



# The Future of Geothermal in Texas

THE COMING CENTURY OF GROWTH & PROSPERITY IN THE LONE STAR STATE



# The Future of Geothermal in Texas

## Contemporary Prospects and Perspectives

**Edited by**  
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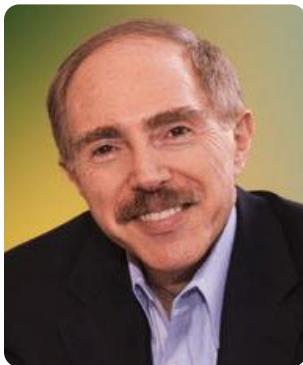


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# Definitions

The terms below are used frequently throughout this Report. Because there is not a universally agreed upon set of definitions to describe geothermal technologies and resources, particularly amongst emerging concepts and applications, authors have adopted prevailing terms used in the Texas ecosystem, while providing variations for some terms where applicable.

**Advanced Geothermal Systems** ("AGS") - AGS is used interchangeably in this Report with Closed Loop Geothermal Systems ("CLGS"). AGS is a geothermal technology that can take any configuration that allows circulation of fluid in the subsurface without flow exchange between the wellbore and reservoir. Fluid is pumped down from the surface, picks up heat from the surrounding formation (in most concepts primarily through conduction), and flows back to the surface, where the heat is harvested for Direct Use or power applications. These systems can be deployed in a variety of rock types, are Closed to Reservoir, and are considered scalable.

**Blind Hydrothermal Systems** ("BHS") - Blind Hydrothermal Systems are much like Conventional Hydrothermal Systems (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. BHS may be present in a range of rock types, but in Texas, they exist primarily within sedimentary rocks, often as subsurface sedimentary aquifers that happen to be located in regions and at depths that place them within optimal temperatures for geothermal development. BHS are an example of a type of sedimentary system that holds great promise for geothermal energy production in Texas.

**Closed to Reservoir Geothermal System** - A geothermal system designed to enable circulation of a Working Fluid in the subsurface without contact occurring between the subsurface reservoir and the Working Fluid. This term is sometimes used synonymously with Advanced Geothermal Systems (AGS) and Closed Loop Geothermal Systems (CLGS).

**Conventional Hydrothermal Systems** ("CHS") - Also known as traditional geothermal systems or conventional geothermal systems, this type of geothermal resource is often close to the surface, and typically has surface manifestations suggesting its presence, such as hot springs, volcanic rock formations, geysers, or steam vents, among others. CHS have 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. Most of the world's developed geothermal capacity currently is produced with CHS.

**Direct Use Geothermal System** - Direct Use Geothermal Systems, also referred to as District Heating and Cooling Systems ("DHCS") in this Report, utilize geothermal heat directly, as opposed to use for powering a turbine to generate electricity. Other widely used terms for Direct Use systems include thermal energy networks, and geogrids. Direct Use systems can be shallow, or deep.

In "Shallow Direct Use" systems, also referred to as "Ground Source" systems, utilize Geothermal Heat Pumps ("GHP") to harvest the constant temperature of the shallow subsurface for a variety of applications, including primarily to heat or cool buildings.



In the “**Deep Direct Use**” context, deeper wells are drilled to reach higher subsurface temperatures, which can be utilized for a variety of applications, including industrial and commercial direct heating, to power heat pumps, or for numerous industrial and manufacturing processes.

When Direct Use geothermal energy is supplied to a large area, clusters of buildings, or in a district from a central location, it is called “**District Heating**,” Thermal Energy Networks (“TEN”), or a variation of these terms, but typically including the word District.

**Engineered Geothermal Systems (“EGS”)**—Also known as Enhanced Geothermal Systems describes a geothermal technology that utilizes hydraulic fracturing (better known as frac’ing) to engineer a subsurface reservoir by creating or enhancing existing fractures in rock. Fluids are then circulated through the fracture network where they heat up, and are then produced to the surface to generate electricity, or for Direct Use. This term includes both Traditional EGS and Next Generation EGS, both defined separately. These systems can be deployed in a variety of rock types, are Open to Reservoir, and are considered scalable.

**Geothermal Anywhere** – A colloquial term used to refer to Scalable Geothermal concepts that could enable development and production of geothermal energy anywhere in the world.

**Geothermal Heat Pumps (“GHP”)** – Also known as ground source heat pumps, harvest the ambient temperature in the top one to two meters of the subsurface, where the ground remains at a relatively constant temperature of 13°C (55°F). GHPs have been traditionally utilized to heat buildings, but are increasingly being utilized in higher temperature industrial and commercial applications.

**Hot Dry Rock (“HDR”)** – A term given to a type of geothermal resource found in rocks that do not have sufficient permeability (pore space) to contain fluids, which therefore makes them “Dry,” but that contain sufficient heat to produce geothermal energy. HDR is the largest geothermal resource in the world, and is globally ubiquitous. All scalable geothermal concepts, including AGS, EGS and Hybrid Geothermal Systems can be deployed in HDR.

**Hybrid Geothermal Systems, or Multi-System Hybrids** – A geothermal technology that couples two geothermal system types, such as EGS and AGS, or CHS and AGS, or two different systems such as solar and geothermal, direct air capture and geothermal, hydrogen and geothermal, energy storage and geothermal, etc. These systems can be deployed in a variety of rock types, and may or may not be scalable, depending on the system combination.

**Next Generation Engineered Geothermal Systems** – Next Generation Engineered Geothermal Systems (“Next Gen EGS”) are defined as an Open to Reservoir Scalable Geothermal concept that utilizes hydraulic fracturing to engineer or enhance a subsurface reservoir for the purpose of producing geothermal heat or electricity, and which incorporates advanced directional drilling and/or frac’ing techniques, including but not limited to, horizontal drilling and multi-stage fracturing. These systems can be deployed in a variety of rock types, but current trends for development are focused on Sedimentary Geothermal Resources.

**Oil and Gas Well Reuse (“Well Reuse”)** – There are two possibilities for producing geothermal energy from existing oil and gas wells. First, an existing hydrocarbon well could be repurposed to produce geothermal energy only, known as conversion. Second, an existing well could produce hydrocarbons and heat simultaneously, known as co-production. We refer to the concepts of geothermal well conversion, and geothermal co-production together as Oil and Gas Well Reuse, or more simply Well Reuse.



**Open to Reservoir Geothermal System** - A geothermal system that allows circulation of a Working Fluid through fractures in a subsurface reservoir, with the Working Fluid coming into direct contact with the rocks in the reservoir. This term is sometimes used synonymously with Engineered Geothermal Systems ("EGS") and Conventional Hydrothermal Systems ("CHS").

**Scalable Geothermal** - A term given to any geothermal resource that has few, if any, geographical limitations on its ability to scale globally (as opposed to locally, or regionally), or to any geothermal technology that, once proven through field trials, could feasibly be deployed anywhere in the world. Hot Dry Rock ("HDR") is thus considered a scalable geothermal resource. Advanced Geothermal Systems ("AGS"), Engineered Geothermal Systems ("EGS"), and some Hybrid Geothermal System concepts are considered to be Scalable Geothermal technologies. Conventional Hydrothermal Systems ("CHS") are not considered scalable geothermal resources under this definition. Blind Hydrothermal Systems ("BHS") may fall somewhere in between scalable and not scalable, having an opportunity to scale beyond local or regional development, but little is currently known about the size of BHS resources globally.

**Sedimentary Geothermal Resource** - A sedimentary geothermal resource is a type of geothermal resource that is found in sedimentary rock formations. These sedimentary rocks, which include sandstone, shale, and limestone, often contain water or steam within the rock pores that can be harvested for geothermal energy production. If these resources have no surface expression of the presence of geothermal, such as geysers, fumaroles, or steam vents, they may be termed Blind Hydrothermal Systems ("BHS").

**SuperHot Rock** ("SHR") - A term given to geothermal technologies that aim to exploit geothermal resources above 373°C, the supercritical point of water. In volcanic regions of the world, SHR may be encountered relatively close to the surface, while in locations away from volcanic regions, SHR may exist at 10 kilometers or more in depth, and are thus sometimes referred to interchangeably as "Deep Geothermal."

**Traditional Engineered Geothermal Systems** - Traditional Engineered Geothermal Systems ("Traditional EGS") are defined as an Open to Reservoir Scalable Geothermal concept that utilizes hydraulic fracturing to engineer or enhance a subsurface reservoir for the purpose of producing geothermal heat or electricity, but that does not utilize advanced directional drilling and multi-stage frac'ing techniques. These systems are typically developed by drilling vertical or deviated wells, and can be deployed in a variety of rock types, but development of these systems has historically focused on basement rock formations.

**Working Fluid** - A term given to the fluid used to harvest geothermal heat from the subsurface and deliver it to the surface so that it may be used for Direct Use applications, or power production. Working Fluids can be, and have been historically, water or brine. Next Generation geothermal concepts seek to use novel, non-water "Engineered Working Fluids" to increase system efficiencies and performance, particularly in lower temperature geothermal resources. Examples of Engineered Working Fluids undergoing research and development currently include supercritical carbon dioxide ("sCO<sub>2</sub>"), combinations of organic fluids, or combinations of both sCO<sub>2</sub> and organic fluids.



# Abbreviations List

<b>AAPG:</b> American Association of Petroleum Geologists	<b>FORGE:</b> Frontier Observatory for Research in Geothermal Energy
<b>API:</b> American Petroleum Institute	<b>FTE:</b> Full Time Equivalent
<b>BEG:</b> Bureau of Economic Geology, University of Texas at Austin	<b>GCGZ:</b> Gulf Coast Geopressured Zone
<b>BHS:</b> Blind Hydrothermal Systems	<b>GEODE:</b> Geothermal Energy from Oil and Gas Demonstrated Engineering Initiative
<b>BHT:</b> Bottom Hole Temperature	<b>GEO:</b> Geothermal Entrepreneurship Organization
<b>°C:</b> Degrees Celsius	<b>GHG:</b> Greenhouse Gas
<b>CATF:</b> Clean Air Task Force	<b>GLO:</b> General Lands Office (Texas)
<b>CEPP:</b> Proposed Clean Electricity Performance Program	<b>GTO:</b> United States Department of Energy, Geothermal Technologies Office
<b>CHP:</b> Combined Heat and Power	<b>H2S:</b> Hydrogen Sulfide
<b>CHS:</b> Conventional Hydrothermal Systems	<b>HDR:</b> Hot Dry Rock
<b>CLGS:</b> Closed Loop Geothermal Systems	<b>HF:</b> Hydraulic Fracturing or Frac'ing
<b>CREZ:</b> Competitive Renewable Energy Zone	<b>HGS:</b> Hybrid Geothermal Systems
<b>CSP:</b> Concentrating Solar Power	<b>HPHT:</b> High Pressure, High Temperature
<b>DAC:</b> Direct Air Capture	<b>HSE&amp;S:</b> Health, Safety, Environment, and Sustainability
<b>DCL:</b> Deep Closed Loop	<b>IEA:</b> International Energy Agency
<b>DDU:</b> Deep Direct Use	<b>IOC:</b> International Oil Company
<b>DEEP:</b> Deep Earth Energy	<b>IOCC:</b> Interstate Oil Compact Commission
<b>DHCS:</b> Deep Direct Heating and Cooling Systems	<b>IRENA:</b> International Renewable Energy Agency
<b>DOD:</b> United States Department of Defense	<b>ISRU:</b> In-situ Resource Utilization
<b>DOE:</b> United States Department of Energy	<b>ITC:</b> Investment Tax Credits
<b>E&amp;P:</b> Exploration and Production	<b>JEDI:</b> NREL Jobs and Economic Development Impacts Model
<b>EDT:</b> Economic Development & Tourism (Texas)	<b>k:</b> Thermal Conductivity
<b>EF:</b> Eagle Ford Shale	<b>LCOE:</b> Levelized Cost of Electricity
<b>EGS:</b> Enhanced or Engineered Geothermal Systems	<b>LCOH:</b> Levelized Cost of Heat
<b>EIA:</b> Energy Information Administration	<b>MNEV:</b> Mobil New Exploration Ventures
<b>EMP:</b> Electromagnetic Pulse	<b>MVC:</b> Mechanical Vapour Compression
<b>ERCOT:</b> Electric Reliability Council of Texas	<b>MWD:</b> Measured While Drilling
<b>ESG:</b> Environmental, Social, and Governance	<b>NASA:</b> National Aeronautics and Space Administration
<b>ESP:</b> Electrical Submersible Pump	
<b>°F:</b> Degrees Fahrenheit	
<b>FO:</b> Forward Osmosis	



**NGCC:** Natural Gas Combined Cycle

**NOC:** National Oil Company

**NREL:** National Renewable Energy Laboratory

**NSF:** National Science Foundation

**O&M:** Operations and Maintenance

**ORC:** Organic Rankine Cycle

**PDC:** Polycrystalline Diamond Compact

**PSF:** Texas Permanent School Fund

**PTS:** Flowing pressure/temperature/spinner

**PTC:** Production Tax Credits

**PUCT:** Public Utilities Commission of Texas

**PUF:** Permanent University Fund

**R&D:** Research and Development

**RD&D:** Research, Development, and Demonstration

**RO:** Reverse Osmosis

**ROACE:** Return on Average Capital Employed

**SPE:** Society of Petroleum Engineers

**SMR:** Steam Methane Reforming

**SMU:** Southern Methodist University

**SMU-NGDS:** Southern Methodist University - National Geothermal Data System

**sCO<sub>2</sub>:** Supercritical Carbon Dioxide

**SH<sub>min</sub>:** Minimum Horizontal Stress

**SH<sub>max</sub>:** Maximum horizontal stress

**SHR:** Super Hot Rock

**TAC:** Texas Administrative Code

**TDS:** Total Dissolved Solids

**TEG:** Thermoelectric Generator

**TexNet:** Seismic Monitoring Program, Bureau of Economic Geology, University of Texas at Austin

**THMC:** Thermal/Hydrological/Mechanical/Chemical

**TPS:** Thermal Protection System

**TRL:** Technology Readiness Level

**TXDeCarb:** Texas Decarbonization Study

**RRC:** Texas Railroad Commission

**UL:** University Lands





# Introduction

## Geothermal and the Lone Star State

Jamie C. Beard, Esq.

Texas is hot, and it's not just the climate. It's hot under our feet as well. The core of the Earth is 6,000°C (10,832°F), the same temperature as the surface of the sun. The Earth's crust is an excellent insulator, shielding the surface from the enormous amount of heat that lies below. One needs only to stand near an erupting geyser, or visit a volcano to experience the immense power of this energy resource. And it is everywhere - ubiquitous. At any point on Earth, if you drill deep enough, you reach temperatures sufficient to produce electricity. Geothermal is an untapped subsurface energy giant.

The Union of Concerned Scientists estimates that the amount of available geothermal energy beneath our feet is 50,000 times more than the global total of oil and gas resources combined (UCS, 2014). Put another way, the oil and gas industry has powered the world through the industrial revolution and into modern times on the much smaller of our two subsurface resources – hydrocarbons and heat.

Texas geologies, including geothermal resources in the State's sedimentary basins, along with the State's status as the epicenter of the oil and gas industry, present a large and promising opportunity to develop geothermal resources in the State.

But why geothermal in Texas now? Over the past two decades within the oil and gas industry, there have been significant and enabling technological advances as a result of deepwater oil and gas exploration, and the invention of directional drilling technologies and hydraulic fracturing techniques – the enabling features of the 'shale boom.' New technologies and methodologies emerging from and perfected by the oil and gas industry over the past twenty years, such as horizontal drilling, multi-stage fracturing, and managed pressure drilling, have proven so disruptive that over the past decade they have rearranged global geopolitics and propelled the United States into energy independence (Olien, 2022). But these disruptive technologies and ways of working in oil and gas have just barely begun to be applied in the geothermal context, and when these technologies are transferred through oil and gas industry engagement in geothermal, we should expect, and even plan for, breakthrough impact, and fast, exponential leaps in capabilities and performance in the years to come. You'll see examples of these leaps in the pages of this Report.

Curiously however, most, if not all geothermal focused vision statements and analyses over the years have failed to take into account the swift and dramatic impact oil and gas industry engagement would have in



geothermal development and scale over the coming decades. As a result of either underestimation, or failure to acknowledge the impact of technology transfer, fast innovation, and engagement at scale by the oil and gas industry, geothermal growth lingers consistently in single or low double digit growth over the coming decades in energy transition reports and models (EIA, 2022). These numbers have failed to motivate entrepreneurs, funders, governments, and even industry to acknowledge the sleeping clean energy giant beneath our feet as a potentially significant player in the energy transition. This failure of enthusiasm isn't particularly surprising, as imagining the limits of what is possible is where innovators and entrepreneurs find inspiration.

Much like the rise of unconventionals, whose meteoric ascent largely took the world by surprise, geothermal is poised for similar, exponential growth should technology development and transfer follow the footsteps of the shale boom. Given increasing oil and gas industry engagement in this space, which is explored in depth in the pages of this Report, this is a possibility that should no longer be

overlooked as the world searches for energy transition strategies. Globally scalable geothermal development looks increasingly approachable to oil and gas entities if the past several decades of expertise are fully leveraged and optimized for geothermal development, and you'll see data in support of this in the coming Chapters. Further, geothermal entrepreneurship has entered a period of renaissance, with more geothermal startups launching over the past two years than in the past ten years combined, many buoyed by oil and gas investments, and a majority being led by lifelong oil and gas industry veterans. Several of these companies are planning or currently executing pilot projects and demonstrations in Texas.

It's not just industry and startups who are eyeing geothermal as an option for Texas' energy future. Recent polling data shows that geothermal is a uniquely bipartisan technology that Republicans, Democrats, and Independents wish to see greater emphasis on (CTEI, 2021). In a September 2022 survey of Texas voters, the second highest policy concern, behind immigration, was

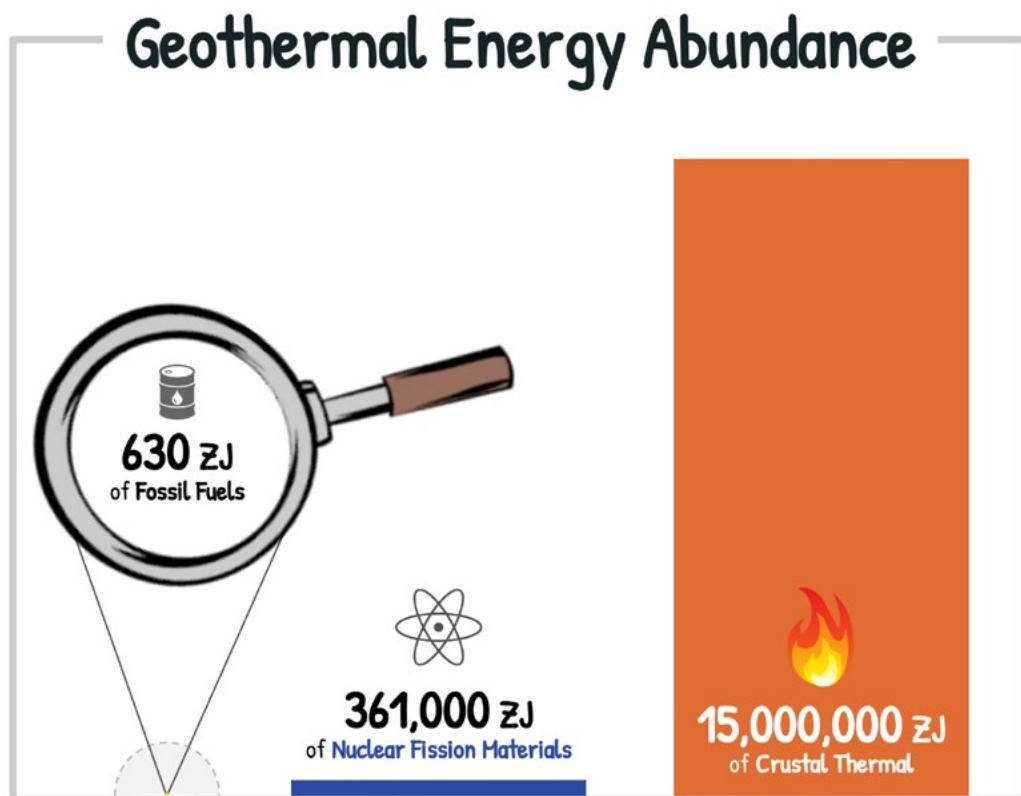


Figure. 0.1. Comparison of total heat energy in Earth's crust, compared to fissionable materials, and fossil fuels. Note that total fossil fuels, when compared with crustal thermal energy, is the equivalent of less than one pixel at the bottom of the graphic. Source: Adapted from Dourado, 2021



## Likely Texas Voters

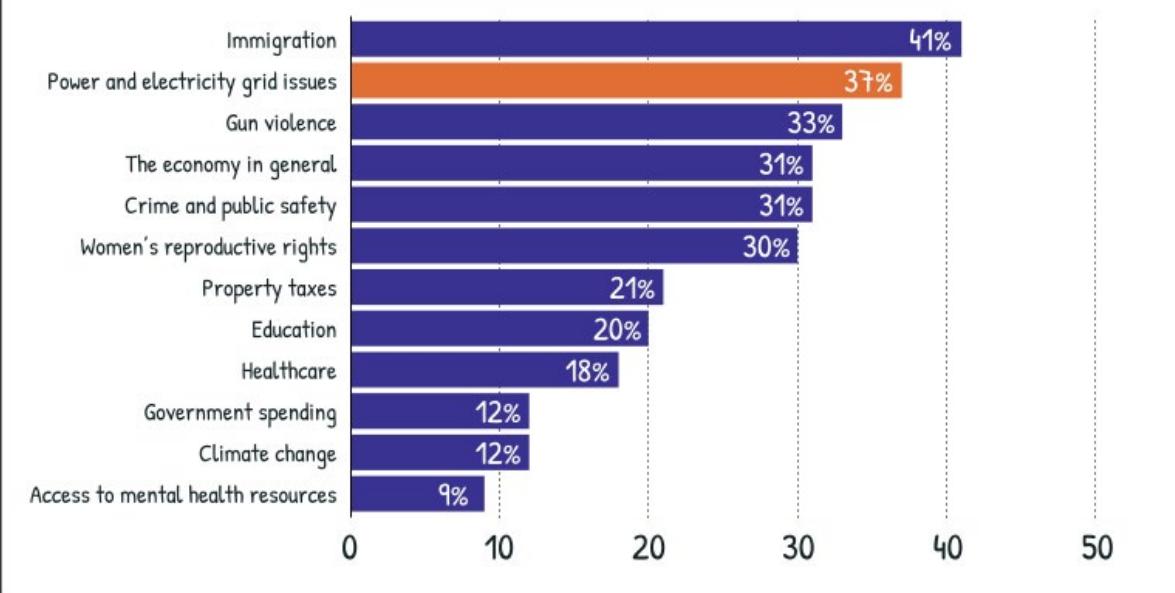


Figure 0.2. Top policy concerns for Texas voters during the 2022 midterm elections. Concerns about the electrical grid in Texas are second only to immigration as top of mind for Texas voters. Source: Adapted from DFP, 2022.

power and electricity grid issues. 73 percent of Texas voters support investments into new energy technologies that will alleviate periods of high stress on the electric grid in Texas (DFP, 2022). Additionally, geothermal energy has the lowest unfavorable ratings compared to all energy sources among Texas voters (DFP, 2022). Texas voters who are knowledgeable about geothermal express high levels of favorability toward the energy source, though data suggests we have a long way to go in familiarizing the public with geothermal, particularly in States like Texas where the resource has no surface manifestations, and is effectively invisible. Nevertheless, Republicans, Democrats, and Independents all support a greater emphasis on geothermal energy technologies, and view geothermal as a part of the future energy mix in the State of Texas (DFP, 2022; CTEI, 2021).

