

Figure. 1.2. Much of the geothermal energy we seek to harvest near the surface is a result of radioactive decay of isotopes such as uranium and thorium in Earth's mantle and crust. *Source: Future of Geothermal Energy in Texas, 2023.*

Depending on your location and specific subsurface conditions, thermal energy from the Earth's crust at temperatures sufficient for electricity production lies between several feet and several miles beneath the surface of the Earth. In locations where surface geothermal features, such as steam vents, hot springs, and geysers are present, developable geothermal resources are often shallow and easily developable utilizing existing, fully enabled technologies and methods. But geothermal energy exists in the subsurface beneath every location on Earth, with temperatures rising as depth increases.

Below, we will consider geothermal concepts that can be utilized for electricity production. Aside from electricity production, several of these concepts may also be used for Direct Use heat applications, meaning utilization of produced heat directly to heat buildings, or for commercial applications that utilize heat, like agriculture or industrial processes. These Direct Use applications offer a significant opportunity for geothermal to contribute to heat decarbonization efforts globally (Ree, et al., 2021; Richter, 2021c), and will be explored in further detail in Chapter 2, Direct Use Applications and Chapter 3, Other Concepts with Unique Application in Texas.

II. Geothermal Systems for Electricity Production

Geothermal systems for electricity production can be divided into four categories, which we will consider in turn:

A. Conventional Hydrothermal Systems ("CHS"),

B. Engineered (or Enhanced) Geothermal Systems ("EGS");

C. Advanced (or Closed Loop) Geothermal Systems ("AGS"); and

D. Multi-System Hybrids (or Hybrid Geothermal Systems)

Note that while CHS are limited geographically to areas such as Iceland, Hawaii, and the Ring of Fire where specific and unique subsurface conditions exist naturally, the other three categories have the potential to be deployed globally including, for example, in sedimentary basins and SuperHot rock ("SHR"), as described below.

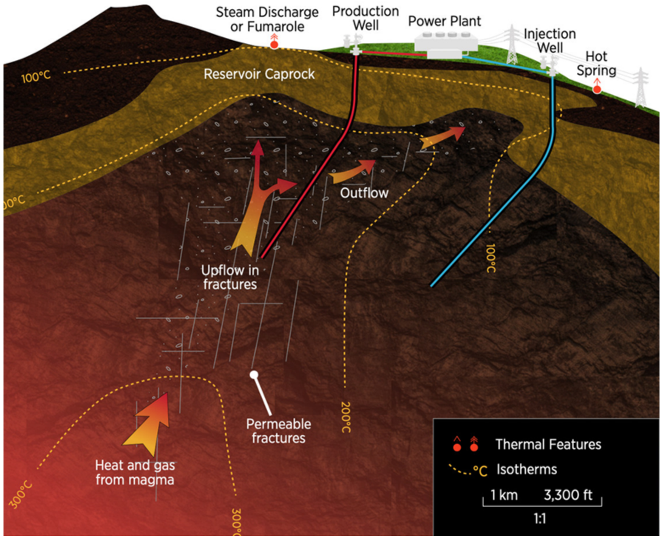

Figure. 1.3. Simplified schematic of a CHS development. *Source: Richter, 2021b.*

A. Conventional Hydrothermal Systems ("CHS")

CHS comprises nearly all geothermal electrical power generation existing today (IRENA, 2017). CHS exist where geothermal reservoir temperature and production flows are naturally sufficient to produce electricity, meaning that the combination of sufficient porosity in the subsurface, sufficient heat transfer into the system, and the natural presence of water combine to produce a near surface, developable resource. Heat transfer from the mantle to shallow porous rock, and to fluids present within the rock pore space, relies primarily on convection, and secondarily on conduction. Temperatures above 225 °C (437 °F) are optimal for higher power plant efficiency (EGEC, 2020).

CHS were first used to generate electricity in Italy in 1904, and have since grown to over 16 gigawatts of electricity generated per year (GreenFire & Scherer, 2020). While the technology is mature, it is limited in supply globally as locations with sufficient heat and fluid flows for power generation are largely confined to areas with active basaltic volcanism, or continental plate boundaries (DOE, 2019; Wendt, et al., 2018). Current conventional hydrothermal regions include those along major tectonic plates, such as the western United States, Turkey, Iceland, Kenya, Philippines, and Indonesia. As such, a very limited part of the world has accessible CHS potential.

It is important to note that in the International Energy Agency's Net-Zero Emissions by 2050 Scenario, CHS grows by eight-fold, indicating that where conventional resources are available, they scale up significantly from today's levels (IEA, 2021c; GreenFire & Scherer, 2020). It is the geographically limited nature of CHS, and therefore its inability to scale globally, combined with higher exploration risk than what is typically encountered in oil and gas exploration, that is the likely driver behind the failure of the oil and gas industry to invest significantly in this space in the past. However, several oil and gas entities have publicly announced CHS projects in various locations around the world over the past year, including a CHS exploration project undertaken by Repsol in the Canary Islands, serving as an example (Richter, 2021e).

While there are no CHS in Texas, we consider them in this Report due to increasing oil and gas industry engagement in this geothermal technology. As will be explored further in Chapter 6, Oil and Gas Industry Engagement in Geothermal, a survey conducted for this Report of oil and gas entities indicated that 73 percent of interviewed entities, which included oil and gas majors from all industry sectors, were either actively engaged or considering hydrothermal engagement. Given that these resources have a poor ability to scale, reasoning behind oil and gas engagement in this space is explored further in later pages of this Report.

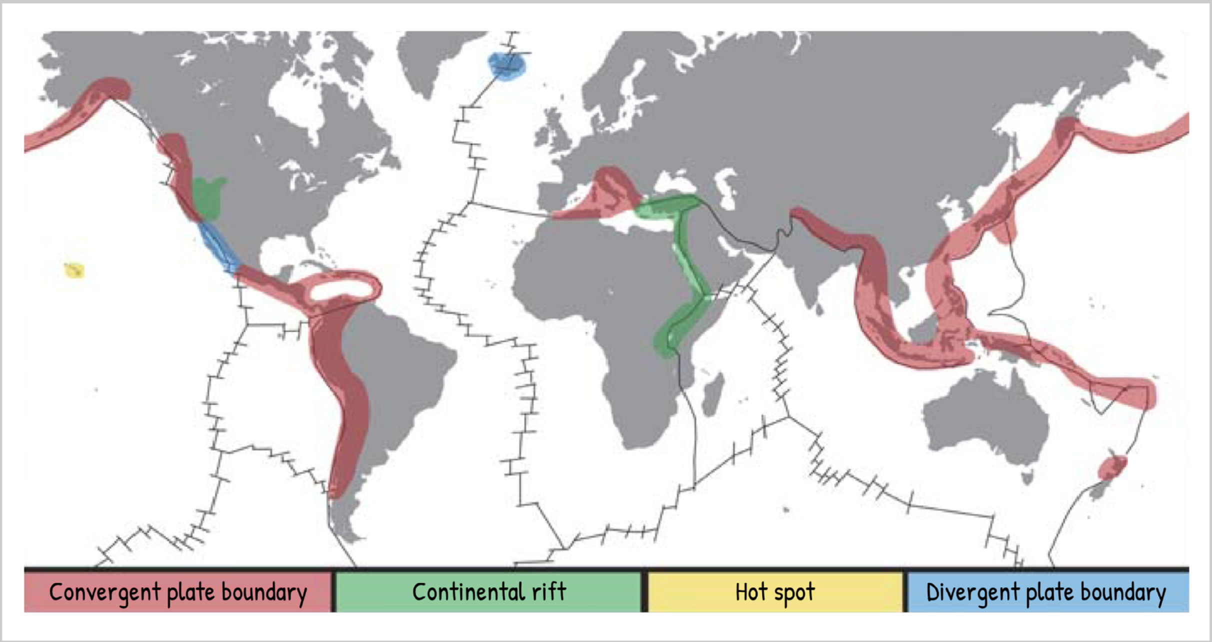

Figure. 1.4. High heat flow to the surface and conventional hydrothermal regions. *Source: Ball, 2021.*