Through an exploration of a variety of topics relevant to the growth of this resilient, secure, baseload, clean energy source in Texas, this Report aims to reframe the conversation about geothermal to the upper limits of possibility, placing the technical, regulatory, legal, educational, and scaling barriers of geothermal into the backdrop of the Lone Star State, where 'everything

is bigger' - and asking the question - how would the millions of innovators, regulators, entrepreneurs, oil and gas workforce, academics, and industry entities in the State nurture and grow this resource, as they did oil and gas over the past century. Many authors of this Report, including myself, were inspired to study or pursue careers in geothermal by what remains the most visionary, comprehensive, and forward-looking work in this field, *The Future of Geothermal Energy*, published by the Massachusetts Institute of Technology Energy Initiative in 2006 (Tester, et al., 2006). At the risk of understatement, a significant amount of extremely consequential, breakthrough innovation in drilling and subsurface engineering, led by the oil and gas industry, has happened since that time. So it's time for an update, taking the technology advancements of the past two decades, oil and gas industry capabilities, and synergistic assets present in Texas into account in exploring the Future of Geothermal in Texas. We hope that the next generation of geothermal innovators, entrepreneurs, pioneers, and advocates will find inspiration here the way we did years ago. Enjoy the ride, and since a geothermal pun seems like the best way to kick off this Report, *Full Steam Ahead*. 🔥



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## Conflict of Interest Disclosure

**Jamie Beard** serves as Executive Director of Project InnerSpace, a 501(c)(3) organization that works on issues within the subject matter of this manuscript. She further serves in a non-compensated role as a founding member of the board of the Texas Geothermal Industry Alliance. Outside of these roles, Jamie Beard certifies that she have no affiliations, including but not limited to 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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# PART I

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## Geothermal Concepts with Applicability in Texas



## Chapter 1

# Geothermal and Electricity Production: Scalable Geothermal Concepts

S. Livescu, B. Dindoruk, R. Schulz, P. Boul, J. Kim, and K. Wu

***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.

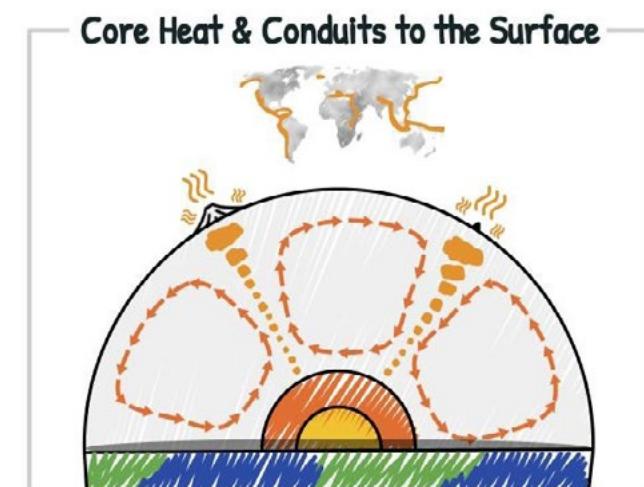


Figure 1.1. An artist's illustration of global heat flow to the surface and convective currents, with plate boundaries and the Ring of Fire highlighted above. Source: Future of Geothermal Energy in Texas, 2023.



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.

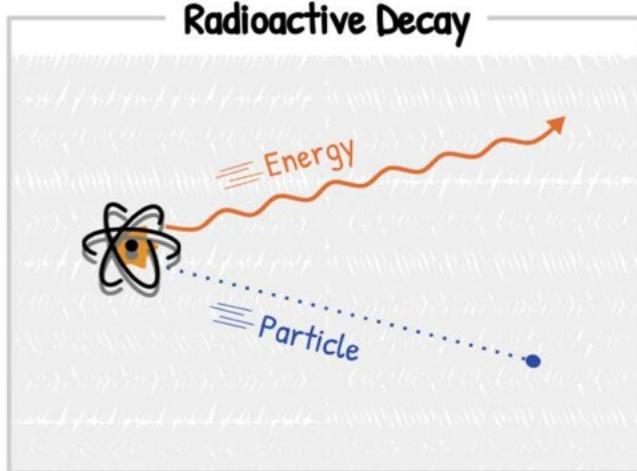


Figure 1.2. Much of the geothermal energy we seek to harvest near the surface is a result of radioactive decay of isotopes such as uranium and thorium in Earth's mantle and crust. Source: Future of Geothermal Energy in Texas, 2023.

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.

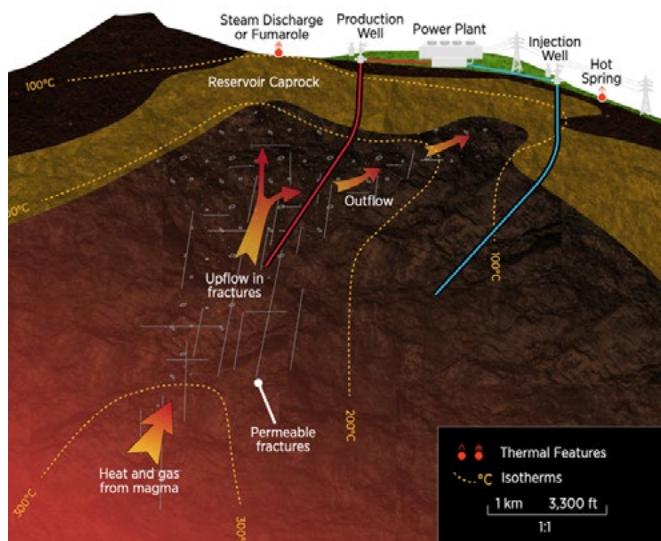


Figure 1.3. Simplified schematic of a CHS development. Source: Richter, 2021b.



## 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.

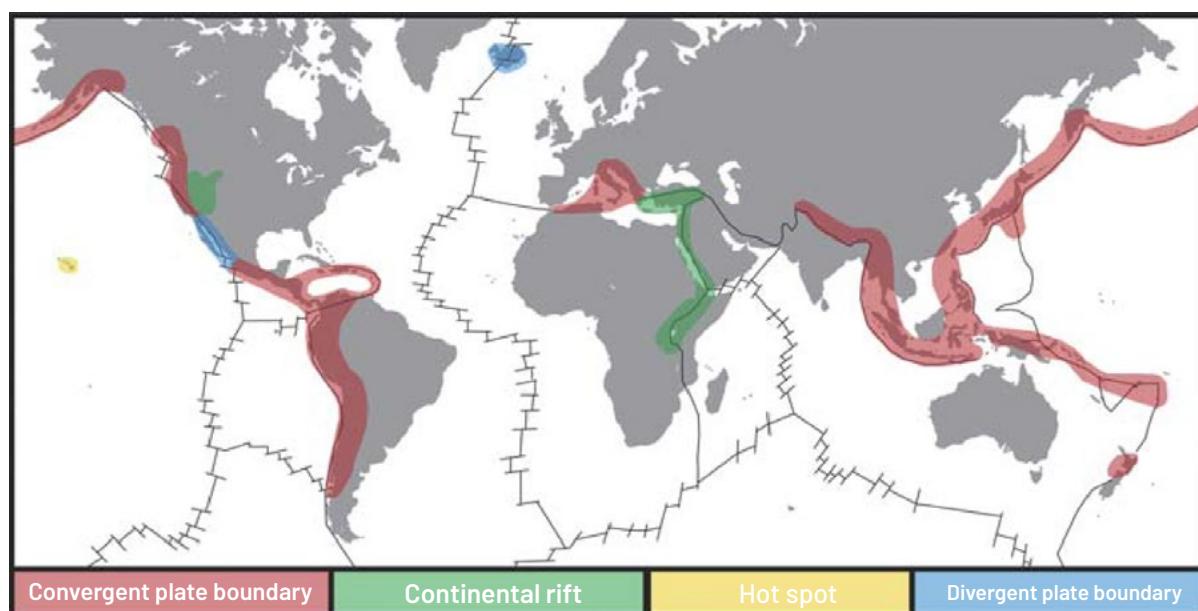


Figure 1.4. High heat flow to the surface and conventional hydrothermal regions. Source: Ball, 2021.





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](#).

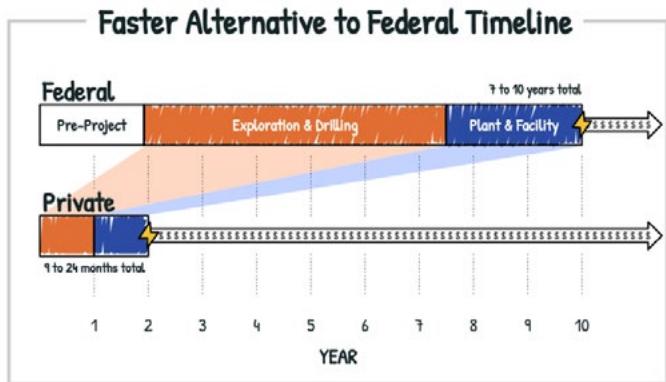


Figure 1.6. Comparison of geothermal development timeline on Federal land vs. private land. The private timeline is based on the trajectory of an ongoing geothermal pilot in South Texas. Source: Adapted from DOE.

## 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.

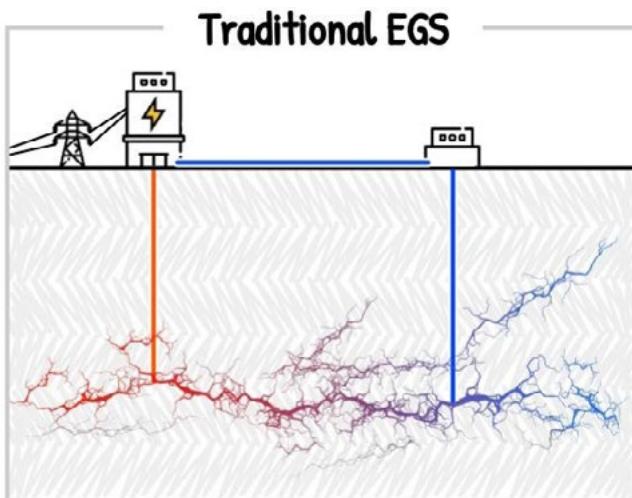


Figure 1.7. Schematic of a Traditional EGS approach, featuring two vertically drilled wells, with a fracture network connecting them in the subsurface. Source: *The Future of Geothermal in Texas, 2023*.

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 occurring 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](#).

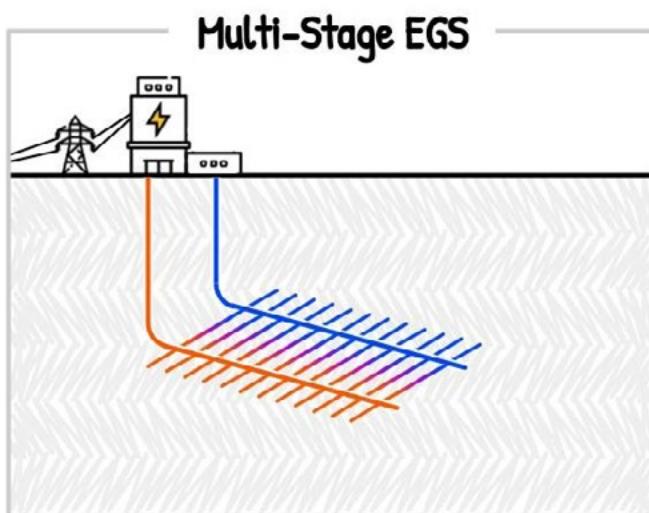


Figure 1.8. Schematic of Next Generation EGS or EGS 2.0, utilizing advanced techniques from the oil and gas industry, including horizontal drilling and multi-stage fracturing techniques. Source: *The Future of Geothermal in Texas, 2023*.

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
<b>Spatial scale</b>	Reservoir	32.8 feet (ten meters)
<b>Access to Rock</b>	Short boreholes	Deep wells
<b>Instruments</b>	Nearby	Standard field geophysical
<b>Environmental Conditions</b>	Cool rock at reasonable stress	Hot rock at reasonable stress
<b>Focus</b>	Direct investigation	Development of a testbed and management of a research program
<b>Project Structure</b>	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 ("sCO<sub>2</sub>"), 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).

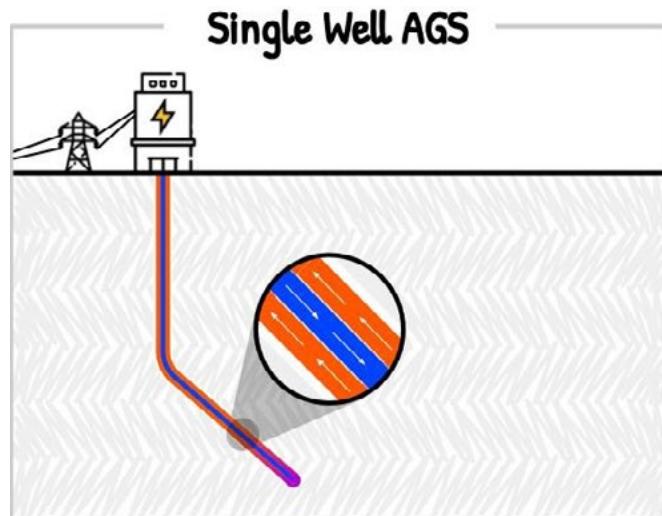


Figure 1.10. Schematic of a single well, concentric 'pipe-in-pipe' AGS concept, demonstrating fluid flow through the system. Source: Adapted from Greenfire, 2022.

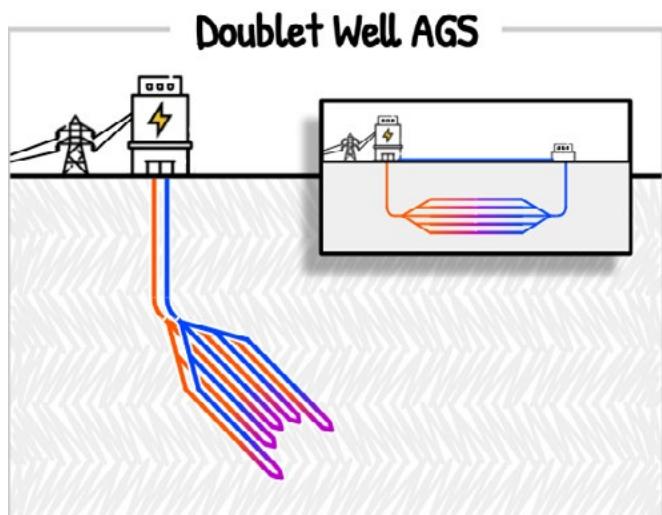


Figure 1.11. Schematic of a doublet well AGS concept, one in a deviated forked configuration, and the other in a multi-pronged horizontal configuration. Source: Adapted from Eavor, 2022.



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 ("sCO<sub>2</sub>"), 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 sCO<sub>2</sub> 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).

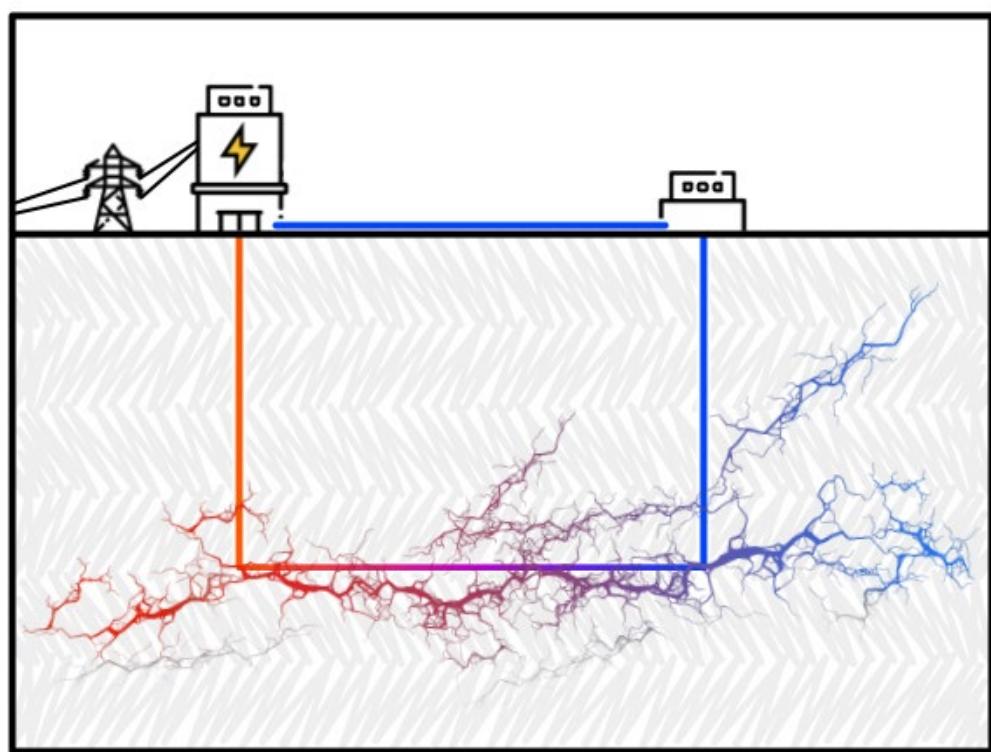


Figure 1.12. An artist's illustration of an EGS/AGS hybrid concept, with a fracture network to enhance heat transfer from the reservoir to the wellbore. Source: *Future of Geothermal in Texas*, 2023.



#### 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 sCO<sub>2</sub> as the Working Fluid, combined with a bespoke sCO<sub>2</sub> 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; Zagos, 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 unconventionalals 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 sCO<sub>2</sub>, 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

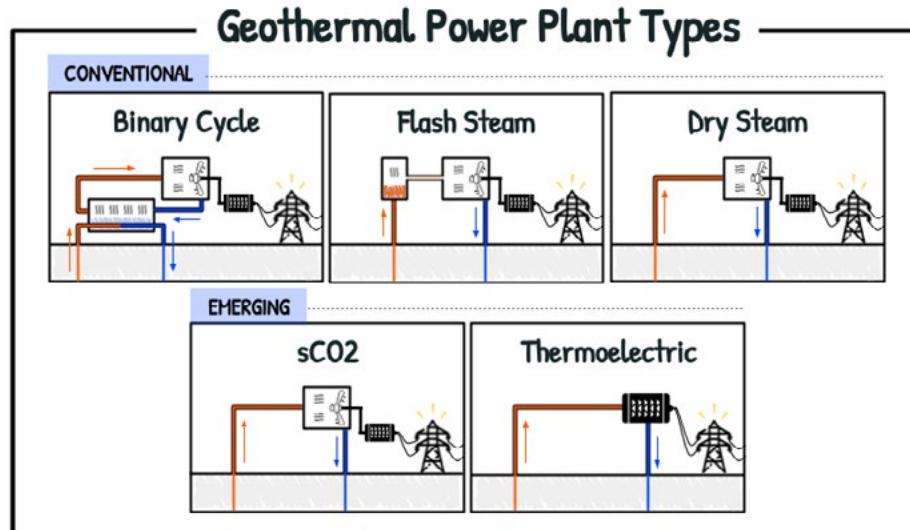


Figure 1.15. Comparison of geothermal power plant types, grouped by conventional and emerging technologies. Source: Adapted from EIA



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, sCO<sub>2</sub> 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 sCO<sub>2</sub> with respect to other Working Fluids make it more energy-dense, meaning that turbines designed to be driven directly by sCO<sub>2</sub> 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.

## Blind/Sedimentary Geothermal

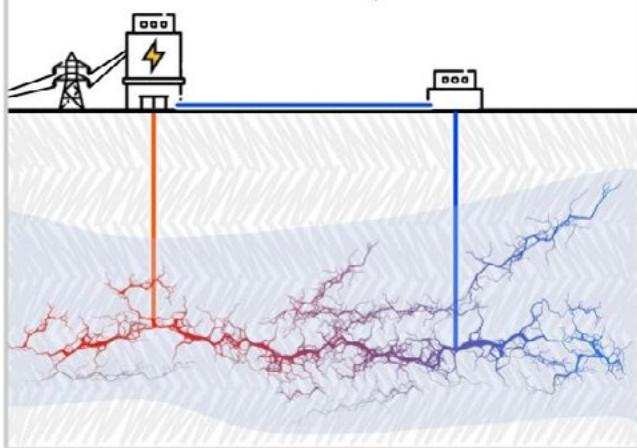


Figure 1.16. Schematic of an EGS concept constructed in a "Blind" sedimentary aquifer. Note the natural presence of water in the reservoir.

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 point 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 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.



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## Conflict of Interest Disclosure

**Silviu Livescu** serves as a faculty member in the Petroleum and Geosystems Engineering Department and a co-principal investigator for the HotRock Industry Affiliates Program, both at the University of Texas at Austin, and is compensated for this work. He is also a co-founder of Bedrock Energy, a geothermal heating and cooling startup, and the editor-in-chief of Elsevier's Geoenergy Science and Engineering. Outside of these roles, Silviu Livescu 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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**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.

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## Chapter 2

# Direct Use Applications: Decarbonization of Industrial Processes, and Heating and Cooling Scenarios

S. Kapusta, S. Livescu, B. Dindoruk, R. Schulz, M. Webber

***Geothermal heating and cooling applications are technologically enabled and deployable in every region of Texas, presenting a significant opportunity to reduce energy usage, and increase indoor comfort and reliability for Texans in both winter and summer.***

## I. Introduction

In this Chapter we explore the application of Direct Use geothermal, both in high temperature applications to provide heat for industrial processes, buildings, agriculture, and manufacturing, and low temperature applications to provide cooling for indoor environments during summer months, and heating for cooler months. Systems for heating and cooling applications utilizing geothermal are fully technologically enabled, and appropriate geothermal resources, particularly for low temperature heating and cooling applications, are located everywhere in Texas, just beneath our feet.

Direct Use Geothermal Systems, also referred to as District Heating and Cooling Systems ("DHCS") in this Report, utilize geothermal energy directly, as opposed to use for powering a turbine to generate electricity. Direct Use systems can be shallow, or deep. In "Shallow Direct Use" systems, also referred to as "Ground Source" systems, utilize Geothermal Heat Pumps ("GHP") to harvest the constant temperature of the shallow subsurface for a variety of applications, including primarily to heat or cool buildings. In the "Deep Direct Use" context, deeper wells are drilled to reach higher subsurface temperatures,



which can be utilized for a variety of applications, including industrial and commercial direct heating or to power heat pumps, or for numerous industrial and manufacturing processes.

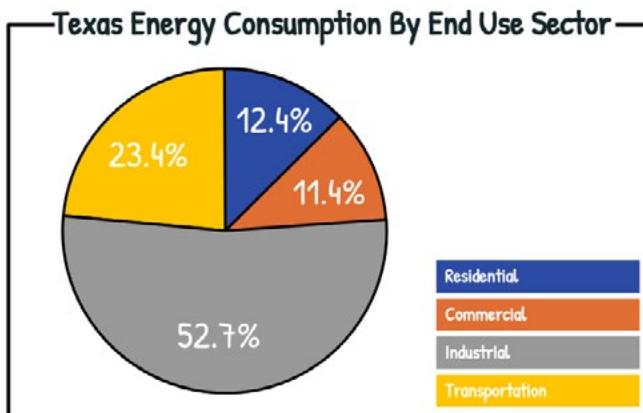


Figure 2.1. Texas energy consumption by end-use sector, 2019. Source: Adapted from EIA, 2022.

This Chapter will begin with an overview of the types of Direct Use Geothermal Systems, will then discuss the economic applications of Direct Use, and ends with a discussion of the environmental benefits of Direct Use utilization in Texas. But before we explore further, it may be helpful to put the utilization of heat into context for Texas.

About three quarters of the energy used in Texas is consumed to heat and cool homes (12.4 percent), commercial buildings (11.4 percent) and industrial facilities and processes (52.7 percent)(see Figure 2.1).

Thus, Direct Use geothermal cooling and heating, if widely deployed in the State, could generate significant operational cost savings for users, relieve grid strain, and can make a substantial and material contribution to the decarbonization of the Texas grid. But perhaps more importantly, recent heat waves and deep freezes in Texas, with record temperatures that threaten food production, energy systems, and human well being, have highlighted an important fact: the consequence of a changing climate is the increasing need for resilient and reliable heating and cooling strategies.

## II. Types of Direct Use (“DU”) Geothermal Heating and Cooling Systems

Direct Use (“DU”) geothermal for heating and cooling historically includes using shallow and low-temperature reservoirs (generally between 50 and 1,000 meters below the surface) to exchange cold and hot with the subsurface, depending on seasonality and needs. DU systems include both Geothermal Heat Pumps (“GHP”)

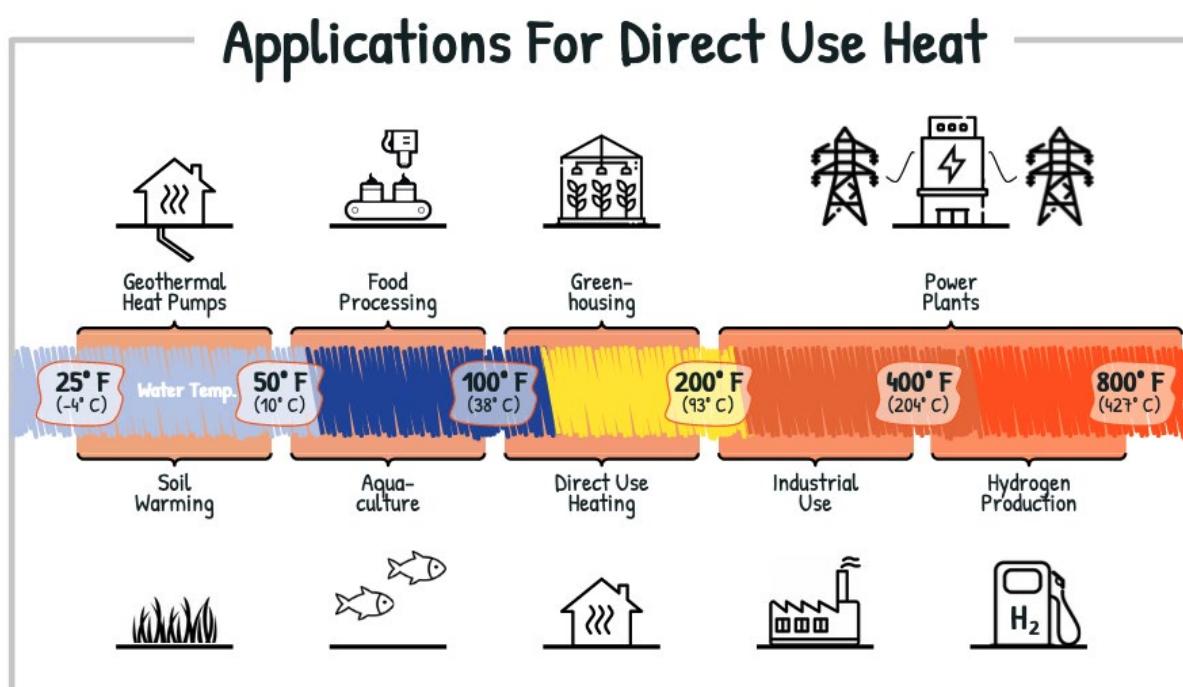


Figure 2.2. Direct Use applications of geothermal energy. Adapted from DOE, 2019.



for buildings and, more recently but with a less mature market base, networks of wells for clusters of buildings, agriculture, aquaculture, food processing, and other light industry (Beckers, et al., 2021; Weijermars, et al., 2018).

DU systems are a mature, well-established technology that will benefit from further spillover of oil and gas technologies and know-how, as further explored in [Chapter 5, The Oil and Gas Industry Role](#). According to the U.S. EPA, GHPs save building owners between 30 and 70 percent in heating costs, and between 20 and 25 percent in cooling costs compared to conventional systems such as air source heat pumps, natural gas furnaces, and traditional air conditioning systems (EPA, 2022).

Higher geothermal gradient areas remain more attractive targets for DU and Deep Direct Use ("DDU") applications because of reduced drilling costs and subsurface risk. As discussed in detail in [Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development](#), the densely populated and industrial regions of Texas possess ideal suitability to deploy DDU for industrial heating applications. The standout region is the greater Houston and northern Gulf Coast area, which is both heavily urbanized and industrialized, and is underlain by favorable geothermal gradients. Also of interest are the greater Dallas-Fort Worth and greater Corpus Christi metro areas. The Austin/San Antonio corridor has less favorable geothermal gradients for high temperature DU applications. However, all regions of Texas have more than ample geothermal temperature gradients to deploy GHPs, details of which will be discussed later in this Chapter.

In DU applications that utilize shallow subsurface depths, systems of pipes (often manufactured from polypropylene random copolymer, high density polyethylene, and steel) are laid below or nearby buildings or structures that require seasonal heating or cooling. Shallow DU systems for heating and cooling have historically been applied where the near subsurface is a constant 16°C (60°F), depending on the latitude (DOE, 2022). DU applications at deeper depths, often referred to as Deep Direct Use ("DDU"), are currently being demonstrated to access hotter reservoirs in the subsurface. These deeper applications are utilized where higher temperatures are needed at the surface, for industrial or manufacturing processes for example, or where a large building with significant heating needs has a small surface footprint, for instance in a densely populated area, in which to install a system.

DU systems can be both Open to Reservoir (i.e., direct heat and fluid exchange with the reservoir) or Closed to Reservoir (i.e., no fluid exchange with the reservoir, only heat exchange via conduction through the fluids, pipes and reservoir) to provide heat during winter months and cool during summer months (DOE, 2019).

DU systems are a proven technology, utilizing shallow depths, and were first used in the United States in Boise, Idaho, in the 1890s. First use outside of the United States began decades earlier (Robins, et al., 2021). Globally, direct use of geothermal heat has grown by more than 50 percent from 2015 to 2019 to about 107 gigawatts thermal. The market in the United States has grown much less than in Europe and China, which collectively account for two-thirds of global direct heat consumption (Mullane, et al., 2016).

In 2013, the World Energy Council estimated the global resource availability of DU geothermal to be about 140 exajoules per year (roughly 38,900 terawatts per hour), excluding recent trends that include application of DDU targeting deeper depths (DOE, 2016). Globally, total energy consumption for heating and cooling is approximately 410 exajoules per year, or roughly 113,889 terawatts per hour (IEA, 2021a). The potential size of the global market for DU geothermal is not well described, but it is potentially more expansive than previously estimated. For instance, recent analysis indicates that between 56 to 85 percent of Spain's industrial energy demand could be converted to DU systems, using geothermal reservoirs up to 100°C to 150°C (212°F to 302°F), respectively (IEA, 2021b). And as we will see in [Chapter 7, The Geothermal Business Model & the Oil and Gas Industry](#) of this Report, the heat demand that could be satisfied by DU geothermal in Texas is staggering.

#### A. Heating and Cooling with GHPs

The application, and even manufacturing, of GHPs could be nurtured into a massive new industry in Texas. Driven by recent Federal incentives, the heat pump market is exploding in the United States, with most heat pumps manufactured in Illinois, New York, Pennsylvania, and New Jersey. Revenue from the manufacturing of heat pumps in those states is an \$80 billion annual business.

Traditional air conditioning methods, using air source heat pumps, don't remove or eliminate heat, but rather move it from one location to another. When a building interior is



cooled, that thermal energy is transferred to the exterior environment. In dense urban areas throughout Texas, this effect increases local temperatures, exacerbating summer heat waves in places that are already heat islands as a result of urbanization. The solution to mitigate this public health issue is to transfer that heat to the subsurface, using GHPs instead.

Whisper Valley is a residential housing development near Austin, Texas that already incorporates GHPs into their new construction, with resulting energy savings. Other large volume residential and commercial developers should follow that lead, utilizing GHPs in new construction throughout Texas, addressing a root cause of urban summer heat waves that pose a public health danger to Texans. GHPs are also resilient and versatile for heating in the winter months, and are more reliable in extreme weather events, such as winter storms like Uri.



Figure 12.6. Houses in the Whisper Valley subdivision are heated and cooled with Geothermal Heat Pumps. Photo taken during Winter Storm Uri. Photo credit: O.Nealio.

Let's consider in lay terms how GHPs function. The temperature of the shallow subsurface, only a few feet down, is constant and experiences little fluctuation or variation throughout the year, remaining around  $13^{\circ}\text{C}$  ( $55^{\circ}\text{F}$ ), depending on the latitude. Currently, we heat and cool our buildings to a comfortable  $21^{\circ}\text{C}$  ( $70^{\circ}\text{F}$ ) from the ambient temperature outside. So in Winter Storm Uri, for example, when temperatures in Texas were  $-12^{\circ}\text{C}$  ( $10^{\circ}\text{F}$ ) in places, Texans were trying to heat their homes and buildings from  $-12^{\circ}\text{C}$  ( $10^{\circ}\text{F}$ ) to  $21^{\circ}\text{C}$  ( $70^{\circ}\text{F}$ ), which is a  $33^{\circ}\text{C}$  ( $60^{\circ}\text{F}$ ) difference using natural gas or electricity. Now consider if our homes and businesses had been utilizing

GHPs during that same cold snap, Texans would only have needed to heat its structures from  $13^{\circ}\text{C}$  ( $55^{\circ}\text{F}$ ), or the consistent temperature of the subsurface, to  $21^{\circ}\text{C}$  ( $70^{\circ}\text{F}$ ). This is a significantly smaller temperature difference of only  $8^{\circ}\text{C}$  ( $15^{\circ}\text{F}$ ) using GHP technology. This avoidance of strain on the Texan grid could have significantly reduced the impact of Uri's tragic outcomes, all utilizing a fully enabled technology that is deployable anywhere in Texas.



Figure 2.4. Geothermal heat pump coils being buried underground in a horizontal loop configuration. Photo credit: Kody Nelson.

So what do these systems look like? Direct Use Heating and Cooling Systems consist of a heat pump connected to a series of buried pipes. One can install the pipes either in horizontal trenches just below the surface, or in vertical boreholes that go several hundred feet below ground, with less disturbance to the surface. The heat pump circulates a fluid, often water or a glycol based solution, through the pipes to move heated fluids (or cooled fluids, depending on the season), from point to point.

In winter, when the temperature under the ground is warmer than the temperature outside, the GHP moves heat from the warmer subsurface into the structure. The heat pump can also reverse course in summer, moving heat from the air in a structure into the ground, thereby cooling the building. GHPs use less electricity, and are much more efficient, than traditional air conditioning units, and even more efficient than air source heat pumps (DOE, 2022; EPA, 2022). For every unit of electricity used in operating a GHP, the system can deliver as much as five times that energy in the form of heating or cooling from the ground. (DOE, 2022; EPA, 2022).



## Geothermal Heating & Cooling

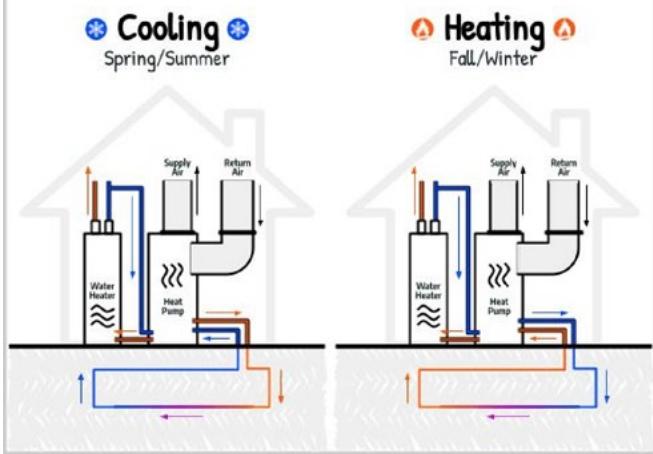


Figure 2.5. Illustration of how Geothermal Heat Pumps deliver cold air into structures in the spring and summer, and hot air in the fall and winter.

Source: Adapted from DOE, 2019.

There are four main configurations of these systems: horizontal, vertical, pond, and open-loop. In the horizontal configuration, pipes are laid in rows parallel to each other and the surface. This configuration is good for places with ample amounts of land. The vertical configuration packs pipes into a smaller area by drilling deeper holes for the pipes to lace through. This configuration works well when there is a small surface area for system installation, in urban areas, for instance. The pond configuration runs pipes through a nearby water source, relying on water's ability to retain heat or cool, and the open-loop system is similar to the pond configuration in its use of a water resource as the exchange medium, but utilizes direct exchanges with the water source.

Using geothermal energy to heat and cool residential and commercial buildings is one of the most proven and widely deployed uses of geothermal resources, and several startups are taking advantage of the opportunity. Dandelion Energy is introducing new business and financing models to make installation of GHPs cheaper for homeowners, similar to the models used for rooftop solar. Bedrock Energy seeks to decarbonize existing large commercial and residential buildings in high-density population centers, with a novel compact drill rig and system design. And EU based Celsius Energy, a spin-off of oil giant SLB, recently opened a sales office in Massachusetts to begin deploying DU technologies for customers in the Northeastern United States.

With historically cheap electricity and natural gas, and no carbon pricing burden, there has been no financial incentives for Texan homeowners to adopt GHPs. As Texans become more incentivized to increase the efficiency of their homes, realize energy savings by reducing fuel costs, reduce emissions, or increase their resilience to extreme weather events, GHPs will become a viable solution ripe for widespread adoption in Texas. In that context, the capability to inexpensively retrofit properties with GHPs will become increasingly important.

To summarize, GHPs will play a significant role in the coming years in increasing reliability and security of heating and cooling systems in Texas, while reducing strain on electric grids during extreme weather events. Further, GHPs are far more efficient than their air sourced counterparts, especially at temperature extremes. GHPs have been historically preferred in the United States in cooler northern latitudes, where fossil fuel costs are higher than average in the United States. Therefore, cost savings from reduced energy use will factor into decisions to deploy GHPs in Texas, and can be a focus area for policy and incentives to help speed adoption.



Figure 2.6. A geothermal drill rig used by Dandelion Energy to install Geothermal Heat Pumps in New York State. Source: Dandelion Energy, 2022.

### B. Heating and Cooling with District Systems

District Heating and Cooling Systems ("DHCS") typically use hot water from springs or reservoirs located near the surface of the Earth to heat and cool networked clusters of structures. DHCS, also known as thermal energy





Figure 2.7. Select projects where entities have or are in the process of converting heating and cooling from gas/steam systems to geothermal/hot water systems, from 2017 to present day.

Source: Urlaub, 2022.

networks, provide heat for buildings in Reykjavik, Iceland; Paris, France; Munich, Germany; and an increasing number of locations in the United States. Reykjavik, Iceland is one of the earliest examples of a Direct Use district system in the modern era.

Over the past five years, DHCS for densely clustered buildings have enjoyed renewed attention. For the first time since the oil crises in the 1970s, DHCS have been placed on the master plans of corporate headquarters, university campuses, dense suburban and urban centers, and even DOE national laboratories, such as Argonne National Lab. Figure 2.7 depicts select projects that are converting from gas/steam systems to geothermal/hot water systems since 2016. The Epic Systems Corporation, headquartered in Verona, Wisconsin, has completed its conversion project, and is now the largest DHCS in the United States, with a system covering 8 million square feet, generating 15,000 tons of cooling capacity, and over 95 million British thermal units per hour of heating capacity (Urlaub, 2022).

Commercial businesses are increasingly turning their attention to DHCS, such as Microsoft's Headquarters in Seattle, Washington; Google in Silicon Valley, California;

Ford Motors in Detroit, Michigan; and Yahoo! Headquarters in Omaha, Nebraska, with additional focus on geothermal energy to heat, cool, and power data centers across the United States. Universities throughout the country have identified DHCS as a viable option for operational cost savings, coupled with a clean, carbon-free energy. For example, Ball State University ("BSU") in Muncie, Indiana saves over \$2 million per year from reduced energy costs, eliminating 85,000 tons of carbon dioxide emissions, 3,400 tons of coal ash, and 36,000 tons of coal annually by converting from a coal/steam system to a geothermal/hot water system. The BSU geothermal system heats and cools 47 buildings, producing 10,000 tons of cooling capacity, and 152 million British thermal units per hour of heating capacity for a 5.6 million square foot system (Urlaub, 2022). Universities in Missouri, Iowa, North Carolina, Pennsylvania, Maine, Ohio, Michigan, and even a Department of Veterans Affairs medical center in Texas have heating and cooling conversion to geothermal systems currently under construction, or built into shovel-ready master plans.





Figure 2.8. Coils being laid for a geothermal district system. Source: Urlaub, 2022.

In the United States, entities such as the nonprofit Home Energy Efficiency Team ("HEET") are pushing forward with networked geothermal boreholes in Massachusetts and New York. HEET advocates for a district system (the organization uses the term network system) "connected by a shared loop in the current gas right-of-way that provides thermal energy to customer buildings" (HEET, 2022). HEET is deploying "GeoMicroDistricts," a proven technology already used in the United States and Europe (Figure 2.8).

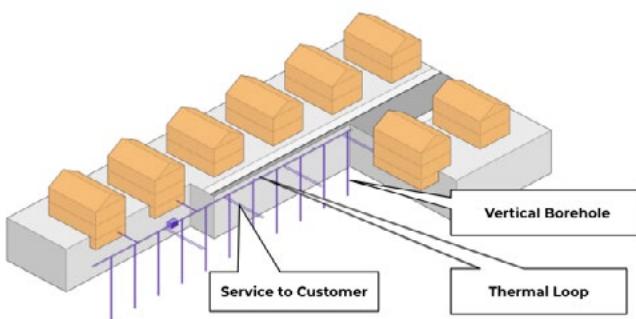


Figure 2.9. A networked geothermal system as envisioned by HEET. Source: HEET, 2022.

Commercial and industrial buildings have the same cooling and heating needs as homes, except that large buildings and campuses have heating/cooling power demands measured in megawatts rather than kilowatts, and therefore require deployment of industrial scale GHPs. Commercial buildings also offer the opportunity for energy sharing, often using geothermal reservoirs

as a storage mechanism. Geothermal storage can displace peak demand through a temporal shift, with the heat rejection of the commercial building heat at 3pm, for instance, becoming the supply for the residential structure at 4am.

The United States military has begun to view geothermal as an attractive resiliency and security play, as will be explored in detail in [Chapter 8, Other Strategic Considerations for Geothermal in Texas](#). Two military bases in the State of Georgia use geothermal technologies to store cold or warm water to be used later, using less energy and saving money for the two military installations (Jones, 2022). Marine Corps Logistics Base Albany and Fort Benning, near Columbus, Georgia, use a subsurface aquifer to store heat for use in the winter, and cold for use in the summer.

The opportunity for deployment of geothermal District Heating and Cooling Systems is significant, and can begin in Texas with corporate headquarters, universities and community college campuses, military installations, residential and commercial developers, or commercial building owners. Given the cumulative effect that commercial deployment of GHPs would have on reducing grid strain in Texas, these sectors should be a primary focus for deployment of DU geothermal in Texas, and a focus of policymakers.

### C. Heating for Industrial Processes

The industrial sector uses heat for a wide variety of applications, including washing, cooking, sterilizing, drying, preheating of boiler feed water, process heating, and much more. Altogether, the United States industrial sector uses an estimated 24 quadrillion British thermal units, or roughly one-third of the nation's delivered energy supply (EPA, 2022; EIA, 2014). Process heating applications alone account for approximately 36 percent of total delivered energy consumption within the manufacturing sector, a subset of the industrial sector (EIA, 2014). Approximately 30 percent of industrial heating applications require temperatures below 100°C (212°F), and another 15 percent can be met with temperatures between 100 and 150°C (212 and 302°F). The vast size and scale of industrial heating energy use represents a unique opportunity for geothermal deployment, and is explored in detail in [Chapter 7, The Geothermal Business Model & the Oil and Gas Industry](#).



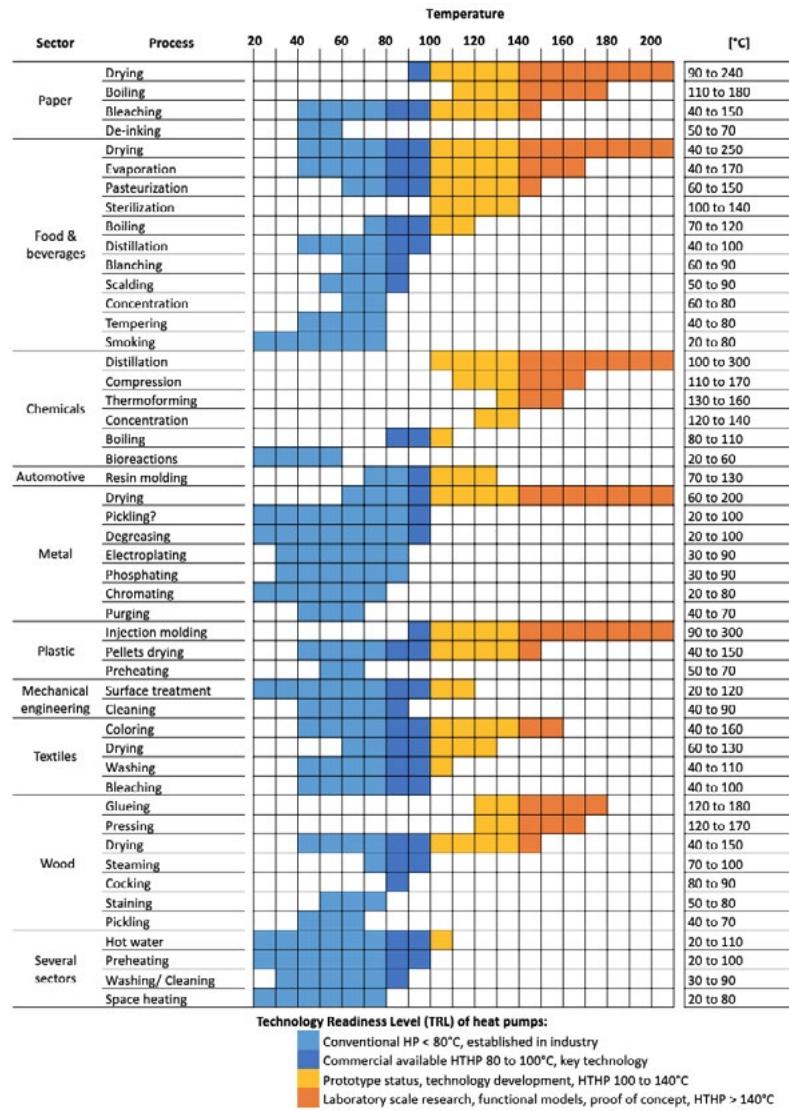


Figure 2.10. Overview of processes in different industrial sectors structured by typical temperature ranges and Technology Readiness Level (TRL) of heat pumps, data compiled from various literature data. Source: Adapted from Arpagaus, et al., 2018

Industrial heat pumps are very efficient boosters of available ambient heat, often using one unit of electrical energy to deliver three units of heat to the process (DOE, 2022; EPA, 2022). Utilization of heat from geothermal resources with an industrial heat pump can reduce operational costs, while leveraging a local, reliable, clean energy source. Economic benefits of DHCSS for industrial heat processes include operational savings, the utilization of existing skill sets of the Texas workforce, and employment opportunities for Texans.

In this Section, we will consider various high and low temperature industrial processes which are relevant to Texas, and could benefit from and be served by geothermal heat.

### 1. High-temperature Industrial Applications

Industry in Texas is dominated by oil refining, petrochemicals, and power generation, most of which require temperatures of more than 200°C, or 392°F. (Figure 2.2) These temperatures are available in Texas, though a DDU approach will be required to reach them.

#### a. The Chemical and Petrochemical Industry

The chemical industry is undergoing a major restructuring and period of innovation. Sometimes called Industry 4.0, but also known as the “Future of Manufacturing,” the goal is deployment of digitization to drive improved



efficiency and productivity in the design, development, and production of goods (Dalenogare, et al., 2018; Lasi, et al., 2014). The main motivation for this fourth wave of industrial innovation is integration of sustainability in a resource challenged world, including consideration of topics like zero emission design, circular economy, and resilience to/mitigation of climate change. Geothermal, with its 24/7 availability, extreme weather resilience, and small footprint, allowing it to be co-located with industrial heat offtakers, offers a unique opportunity to meet these challenges in the particularly difficult to decarbonize industrial sector.

#### b. Oil Refining

There are some portions of the oil refining process that could benefit from geothermal Direct Use heat resources. Auxiliary oil and gas processes, such as boiler water preheat, sour water stripping, and product quality assurance operate within temperature ranges where geothermal industrial heat is possible, and potentially economically attractive within swaths of the Texas geothermal resource.