Figure 1.5. A steam vent, which is a surface manifestation of a subsurface geothermal resource, in Námaskarð geothermal area, Iceland. Texas has few surface manifestations of its geothermal resources, making use of advanced exploration techniques a necessity. *Source: Stock photography.*

Exploration for conventional hydrothermal reservoirs with sufficient porosity and permeability to produce electricity tend to rely on the presence of surface expressions indicative of a geothermal resource, such as geysers, steam vents, or other thermal features. Conventional petroleum exploration applications, such as seismic and gravity magnetics, are limited in their ability to effectively discern between good and poor reservoir quality due to lack of impedance (the product of density and sonic velocity), and contrast (oil and gas, being lower density than water, is highlighted more readily).

Additionally, conventional hydrothermal reservoirs can have rapidly changing pressure regimes due to tectonic histories altering flow pathways in the reservoir. Deeper, hotter reservoirs accelerate natural diagenetic processes that occlude porosity and permeability, making the rock matrix denser and more difficult to drill effectively. At the same time, geothermal power generation may require up to a magnitude more fluid production than is encountered in conventional oil and gas reservoirs. These issues translate into high exploration risk, with private industry historically funding exploration in its early phases (Ball, 2021).

Much of the 'low hanging fruit' that is currently technologically enabled for geothermal development in the United States can be categorized as CHS, exists on Federal land, and development of those resources is currently constrained by permitting and regulatory obstacles, not technology challenges (IRENA, 2017). This land ownership obstacle is however, not present in Texas, where a majority of the State's geothermal resources are found on State or private land, as will be explored in further detail in Chapter 13, State Stakeholders: Implications and Opportunities - General Lands Office and University Lands.

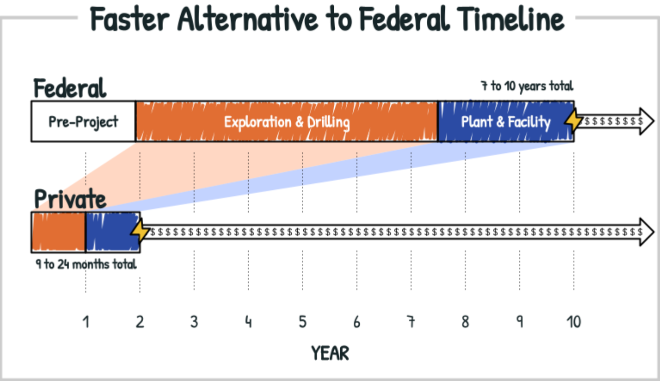

Figure. 1.6. Comparison of geothermal development timeline on Federal land vs. private land. The private timeline is based on the trajectory of an ongoing geothermal pilot in South Texas. *Source: Adapted from DOE.*

B. Engineered (or Enhanced) Geothermal Systems ("EGS")

EGS is a scalable geothermal technology where one or more wells are drilled, and either via natural or hydraulically-stimulated fractures, the wells are connected to one another in the subsurface, creating an engineered reservoir. Water is then injected into the reservoir, where it absorbs heat from hot rocks it is circulating through. It is then produced to the surface, where the fluid or steam is passed through a turbine, and used to generate electricity.

Thanks to recent technological advancements such as deep well drilling, logging, and construction, as well as improvements in materials, such as cement and well casing, untapped geothermal resources in hot, dry rock ("HDR") with little or no permeability or naturally occurring fluids, are now accessible (DOE, 2021a; Wendt, et al., 2018;

Koelbel & Genter, 2017; Li, et al., 2016; Blackwell, et al., 2006; Tester, et al., 2006). The challenge that all scalable geothermal technologies aim to address is turning accessibility into an economically viable exploitable resource.

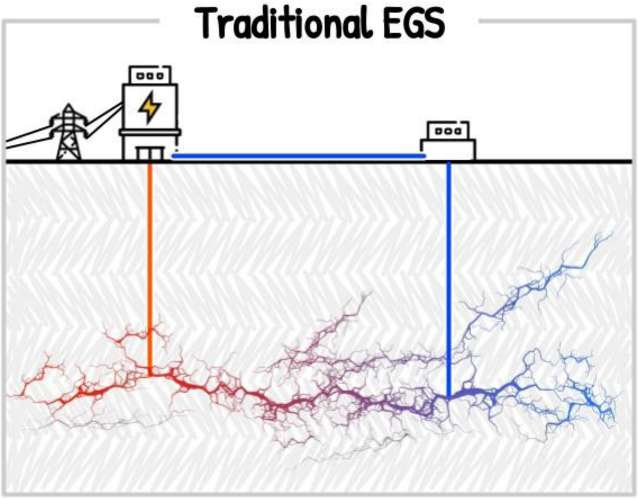

Figure 1.7. Schematic of a Traditional EGS approach, featuring two vertically drilled wells, with a fracture network connecting them in the subsurface. *Source: The Future of Geothermal in Texas, 2023.*

In a "Traditional" EGS configuration, two or more wells are drilled vertically, and hydraulic fractures are utilized between the wells to allow fluid circulation through the formation between them. Fluid-driven fracturing (i.e. hydraulic fracturing) is one of the key techniques being utilized to unlock resources from low-permeable underground formations. Fluid-driven fracturing is a process in which a large amount of high-pressure fluid is injected into the formation to break the rock in order to create or extend a crack or existing fracture. If there are pre-existing fractures in the formation, the created crack can connect with these fractures, resulting in conductive fracture networks.

EGS traditionally targets very hot metamorphic rock, which are typically not porous, and are largely non-producing. Finding or creating sufficient porosity and permeability in deep basement rocks is very challenging, requiring more time, energy, and cost than same-depth hydrocarbon wells (DOE, 2021a).

1. Technological Challenges Associated with EGS

EGS reservoirs have several challenges that must be overcome if they are to be economically viable and reach global scale, including finding or creating sufficient permeability, high operational costs due to well loss or geochemical challenges, failure to achieve sufficient residence time for heat exchange in the subsurface, and the potential for induced seismicity.

EGS fluid flow dynamics are difficult to predict due to limited data on downhole conditions. In reservoirs reliant on natural or induced fractures for fluid flow, the ability to assess a priori the direction of fluid flow is limited, resulting in a trial-and-error approach to EGS exploration and development similar to CHS. Once found, fractures may open or close depending on operating conditions, due to changes in injection fluid make-up or injection pressure differentials.