The most energy intensive process in the oil refining process is crude distillation, which consumes approximately ten percent of the refinery feed as fuel, and requires a process temperature of 340°C (644°F) or more (Errico, et al., 2009).



Figure 2.11. An oil and gas industry refinery in Texas City, Texas. Photo credit: Jamie Beard.

Our understanding of how the Texas industrial complex might utilize geothermal heat will benefit from planned demonstration projects in Texas, such as an industrial heat and power project being pursued by Criterion Energy Partners ("Criterion"). Criterion utilizes a Next

Generation Engineered Geothermal System to combine heat and power with co-located demand for Texas based industrial entities. [Chapter 3, Other Concepts with Unique Applications in Texas](#) explores this topic in further detail.



Figure 2.12. The Criterion Energy Partners Team surveying the site of their planned sedimentary heat and power geothermal demonstration on the Texas Gulf Coast, slated to begin in 2023. Photo credit: Criterion Energy Partners, 2022.

The benefits geothermal technologies and applications offer to industry and citizens are widespread. As illustrated in Figures 2.2 and 2.10, there is an extensive list of industrial heating and cooling applications where geothermal DU can be deployed in Texas. Benefits range from lowering energy bills, reducing operational costs, lowering carbon footprints, avoiding stranded oil and gas assets, utilizing the skills base and knowledge of the oil and gas workforce, and leveraging a core competency of the Texas economy.

In the next Section, we explore the DU applications of low temperature geothermal heat for industrial applications (below 150°C or 302°F), which can drive low enthalpy industrial processes such as agriculture, water desalination, drying, greenhousing, and crystallization, among others.

#### 2. Low Temperature Industrial Applications

Just about everywhere "low temperature" heat is required in an industrial process, it can be provided with geothermal energy. Though there is no broadly accepted



definition of what constitutes low temperature heat, for the purposes of this paper we will consider the upper limit of low temperature to be 150°C (302°F). Figure 2.10 shows the type of industrial processes that fall below this low temperature limit. Below we will consider a few high impact applications of low temperature heat for industrial use.

#### a. Waste Heat Recovery

Emerging from all industrial processes is a stream of waste heat, which is simply heat that is lower temperature than it was when it entered the process, but still hot enough to be useful for other purposes. This concept is what is typically referred to as the “geothermal energy cascade” shown in Figure 2.2 - meaning that geothermal heat can be used again and again for different processes that need progressively lower temperatures, until it reaches essentially the temperature of ambient air. One easy to recognize example of a geothermal energy cascade is the waste heat that emerges from the geothermal power plant at the Blue Lagoon in Iceland, which is then used for a recreational geothermal hot spring.



Figure 2.13. A geothermal power plant operating in subzero temperatures in Iceland. Waste heat exits the plant after the production of electricity, and is then used for a recreational hot spring. Photo credit: Blue Lagoon.

Many industrial processes need less than 21°C (70°F) to make their operation more efficient. Geothermal energy can be used independently, or integrated with the heat from another origin (fossil fuels, electricity, bio energy, etc.), or even used in conjunction with other technologies like heat pumps. Further, many distillation

and separation processes operate within the range of low temperature geothermal, for example, water treatment, product drying, product separation, crystallization, food and timber drying, milk pasteurization, pulp and paper processing, swimming pool heating, aquaculture farming, and warming greenhouses.

#### b. Desalination

Secure access to potable water is becoming an increasing challenge in the United States. Texas has been in a drought since September 2021, and agricultural regions fear of running out of accessible water resources as a result of depleted aquifers. Other states such as Arizona, California, and Nevada import water from other regions and states to satisfy growing urban areas. The Texas population boom, coupled with increasing drought, and the strain of overuse on the Colorado River Basin, threatens to worsen the outlook for abundant and accessible fresh water resources in Texas.

Desalination of brines and seawater is a potential answer to this problem, particularly given the size and industrial nature of the Texas coastline, which could be utilized for the process. But desalination is an energy intensive process, and is used as a matter of course in very few places in the world where the need justifies the cost. Electrically driven Reverse Osmosis (“RO”) is the preferred method used for seawater desalination, but Forward Osmosis (“FO”) and Membrane Distillation (“MD”) are also options (Suwaileh, et al., 2020). All of these processes can be driven either electrically by geothermal power, or thermally by geothermal heat (Díez & Rosal, 2020; Wu, et al., 2020; Lau, et al., 2019). Thermally driven processes, like membrane distillation (“MD”), rely on vapor pressure differences across membranes to facilitate the purification process, and may be best suited of all processes to be driven by geothermally derived or waste heat. MD can be used even when only low grade heat is available.

Another unrelated use case for desalination is uniquely suited for application in Texas. Oil and gas operations frequently produce as waste products substantial amounts of briny water, and large amounts of waste heat that is co-produced with the hydrocarbons. Operators typically incur high costs for the transportation, disposal, or reinjection of these fluids. Geothermal desalination has the potential to reduce the volume and cost of fluid



requiring disposal by treating produced fluids to generate a purified water stream (Suwaileh, et al., 2020; Wu, et al., 2020; Liden, et al., 2019; Gude, 2016).

### c. Evaporation, Distillation, and Drying

Farmers, ranchers, food processors, dairy pasteurization processes, and food manufacturers also can benefit from low temperature geothermal applications. Currently, processed food requires the use of heat, often produced by burning hydrocarbons, to evaporate, distill, dry, or pasteurize food products. Low temperature geothermal resources, ubiquitous in Texas, can be utilized by ranchers, farmers, and food processors to increase the efficiency of their processes. Though the required temperature varies with the particular product being evaporated, in a majority of agricultural processes, operating temperatures of 82°C to 120°C (179°F to 248°F) are sufficient, which are ubiquitous in the subsurface in the Gulf Coast industrial region of Texas.

The application of geothermal heat to power industrial processes is a technologically enabled and straightforward process that does not require any additional technology development to deploy at scale. As we discussed at the beginning of this Chapter, a majority of electricity used in Texas goes to power heating and cooling processes. Therefore, every bit of demand that we can address with

geothermal heat relieves strain from the grid, furthers decarbonization of the Texas grid, and frees up resources for use elsewhere.

## III. Conclusion

Geothermal heating and cooling applications are accessible in every region of Texas, and offer substantial opportunities to reduce operational and energy costs for industry, agriculture, manufacturing, businesses, commercial buildings, and private homes. Further, the economic opportunity in building out DU geothermal in Texas means opportunities for thousands of high paying, local jobs using the skilled oil and gas workforce. Furthermore, many of the hottest areas of the Texas subsurface are located near or under the State's largest population centers, placing geothermal near demand for heating, cooling, and industrial heat loads.

With extreme weather events like heat waves, but also cold weather anomalies like Winter Storm Uri increasing in frequency with a changing climate, DU geothermal presents as the low hanging fruit for increased reliability, resilience, comfort, and peace of mind for the Texas built environment. As a fully technologically enabled solution, it is up to policy makers to develop creative solutions and incentives to spur widespread deployment of this vastly underutilized secure, clean, and ubiquitous resource.



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## Conflict of Interest Disclosure

**Sergio Kapusta** serves as professor and the Director of the Energy and Environment Initiative at Rice University, and is compensated for this work. Outside of these roles, Sergio Kapusta 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.

**Silviu Livescu** serves as a faculty member in the Petroleum and Geosystems Engineering Department and a co-principal investigator for the HotRock Industry Affiliates Program, both at the University of Texas at Austin, and is compensated for this work. He is also a co-founder of Bedrock Energy, a geothermal heating and cooling startup, and the editor-in-chief of Elsevier's Geoenergy Science and Engineering. Outside of these roles, Silviu Livescu 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.

**Birol Dindoruk** serves as a Professor of Petroleum Engineering & Chemical and Biomolecular Engineering at University of Houston, and is compensated for this work. Outside of these roles, Birol Dindoruk certifies that they have 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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## Chapter 3

# Other Geothermal Concepts with Unique Applications in Texas

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**Concepts that couple geothermal energy production with other technologies, such as hydrogen production, energy storage, or carbon capture and storage, although in early stages, have the potential to improve project economics, and enhance both developing and existing industries in Texas.**

## I. Introduction

Geothermal for electricity production or Direct Use can stand alone as an economically viable clean energy solution. However, as we will see in greater detail in Chapter 6, [The Oil and Gas Industry Engagement in Geothermal](#), the oil and gas industry has expressed significant enthusiasm for concepts that combine geothermal with one or more additional outputs or revenue streams due to improved project economics, alignment with existing or future business models, or use of existing assets, including oil and gas wells. Many of these coupled projects, referred to as Hybrid Geothermal Systems, or Multi-System Hybrids, are uniquely applicable to Texas due to existing oil and gas infrastructure, existing investments in future additions to the Texas economy, like CCUS and hydrogen, and favorable subsurface conditions for deployment

and operation of the concepts. In this Chapter, we will consider several coupled geothermal concepts with particular applicability in Texas.

## II. Hydrocarbon Well Reuse and Geothermal

Geothermal energy can be produced from existing oil and gas wells, as either electricity or Direct Use heat, depending on the location, subsurface properties, well parameters (depth, size, age), and other factors. There are two possibilities for producing geothermal energy from existing oil and gas wells. First, an existing hydrocarbon well could be repurposed to produce geothermal energy only, known as conversion. Second, an existing well could



produce hydrocarbons and heat simultaneously, known as co-production (Lund & Toth, 2021; Pilko, et al., 2021; Oldenburg, et al., 2019). Together, we will refer to the concepts of geothermal well conversion, and geothermal co-production as Oil and Gas Well Reuse, or more simply Well Reuse. Both of these concepts are being pursued by several geothermal energy start-ups, who are developing closed-loop technologies using pipe-in-pipe or other configurations (Carpenter, 2022; Casey, 2022; CEP, 2022; Sage, 2022; Ball, 2021; Chao, 2021; Richter, 2021d; Amaya, et al., 2020; Oldenburg, et al., 2019; Augustine & Falkenstern, 2014; Clark, et al., 2011; Abdullah & Gunadnya, 2010). We will consider technologies being developed to enable Well Reuse further below.

It is estimated that approximately 25 billion barrels of warm and hot water is produced annually from oil and gas wells within the U.S. (Transitional, 2022; Oldenburg, et al., 2019). This “co-produced” water has to be managed and disposed of, adding significant operational costs to oil and gas operations. The ratio of produced water to hydrocarbons, either oil or gas, increases over time, meaning that existing hydrocarbon wells may be good candidates for co-production or conversion. In both cases, producing geothermal energy from existing hydrocarbon wells, as electricity and/or low-temperature waste heat, can yield significant advantages over traditional geothermal wells, especially in terms of reduced capital expenditure. They also provide the advantage of energy savings, lower emissions, and extended economic life of oil and gas fields, and profitable utilization oil and gas field infrastructure (Kuru, et al., 2022; Livescu & Dindoruk, 2022a; Oldenburg, et al., 2019; Kitz, et al., 2018).



Figure 3.1. Transitional Energy successfully produced geothermal energy from produced fluids, utilizing a modular ORC unit at an oil and gas well in Colorado in 2022. Source: *Transitional*, 2022.

Co-production or conversion may use surface technologies, such as binary cycle or Organic Rankine Cycle (“ORC”) units, and subsurface technologies such as pipe-in-pipe heat exchangers, to produce electricity. The electricity produced can be used for field operations, or sold onto the grid (CEP, 2022; Doran, et al., 2021; Gosnold, et al., 2020; Gosnold, et al., 2017; Gosnold, et al., 2015).

#### A. Size and Feasibility of the Well Reuse Opportunity

Thousands of abandoned hydrocarbon wells around the world, including in Texas, could be converted to geothermal wells (Carpenter, 2022; Kuru, et al., 2022; Livescu & Dindoruk, 2022b; Ball, 2021; Robins, et al., 2021; Richter, 2017; Augustine & Falkenstern, 2014). For instance, pipe-in-pipe heat exchangers could be inserted in abandoned hydrocarbon wells to generate power for oilfield operations as an alternative to the current diesel generators. This could be especially beneficial for offshore oil and gas operations, such as in the Gulf of Mexico. Additionally, the geothermal heat could be used to help pump hydrocarbons out of wells. The thermosiphon effect of pipe-in-pipe heat exchangers could be used to power a downhole pump, avoiding the cost of electricity that would otherwise be used for electrical submersible pumps (“ESP”) (Lund & Toth, 2021; Oldenburg, et al., 2019).

The concept of producing geothermal energy from existing hydrocarbon wells is not new (Carpenter, 2022; Casey, 2022; CEP, 2022; Sage, 2022; Chao, 2021; Lund & Toth, 2021; Richter, 2021d; Abudureyimu, 2020; Amaya, et al., 2020; Gosnold, et al., 2020; Oldenburg, et al., 2019; Alimonti, et al., 2018; Kitz, et al., 2018; Augustine & Falkenstern, 2014; Clark, et al., 2011). It was technically demonstrated through a project at the Rocky Mountain Oilfield Testing Center in Wyoming, where co-produced geothermal water from oil wells was used to power a 250 kilowatt electrical ORC plant (Gosnold, et al., 2020; Gosnold, et al., 2017; Gosnold, et al., 2015). The total produced power was reported as 1,918 megawatt hours from 10.9 billion barrels of co-produced water, with an ORC unit manufactured by Ormat (Gosnold, et al., 2020).

A simulation study performed in 2013 found a significant number of existing hydrocarbon wells in the U.S. with downhole temperatures and flow rates sufficient for geothermal energy production, but estimated only a modest near-term market potential of about 300



megawatts electrical of electrical output, with marginal economics (Augustine & Falkenstern, 2014). Thus, from a techno-economic point of view, conversion of existing hydrocarbon wells may be more feasible than co-production (Muir, 2020). That study also recommended installing ORCs on the many water flood projects in hydrocarbon basins in the U.S.

A more recent simulation study performed in 2020 for the Bakken basin, located mostly in the U.S. state of North Dakota and in Canada's province of Saskatchewan, indicated that previous analyses of co-production potential were based on total field multi-well pad production volumes, and did not address fluid flow per individual well (Gosnold et al., 2020). In shale plays, such as the Bakken, with temperatures between 100°C (212°F) in the eastern, shallower part, and 140°C (284°F) in the center, deeper part, the total fluid produced from a multi-well pad can be enough for co-production of tens of hundreds of kilowatts to replace the current propane or diesel generators used onsite. Note that Bakken heat flow ranges are between approximately 50 megawatts per square meter, in the eastern part, and approximately 70 megawatts per square meter, in the center. According to Robins et al. (2021), the study by Gosnold et al. (2020) did not find Bakken co-production of brine and hydrocarbons to be commercially feasible for power generation, but did suggest that several megawatts of power can be produced from hotter carbonate rocks underneath the Bakken.

These types of concepts have been discussed recently at numerous oil and gas industry events, and include converting existing hydrocarbon wells for geothermal brine production, rather than co-production (Pilko et al. 2021). Among those conversion scenarios are: 1) recompleting marginally economic existing oil wells and converting them to geothermal brine production; 2) installing ORCs on the many water flood projects in sedimentary basins; and 3) drilling new, deeper geothermal wells, specifically for power production. The geothermal fluids could be used in two stages, first for power production using ORCs, and second for low-cost Direct Use space heating. Producing enough electricity on site to power the oil and gas operations is another potential business case. For instance, an average ESP requires 16 kilowatts, and a 160 kilowatt ORC could supply electricity to pump ten wells.

An earlier study for the Williston basin demonstrated the technical and economic feasibility of generating electricity from non-conventional, low temperature (i.e., 90 to 150°C (194 to 302°F)) geothermal resources from a deep (1.6 miles or 2.6 kilometers) carbonate aquifer using binary technology (CEP, 2022; Doran, et al., 2021). The potential power output from this small-scale project was 250 kilowatts at a cost of \$3,400 per kilowatt. In the beginning, an ORC produced 50 to 250 kilowatts with efficiencies of eight percent to ten percent. A new ORC unit was designed to generate 125 kilowatts with 14 percent efficiency, and could be installed in a multi-unit series to produce a few megawatts of power. The analysis of the entire Williston Basin using data on porosity, formation thicknesses, and fluid temperatures revealed that  $1.36 \times 10^9$  megawatt hours of power could be produced using ORC binary power plants.

Many of the oil fields in the Williston Basin producing from conventional reservoirs, such as the Red River or Madison Formations, have associated water flood projects. The wells that supply these projects offer a long term, reliable source of water at relatively high flow rates (tens of liters per second) which offer a potentially attractive geothermal source where fluid temperatures are more than 100°C (212°F). Preliminary estimates indicate that a single well providing water to an ORC at that temperature could generate over 400 kilowatts of electricity. This is adequate to supply power for all water supply pumping operations, plus a significant amount of excess energy to help reduce lifting costs and supply other local power demand. This potential resource could be optimized in future water flood projects if one of the specific design criteria for the water supply wells is to consider targeting deeper, hotter formations where the revenue from the increased geothermal power production would offset any incremental increase in drilling costs.

## B. Challenges Associated With Well Reuse

Despite the great co-production and conversion potential identified by these studies(Gosnold, et al., 2020; Gosnold, et al., 2017; Gosnold, et al., 2015), several reasons, partly economic and partly infrastructure related, were identified for the lack of geothermal energy development in the Bakken formation and Williston basin. The economic reasons include long-term investment with little return, compared to the oil and gas revenue, and industry skepticism regarding revenue. Infrastructure reasons



include the ability to generate only a few kilowatts of power with large volumes of produced water, high engineering and construction costs, required agreements with local electrical power providers, legal issues and access to the power grid, and water management. The downhole temperatures and sizes of existing hydrocarbon wells may limit their enthalpy output for power production.

Repurposing oil and gas wells for geothermal development in the province of Alberta, Canada was investigated by the Canadian Geothermal Energy Association (CanGEA). As of October 31, 2016, Alberta had more than 60,000 wells with bottom hole temperatures greater than 60°C, which were labeled as well-suited for low temperature Direct Use heat applications, more than 7,700 wells with bottom hole temperatures greater than 90°C, which were labeled as well-suited for industrial Direct Use heat applications, and 500 wells with bottom hole temperatures greater than 120°C, which were labeled as well-suited for power generation (Richter, 2018).

Four key challenges have been identified by Santos, et al. (2022) related to repurposing oil and gas wells for geothermal development: 1) well selection, 2) subsurface data availability, 3) well integrity, and 4) legal and regulatory factors.

For instance, well selection is dependent on the physical properties of a well (i.e., bottom hole temperature, geothermal gradient, etc.), but also on its proximity to end users. Subsurface data availability depends on a well owner's appetite to invest in pre-project reservoir characterization, geomechanical modeling, and productivity analysis. Well integrity is critical for predicting cement and casing life, and safety, but also for estimating groundwater contamination issues. Well integrity failures are quite common among oil and gas wells, with around 35% of wells showing some leakage (Santos, et al., 2022). And legal and regulatory factors are complex, as the concept of repurposing oil and gas wells to geothermal is new, and entities have not fully considered potential ownership, liability, and other legal issues associated with these projects.

Further, and independent of repurposing of oil and gas wells, geothermal resource exploration and production does not have a unified authority, and may fall under existing legislation and regulatory frameworks for natural resources, hydrocarbons, geology, groundwater, and planning. On the other hand, oil and gas wells are regulated

under several subcategories, such as exploration, storage, production, injection, suspended or temporarily abandoned, and plug and abandonment ("P&A") wells, and each of them has distinct requirements. These issues will be addressed by industry as projects proceed, but currently, they present uncertainty.

More research, field piloting, and legal and regulatory framework development are needed to assess the potential of using existing hydrocarbon wells for co-production and conversion to geothermal energy, but the economic benefits for the oil and gas industry in Texas could be significant, given the large number of existing oil and gas wells, if the technological and regulatory challenges are overcome.

### C. The Well Reuse Business Model for Oil and Gas Entities

Recent studies have explored business opportunities for geothermal energy development by oil and gas companies (Carpenter, 2022; Casey, 2022; Livescu & Dindoruk, 2022b; Ball, 2021; Chao, 2021; Lund & Toth, 2021; Pilko, et al., 2021; Amaya, et al., 2020; Gosnold, et al., 2020; Muir, 2020; Birney, et al., 2019; Gosnold, et al., 2017). For instance, some technical challenges and climate transition risks related to societal, regulatory, and capital allocation trends related to re-purposing hydrocarbon wells to geothermal energy production have been recently explored (Ormat, 2022; Pilko, et al., 2021).

One opportunity identified is to use co-production for onsite geothermal power production to replace natural gas electrical energy (Muir, 2020). This could be very advantageous for near-shore and offshore Gulf of Mexico wells and facilities, as many of those wells are deep, have large well and casing sizes, and are high-pressure, high-temperature ("HPHT"). The northern Gulf of Mexico is one of the most active offshore areas in the world, with over 44,000 oil and gas wells drilled since the mid-1900s. A deep-water offshore platform generally requires 100 megawatts of power to operate its pumps, compressors, machinery, and lighting. Smaller shallow water and onshore facilities require 50 megawatts or less. Replacing power generated by natural gas with power generated by baseload geothermal energy, onsite or offsite, can provide significant environmental, social and governance ("ESG") incentives, in addition to operating efficiency incentives, for oil and gas operating companies. It is



estimated that more than one megawatt electric output is needed from an offshore well to justify the deployment cost of geothermal for co-production or conversion, yet if there is co-production of hydrocarbons from the same well, increased efficiencies and synergies can provide cost reductions or increased power generation (Lund & Toth, 2021; Kitz, et al., 2018).

Many Gulf of Mexico wells and facilities will soon reach the end of their planned lives, incurring substantial decommissioning costs. The opportunity to repurpose those wells and facilities to geothermal energy production may offer a significant cost savings for their operating companies.

The potential benefits identified by (Lund & Toth, 2021; Kitz, et al., 2018) could also be applied to onshore wells in Texas. For instance, three Texas resources for the counties of Crockett (West Texas), Jackson (central Gulf Coast) and Webb (South Texas) were analyzed and mapped (Batir and Richards, 2020). Updated temperatures from 1,500 feet (3.5 kilometers) to 32,800 feet (10 kilometers) were calculated. Thus, for Webb County and Jackson County, temperatures of 150°C (302°F) are possible for depths greater than 8,530 feet (2.6 kilometers), while for Crockett County, they are possible for depths greater than 8,858 feet (2.7 kilometers). Updates for all Texas counties may yield results like these, which are more favorable for geothermal development than prior studies.

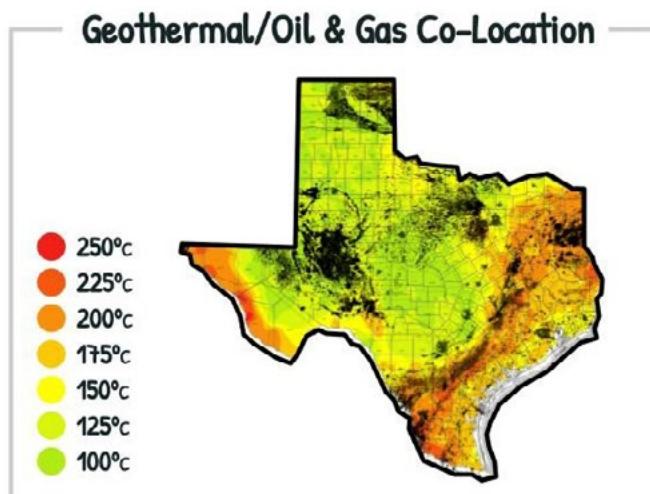


Figure 3.2. Existing oil and gas wells in Texas (black dots) overlaid onto geothermal resources. Source:

*Future of Geothermal Energy in Texas, 2023*

## D. Technology Development Enabling Well Reuse

There are many other theoretical studies evaluating the potential of co-production and conversion of existing oil and gas wells to geothermal energy (Greenfire, 2022; Ormat, 2022; Lund & Toth, 2021; Greenfire & Scherer, 2020; Oldenburg, et al., 2019). Several numerical and analytical solutions have been proposed for closed-loop geothermal systems ("CLGS") using pipe-in-pipe downhole heat exchangers. Recent sensitivity studies have shown the effects on several well parameters, such as the fluid flow rate, well length, inner tubing and annulus diameters, geothermal temperature, type of the Working Fluid (i.e., water-steam and supercritical carbon dioxide, or "sCO<sub>2</sub>"), and overall heat transfer coefficients, on the temperature of the fluid flowing to surface (Livescu, et al., 2021; Livescu & Dindoruk, 2020a; Livescu & Dindoruk, 2020b). While all those parameters have more or less significant effects on power production, the overall heat transfer coefficients are critical for system performance. Quantitatively, modifying the overall heat transfer coefficient between the formation and well, while keeping all other parameters unchanged, may yield a two-fold outlet temperature difference, significantly affecting the economics of a given geothermal project. However, there is very limited information in the public domain of any study for directly and accurately measuring these coefficients, either in the laboratory or in the field. Thus, using theoretical values for the overall heat transfer coefficients may result in highly inaccurate outcomes for heat and electric power generation.