Water injected into the subsurface may pick up naturally occuring minerals or radioactive elements in the subsurface, which can be redeposited, causing scale and/or corrosion in the system, both on the surface and subsurface. This can result in high operational costs, including the need to re-drill wells, or increased environmental concerns. Further, if a limited number of fractures absorb most of the fluid flow, much of the subsurface is bypassed by the circulating fluid, and insufficient heat exchange may occur.

EGS operation can trigger fault activation, followed by induced seismicity. For example, the Pohang earthquake in South Korea was triggered by fluid injection from a nearby EGS, causing damage to private and public properties, including houses, roads, and bridges (Ree, et al., 2021). In Texas, even though no EGS fields have been developed actively, substantial seismic activities due to fault activation have been identified near Azle, Texas, where a considerable amount of wastewater had been injected nearby (Kim, et al., 2015). Thus, it is important to consider both fracture behavior and potential fault activation in siting decisions for EGS.

To this end, it is also necessary to develop a reliable numerical simulator that can model complex and coupled physical processes among non-isothermal multiphase flow, geomechanics, and reactive transport with chemical reactions. While a few simulators have been developed for the modeling of coupled processes

(Stefansson, et al., 2021; Kim, et al., 2015; Battistelli, et al., 1997), it is imperative to develop a new Texas specific numerical simulator, since geology, geomechanics, and geochemistry in Texas may be significantly different from other geothermal systems. By developing an advanced simulator, we can also incorporate high performance computing technologies, combined with machine learning/deep learning methods, to predict reservoir performance fast and accurately.

2. EGS Demonstrations and Learnings

According to Robins et al. (2021), there have been several EGS projects over the past decades, including Fenton Hill (United States), Rosemanowes (United Kingdom), Le Mayet, Soultz and Strasbourg (France), Hijiori (Japan) and Cooper Basin (Australia) (Calpine, 2022; Cyrq, 2022; Li, et al., 2020b; Kneafsey, et al., 2018; Richter, 2017; Allis, et al., 2013; Garcia, et al., 2012). In addition, Calpine's EGS project is in Middletown, California (Calpine, 2022); Ormat's Desert Peak and Brady field projects are located in Churchill Country, Nevada (Ormat, 2022; Richter, 2019; Richter, 2013); and formerly owned by U.S. Geothermal, Ormat's Raft River EGS project is located in Raft River, Idaho (Richter, 2016). Among those, Ormat's Desert Peak and Raft River (Richter, 2013), and Calpine's Geysers EGS operations are commercially active (Calpine, 2022).

The longest operating commercial EGS project generating power currently is the Soultz EGS project in Alsace, France (Koelbel & Genter, 2017). A pilot power plant began operation at Soultz in 2009, with an installed gross capacity of 1.7 megawatts electric (MWe). It has two stimulated reservoirs within fractured granite, one at 2.2 miles (3.5 kilometers) depth, and the other at 3.1 miles (five kilometers) depth, with commercial electricity production beginning in 2016 (Ravier et al. 2019).

a. EGS Pilot Projects by Startups

Since 2007, AltaRock Energy ("Altarock") has worked to develop, demonstrate, and deploy technologies to grow geothermal resource development, especially via EGS, in both natural hydrothermal systems and in Hot Dry Rock (AltaRock, 2022). AltaRock's most significant projects include the greenfield Newberry Volcano EGS Demonstration Project in Bend, Oregon, and the existing hydrothermal field at the Bottle Rock Power geothermal facility in The Geysers area of California.

The Newberry Project consisted of two cold water stimulation campaigns on one well, each of which used high pressure water and thermally degradable diverters to open and expand natural fractures in the rock reservoir. Significant flow was created in at least two stimulated zones over a radial area of 1,640 feet (500 meters) from the injection well, and reservoir injectivity was increased 18-fold. At Bottle Rock, low pressure cold water and degradable diverters were used in stimulation campaigns at three different wells. Flowing pressure/temperature/spinner ("PTS") surveys demonstrated how new flow zones were created, reservoir transmissivity was improved by an average of 30 percent, and long-term production flow rates increased 68 percent. Furthermore, Altarock has been engaged to deploy EGS technologies to improve hydrothermal commercial projects in Mexico, Nevada, California's southern San Joaquin Valley, Iceland, and the Philippines.

At least two start-ups based in Texas, Fervo Energy ("Fervo") and Criterion Energy Partners ("Criterion"), are aiming to prove the economic viability of EGS. Google and Fervo are partnering to deploy an EGS concept in 2022, using advanced drilling techniques, optical fibers, machine learning, and artificial intelligence algorithms to help power Google's Nevada Data Center Campus (Richter, 2020a). Google and Fervo discussed this developing relationship on a panel at the 2022 PIVOT: Hydrocarbons to Heat conference (PIVOT, 2022a). In November 2022, Fervo also announced the execution of a 20 megawatt power purchase agreement to provide 24/7 carbon-free geothermal power to a group of nine California-based community choice aggregators ("CCAs"). The 15-year contract will provide clean energy to households across Southern California (Fervo, 2022).

Criterion is focused on developing distributed energy projects that are co-located with industrial consumers of Direct Use heat and power. In August 2022, the startup closed a 10,000-acre strategic lease position along the Texas Gulf Coast to develop their first commercial project (CEP, 2022). Criterion's objective is to apply ubiquitous and proven techniques from the oil and gas industry, including multi-stage fractures and modern completion technologies to EGS. Criterion intends to begin development in Blind Hydrothermal Systems along the Texas Gulf Coast, which will be discussed further below, where the company believes they have sufficient play fairway to prove their EGS concept before moving into Hot Dry Rock projects. The team announced two strategic investments from oil and gas entities in 2022, including Chesapeake Energy and Patterson-UTI.

Criterion's intended application of advanced drilling, fracturing, and completions techniques from the oil and gas industry, an approach many in industry have labeled "Next Generation EGS" or "EGS 2.0," is being widely adopted within oil and gas entities as they consider which scalable geothermal concepts in which to invest. There is good reason for this, as these advanced methods are likely to alleviate some of the challenges associated with Traditional EGS, but have never before been transferred into the geothermal context. The tremendous success of multi-stage fracturing in Texas' unconventional shale formations can greatly increase the contact area between the wellbore and reservoir, and is a very effective technique to extract resources from the subsurface. Application of advanced techniques like horizontal drilling and multi-stage fracturing in the geothermal context will allow for more precise engineering of the subsurface fracture network, increasing the likelihood that fractures will connect sufficiently to sustain desired flow rates through the system. We will consider the subject of oil and gas engagement in both Traditional and Next Generation EGS in more detail in Chapter 5, The Oil and Gas Industry Role and Chapter 6, Oil and Gas Industry Engagement in Geothermal.

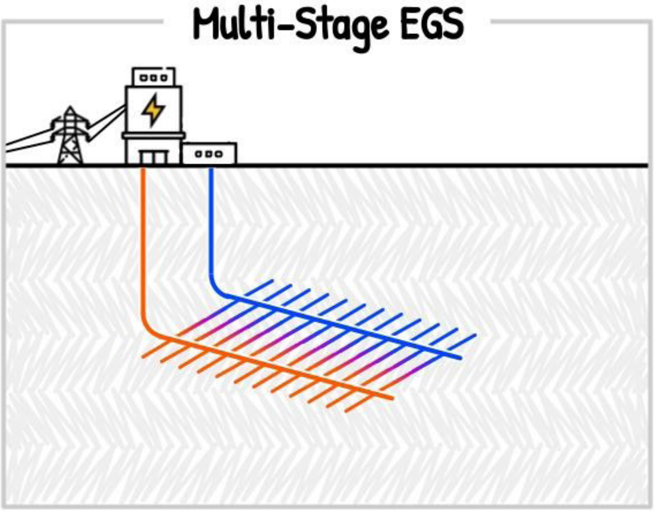

Figure. 1.8. Schematic of Next Generation EGS or EGS 2.0, utilizing advanced techniques from the oil and gas industry, including horizontal drilling and multi-stage fracturing techniques. *Source: The Future of Geothermal in Texas, 2023.*

b. The U.S. Department of Energy and EGS

The U.S. Department of Energy Geothermal Technologies Office ("GTO") has made significant investments in research to eliminate impediments to developing EGS. Two major current projects are Collab, initiated in 2017 (Kneafsey, et al., 2018), and the Frontier Observatory for Research in Geothermal Energy ("FORGE"), initiated with a site selection process in 2015 (FORGE, 2020a; FORGE, 2020b).

Table 1.1. Comparison of DOE GTO Collab and FORGE. *Sources: Kneafsey et al. 2019; FORGE, 2020a; 2020b.*

	Collab	FORGE
Spatial scale	32.8 feet (ten meters)	Reservoir
Access to Rock	Short boreholes	Deep wells
Instruments	Nearby	Standard field geophysical
Environmental Conditions	Cool rock at reasonable stress	Hot rock at reasonable stress
Focus	Direct investigation	Development of a testbed and management of a research program
Project Structure	Single integrated team	Individual research teams

Collab is a collaborative consortium involving US national labs, academia, and industry to focus on EGS reservoir creation, monitoring, and model validation in crystalline rock, including the creation of sustained and distributed permeability for heat extraction through a complex network of artificial and natural fractures. Collab's underground facilities are used to understand permeability enhancement using hydraulic fracturing physics through stimulation, flow, tracer, and thermal experiments for 32.8 feet (ten meters) under relevant in-situ stress conditions (Kneafsey et al. 2019).

FORGE has established an EGS field test site near Milford, Utah for the research and testing of EGS concepts and technologies in order to identify a commercial EGS pathway (FORGE 2020a; FORGE 2020b). A brief comparison of the research methodologies of two DOE GTO projects, Collab and FORGE, is shown in Table 1.1.

Figure. 1.9. Utah FORGE is an underground field laboratory sponsored by DOE for developing, testing, and accelerating EGS technologies. *Source: FORGE, 2020a; 2020b.*

The FORGE team recently completed drilling for the project's first highly deviated deep well in less than half of the originally anticipated drilling schedule. These results were largely enabled by the transfer of technologies, methods, and ways of working from the oil and gas industry into the project, and will be discussed in greater detail in Chapter 5, The Oil and Gas Industry Role and Chapter 11, Geothermal, the Texas Grid, and Economic Considerations. This well will serve as the injector or producer for an injection-production well pair, with temperatures at depth close to 226 °C (438.8 °F) (FORGE, 2020a; FORGE, 2020b).

The FORGE site also includes three seismic monitoring wells. Numerous pre-existing natural fractures were identified at the site, and four hydraulic fracturing tests were conducted in three different sections of the wellbore in 2017 and 2019. The first hydraulic fracturing test was implemented in the open-hole section of the wellbore in 2017, and then this section was re-fractured in 2019. Two additional hydraulic fracturing tests were conducted in 2019 in the cased portions of the wellbore with different orientations of pre-existing fractures behind casing. Pre-existing fractures in one region are parallel to the maximum horizontal stress, which is an optimal orientation for shearing and dilation. The other region contacts fewer fractures oriented at a high angle to the maximum horizontal stress, which requires higher injection pressure to be stimulated. The pressure response of the tests and the formation micro-scanner image log indicate that hydraulic fractures and shearing of pre-existing fractures were initiated and extended.

The preliminary results at FORGE are promising with regard to the viability of EGS, and while EGS contributes a negligible amount toward global power capacity currently, if demonstrated successfully, EGS could scale to become a major contributor to produced power generation (DOE, 2016; Tester, et al., 2006). The U.S. Department of Energy ("DOE") estimates that EGS systems in sedimentary basins could contain as much as 28,000 exa-joules (7,800 million gigawatt hours) of accessible heat (Mullane, et al., 2016).

C. Advanced Geothermal Systems ("AGS")

AGS in many circles has become a catch-all term that includes a variety of next generation and emerging geothermal concepts, including Closed Loop Geothermal Systems ("CLGS"). Even some concepts in the traditional hydrothermal space are now referred to as AGS. For the purposes of this Report, we use AGS interchangeably with CLGS.

CLGS can have any configuration that allows the circulation of fluid without direct contact between the Working Fluid and reservoir. In so called "Closed to Reservoir" concepts such as CLGS (as opposed to "Open to Reservoir" concepts like EGS), fluid is pumped into the subsurface from the surface, picks up heat from the surrounding formation through conduction, and is then returned to the surface, bringing with it heat from the formation. Because these systems function in a closed loop, and thus theoretically do not exchange fluids with the subsurface, the use of engineered, non-water Working Fluids in

CLGS, such as supercritical carbon dioxide ("sCO2"), is an area of fast moving innovation. Because rock is a low conductive medium, lacking significant contributions from convection, CLGS experience inefficient heat transfer from the subsurface to the circulating fluid, and innovation in this area is needed.

CLGS are not a new concept (Livescu & Dindoruk, 2020a; Livescu & Dindoruk, 2020b; Oldenburg, et al., 2019; Morita, et al., 1992; Horne, 1980), but their relative operational simplicity and versatility have gained renewed interest. These technologies are currently in development, and more research is needed, including techno-economic analyses, design and materials optimization, and field scale demonstration (Livescu & Dindoruk, 2020a). Many theoretical studies have been published regarding the heat performance of CLGS, but very limited laboratory and field data is available to validate these theoretical models.

A recent series of feasibility studies for concentric pipe-in-pipe CLGS showed the effects of several well parameters, such as the fluid flow rate, well length, inner tubing and annulus diameters, temperature, type of the Working Fluid, and overall heat transfer coefficients on the output temperature of the fluid flowing to surface (Ratnakar, et al., 2022; Livescu & Dindoruk, 2020a; Livescu & Dindoruk, 2020b). The relationship between thermal and electric energy production and the parameters studied is complex. While all parameters have more or less significant effects on total power generation, the overall heat transfer coefficients are critical for system performance. For instance, modifying the overall heat transfer coefficients while keeping all other parameters unchanged may yield a two-fold outlet temperature difference, significantly affecting the economics of a given geothermal project.

Field trials are needed to demonstrate the physics of heat exchange to the wellbore and within nearby rock, including the ability of these systems to achieve "steady state" output sufficient to create a commercial power generation opportunity. If initial field trials are successful at proving the underlying physics, novel subsurface well lateral configurations are in development that may allow sufficient heat-exchange capacity in the subsurface for long-term operability (Eavor, 2022; Greenfire, 2022; Sage, 2022; Ball, 2021; Beckers, et al., 2021; FORGE, 2020b; Moncarz & Kolbe, 2017).