Another potential source of inaccuracy for estimating the co-production or conversion potential of existing oil and gas wells are the pressure, volume, and temperature ("PVT") properties and phase behavior of the Working Fluids, such as water-steam and sCO<sub>2</sub> (Ratnakar, et al., 2022). Because of convenience and simplicity, some studies assume that the fluids are single-phase, or that the density, viscosity, and thermodynamic properties such as specific heat capacity of the Working Fluid are constant over the entire range of downhole pressures and temperatures. Thus, more research is critical to fully understanding the thermodynamics and heat transfer phenomena related to any co-production or conversion project.



Before co-production and conversion can be field tested, several other topics should be addressed, for which oil and gas professionals have appropriate technical expertise and experience, such as well intervention for preventing flow assurance issues (i.e., scales, corrosion, etc.), well production and facilities, including artificial lift, drilling and completions if the wells need to be re-completed, deepened, stimulated or re-stimulated, and reservoir engineering for estimating the heat and fluid inflow along the well. These topics are addressed regularly within the oil and gas industry for their field development and exploitation in the oil and gas context.

Other potential applications of co-production or conversion include 1) using the produced water to heat or cool buildings nearby, if this would be deemed economical, and 2) managing the produced water at surface instead of re-injecting it into the subsurface, and selling the heat and water to nearby agricultural operations, etc. Both of these topics require much more collaborative research involving the oil and gas industry, government, academia, and professional societies focusing to accelerate the multi-disciplinary innovation needed to make co-production and conversion of existing oil and gas wells to geothermal energy an economically viable reality.

### III. Geothermal and Lithium, Hydrogen, Other Co-Production Scenarios

Hybrid Geothermal Systems are defined as either those combining a geothermal system with any other energy sources (including other geothermal concepts), or those producing two or more products, such as power and minerals (DOE, 2017). Hybrid concepts are explored in more detail in [Chapter 1, Geothermal and Electricity Production](#) of this Report. Hybrid Geothermal Systems combining different energy sources take advantage of pairing baseload geothermal with other energy sources, such as thermo-electric power generation technologies, including solar thermo-electric, coal thermo-electric, and natural gas thermo-electric hybrid power generation systems (DOE, 2017). This is beneficial during peak hours, for instance, to offset the productivity decline of variable energy sources. In addition, Hybrid Geothermal Systems could decrease geothermal power generation costs, and increase the viability of low temperature geothermal resources. In the Texas context, hybrid geothermal systems combining geothermal and other renewable energy sources could also be critical to minimize, or even

avoid, weather-related power outages such as the one that occurred during Winter Storm Uri in 2021 (Reinhardt, et al., 2011).

Other applications of Hybrid Geothermal Systems can also include carbon dioxide capture from fossil thermo-electric plants, thermal desalination, and compressed air energy storage (Howarth & Jacobson, 2021), but more research and innovation are needed. Research has been performed on coupling geothermal energy with Concentrated Solar Power ("CSP"), as the two systems can share their thermodynamic cycle, lowering the total capital cost (Richter, 2021d; Robins, et al., 2021; Muir, 2020; Wendt, et al., 2019; Wendt, et al., 2018). CSP can be used to increase the output temperature of the geothermal fluid, and improve geothermal power generation efficiency, while the geothermal fluid can serve as storage for the CSP power. Hybrid systems with solar PV panels, coupled with geothermal power have the potential to extend the power output of the coupled system past the daytime (Wendt, et al., 2019; Wendt, et al., 2018). Geographically, Texas is among the many locations in the U.S. with abundant solar and geothermal resources. However, Hybrid Geothermal Systems are a relatively new concept, and detailed techno-economic analyses need to be developed (Robins, et al., 2021). There are only a few demonstration scale Hybrid Geothermal Systems that incorporate solar power. Among those are Enel Green Power's Stillwater hybrid geothermal plant (Richter, 2021c), Cyrrq Energy's 14.5 megawatt electric solar PV array, added to its Patua geothermal plant (Richter, 2017), and Ormat Technologies' seven megawatt electric solar PV system, added to their Tungsten Mountain geothermal plant (Richter, 2019).

#### A. Geothermal and Lithium

Lithium is another resource that has received significant attention recently, especially in regions with high lithium content in geothermal brines. Currently, lithium is mostly produced from hard rock mines in Australia, or from subsurface brine deposits in Chile and Argentina (Richter, 2021a). The environmental impact and carbon footprint of current lithium production methods is quite severe, with estimates of around 15 tons of CO<sub>2</sub> for each ton of lithium produced. The method used for lithium production from geothermal brines is likely to have a smaller environmental footprint compared to other methods (Chao, 2020; 2021). Further study is needed as projects are developed.



Geothermal brine may contain minerals, such as iron, magnesium, calcium, sodium, and lithium. However, the extraction of lithium from geothermal brine is still in a nascent phase. Most efforts, especially in the U.S., Germany and New Zealand, focus on a technique called Direct Lithium Extraction (“DLE”), with about 60 different variants of that technology. All of them use some kind of chemical separation method, such as nano-filtration or ion exchange resins, to target the separation of lithium chloride, purifying it to produce lithium hydroxide, which is then used for batteries. Many oil and gas companies, geothermal companies, and mining companies are evaluating lithium production from their assets, either as a by-product or as a main product, as the price of around \$12,000 per ton of lithium can be a significant source of revenue (EERE, 2021; Richter, 2021a).



Figure 3.3. Controlled Thermal Resources’ Hell’s Kitchen Lithium and Power project, being developed in the Salton Sea Geothermal Field in Imperial Valley, California. This is an example of a Hybrid Geothermal System. Source: Controlled Thermal Resources, 2022.

## B. Geothermal and Green Hydrogen

Texas uses roughly one-third of the hydrogen consumed in the United States, about 9 million kilograms per day (DOE, 2017). Multiple recent announcements in Iceland (Richter, 2021b), Canada (Bennett, 2021), and Japan (Richter, 2021d) have explored the concept of pairing geothermal energy production with green hydrogen production. By conventional terminology, green hydrogen is produced from water via electrolysis powered by renewable electricity, which does not emit carbon dioxide at the point of hydrogen generation, unlike the traditional,

natural gas-fed steam methane reforming (“SMR”) process. Deploying geothermal power plants coupled with hydrogen production could be one way of developing a domestic or international green hydrogen market. As far back as the 1920s (DOE, 2017), a few electrolyzer facilities were built next to hydroelectric power plants. Co-locating facilities may also reduce transmission costs.

Electrolyzer costs are currently high, so they are often operated constantly to reduce per-unit hydrogen production costs. This requirement complements the constant energy production of geothermal power plants, and the waste heat of the plant can also increase the efficiency of the electrolysis process by preheating the water.

## C. Geothermal and Direct Air Capture

Direct air capture (“DAC”) is the process of capturing carbon dioxide from the atmosphere to be utilized in other industries or stored underground. The two main methods for direct air capture are liquid systems (“L-DAC”) that pass air through chemical solutions, and solid systems (“S-DAC”) that pass air through solid sorbent filters that chemically bind with carbon dioxide. Solid systems require 80 to 120°C (176–248°F) to release captured carbon dioxide, compared to liquid systems requiring more than 800°C (1,472°F). Thus, solid systems may be able to use waste heat from geothermal energy production alongside the energy that is already being produced (Kurk, et al., 2022).

To maximize DAC systems, it is important to balance the placement of DAC facilities between the energy source and the carbon storage or utilization site. Doing so could also reduce the cost of power transmission, and the cost of carbon dioxide transportation. Many of the best locations for geothermal power production in Texas (e.g., East Texas) also contain promising potential storage sites in the subsurface.

A recent techno-economic analysis (Kuru, et al., 2022) of three specific regions within the United States (Texas Gulf Coast, Los Angeles Basin, Alaska’s Cook Inlet) and one European region (Netherlands Groningen Gas Field) that may potentially be attractive S-DAC sites suggests a S-DAC cost range of \$200 to \$1,040 per tonne of carbon dioxide captured, depending on the underlying cost model and the region of the S-DAC facility. However, the savings calculated from using geothermal resources



to provide the thermal energy are more consistent. The averages of the models by region indicate that the Texas Gulf Coast would be the lowest cost S-DAC region, while Alaska's Cook Inlet would be the most expensive.

Another possibility is to use the captured carbon dioxide as the geothermal Working Fluid (King, et al., 2021). Using carbon dioxide as the Working Fluid has a few benefits: as we explored further in [Chapter 1, Geothermal and Electricity Production](#). Carbon dioxide has a higher heat extraction rate than water, it is a poor solvent for minerals, and it generates buoyancy force. Additionally, fluid loss in the subsurface with carbon dioxide would actually be a climate benefit as the lost carbon dioxide would then likely be sequestered underground. With S-DAC, it might be possible for geothermal power production to have net negative emissions.

#### D. Geothermal and Brackish Water Mineral Production

In some locations, the hot water used to drive geothermal energy production might contain valuable minerals other than lithium as discussed above, including calcium carbonate, among others (EERE, 2021; Richter, 2021a). If these minerals could be efficiently extracted, it is possible that the economics of geothermal could improve and simultaneously provide a useful product for other energy sectors (Veil, 2020; DOE, 2017; Clark, et al., 2011). A water quality analysis (i.e., what minerals are present at what concentrations) would be key to determining the viability of recovering minerals from individual wells. While many existing geothermal power plants re-inject water that comes to the surface back into the reservoir, it may be possible to process minerals from the water within the normal operation of the facility, without the use of holding ponds, before re-injection. This is an area of innovation that is being pursued currently by several startup companies, including California based Lilac Solutions.

#### E. Geothermal and Oil & Gas Produced Fluids

Geothermal plants may also reuse treated, produced water from nearby oil and gas operations as the source water or cooling water for geothermal operations that use water as the Working Fluid. For instance, EGS requires 510 gallons of water downhole per megawatt hour (DOE, 2017), and geothermal power plants require 1,700 to

4,000 gallons of cooling water per megawatt (UCS, 2013). Treating and reusing nearby oil and gas produced water would reduce the strain on local surface or groundwater resources, but it could also introduce logistical challenges, like ensuring there is adequate produced water of appropriate quality in the vicinity. However, this approach could allow both industries to operate within a potentially smaller environmental footprint. The development and use of Engineered Working Fluids would of course negate the high water needs of EGS, AGS, and other scalable geothermal concepts.

### F. Geothermal and Blue Hydrogen

Blue hydrogen refers to the production of hydrogen through Steam Methane Reforming ("SMR"), with added carbon capture and storage. The goal is to produce reduced amounts of greenhouse gasses in the production of hydrogen, as compared to SMR by itself. However, emissions from blue hydrogen still exceed that of burning natural gas, and are only marginally better than SMR (Howarth & Jacobson, 2021). This is primarily due to the use of natural gas to supply the hot steam needed for SMR, and power needed for carbon capture. It is possible that geothermal energy could be utilized to make blue hydrogen less polluting. The two areas where geothermal energy could be applied are the initial steam supplying step of SMR, and the final step of carbon capture. The steam for SMR needs to be at least 700°C (1,292°F), so it would not be possible for geothermal heat to provide all of the energy needed to create this steam. However, geothermal energy could be used to preheat the water, and even create a low-grade steam that could then be further heated by natural gas. Geothermal could also be utilized in the carbon capture step of blue hydrogen as the heat supply to degas the carbon dioxide from the solid sorbent of S-DAC, which only requires temperatures between 80-120°C (176-248°F)(Kuru, et al., 2022).

## IV. Geothermal and Agriculture

There are many applications of geothermal heat and geothermal water in the realm of agriculture. One of the most commonly used applications is greenhouse heating. Depending on the temperature of the geothermal source, there are many ways to design the greenhouse to best take advantage of the heat. The simplest method is to use Direct Use heat to maintain temperatures inside the



greenhouse. Additionally, geothermal water can be used to help maintain the humidity within a greenhouse, or to water the crops. In a similar manner, geothermal heat can also be used to heat up soil to extend the growing season of crops. This would primarily be done by running pipes that would circulate geothermally heated fluid underground, which would prevent the ground and air from dropping too low. Extension of the growing season may be the most relevant concept for Texas, and geothermal in most regions of the State may have the potential to extend the growing season to year round.

As discussed in further detail in [Chapter 2, Direct Use Applications](#), another application of geothermal heat is crop drying. Temperatures as low as 40°C (104°F) can be used to dry crops and lumber. Waste heat from geothermal power facilities or hot steam from reservoirs that may not be hot enough to generate power can be passed through a heat exchanger to dry crops. In a best case scenario from a heat utilization perspective, waste heat from geothermal power plants could be used to dry several different crops (which dry at different rates and temperatures) as the quality of the heat degrades. The primary limiting factor for crop drying is the needed proximity to sources of geothermal heat, therefore co-location of agricultural and geothermal facilities would be required (Abdullah & Gunadnya, 2010). Texas based startup Viridly is pursuing such a co-location concept.

## V. Geothermal and Subsurface Energy Storage

Wind and solar, either PV or CSP, are intermittent energy sources. As increasing amounts of intermittent renewable energy is added to the electric grid, more dispatchable power sources, such as those provided by geothermal energy, will be required to maintain grid stability. Geothermal energy can provide this dispatchability, independent of time of the day or weather conditions (Casey, 2022; Cestari, et al., 2022; EarthBridge, 2022; Quidnet, 2022; Sage, 2022; Kitz, et al., 2018). Geothermal storage, or underground thermal storage, shows promise by offering small footprint stability and predictability to the energy system, but the concepts remain in their nascentcy.

Pumped hydro is a centuries-old, gravity-based energy storage technology that has been reborn due to the excess wind and solar power (Casey, 2022). It works by pumping water to an upper reservoir whenever excess wind or solar power is available. When needed, water from the reservoir flows downhill to a power station, where it runs turbines to generate electricity. Even if pumped hydro still accounts for about 93 percent of utility-scale energy storage capacity in the United States, these conventional ‘water batteries’ involve a massive amount of above-ground infrastructure, and they require topography that provides for the difference in elevation.

Quidnet Energy, headquartered in Texas, uses a version of the water storage concept which, relies on use of the subsurface as energy storage (Quidnet, 2022). Their facilities operate with closed-loop water systems, to prevent evaporative loss. The energy-storing rock bodies are non-hydrocarbon bearing, and found abundantly throughout the world, intersecting with major electricity transmission and distribution hubs. Conceptually, their workflow is as follows: first, when electricity is abundant, it is used to pump water from a pond down a well and into the subsurface; second, the well is closed, keeping the energy stored under pressure within the subsurface; and third, when electricity is needed, the well is opened to let the pressurized water pass through a turbine to generate electricity, and return to the pond ready for the next cycle (Quidnet, 2022).

EarthBridge Energy is pursuing a similar thermal storage concept for sedimentary basins, which are plentiful in Texas (EarthBridge, 2022). The thermal energy stored in sedimentary basins contains a tremendous amount of development potential (Johnston, et al., 2020; Augustine & Zerpa, 2017; Augustine, 2016). If geothermal gradients are high enough, thermal energy storage from sedimentary basins, combining technologies from the oil and gas industry and power generation industry, could provide clean, baseload power and Direct Use heat. The prospect of combining geothermal with subsurface energy storage was explored by a panel of experts at the PIVOT2022 conference, who considered these, as well as other subsurface energy storage concepts (PIVOT, 2022).



## VI. Conclusion

This Chapter explored geothermal concepts with unique applications to Texas, such as co-production and conversion of existing oil and gas wells to geothermal energy production. While high-pressure, high-temperature near-shore and offshore wells have great potential for co-production or conversion to produce electricity, some onshore wells also have potential for both power and Direct Use heat production. Heat from produced water could also be used to heat or cool buildings nearby, or for nearby agricultural or industrial operations, instead of re-injecting it into the subsurface.

The oil and gas industry has the expertise and experience to address these co-production and conversion applications, but much more collaborative research is needed to make co-production and conversion a reality. Concepts such as co-production of lithium, hydrogen, and brackish water minerals, and using geothermal to reduce the S-DAC cost were also explored. While these concepts are emerging, a significant amount of fundamental and applied research literature already exists, and they present potentially significant opportunities for Texas as geothermal is increasingly deployed in the State.



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## PART II

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# Geothermal and Texas Resources



## Chapter 4

# The Texas Geothermal Resource: Regions and Geologies Ripe for Development

K. Wisian, S. Bhattacharya, M. Richards

***The total amount of heat in the upper ten kilometers of the Texas subsurface is approximately one million exajoules. That is roughly half a million times Texas' annual electricity generation of 500 million megawatt hours. Put simply, even accounting for low efficiency of extraction, there is enough energy to meet electric and thermal demand in Texas for thousands of years just a short distance under our feet.***

## I. Introduction

Texas is known as the energy State. It has led the growth and development of the world's petroleum industry, and is responsible for the United States becoming a world leader for gas production as a result of the shale boom. And in the last two decades, a different form of energy production boomed in Texas – wind. Texas leapt into the lead in wind power production nationally after initially lagging behind other states at the beginning of this century (DOE, 2022). Texas has the opportunity to become a global leader of yet another source of energy – geothermal. In this Chapter, we explore the abundant subsurface heat that may provide the next opportunity for Texas to lead the world in energy – the concept of 'Geothermal Anywhere.'

Texas is not on the list of conventional geothermal production zones in the United States. To date, geothermal energy production has been (with negligible exceptions) concentrated west of the Rockies in a region referred to by geologists as the Great Basin. Traditional hydrothermal resources, referred to in this Report as Conventional Hydrothermal Systems ("CHS"), are geographically limited. CHS requires the presence of natural, dynamic or static water/steam in the subsurface. The location of these systems is connected with tectonics, either volcanism or deep fault lines. These geological settings, in turn, occur mainly in the Great Basin, a geographic range that includes most of Nevada, reaches north to the Columbia Plateau in



central Oregon and southern Idaho, encompasses half of Utah to the Wasatch Mountain Range to the east and the Sierra Nevada mountains of California to the west, and stretches south through the Mojave Desert and Imperial Valley in California and Sonoran Desert in Mexico.

Additionally, the Pacific coastal area of the western United States and Hawaii have visible tectonic activity. Worldwide, the close coupling of geothermal development and tectonics occurs around the “Ring of Fire” of the Pacific Ocean, the East African Rift, and one-off hotspots (Iceland and Hawaii, for example), as well as near other tectonic plate boundaries.

Texas is hot. The total amount of heat in the upper 6.2 miles (ten kilometers) of the Texas subsurface is approximately one million exajoules (Tester, et al., 2006). That is;  $10^{24}$  joules,  $9.4 \times 10^{20}$  British thermal units, 163,000 billion barrels of oil equivalent, or  $2.8 \times 10^{11}$  gigawatt hours. Pick your units any way you want – Texas has roughly half a million times its annual electricity generation of 500 million megawatt hours in geothermal energy potential just below the surface of its ranches, farms, cities, and towns (EIA, 2022). This however is energy content, not extractable energy. The purpose of this Report is to provide policy-makers, investors, and the general public a greater appreciation as to how much of this energy is recoverable, both in the near term, and with the application of new technologies in the future.

The history of geothermal energy in Texas is comparatively brief. There have been small periods of interest and research in the past, mainly in the 1970s and 1980s. The unique Gulf Geopressure Zone, located in the subsurface along the Texas Gulf Coast, generated interest in the past, and has sustained intermittent attention since. A geothermal demonstration plant in Pleasant Bayou in Brazoria County was built and operated briefly in the 1990s (John, et al., 1998). Excellent fundamental work was done in the period between 1979 and 1990, and the publications resulting from this work form a solid foundation of understanding about the State’s geothermal resources, as referenced in this Chapter<sup>1</sup>. Since this foundational work was performed in Texas, technologies, science, and the world’s priorities with regard to clean energy technologies have significantly changed, and altered

the lens through which we should view the geothermal opportunity in Texas.

Recent and continuing advancements in drilling technologies, as well as technologies related to the conversion of heat into electricity, are changing the picture and opening the door to Texas adding a significant new power source to its grid, as well as creating and leading a major new world-wide industry – geothermal energy. These technological advances are breaking the geographic constraint of days past of where geothermal can be developed, creating an opportunity for the emergence of the next generation of “geothermal anywhere.” In light of this new paradigm, as well as the increased availability of subsurface data, we re-examine the geothermal potential of Texas.

First, some caveats: in this Chapter, we focus on the subsurface, as opposed to on specific geothermal technologies. Technologies such as Direct Use heat and power production concepts are considered in detail in other Chapters. Additionally, Conventional Hydrothermal Systems (“CHS”), though limited in Texas, do exist, and will be addressed in this Chapter. The semi-conventional gulf coast geopressure resource is perhaps the most currently exploitable opportunity in the realm of CHS. Geopressure allows for both the thermal and mechanical energy of over-pressured, deep formations to be harnessed, resulting in more economically attractive geothermal projects, which may also be co-produced with gas.

## II. What’s New

A significant difference between this study and previous work performed in Texas is the inclusion of all types of geothermal resources in our analysis – not just CHS, geopressure, and Direct Use. The “geothermal anywhere” paradigm opens opportunities for application of new technologies, and exploitation of resources in new regions that may have previously been infeasible. The next generation of geothermal anywhere takes advantage of multiple proven and emergent technologies to enable the creation of artificial systems to extract heat from the crust, without relying on nature to concentrate the heat in visible surface anomalies. These proven and

<sup>1</sup>For a concise listing please search the Bureau of Economic Geology Bookstore with “geothermal”  
[https://store.beg.utexas.edu/search?controller=search&orderby=position&orderway=desc&search\\_query=Geothermal&submit\\_search=](https://store.beg.utexas.edu/search?controller=search&orderby=position&orderway=desc&search_query=Geothermal&submit_search=)



emergent technologies are covered elsewhere in this Report. We refer to these collectively as Next Generation technologies.

Geothermal anywhere opens up all of Texas, not just the select areas of the past, to geothermal energy production. As such, geothermal anywhere will demand new ways of city planning. For example, when power generation is embedded in a decentralized, organic way at the scale of a few or tens of megawatts per plant, cities will need to fold geothermal infrastructure into growth plans as now they do with power substations. This approach means the generation is close to the customer or what grid operators call the demand, or load center.

The State's geothermal resources are, in many instances particularly along the Gulf Coast industrial regions in Texas, co-located with industrial off-takers, which means industry in the future may have their own on-site geothermal energy source, and use it in whatever way is most efficient for them. Thus, an area of continued research for geothermal in Texas will be the integration of geothermal energy use and urban/growth planning.

With the flourish of recent technological advancements, deep oil and gas producing basins are becoming viable as geothermal producers. Even hard-rock zones, such as the Llano uplift, could become geothermal energy producers. The energy industry is increasingly interested in the potential of energy generation that can take advantage of vast existing infrastructure already in place in areas such as the Permian Basin oil and gas fields, and underneath decommissioned coal power plants. In part, stakeholders see the expansion of low or zero-carbon technologies as a crucial enabling technology in their plans to mitigate greenhouse gasses created by their continuing oil & gas production.