AGS has begun to receive renewed interest in the past few years due to their potential to produce any combination of power and Direct Use heat, their projected ability to utilize non-water engineered Working Fluids, and their ability to be developed with limited or no use of hydraulic fracturing. Proponents are piloting these technologies within a wide range of temperature and rock conditions, including in low-temperature sedimentary zones, and high-temperature dry rock formations (Robins, et al., 2021).

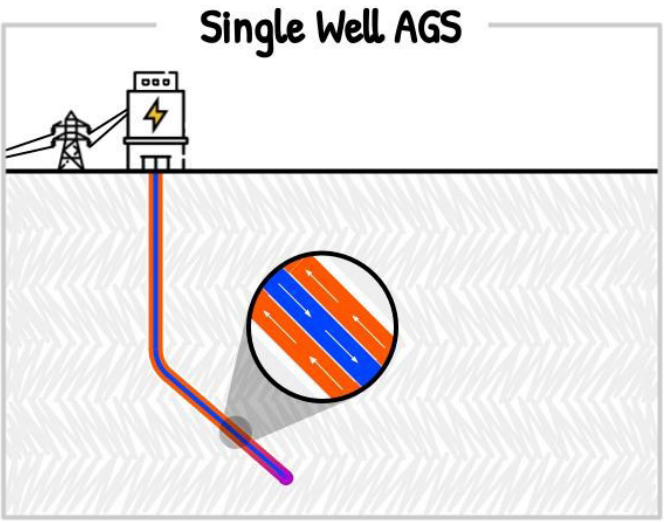

Figure. 1.10. Schematic of a single well, concentric 'pipe-in-pipe' AGS concept, demonstrating fluid flow through the system. *Source: Adapted from Greenfire, 2022.*

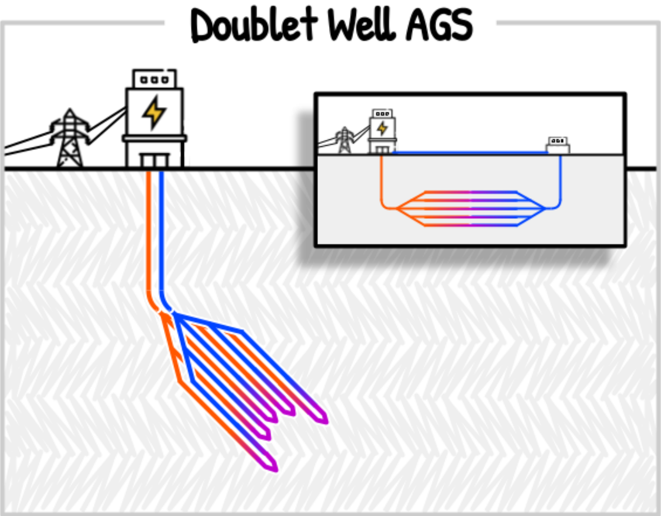

Figure. 1.11. Schematic of a doublet well AGS concept, one in a deviated forked configuration, and the other in a multi-pronged horizontal configuration. Source: Adapted from Eavor, 2022.

In addition, AGS are viewed as potentially viable geothermal projects globally as a result of their potential application to unproductive geothermal wells, in co-production scenarios on existing oil and gas wells, or in locations in the world that have banned the use of hydraulic fracturing (Livescu & Dindoruk, 2022a; Amaya, et al., 2020; FORGE, 2020b; Greenfire & Scherer, 2020; Alimonti, et al., 2018; Elders & Moore, 2016; Gosnold, et al., 2015).

As will be explored in detail in Chapter 3, Other Concepts with Unique Applications in Texas, several entities in the oil and gas industry are assessing the potential of converting existing hydrocarbon wells to geothermal producing wells. The advantage of such a conversion is that, because no fluid is lost to the surrounding formation, the environmental permitting process can be simplified, and alternative Working Fluids, such as supercritical carbon dioxide ("sCO2"), can be used for more effective heat transfer to the surface (Amaya, et al., 2020). However, converting existing oil and gas wells remains commercially unproven, and there are technological challenges associated with the approach, including well integrity issues, and insufficient casing sizes for required flow rates, among others (Livescu & Dindoruk, 2022a).

Although no CLGS concept has reached the stage of commercial deployment, several start-ups have ongoing demonstration projects (Causeway, 2022; Eavor, 2022; Greenfire, 2022). For instance, GreenFire Energy has installed a downhole heat exchanger in a CLGS at the Coso Geothermal Field in California, where the target well had several megawatts of potential, but was not used due to high non-condensable gas content (Greenfire, 2022; Amaya, et al., 2020). The downhole heat exchanger consisted of vacuum-insulated tubing ("VIT") inside of a larger tubing, creating a concentric pipe-in-pipe closed path in which water and sCO2 were used as Working Fluids. In 2019, Eavor Technologies completed its Eavor-Lite demonstration project near Rocky Mountain House, Alberta, Canada (Eavor, 2022). Their pilot project had three objectives: drill and intersect a multilateral with two lateral wellbores from each vertical wellbore; seal lateral open-hole wellbores while drilling; and validate thermodynamic performance and demonstrate a thermosiphon effect. The thermosiphon effect, a method of passive heat exchange based on natural convective processes, negating the need for a mechanical pump, has also been proven by other start-ups such as GreenFire and Sage (Greenfire, 2022; Sage, 2022).

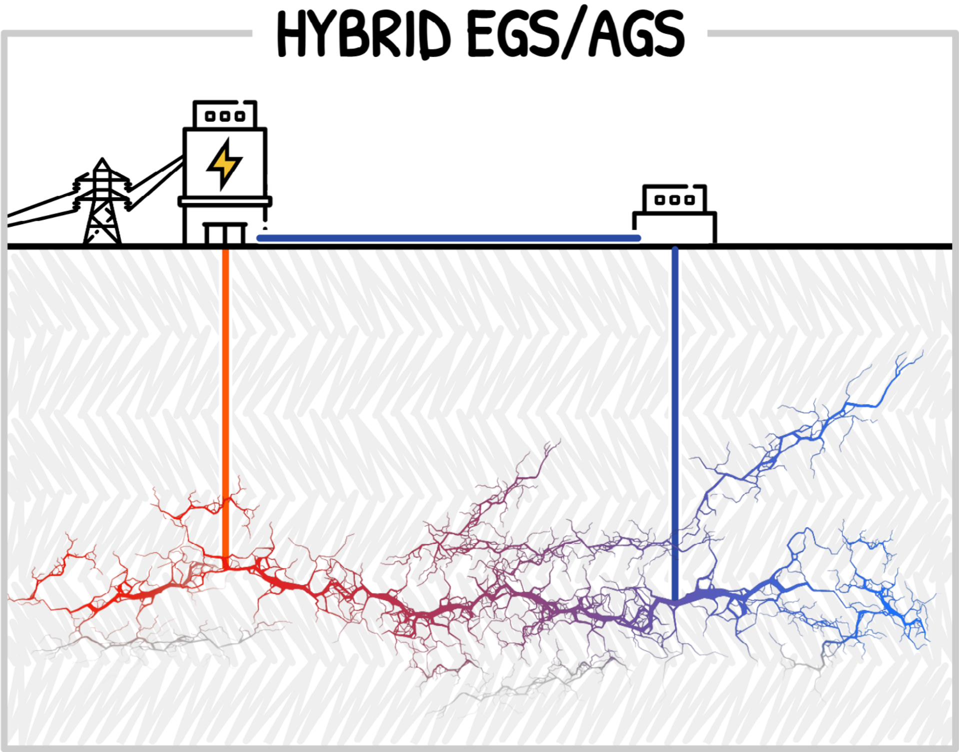

Figure. 1.12. An artist's illustration of an EGS/AGS hybrid concept, with a fracture network to enhance heat transfer from the reservoir to the wellbore. *Source: Future of Geothermal in Texas, 2023.*

D. Multi-System Hybrids

Multi-System Hybrids, also known as Hybrid Geothermal Systems, are systems that couple two geothermal systems, such as EGS and AGS (Sage, 2022) or CGS and CLGS (Greenfire, 2022; Greenfire & Scherer, 2020), or two different systems such as solar photovoltaic ("PV") and geothermal, concentrated solar power ("CSP") and geothermal (Sage, 2022), direct air capture ("DAC") and geothermal (Kuru, et al., 2022), carbon capture, usage, and storage ("CCUS") and geothermal, etc.

As an example of a Texas based hybrid approach, Sage Geosystems is developing geothermal power production and subsurface energy storage concepts, deploying an AGS/EGS hybrid in sedimentary formations. They target bottom of well temperatures as low as 100 °C (212 °F) and up to 250 °C (482 °F), which are present at depths of 1.9 to 3.7 miles (three to six kilometers), making them accessible using traditional drilling techniques, equipment, and service providers (Sage, 2022). Sage has developed multiple geothermal designs, adopting the model that no single geothermal concept is suited to serve all geologies: HeatRoot, for deeper Hot Dry Rock at 150 °C (302 °F) or greater (a downward-oriented fracture that acts as a chimney for heat from deeper hotter formations, with brine circulating inside to bring heat to the downhole heat exchanger); HeatLoop (a variant of HeatRoot where multiple lateral well sections are drilled, and fractures connect them; and HeatFlood (wells that extract heat from porous sand formations that can flow hot produced fluids at high rates). Using sCO2 as the Working Fluid, combined with a bespoke sCO2 turbine developed with their partner SWRI, offers several major advantages that are expected to double efficiency compared to traditional geothermal plants: a dramatically smaller and cheaper turbine; reduced energy losses to mechanical friction; and reduced pumping costs as a result of natural thermosiphon.

III. The Texas Subsurface and Scalable Geothermal Systems

As noted above, no single geothermal concept offers a "one size fits all" approach to all geologies and locations. As such, each of the scalable geothermal concepts discussed above, EGS, AGS, and Multi-System Hybrids, may all be deployed, and perform differently, in different situations, locations, temperatures, depths, and geologies. It is thus important when considering the proper geothermal technology to deploy in any given region to consider site specific conditions that may impact system performance, or characteristics of the particular location, including regulatory considerations and incentives, that make one technology more attractive than others. In this next Section, we will explore the various geothermal resources available in Texas, with consideration of how the various geothermal technologies may be deployed within them.

Figure. 1.13. A Sage Geosystems demonstration project in 2022, located near McAllen in South Texas. *Source: Sage, 2022.*

A. Texan Sedimentary Formations and Geothermal

As will be discussed in detail in Chapter 4, The Texas Geothermal Resource, most of the rock formations in Texas are sedimentary, and usually associated with hydrocarbon production. Sedimentary geothermal formations are defined as "thermal sedimentary aquifers overlain by low thermal-conductivity lithologies [that] contain trapped thermal fluid and have flow rates sufficient for production without stimulation" (Augustine & Falkenstern, 2014; Allis, et al., 2013; Ziagos, et. al., 2013). The DOE GeoVision report ("GeoVision") estimated that United States sedimentary resources, including those traditionally used for oil and gas production that also exhibit elevated temperatures, have an energy potential of 29.3 gigawatts thermal (DOE, 2019).

By comparison, the total low-grade conventional geothermal resource in the United States capable of supporting geothermal Direct Use heat applications (non-electric sector with temperatures below 150 °C, or 302 °F) is approximately 13.7 gigawatts thermal - making the potential for development of sedimentary resources more than double that of hydrothermal for Direct Use cases. By comparison to demand, in 2016, the entire United States residential sector used about 5.1 gigawatts thermal of natural gas for heating, cooking, and clothes drying (Robins, et al., 2021).

Figure 1.14. A hydraulic fracturing stack, composed of a series of high pressure components that protect the production wellhead during hydraulic fracturing operations. *Source: Stock photography*

1. Impact of Oil and Gas Data and Technology Spillover on Sedimentary Geothermal

Geothermal energy production from sedimentary reservoirs was predicted in 2013 to be feasible if the levelized cost of energy ("LCOE") was smaller than ten cents per kilowatt hour, requiring at least 80 megawatts per square meter of heat flow, at least 175 °C (347 °F) reservoir temperature, and at most four kilometers depth (Johnston, et al., 2021; Augustine & Zerpa, 2017; Augustine, 2016; Poro, et al., 2012). But since 2013, technologies for the production of unconventionals have greatly improved, yielding significant operational cost savings. For instance, the average break-even price per barrel for the major oil shale plays in Texas has decreased from more than $80 in 2013 to less than $40 in 2021.

Depending on their permeability and temperature, sedimentary geothermal resources offer opportunities to use existing downhole data and technologies from the oil and gas industry to develop geothermal resources. Coupling existing oil and gas data, technologies, and expertise with the size of the sedimentary resources in the State has the potential to yield scalable, reliable, economical geothermal energy for Texas.

Further, as a general matter when considering sedimentary geothermal as a global opportunity, producing geothermal energy from sedimentary formations may have several advantages over production from Conventional Hydrothermal Systems. Geothermal resource characterization and exploration costs can be lowered using subsurface data from previous hydrocarbon exploration and operations (Abudureyimu, 2020; Weijermars, 2018; Poro, et al., 2012).

For instance, a geothermal energy datathon was organized in 2021 by the Society of Petroleum Engineers, International ("SPE") sections in Calgary, Alberta, Canada and Houston, Texas, and Untapped Energy, a non-profit data science organization, to connect the geothermal and petroleum communities to research repurposing oil and gas wells for geothermal energy production (Livescu, et al., 2021). More than 240 participants from 13 countries assessed the potential for geothermal conversion utilizing information available from drilling, completions, and production from existing oil and gas wells in two prospective basins, one in Alberta and one in Texas, to develop machine learning algorithms for estimating the bottom-hole temperatures in those two basins. In short, application of oil and gas data, much of which is derived from oil and gas development and production in sedimentary basins, is low hanging fruit to fast-forward geothermal development in those same basins. Analysis of the impact that oil and gas spillovers may have on various geothermal technologies is explored in depth in Chapter 5, The Oil and Gas Industry Role.