### III. Risk Reduction vs. Conventional Geothermal and Oil & Gas

Perceived risk is a crucial difference between developing an oil and gas field and a geothermal resource. Oil and gas risk remains high until the well is completed in the production zone, due to the local and small-scale heterogeneities in key production factors such as porosity and permeability. While the ability to predict these variables in advance has improved considerably in recent

decades, a fundamental level of risk for successfully completing a producing zone remains. A similar risk exists in Conventional Hydrothermal System development, but perhaps not in some new technologies, as will be explored further below. The usual geothermal targets, which are hot fluid upflow channels and a sufficient rate of fluid flow, can be challenging to pin down in advance, and therefore success cannot be known until the expensive process of drilling the well is mostly complete.

Next Generation geothermal methods permit the exploration of geothermal resources beyond Conventional Hydrothermal Systems dominated by advection and convection (moving fluids) to permit exploration in conduction dominated systems, such as sedimentary basins or stable hard-rock cratons.

Conduction is a diffusive process, which is the exchange of energy between adjacent molecules and electrons. It is the dominant heat transfer mechanism for most of the lithosphere, as the rigid lithosphere is unable to support large convection cells. In a conductive (diffusive) setting, temperature does not vary laterally nearly as rapidly as other rock properties such as porosity or mineral content. In other words, you will not find a change of ten degrees across one centimeter (0.4 inches), whereas you might find a complete mineralogy change across the same distance due to depositional or diagenetic controls.

The Earth's core is as hot as the surface of the sun, and in general, the Earth's temperature increases with depth, although it does not do so at a uniform rate. In theory, a desired target temperature can always be reached, it is just a matter of at what depth, and in what rock formation it will occur. Estimates of heat transfer in conduction dominated systems are governed by Fourier's Law. The rate at which heat is conducted through a material (heat flow) is directly proportional to the temperature gradient across the material and the thermal conductivity of the material, and is inversely proportional to the thickness of the material. Therefore, geothermal gradients and conductivity of the rock as well as fractures are key to understanding heat transfer. Variations of thermal conductivity related to the change of lithology have a significant impact on temperatures.

The geothermal gradient element of Fourier's Law are calculated from drilling data. Temperatures measured-while-drilling ("MWD") or measured at the bottom of



the hole via a Bottom Hole Temperature ("BHT") tool after drilling is complete are highly disturbed (generally registering as cooler than equilibrium) by the drilling activity itself and require correction. Errors in estimation of both conductivity and expected geothermal gradient prior to drilling can mean deeper drilling is needed, or worse, that you reach the desired temperature in a different formation and with different properties than planned. The fact that if drilling continues, it will eventually hit the desired temperature, does not minimize the need for fundamental geologic and geophysics analysis of a project site. Detailed pre-drill geological studies are still critical to the success of a project.

Thus, while the risk in Next Generation geothermal is reduced compared to Conventional Geothermal Systems and oil and gas, it is not eliminated. Understanding local technical details is a high-skill pursuit, and represents employment opportunities for talent looking to transfer their efforts from oil and gas operations.

As in all other forms of energy and mineral resources, the pursuit of random drilling programs is not a recipe for success. Wells, including geothermal wells of all types, are expensive prospects, typically millions to tens of millions of dollars per well. Before committing to expenditures of that sort, the best possible understanding of the subsurface is needed. While, in general terms, the Earth does get hotter the deeper one drills, the variations are immense. As we will see later in this Chapter, some areas of Texas can probably produce viable geothermal energy from wells a few kilometers deep, while other areas would need a well nearly ten kilometers deep to reach the same temperatures. This variability does not include the local variations driven by the presence of salt domes, faults and fractures, rock and fluid types, and many other complications in drilling to extract heat from the Earth.

This Chapter will provide an up-to-date assessment of Texas' geothermal potential at the whole-State level down to the regional/basin level and, in some cases, to the county level. We will look at the resource (temperature), as well as the other geologic and geophysical aspects of the various regions of Texas.

## IV. Texas Regions

Texas is diverse geologically and geographically (Figures. 4.1 and 4.2). It ranges from deep sedimentary basins to basement uplift, and from mountains to coastal plains. The State's mineral and energy resources are similarly heterogeneous. Texas' oil and gas development is distinctly zoned in time and space, with areas such as East Texas, the coast, offshore, and the Permian Basin (among others) experiencing one or more periods of intense exploration and production.

In this Chapter, we will divide Texas up into specific regions based on multiple factors. We will then assess the geothermal potential of these regions as the data permits, bearing in mind that some regions have very limited data. Broadly speaking, we break Texas into two types of regions. The first set of regions have abundant oil and gas exploration data, while the second set generally has a much lower density of data available (Figure. 4.3). The regions we explore in this Chapter include:

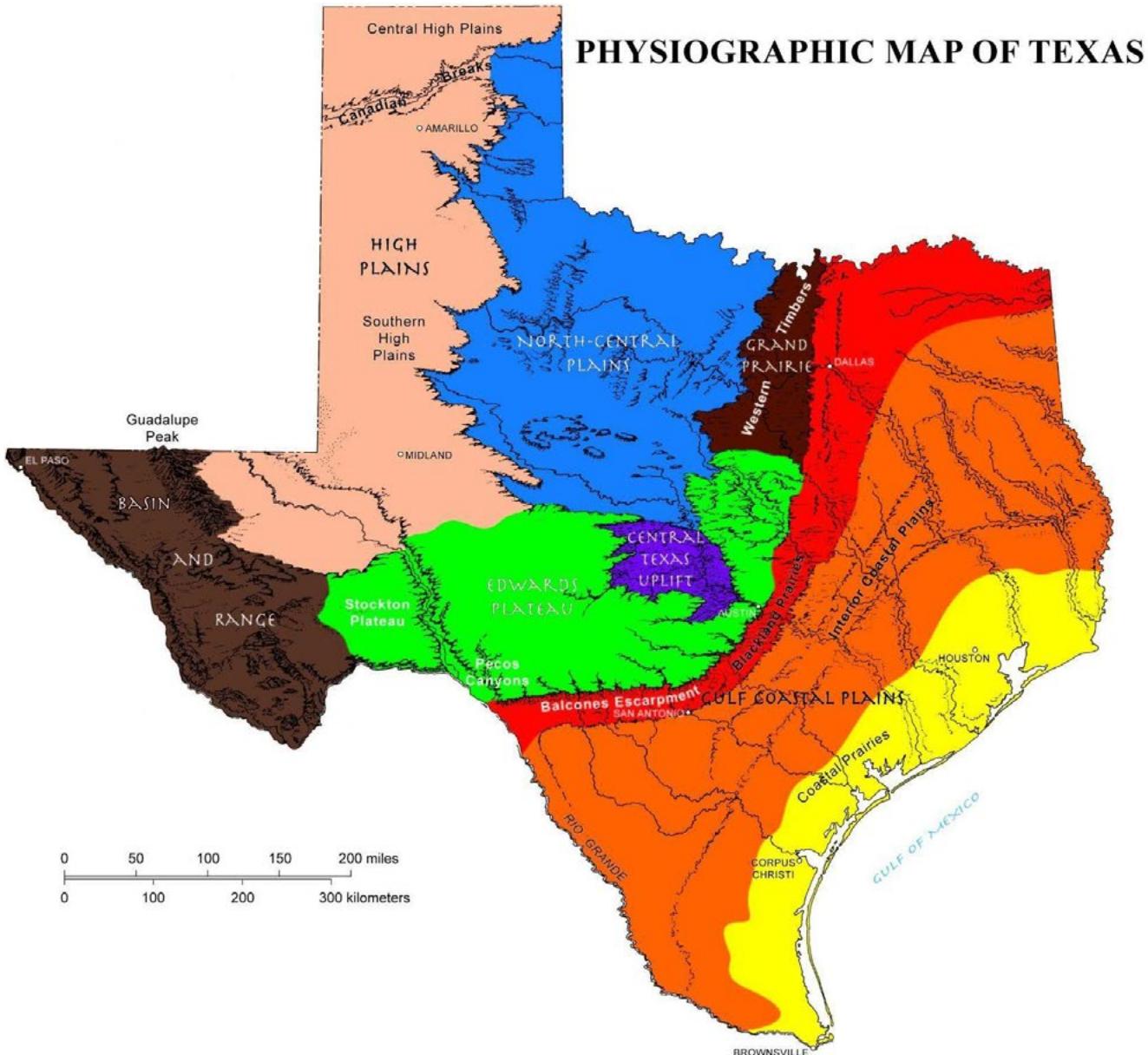
### 1. Sedimentary basins

- a. North-Central/Fort Worth Basin
- b. The Gulf Coast/Geopressure Zone
- c. East Texas
- d. West Texas/Permian Basin
- e. Panhandle/Anadarko Basin

### 2. Other regions

- a. The Llano Uplift
- b. Central Texas/Hill Country
- c. El Paso/The Basin and Range





PROVINCE	MAX. ELEV. (ft)	MIN. ELEV. (ft)	TOPOGRAPHY	GEOLOGIC STRUCTURE	BEDROCK TYPES
<b>Gulf Coastal Plains</b>					
Coastal Prairies	300	0	Nearly flat prairie, <1 ft/mi to Gulf	Nearly flat strata	Deltaic sands and muds
Interior Coastal Plains	800	300	Parallel ridges (questas) and valleys	Beds tilted toward Gulf	Unconsolidated sands and muds
	1000	450	Low rolling terrain	Beds tilted south and east	Chalks and marls
	1250	450	Low stairstep hills west; plains east	Strata dip east	Calcareous east; sandy west
	3000	450	Flat upper surface with box canyons	Beds dip south; normal faulted	Limestones and dolomites
	2000	1200	Steep-walled canyons		Limestones and dolomites
	4200	1700	Mesa-formed terrain; highs to west	Unfaulted, near-horizontal beds	Carbonates and alluvial sediments
	2000	800	Knobby plain; surrounded by questas	Centripetal dips, strongly faulted	Granites; metamorphics; sediments
	3000	900	Low north-south ridges (questas)	West dip; minor faults	Limestones; sandstones; shales
<b>High Plains</b>					
Central	4750	2900	Flat prairies slope east and south	Slight dips east and south	Eolian silts and fine sands
Canadian Breaks	3800	2350	Highly dissected; local solution valleys		
Southern	3800	2200	Flat; many playas; local dune fields		
	8750	1700	North-south mountains and basins	Some complex folding and faulting	Igneous; metamorphics; sediments

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Figure 4.1. Texas Physiographic Regions. The Physiographic Regions of Texas encompass a large, sweeping coastal plain in the southern and eastern third of the State, the "Hill County" and Llano uplift in the center of the State, various plains in the north and north-central area and mountainous basin and range terrain in the far west. These zones correlate closely with geology (Figure 4.2).

Source: Wermund, 1996.



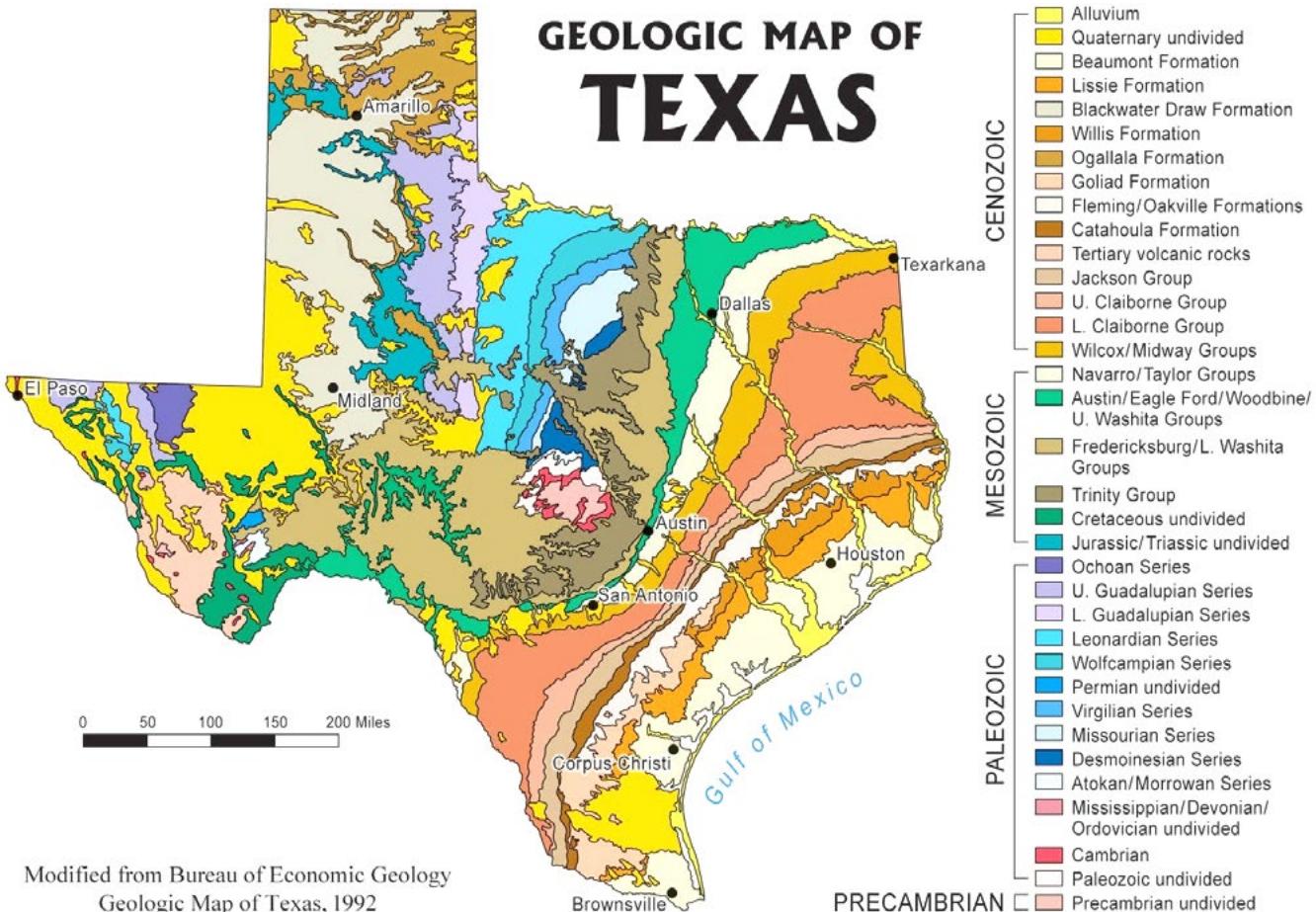


Figure 4.2. Geologic Map of Texas. Similarly varied as the physiographic zones, the geology of Texas ranges from relatively young coastal sediments to “dinosaur age” Cretaceous limestones in central Texas to volcanic and Precambrian igneous formations in west Texas and the Llano area.

Source: Hartman & Scranton, 1992.

#### A. The Foundational Data

This heterogeneity in hydrocarbon resource exploration creates a parallel heterogeneity in the geothermal data available for Texas (Figure 4.3). The data points in Figure 4.3 represent the foundational data on the thermal state of the lithosphere of Texas. Each point is a well that has been logged at some time, usually during or shortly after drilling. In areas with oil and gas production, the density of data points is very high, however as noted above, BHT measurements are generally not at equilibrium conditions. Correspondingly, where there is no petroleum potential, the map is mostly blank. This is not to say that there are no wells in the empty map areas, as there are ubiquitous and relatively shallow water wells. However, wells of this type rarely have useful recorded information and their temperatures, if known, are disturbed by the aquifer flow.

Although this dataset where present is very dense, it is usually not particularly robust and accurate regarding temperatures. This is a concern since the temperature measurement is the sought after information. Other well log data such as porosity and mineralogy are generally much more reliable. The “gold standard” data is an equilibrium temperature of the rocks, measured long after the well is drilled and the disturbance of drilling has passed. However, when a well is drilled, the return to thermal equilibrium takes on the order of months to years. It is not economically viable to let a completed well sit idle for that long to get good temperature data. Therefore, the temperature is typically measured before the drilling-induced temperature disturbance returns to the in-situ equilibrium value. This disturbed value may be up to tens of degrees different from equilibrium. Typically, the temperature is collected in the form of a BHT shown on the strip log of a well and/or recorded as



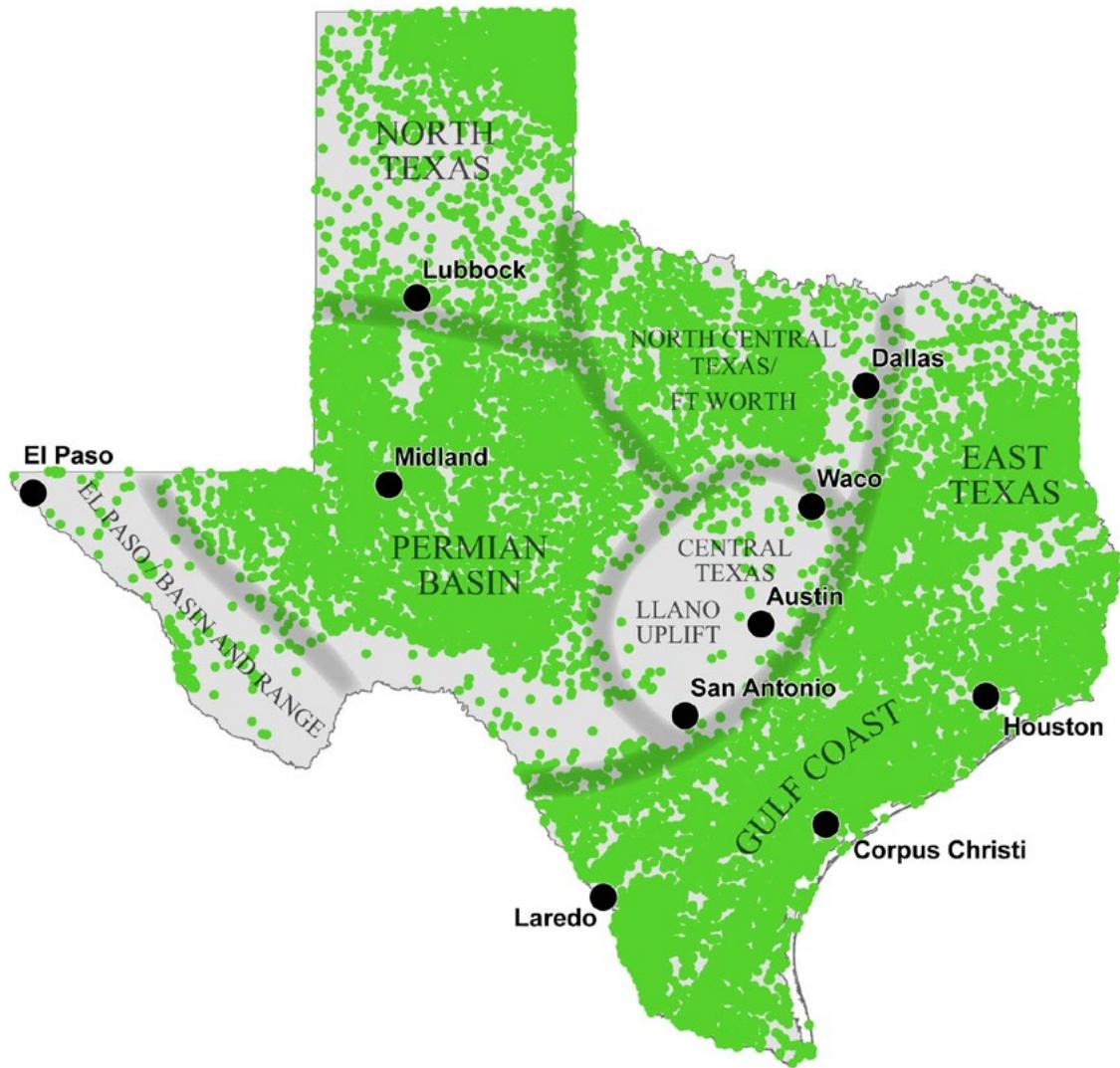


Figure 4.3. The SMU-NGDS (National Geothermal Data System) geothermal dataset for Texas, [geothermal.smu.edu](http://geothermal.smu.edu). Also shown are the approximate boundaries of the regions discussed in this Chapter. Source: Adapted from Blackwell, et al., 2011a.

a maximum temperature on the well log header. Thus we resort to applying crude corrections to the measured (disturbed) temperature to get an estimate of the equilibrium (undisturbed) temperatures (Schumacher & Moeck, 2020). Undisturbed temperatures are critical to understanding the resource in place. And where it is possible to obtain precision, equilibrium temperature data is valuable in and of itself and as a calibration for the “noisy” BHT data.

A similar problem to the potential for temperature errors exists in the data on rock thermal conductivities. Thermal conductivity, (“K”), is the measurement of how well a rock

conducts heat and, inversely, how well it can act as an insulating “blanket” and thus is also a critical parameter in understanding geothermal potential. These values are rarely experimentally measured. There are rock physics models for estimating k based on the rock composition, such as mineral type and percentage, porosity, and fluid content. As with temperatures, however, k estimates are crude and subject to considerable error (Vasseur, et al., 1995; Vacquier, et al., 1988; Jennings, et al., 2019).

Thermal conductivity is critical for extrapolating temperatures below known points. Assuming that BHT can be corrected to yield the in-situ temperature at the



bottom of a well, can temperatures below that point be accurately estimated? Figure 4.7, the temperature map of Texas at 6.2 mile (10 kilometer) depth, is not a map of measured data - there are no temperatures from that depth. Instead, it is calculated using heat flow, an estimate using the temperature difference (gradient) times the thermal conductivity, detailed stratigraphic columns for assigning k values, depth to the basement (e.g., the thickness of sediments), and radiogenic heat production. All these parameters are part of the temperature-at-depth model (Batir & Richards, 2021; Negru, et al., 2008).

With greater numbers of data points, the aerial coverage of temperature is improved, but unless the raw BHT's are appropriately corrected, then the end temperatures are only estimates based on wrong inputs - thus, more inaccurate data are not always better. With a greater number of and more accurate thermal conductivity measurements, the details of the temperatures throughout the stratigraphy improve, thereby refining the details at all depths. This is why improving k estimates and BHT corrections are worth a significant investment. The sum total of the errors in temperature and k can add up to be on the order of 25 percent (Batir & Richards, 2020) - a variance that can induce investors and project managers to invest in improving geothermal technology.

Despite the awareness of data concerns discussed above, numbers can be a significant compensating factor. The extraordinary density of data points allows, as we will show later in this Chapter, the aggregation of "noisy" data into a more coherent picture. Thus, we can make relatively well informed assessments of most regions in this Report, though in some regions only at larger scales/ lower resolution. Understanding the data limitations is of utmost importance, as it highlights areas for future research, with an eye toward risk reduction, realizing that the thermal picture could change with better data. This provides a focus for specific items of data collection for project success.

## B. Future Research

Both BHT and k determination are high priority issues for further research, as they would provide a substantial return on investment in reducing uncertainty in our understanding of the resource. In particular, BHT and k are possible subjects for machine learning approaches

because of the nature of the data available. As is well demonstrated in Batir and Richards (2020), a detailed knowledge of radiogenic heat production throughout the stratigraphic column and into the basement is also a key variable needed in refining temperatures at depth. Note also that a Report such as this one, while a source of information for planning geothermal development, is not sufficient in and of itself for siting a project. The uncertainties and heterogeneities in the data mean that detailed site-specific geologic and geophysical studies are still an essential step in building a geothermal prospect.

# V. Texas as a Whole

## A. Heat Flow

Heat flow, as used in this Report, is the conductive transfer of heat through the upper crust. When compiling heat flow data, every effort is made to eliminate heat flow data affected by convection (Blackwell, et al., 1990; Richards, et al., 2012). In the Texas case, with no active magma movement in the subsurface, this leaves water movement in the ground, which can swamp the conductive signal even with very slow fluid movement. This is most often caused by shallow groundwater flow, which can mask the deeper conductive heat flow. These disturbances can be readily recognized in good quality data.

In broad terms, the heat flow of Texas can be divided up into a few main areas (see Figure 4.4). A large swath of elevated heat flow exists along the Gulf Coast and broadens out into inland East Texas, with values generally in the 65 to 85 milliwatts per square meter range. A broad area of low to moderate heat flow (about 30 to 60 milliwatts per square meter) runs from central Texas up through the panhandle. The highest heat flows are confined to far western Texas along the Rio Grande, and in the El Paso area. This zone has the highest heat flows in Texas, exceeding 90 milliwatts per square meter, and represents the eastern end of the Basin and Range province of the western United States, a well-known rich conventional geothermal producing region outside of Texas.