Notable advantages of sedimentary geothermal reservoirs over Conventional Geothermal Systems include smoother reservoir characterization, faster well drilling, significant existing infrastructure, and proximity to large population areas (Ponmani, et al., 2016). And as noted above, many sedimentary formations in the U.S. have been drilled for oil and gas, providing extensive well and reservoir data that can be leveraged to conduct low-cost geothermal exploration and production (Augustine & Zerpa, 2017; Augustine, 2016). Sedimentary geothermal reservoirs are also likely to be larger (i.e., hundreds of square kilometers) than Conventional Hydrothermal Systems, which are typically as large as a few square kilometers.

2. Sedimentary Geothermal and Electricity Production

The feasibility of using sedimentary resources for electricity generation has been the subject of some controversy (Ball, 2021; Augustine & Zerpa, 2017; Augustine, 2016; Allis, et al., 2013; Poro, et al., 2012). Augustine (2016) found that few basins in the U.S. have enough enthalpy (i.e., permeability and temperature) for power generation. Other studies have shown that reservoir permeability must be more than 50 millidarcies to sustain productivity (Johnston, et al., 2020; Poro, et al., 2012; Blackwell, et al., 2006), but more research and piloting is needed to fully assess the feasibility of using sedimentary resources for power generation. Notably, the use of engineered, non-water Working Fluids with lower supercritical points than water, such as sCO2, may provide a paradigm shift in our ability to utilize sedimentary resources as power sources, and these concepts are being pursued currently in Texas based research and deployments. Let's consider this concept briefly.

The energy content of water, the Working Fluid in CHS, and for modeling EGS and AGS, increases with temperature and pressure as it approaches the critical point, 373 °C (707 °F) and 22 megapascals, respectively (Yoshida et al., 2021). Above this critical point (where water behaves both like a liquid and a vapor), phase change allows the energy density of supercritical water to be significantly greater. For example, the enthalpy of water increases 244 kilojoules per kilogram between 250 °C (482 °F) and 300 °C (572 °F), but enthalpy increases by 955 kilojoules per kilogram between 350 °C and 400 °C (662 and 752 °F), four times more energy for the same increase in temperature. Hotter fluids also allow power plants to operate more efficiently. Today's high-temperature geothermal plants (200–350 °C (392–662 °F) input) use a steam turbine with net efficiencies of 13–23 percent. Lower temperature

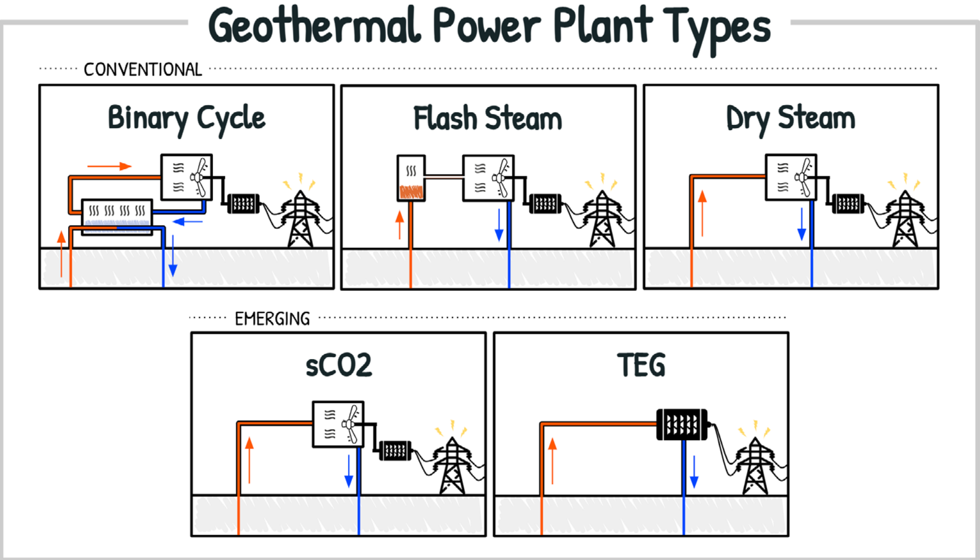

Figure. 1.15. Comparison of geothermal power plant types, grouped by conventional and emerging technologies. *Source: Adapted from EIA*

plants (125–175 °C (257–347 °F) input) use binary power generation with net efficiencies of only 6 to 12 percent. The average power generation efficiency is between 12 percent and 14 percent (Livescu & Dindoruk, 2022a; EGEC, 2020; Alimonti, et al., 2018; Birney, 2019).

By contrast, sCO2 is nearly twice as dense as steam. The critical point is 30.98 °C (87.76 °F), and 7.3773 megapascals, lower than water. "The high density and volumetric heat capacity of sCO2 with respect to other Working Fluids make it more energy-dense, meaning that turbines designed to be driven directly by sCO2 are dramatically smaller than conventional turbines, and have thermal net efficiencies upwards of 50% percent, producing more power from smaller plants (Talbot, 2016). These innovations may prove pivotal in the coming years in Texas, as entities seek to deploy scalable geothermal technologies in the State's sedimentary basins (Ratnakar et al., 2022).

B. Blind Hydrothermal Systems ("BHS") in Texas

Blind hydrothermal systems ("BHS") are much like CHS, in that a combination of sufficient porosity in the subsurface, sufficient heat transfer into the system, and the natural presence of water combine to produce a developable geothermal resource. However, in the BHS context, these systems exist entirely underground, with no indications on the surface, such as geysers, fumaroles, or steam vents, that would suggest a geothermal resource lies below. This sets them apart from CHS, and is the reason they are named "Blind." BHS are subsurface sedimentary aquifers that happen to be located in regions and at depths that place them within optimal temperatures for geothermal development, and they represent an example of a type of sedimentary system that holds great promise for geothermal power production in Texas.

A notable example of a BHS that has been successfully explored and developed for power production is being undertaken by Deep Earth Energy ("DEEP"), a startup based in Saskatchewan, Canada. In 2020, DEEP drilled a series of wells into a BHS in the Saskatchewan side of the Bakken formation, utilizing the directional drilling technologies of the oilfield service company Weatherford, to produce the first 90 degree horizontal fluid production well to be drilled and stimulated for the purpose of geothermal power production in the world.

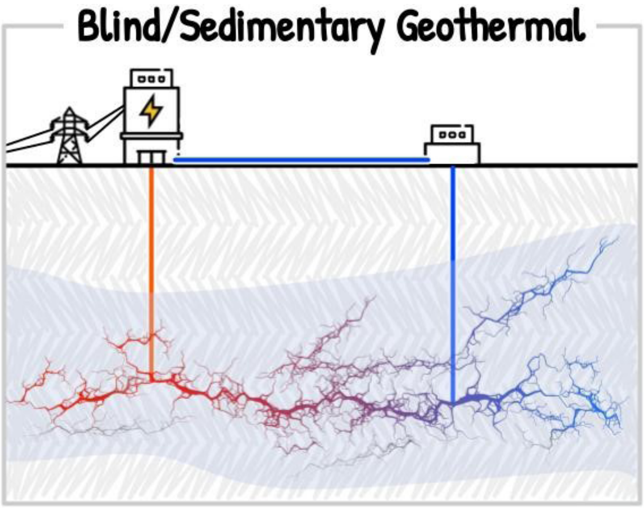

Figure. 1.16. Schematic of an EGS concept constructed in a "Blind" sedimentary aquifer. Note the natural presence of water in the reservoir. *Source: Future of Geothermal in Texas, 2023.*

Installation of a 20 megawatt power plant is currently slated for the site. Total capital costs for the first facility are estimated at approximately $5.4 million per megawatt electric (Richter, 2021b).

The DEEP project is an example of a repeatable and manufacturable well design utilizing off the shelf technologies from the oil and gas industry to pursue previously undiscovered or undevelopable geothermal resources. BHS has captured the attention of international oil companies in recent months, who are increasingly looking to internal oil and gas exploration data to help predict where in the world BHS may be located worldwide, including in Texas.

It is presently not well understood how much BHS exists globally, or if this resource is present in enough locations to support the type of scale desired by oil and gas companies to support engagement. BHS is likely, however, to play a significant role in the development trajectory of geothermal in the coming years in Texas as the 'low hanging fruit' of geothermal development is pursued, as there are BHS present within the Gulf Coast Geopressured Zone ("GCGZ"). The GCGZ will be explored in detail in Chapter 4, The Texas Geothermal Resource.

Figure. 1.17. DEEP drilled and hydraulically stimulated the deepest horizontal well in Saskatchewan, and the first 90 degree horizontal fluid production well in the world for geothermal power generation. Source: DEEP, 2022.

C. SuperHot Rock ("SHR") in Texas

SuperHot Rock ("SHR") is a term given to geothermal technologies that aim to exploit geothermal resources above 373 °C, the supercritical temperature of water. Resources of that temperature tend to be, but are not always, located at depths greater than sedimentary and hydrothermal geothermal resources, and are thus sometimes referred to interchangeably as "Deep Geothermal." In volcanic regions of the world, SHR may be encountered relatively close to the surface, while in locations away from volcanic regions, SHR exists all over the earth at depths between 2 and 12 miles (Clifford, 2022). Many of the next generation energy based drilling technologies in development today, like the technologies pursued by startups Quaise and GA Drilling, have the SHR market and its potential global footprint in mind. As discussed above, because the energy content of water increases with temperature and pressure, and higher temperature fluids increase the power conversion efficiency of geothermal plants, SHR is often labeled the "holy grail" of geothermal resources.

SHR exists everywhere on earth, even in Texas, if we drill deep enough. In Texas, SHR resources are encountered at 10 kilometers or more in depth, depending on your location in the State (CATF, 2021). These depths result in SHR being prohibitively expensive currently, with technology and materials science innovations needed to drive down cost.

Three developments are needed to enable future development of SHR:

1. Drilling technologies are significantly improved, allowing developers to reach rock deeper than 6.2 miles (10 kilometers) and hotter than 400 °C (752 °F);

2. Well completion technologies (e.g., casing, joints, and cementing) are improved to withstand these high-temperatures; and

3. Tools, instruments, and techniques are developed to create and maintain permeable reservoirs within semi-ductile rock (20+ megapascals and 400+ °C, or 752+ °F).

These forward facing technical challenges, along with an exploration of historical pilots in the SuperHot Rock space, were explored by two panels of experts at the PIVOT2022 conference, and serve an as excellent starting point for understanding where we are now with research and development, and what has been accomplished in past experiments in SuperHot Rock (PIVOT, 2022b; PIVOT, 2022c).

IV. Making Geothermal Dispatchable

The potential and desirability for geothermal to operate as a dispatchable resource (i.e., holding capacity in reserve) may increase as other variable renewable sources continue to expand. Because of the variability of intermittent renewable energy sources such as wind and solar, geothermal systems have the potential to complement as a dispatchable power source, negating the need for battery storage.

Geothermal plants can exist as dispatchable energy sources if their power purchase agreements include the value of providing such a service (Richter, 2019; Richter, 2020b). Their economics are driven by high capital costs and low operating costs, so the value of providing baseload power is straightforward. An example of such a commercial agreement is Ormat's Puna Geothermal Venture subsidiary and Hawaiian Electric's Hawaii Electric Light subsidiary, the first fully dispatchable geothermal power plant on the Big Island of Hawaii (Richter, 2020b). Other examples of dispatchable geothermal energy exist in Europe, including five plants in Munich, Germany (EGEC, 2020).

Large-scale deployment of dispatchable geothermal energy is more of an economic, rather than technical, problem. New partnerships among utilities and geothermal power providers are critically needed for both research and field testing to evaluate the commercial models of dispatchable geothermal energy, and the impact of baseload and dispatchable power on future electricity grids. (DOE, 2021a; Robins, et al., 2021; DOE, 2016). There are several ventures headquartered in Texas who are planning or have ongoing "subsurface as energy storage" pilots in the State, including Sage Geosystems, EarthBridge Energy, and Quidnet Energy. These concepts are considered in further detail in Chapter 3, Other Geothermal Concepts with Unique Applications in Texas.

V. Conclusion

Of the four major types of geothermal technologies, three of them, EGS, AGS and Multi-System Hybrids may find a home in Texas as geothermal grows as a resource in the State. Geothermal may also be deployed in Texas in Direct Use heating and cooling applications, as will be discussed further in Chapter 2, Direct Use Applications, or as dispatchable short or long term subsurface energy storage systems. Further, Texas has a number of geologies where these technologies may be deployed in the near term, including in the State's sedimentary basins, in the Blind Hydrothermal Systems of the Texas Gulf Coast region, or even in the deeper SuperHot resources in the future.

As we will consider in detail in Chapter 5, The Oil and Gas Industry Role, many if not all of the technical challenges associated with EGS, AGS, and Multi-System Hybrids can be overcome with oil and gas technologies and know-how. Much more investment is needed, however, for field deployments of power and heat generation projects utilizing scalable geothermal technologies like EGS and AGS. The current level of investment in the EGS and AGS start-ups, as well as the two DOE GTO-funded projects, Collab and FORGE, is less than $2 billion compared to, for instance, the $24.6 billion of investment in new wind power projects for utility-scale land-based wind power capacity added in 2020 (DOE, 2021a; DOE, 2021b; DOE, 2021c).

Nevertheless, considering the size of the resource, Texas' status as the epicenter of the oil and gas industry and its applicable core competencies, low hanging fruit in the State's sedimentary and Blind Hydrothermal Systems for geothermal deployment, and a favorable and business friendly regulatory environment, geothermal may be poised for significant growth and expansion in Texas in the coming years. We will consider what that growth and expansion might look like, and what implications it may have for the State, in the coming Chapters.

Conflict of Interest Disclosure

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Rebecca Schulz serves as an energy and investment consultant on the World Energy Outlook team seconded from Shell to the International Energy Agency in Paris, France, and is compensated for this work. She further serves a non-compensated role as the founding chairperson of the Society of Petroleum Engineers Geothermal Technical Section. Outside of these roles, Rebecca Schulz certifies that she has no affiliations, including board memberships, stock ownership and/or equity interest, in any organization or entity with a financial interest in the contents of this manuscript, and has no personal or familial relationship with anyone having such an affiliation or financial interest.

Peter Boul serves as an Adjunct Professor Materials Science and Nanoengineering at Rice University and manager for composites research and development at Lyten, Inc, and is compensated for this work. His main area of research for over 25 years in applied nanomaterials. Outside of these roles, Peter Boul certifies that he has no affiliations, including board memberships, stock ownership and/or equity interest, in any organization or entity with a financial interest in the contents of this manuscript, and has no personal or familial relationship with anyone having such an affiliation or financial interest.

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