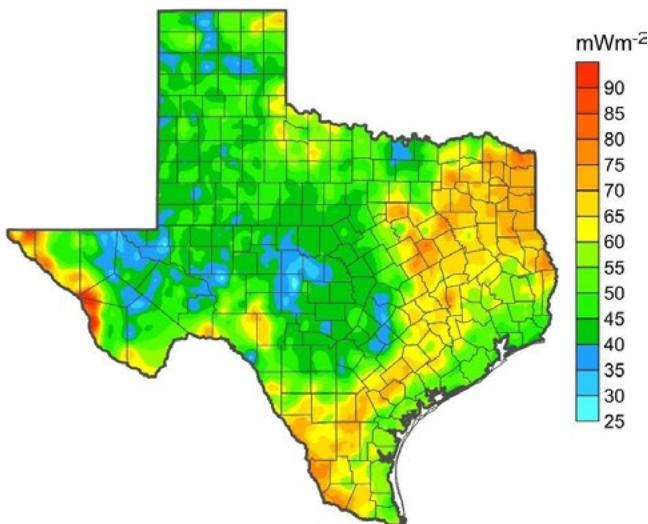


Figure 4.4. This heat flow map generally presents the best estimate of the average shallow crustal conductive heat flow (the heat continually flowing from the hot core to the surface of the Earth).  
Source: SMU Geothermal Laboratory Texas Heat Flow Map (Blackwell, et al., 2011a).

### B. Temperature at Depth

Estimated temperatures at various depths below the surface in Texas are shown in Figures 4.5 through 4.8. Besides obviously becoming hotter with depth, the general temperature patterns follow that of the heat flow map. This pattern is to be expected, since heat flow is directly proportional to thermal gradient via the thermal conductivity. As the individual regions will be discussed in detail below, one main point that will be highlighted; in terms of temperature, the Gulf Coast and East Texas are largely comparable to the Permian Basin section of Texas. The Permian Basin is part of the Basin and Range physiographic province that stretches from Oregon to central Mexico. The Basin and Range physiographic province has high heat flow and temperatures due to extensional thinning of the crust. The high temperatures along the coast and in East Texas are due to multiple factors, including the low thermal conductivity of the sediments, which act as a "blanket" to contain the heat. For the same reason, parts of the Fort Worth basin of North Texas also show up as distinct areas of elevated temperatures.

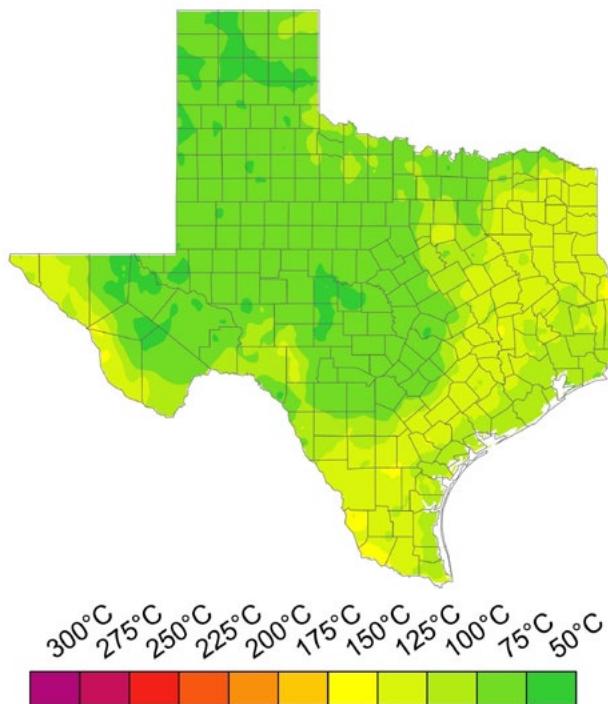


Figure 4.5. This represents a cut through Texas at a depth that is reasonably accessible and useful for direct-use applications. At this depth, temperatures in some regions are getting into the range at which a modern binary geothermal plant can effectively operate (around 125–150°C or 257–302°F). Also, a general trend of higher temperatures along the coast from South Texas into East Texas and the far west is emerging at this depth. Source: SMU Geothermal Laboratory Texas Heat Flow Map (Blackwell, et al., 2011b).

Also, when looking at the deeper temperatures, Texas' relatively low heat flow areas still get reasonably hot (greater than 125°C, or 257°F) by four miles in depth (6.5 kilometers). As power conversion technology continues to advance and drilling costs decrease, these regions will rapidly become more economically viable for geothermal development. These areas are beginning to attract interest and funding, but more is still to be done to prove the viability of these lower-grade resources for development. Thus, in an over simplified, first order reconnaissance, East Texas and the Gulf Coast plus the Permian Basin are Texas' most attractive geothermal resource areas.



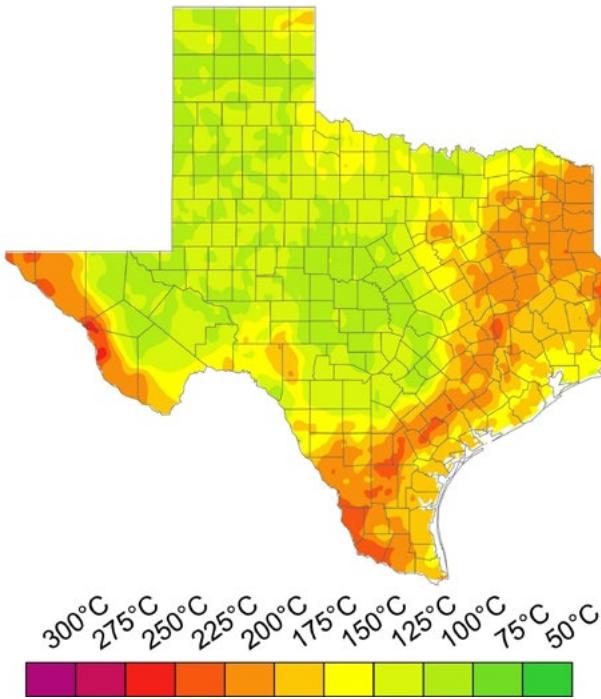


Figure 4.6. Most of the oil and gas drilling is shallower than this depth, and therefore, the temperatures represent primarily calculated values, tuned to fit the rare well penetrations drilled to this depth. As mapped, much of the State is at or near conventional minimum viable temperatures for geothermal power generation. Source: SMU Geothermal Laboratory Temperature Map at 6.5 kilometers (21,320 feet) Depth. (Blackwell, et al., 2011b).

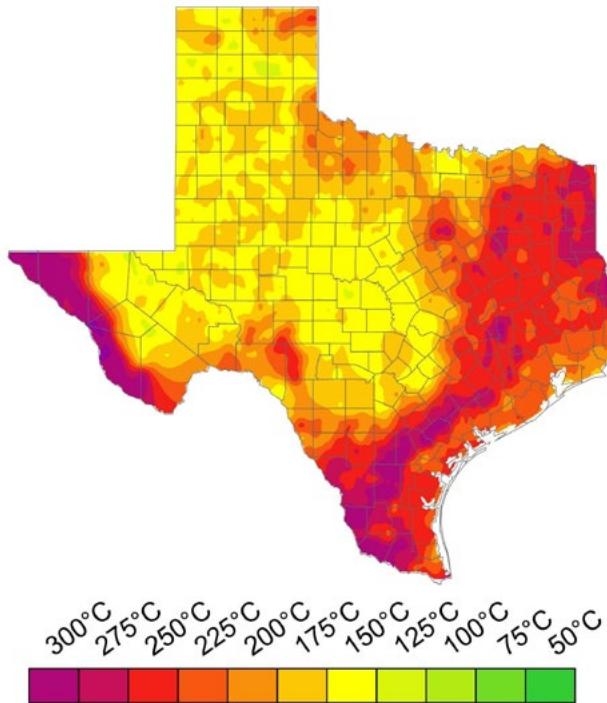


Figure 4.7. Rarely do the oil and gas industry drill to these depths outside the Permian Basin, but drillers do have the capability. Temperatures at this depth are all calculated, not measured. This depth is at the deep end of reasonably envisioned geothermal drilling. At this depth, the entire State is at temperatures that could economically generate power if brought to the surface. Source: SMU Geothermal Laboratory Temperature Map at 10.0 kilometers (32,808 ft) Depth (Blackwell, et al., 2011b).

### C. Heat Flow Versus Heat Content:

A brief explanation of heat flow, heat content, and temperature-at-depth are helpful at this point. The Earth's core is approximately 6,000°C (10,800°F). The surface of the Earth has an average temperature of approximately 15°C (59°F). The core-to-surface temperature gradient creates a heat flow outward through the surface of the Earth of approximately 90 milliwatts per square meter. Integrating this heat flow over the entire Earth surface yields an estimate of total heat flow of about 47 terawatts thermal that is continually flowing past us into space (Davies & Davies, 2010). Such heat flow yields a lot of energy, if it can be tapped. This is because rock is a thermal "sink" or "battery." Also, note that converting thermal energy into electricity is less than 100 percent efficient.

For example, at the temperatures in the Gulf Coast geopressure region available subsurface at about 2.2 miles (3.5 kilometers), the thermal-to-electrical conversion efficiency is only about 5 percent with current technology.

## VI. North - Central Texas

The historical record reports flowing geysers in many north-central Texas communities. Waco was known as the "City of Geysers," and the town of Mineral Springs built multiple hotels around their springs. Geothermal hot water was used to preheat the boiler for the community hospital in Marlin (Woodruff & McBride, 1979). The water table in the past was closer to the surface, allowing the heated water to flow along breaks and faults in the rocks to reach the surface.



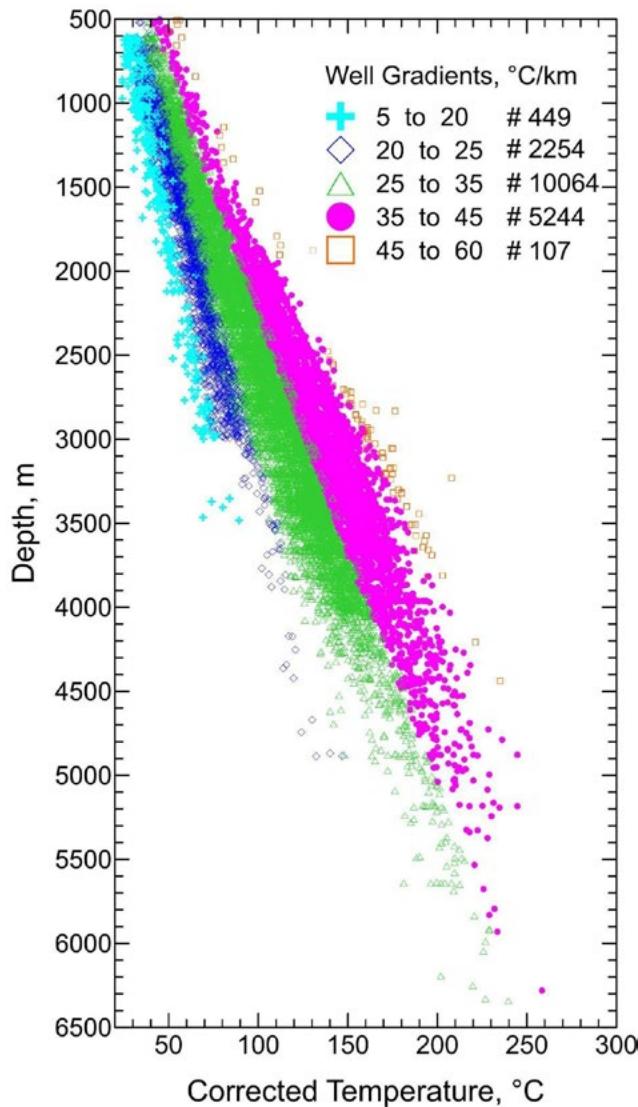


Figure 4.8. The well temperatures plotted are corrected using the SMU-Harrison Correction method. Well-site gradients (depth - surface) are subdivided to depict geothermal gradients of 'high' (35 to 60 °C per kilometer), 'normal' (25 to 35 °C per kilometer), and 'low' (5 to 25 °C per kilometer). In the legend, the number of site values for each gradient interval are shown after the interval, with the gradients from 25 - 35 °C per kilometer being the most common with a count of over 10,000 wells. High gradients deeper than three kilometers are of most interest as a geothermal resource. Source: The SMU-NGDS Data of Texas Wells Corrected Bottom-Hole Temperatures and Blackwell, et al., 2011a:b.

Evaluation and research of the regional thermal regime focused initially on the Balcones, Luling, Mexia, and Talco fault zones, and on Cretaceous aquifers located in North and Central Texas (Woodruff & McBride, 1979). These faults roughly follow the edge of the Llano granitic exposure in Central Texas, then arch up towards Dallas before running east into northeast Texas (Figure 4.1).

On the other side of the buried Ouachita Overthrust Belt from East Texas is the North Texas region (Negru et al., 2008). This stratigraphic and structural change in the geology is the cause for a decrease in heat flow in North Texas compared to East Texas. The current thermal data suggest the basement rock beneath the Fort Worth Basin is Precambrian granite, similar to the Llano Uplift observed at the surface in central Texas (Figure 4.9). The gas-producing zones in the Barnett formation are associated with local thermal anomalies from multiple paleotectonic events that brought heat into the zone, one of them possibly from the Ouachita Thrust Fault (Negru, et al., 2008).

The geothermal resources for North - Central Texas are considered low to moderate, as the thermal gradients are rarely over 35°C per kilometer, with most well gradients between 20°C and 30°C per kilometer (Figure 4.10). The wells drilled deeper than 2.2 miles (three kilometers) are scattered, with only three more than 13,120 feet (4,000 meters). These deeper wells are of most interest to review for their temperature at the bottom of the hole, especially if they have been shut-in for months to years and have achieved an equilibrium temperature. The deepest wells are the Ellenburger injection wells, reported to inject at rates from 1,500 barrels of water per month (240 cubic meters per month) up to 100 times that rate (Frohlich, 2012). The injected fluids are at surface air temperatures, thus considered a cold water for the formation. The thermal impact of this much fluid injected over a decade into the Ellenburger Formation has not been mapped, and is thus a target for further research.

#### A. Detailed Review of Barnett Shale Play: Hood, Johnson, Parker, and Tarrant Counties

The Barnett Shale play provides a significant quantity of new oil and gas well data from the past 20 years. In this Section, we examine the thermal data for Hood, Johnson, Parker, and Tarrant Counties. The entire play includes Jack, Wise, and Denton counties, all on the northern edge of the play (Figure 4.10). Although many oil



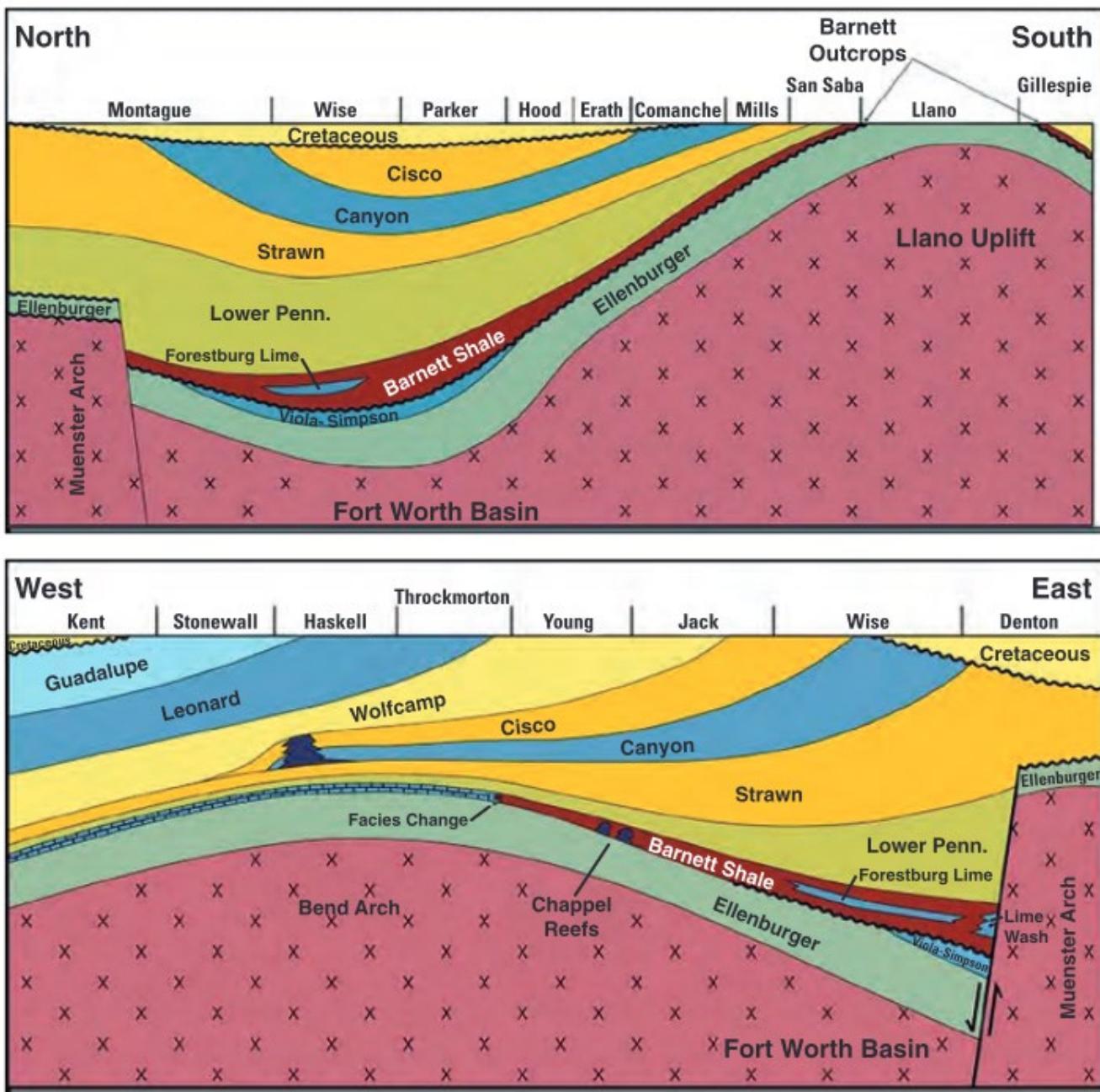


Figure 4.9. Fort Worth Basin stratigraphy across North Central Texas. County names are listed at the top of the sections for reference. Source: Burner & Smosna, 2011.

and gas wells are drilled in Jack and Wise counties, the related well log headers have not had the temperature extracted from them yet to use in a geothermal resource calculation. The available BHT data within the National Geothermal Data System are corrected for drilling impact using the Southern Methodist University ("SMU") Harrison Correction (Blackwell, et al., 2011b; Richards & Blackwell, 2012; Blackwell, et al., 2010). These temperatures and related thermal gradients are plotted in Figures 4.11 and 4.12.

These well locations are a small subset of the drilled wells. Most of the wells are drilled into the Barnett Shale for production, and the Ellenburger Formation below it for injection. The Ellenburger Formation is part of a carbonate system with a high porosity and permeability karst structure. As shown in the temperature-depth plot (Figure 4.11), the general trend of maximum temperatures is within the 100 to 150°C (212 to 300°F) range at the depths currently drilled. There are higher thermal gradients (35 to 60°C per kilometer), especially in Johnson County.



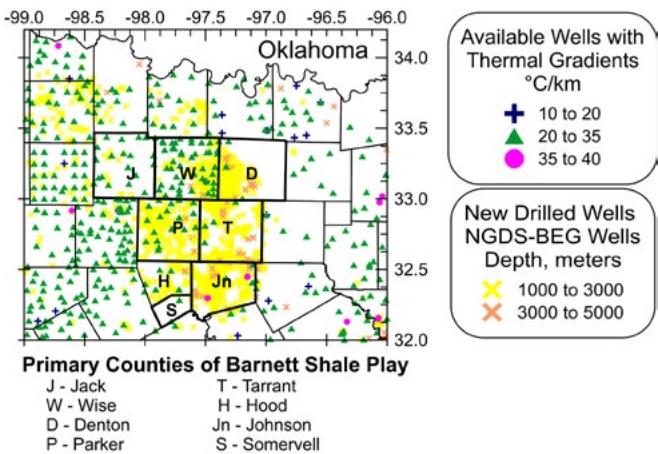


Figure 4.10. Map of North - Central Well Locations. Existing wells used in previous maps are shown as “thermal gradients,” and new additional data shown as “NGDS-BEG well depths.” The thermal gradient wells were used to map the 2011 Heat Flow map and Temperature-at-Depth maps (Figures 4.5 through 4.7). Additional wells with temperature data have been provided by BEG, plotted by their depths, will be included in future resource assessments. These newer wells are primarily from the Barnett Shale Play and show a significant increase in data density in the area. Source: Future of Geothermal Energy in Texas, 2023.

As this is only an initial review of the data, these higher values need to be examined for geological reasoning behind the higher gradients. They may represent zones of fluid movement, or correlate to higher oil and gas thermal maturation.

One area of concern for using the Barnett Shale play as a geothermal resource is the potential of induced seismicity. In Barnett Shale play, induced seismicity related to oil and gas operations is linked to injected water causing reactivation of deep faults (Hornbach, et al., 2015) below the Ellenburger formation. The injection of the produced fluids in a large well for an extended time changes the stress dynamics and can lead to induced seismicity. There is now a network of seismometers across Texas, run by TexNet of the University of Texas at Austin’s Bureau of Economic Geology, to improve the monitoring and understanding of this phenomenon (TexNet, 2022). This concern is offset, however, by the technological developments of the geothermal anywhere movement. These approaches use much less or no fracking fluids, nor do they inject spent fluids back into the subsurface, thereby reducing the risk of induced seismicity.

## B. Detailed Review of Dallas County

Dallas is not considered a place for deep well drilling because the Ouachita overthrust brought basement rocks closer to the surface than in counties to the east and west of Dallas (Woodruff, et al., 1984). Dallas County does have high flow groundwater aquifers, flowing through three cretaceous sandstone aquifers: the Hosston/Trinity, the Paluxy, and the Woodbine Sandstone. In the 1980s, there was an assessment of geothermal resources across Texas, and in eastern Dallas County groundwater from wells drilled into the Trinity formation were measured to be more than 54°C (130°F) (Woodruff et al., 1984). Today temperatures of approximately 54°C represent an opportunity to use the geothermal resources for Direct Use applications.

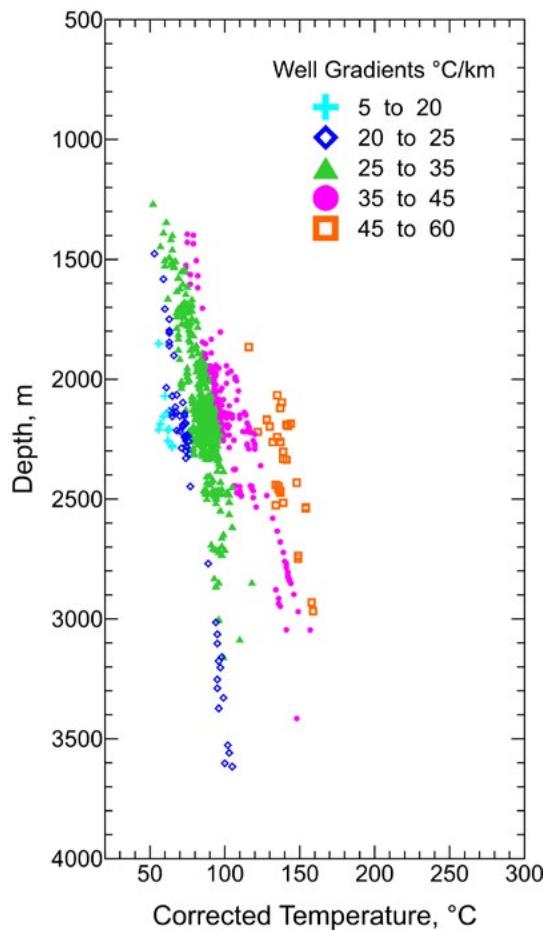


Figure 4.11. Corrected well temperatures and gradients for the Barnett Shale play. The well sites are plotted for comparison to values plotted in Figure 4.10. Source: Future of Geothermal Energy in Texas, 2023.



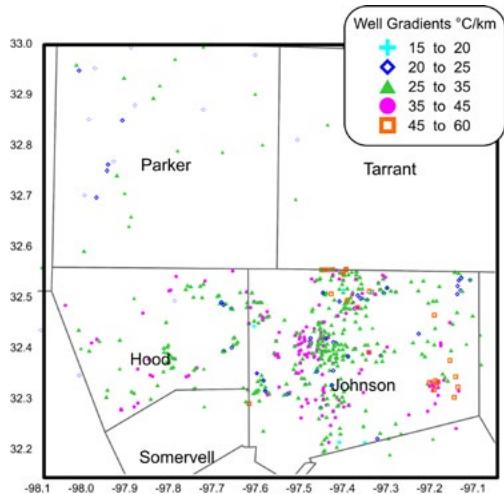


Figure 4.12. Well temperatures and gradients for the southwestern Barnett Shale counties. The locations correspond to the data in Figure 4.11.  
Source: Future of Geothermal Energy in Texas, 2023.

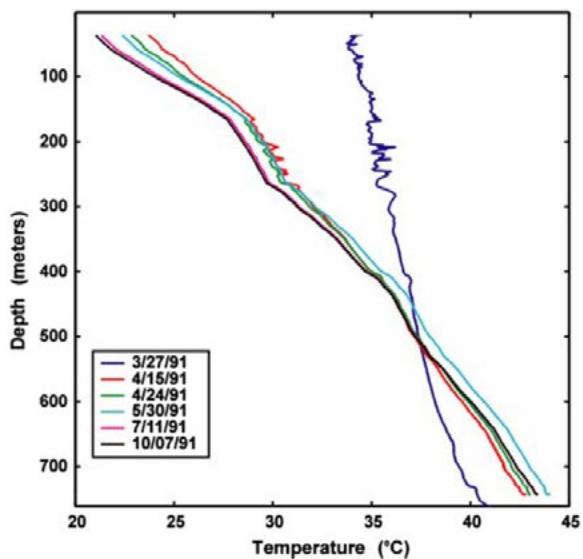


Figure 4.13. Temperature Measurement Series for Mobil New Exploration Ventures ("MNEV") Well. The well is located in Farmer's Branch and represents the typical drilling influence of drilling muds on well temperatures measured after drilling. The temperature changed from too cold at depth to warmer temperatures as the impact of the drilling fluids subsided over seven months to reach equilibrium with the surrounding formations.  
Source: Negaruet al., 2008.

Only one oil and gas well has been drilled in Dallas County: the Mobil New Exploration Ventures ("MNEV") well. It is located on the property of the Mobil Research campus in Farmer's Branch, on the north side of Dallas County. Mobil worked with the SMU Geothermal Laboratory to collect temperature logs over seven months at intervals along the borehole length (Negarau, et al., 2008) (Figure 4.13). The results highlight that wells recently drilled contain temperatures hotter than equilibrium at the surface, yet colder at the bottom than a BHT would record. Seven months later, the final temperature log shows the well reached a thermal equilibrium within the surrounding formations with a cooled surface value and a hotter temperature at depth. Well temperatures return to equilibrium temperatures at a rate based on the type of mineralogy, permeability, amount and type of mud, and the surface and/or drill head temperatures.

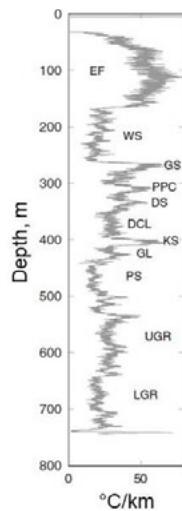
As part of the research for the MNEV well, thermal conductivity values were measured (Table 4.1) (Negarau, et al., 2008). The Eagle Ford Shale is located at the top of the stratigraphic column at this location in Dallas County. These measurements are unique in that they were analyzed shortly after being brought to the surface. Typically, a shale sample dries out before analysis, and the anisotropy of the clay particles causes thermal values to be too high (Negarau, et al., 2008; Blackwell, et al., 1990). This is not the best-case scenario, because the deeper sediments will have higher thermal conductance because of decreased porosity and increased mineral aging (Pribnow & Sass, 1995). Thus, further work and research with regard to actual  $k$  values will be helpful for refining the geothermal resource of a location.

As part of the research completed on geothermal resources, the SMU Geothermal Laboratory focused for more than 40 years on collecting temperatures in wells that are at equilibrium with the surrounding geological setting, similar to the MNEV well. This focus on temperature measurements with high precision logging probes is the foundation of a database of well measurements included in the SMU Node of the National Geothermal Data System ("NGDS"). Wells such as these are essential tools in determining the accuracy of a collection of raw BHT data, and the type of temperature correction to use on them.



**Table 4.1. Measured Thermal Conductivities (k) for the MNEV Well.** Geological formations listed in the Table correspond to their temperature gradients plotted to the right. Eagle Ford Shale, etc. Note the strong and relatively consistent correlation of k with lithology, such that shales are low (1.0 to 1.5 watts per meter Kelvin), limestones are approximately 2.0 watts per meter Kelvin, and the sand - sandstone formations are the highest with values of over 3 watts per meter Kelvin. Source: adapted after Negaruet al., 2008.

Formation	Calculated average thermal conductivity ( $\text{Wm}^{-1} \text{K}^{-1}$ )
Eagle Ford Shale	1.13
Woodbine Sand	2.95
Grayson Shale	1.37
Main Street Limestone	2.05
Paw Paw Clay	1.25
Weno Formation	1.72
Denton Shale	1.58
Duck Creek Limestone	1.99
Kiamichi Shale	1.06
Goodland Limestone	2.10
Paluxy Sandstone	3.42
Glenrose Formation	2.05

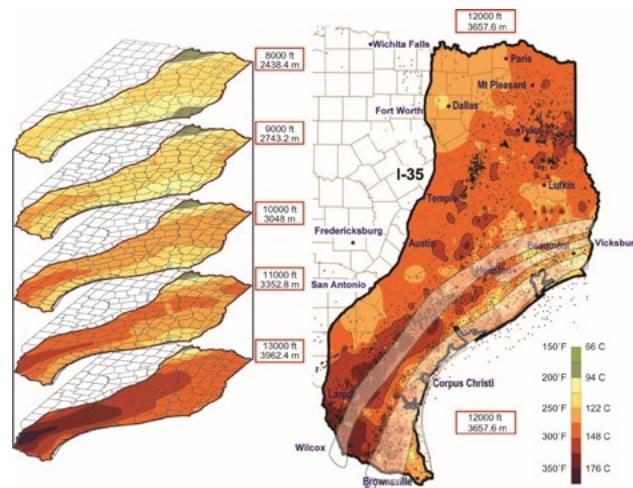


The ability to collect equilibrium temperatures is rare. To do so means a well is shut-in for months to years. As geothermal research uses well temperatures, the full borehole equilibrium temperature logs help calibrate other raw BHT temperatures nearby, or within the same geological setting. Correcting for all the possible parameters is complex (Jordan, et al., 2016), and instead, a common practice is to apply a uniform correction across the entire well data set (Richards, et al., 2012). The temperature data within the NGDS on the SMU Node follows the SMU-Harrison Correction method (Blackwell, et al., 2011b; Richards & Blackwell 2012).

## VII. I-35 Corridor and North East Texas

A review of the possible geothermal resources was the focus of a Texas State Energy Conservation Office grant to the SMU Geothermal Laboratory (Blackwell, et al., 2010). This assessment focused on well temperatures at different depths to determine where geothermal resource potential existed. The findings were limited in the North Texas area because BHT data were unavailable from the Barnett Shale Play. Still, the results represent the general

trend of North Texas having cooler geothermal resources at the same depths as those in East Texas and the Gulf Coastal region (Figure 4.14).



**Figure 4.14.** On the left are Isotherm maps for North and East Texas at six depths between 8,000 and 13,000 feet (2,440 and 3,963 meters), based on well data. Marked on the 12,000 feet isotherm map (on the right) are the Wilcox, Vicksburg, and Frio formation focused oil & gas regions. Source: SMU Geothermal Laboratory maps with overlays by Weijermars, et al., 2018.

## VIII. The Texas Gulf Coast

The Gulf Coast Region, located in Texas and Louisiana, is approximately 750 miles (1,200 kilometers) long and 100 miles (160 kilometers) wide onshore (Wallace, et al., 1978; Davis, et al., 1981). Figures 4.15 and 4.16 show the location of the Gulf Coast and generalized stratigraphy. The geology of the Gulf Coast area is complex due to the cyclical deposition of prograding deltaic sedimentary facies during the Paleogene and Neogene (Tertiary). During this time, the uplift of the Rocky Mountains during the Laramide Orogeny provided an enormous sedimentary influx deposited on the continental shelf in the form of wedges that thicken and dip toward the gulf. This rapid deposition caused the growth of syndepositional normal fault systems parallel to the coastline by the movements of deep units and the collapse of shallow deposits (Ewing & Salvador, 1991). The development of growth faults resulted in the landward thickening of sand packages inside each fault compartment, like a prism. As a result, porous sandstone reservoirs were displaced downward



and came in contact with impermeable shale across the fault. This developed the clastic reservoirs in the Gulf Coast (Figure 4.15).

The Gulf Coast region has the highest overpressure and geothermal temperature gradient in sedimentary basins in Texas. The U.S. Geological Survey (Burke, et al., 2012) published the regional extent of the overpressure in the Gulf of Mexico, including the onshore coast. Sediments and fluids in an “overpressure” situation are at a higher than expected pressure than if the sediments had been deposited and buried slowly. Instead, the sediments are buried quickly and are not allowed to accommodate and dewater as normal, leading to a situation where the fluids will vigorously flow to the surface without pumping if a well is drilled into them – ‘gushers’ to use oil and gas vernacular.

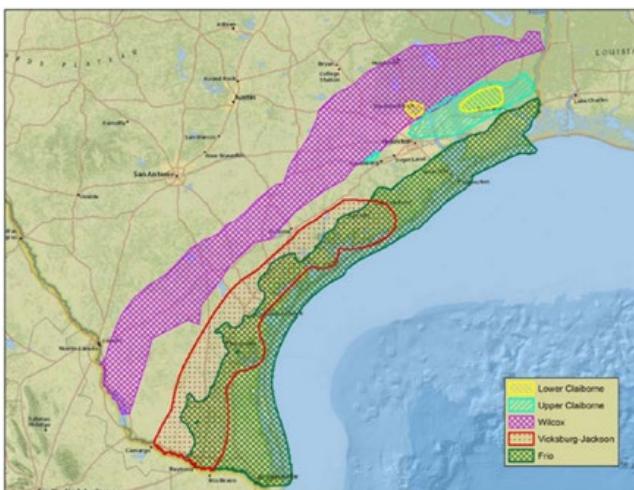


Figure 4.15. The geologic trends of potential geothermal reservoirs in the Gulf Coast, Texas.

Source: Esposito and Augustine, 2012.

These high overpressure and high geothermal gradients develop in the Gulf Coast due to many geologic processes and products over time, such as high sedimentation rate, sandstone, and clay diagenesis (smectite-to-illite), salt diapirs, and migration of pore fluid through faults (Nagihara and Smith, 2008; Christie, 2014). Salt diapirs can impact the 3-D thermal picture of a target due to salt’s relatively high thermal conductivity. Disequilibrium compaction is another potential factor, but it is temperature-independent and can occur at any depth as long as the pressurized zone has not been breached through faults and fractures.

PERIOD	EPOCH	AGE		GROUP OR FORMATION
		P. H. Q.	P. E. Q.	
QUAT.			Calabrian	Undifferentiated
TERTIARY	NEOGENE	MIOCENE	Piacenzian Zanclean	Undifferentiated
	PALEOGENE	OLIGOCENE	Messinian Tortonian Serravallian Langhian Burdigalian Aquitanian	Fleming Fm.
	PALEO	EOCENE	Chattian	Anahuac Fm. Catahoula Fm. Frio Fm.
			Rupelian	Vicksburg
			Priabonian Bartonian Lutetian Ypresian	Jackson Claiborne Gp.
			Therrian Selindian Danian	Wilcox
CRETACEOUS	UPPER			Midway Gp.
			Maastrichtian	Navarro (Olmos Fm. / Escondido Fm.)
			Campanian	Taylor Gp. (Anacacho Ls./ San Miguel Fm. / Ozan Fm. / Annona Chalk)
			Santonian Coniacian	Austin Gp. / Tokio Fm. / Eutaw Fm.
			Turonian Cenomanian	Eagle Ford Woodbine/ Tuscaloosa Washita Gp. (Buda Limestone) Fredericksburg Gp. (Edwards Ls. / Paluxy) Glen Rose (Rodessa Fm.)
	LOWER		Albian	Pearsall Fm. – James Ls. Sligo Fm.
			Aptian	Hosston Fm. (Travis Peak Fm.)
			Barremian Hauterivian	Cotton Valley Bossier Fm.
			Valanginian Berriasian	Haynesville Fm. / Gilmer Ls. Smackover Fm. Norphlet Fm.
JURASSIC	UPPER		Tithonian	Louann Salt Werner Fm.
	MID		Kimmeridgian	
	UP.	L	Oxfordian	Eagle Mills Fm.
			Callovian Bathonian	
			Hettangian	
			Rhaetian Norian Carnian	

Figure 4.16. Generalized Stratigraphy of the Gulf Coast region. Source: Adapted from Swanson, et al., 2013.



McKenna (1997) suggests that hot fluids expelled from overpressured sediments and migrating upward through faults cause high heat flow anomalies along the Wilcox fault zone in the Texas coastal plain (Figure 4.17). In contrast, the Frio Fault zone (Figures 4.17 and 4.18) has no thermal anomalies. Further work will be needed to understand the reasons behind thermal anomalies across various fault zones in the Gulf Coast. The contribution from radiogenic heat varies, depending on the sediment thickness in the Gulf Coast (Christie, 2014; Nagihara, et al., 1996). Very few studies have been published to understand the relation between overpressure and high geothermal gradient in the Gulf Coast, and to decouple them (Cornelius & Emmet, 2020). In several areas, the geopressure gradient is more than 0.7 pounds per square inch per foot (also known as hard overpressure), corresponding to greater than 7,500 feet (2,286 meters) depth along the coast. Inland, the geopressed gradient decreases.

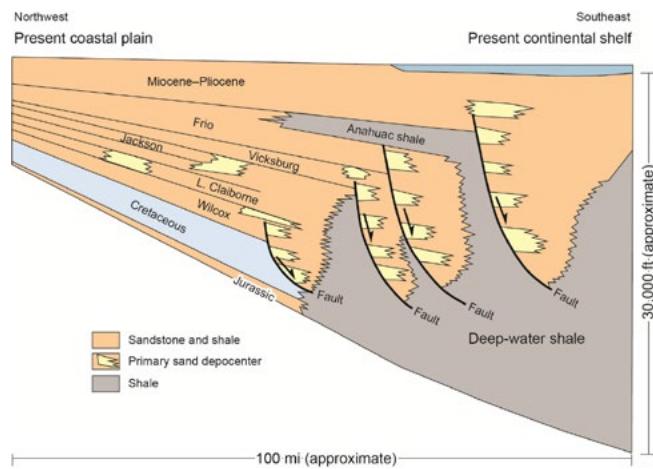


Figure 4.17. Schematic cross-section through the central area of the Texas Gulf Coast. Source: Adapted from Land and Fisher, 1987.

#### A. Potential Gulf Coast Geothermal Reservoirs and Reservoir Properties

Based on the publicly available pressure, temperature, porosity, permeability, and salinity data, a few formations (Frio, Wilcox, and Edward Group) could be potential conventional geothermal reservoirs. These formations are of particular interest due to several attributes, including overpressure, high geothermal gradient, relatively high water production, and extensive oil and gas industry experience.

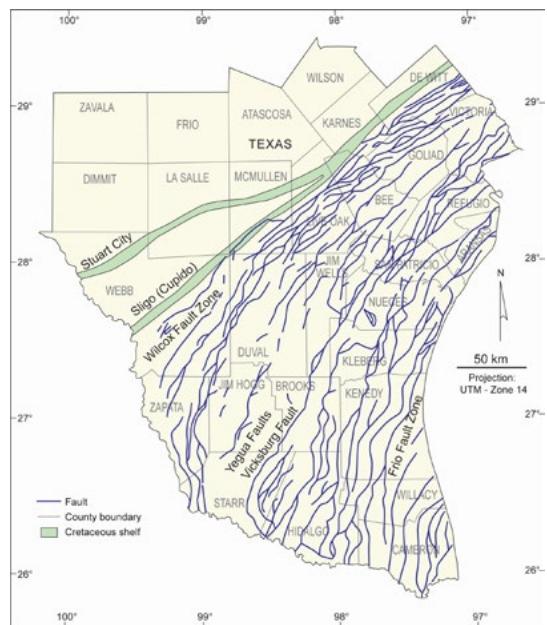


Figure 4.18. Spatial location of major fault zones (Wilcox, Vicksburg, and Frio fault zones) in the Gulf Coast, Texas. Source: McKenna, 1997.

#### 1. Frio Formation

The Frio Formation is a major hydrocarbon producer from the Paleogene in the Gulf of Mexico. It is composed of a sequence of deltaic and marginal-marine sandstones and shales. In terms of structural elements, the Frio Formation is defined by a series of salt diapirs and associated faulting, growth faults, and associated shale ridges (Bruce, 1973; Galloway, et al., 1982; Swanson, et al., 2013). These elements can be a potential conduit of heat from the deep subsurface. In addition, the development of growth faults due to rapid sedimentation helps develop potential clastic reservoir wedges. Such reservoirs are thicker toward the fault and thinner away from the fault. However, some of the faults are very shallow and may contribute instead to heat loss.

Most Frio sandstones are lithic arkoses and feldspathic litharenites (Land, 1984). Litharenites or lithic arenites are types of sandstones with a large fraction of rock fragments greater than five percent. Compositional variation controls the reservoir quality of the Frio sandstones. The reservoir quality of Frio sandstone varies regionally and with depth due to a combination of changes in rock composition, degree of diagenesis, and geothermal gradient. Loucks, et al., (1984) reported good to excellent reservoir quality in the Frio sandstones in the upper and middle Texas Gulf Coast. The permeability is



as high as 1,000 millidarcy in this area (1 millidarcy is 10–16 square meters). Based on data from NRG (2006) and Nehring (1992), the average porosity of Frio sandstone reservoirs, excluding the Hackberry trend in southwest Louisiana, is 27 percent, and the average permeability is 685 millidarcy.

In contrast, the reservoir quality is poor in the lower Texas Gulf Coast. Permeability measured in sandstone cores deeper than 2.5 miles (four kilometers) in the Lower Texas Gulf Coast averages one to two millidarcy. Secondary porosity in the Frio sandstones is volumetrically significant (Loucks, et al., 1979). Lindquist (1976; 1977) concluded that most deep Frio reservoirs are cemented with late-forming kaolinite, Fe-rich calcite, and dolomite. This cement would result in poor heat production due to internal fluid flow barriers, which cannot be fractured effectively due to the presence of kaolinite. In contrast, permeability in deep sandstones in the Upper Texas Gulf Coast ranges up to hundreds of millidarcies. This higher permeability is interpreted as the result of the less well developed late carbonate cementation stage. According to Hovorka, et al. (2001) and other studies, the formation water salinity in the Frio is around 100,000 parts per million (Macpherson, 1992; Kreitler, et al., 1990), potentially causing the formation of mineral scaling and corrosion of pipes if formation fluids are produced in a geothermal system.

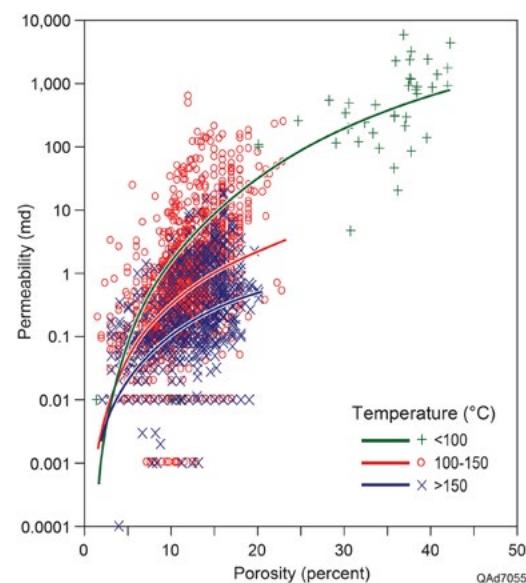
## 2. Wilcox Formation

The Paleogene-aged Wilcox Group extends across the entire Texas Gulf Coast. The formation is composed of a wedge of sandstone and shale that thickens and dips toward the coast. The Wilcox has been interpreted to be primarily deposited in a deltaic setting (Endicott, 1995; Fisher, et al., 1969; Lofton & Adams, 1971; Womack, 1971; Edwards, 1981; Dutton & Loucks, 2010). The Wilcox is divided into three parts. The first two are the sandstone-rich upper and lower sections, which represent two major progradational cycles, and the third is the shale-rich middle section, which in part represents a major transgression.

The quality of the Wilcox sandstones varies spatially and with depth. Porosity and permeability of the Wilcox sandstone vary between 5 and 25 percent and 0.01 to 100 millidarcy; however, there are sections where higher porosity and permeability are present. Dutton and Loucks (2010) studied the impact of temperature dependent

burial diagenesis on porosity and permeability of the Wilcox sandstones in onshore wells. Primary porosity and permeability are reduced as temperature increases, while the secondary porosity remains unchanged. These sandstones show progressive porosity and permeability reduction from an average of 33 percent at 38°C (100°F) to 12 percent at 132°C (270°F), with minor loss beyond that due to burial and compaction (Figure 4.19). Bebout, et al. (1982) mention the variation of formation temperature within the Wilcox relative to dip, the lithology, the location of growth faults, and the location along the Gulf Coast. Formation water salinity increases with depth in the hydropressured zone, and it varies in the overpressure zone between 20,000 to 100,000 parts per million (Bebout, et al., 1981).

The geothermal gradient in the Wilcox is 2.1 to 3.1°F per 100 feet (38 to 57°C per kilometer). A previous study (Blackwell et al., 2010) found the temperature range of the formation to be 88°C and 205°C (190°F and 400°F). Such temperatures, coupled with the near lithostatic geopressure and high permeability and porosity, point to moderate potential for geothermal development.



**Figure 4.19:** Different trends of porosity-permeability in the Wilcox sandstones at different temperatures. Source: Adapted from Dutton and Loucks, 2010. Reprinted from *Marine and Petroleum Geology*, 27, 1, Dutton and Loucks, *Diagenetic controls on evolution of porosity and permeability in lower Tertiary Wilcox sandstones from shallow to ultradeep (200–6700m) burial, Gulf of Mexico Basin, U.S.A.*, 69–81, Copyright (2010), with permission from Elsevier.



### **3. Edwards Group**

The deeper Cretaceous-aged Edwards Group, near the Stuart City Reef, is another potential geothermal reservoir often overlooked in most published studies. The Edwards Group was deposited in shallow-marine environments and underwent normal early diagenesis, forming dolomites and micrites at places (Longman & Mensch, 1978). The Stuart City Reef is divided into two portions: Lower Edwards ("B"), which is interpreted to be a barrier-type reef margin, and upper Edwards ("A"), which is primarily bioherms (Waite, 2009). The average porosity and permeability of the Edward Group are 14 percent and 41 millidarcy. The Edward Group contains fractures and vugs, which enhance its pore volume and fluid flow.

### **4. Smackover/Norphlet Formation**

The Jurassic-aged Norphlet and Smackover formations in South Texas pinches out in the deep subsurface against subjacent Paleozoic rocks of the Ouachita Fold Belt. There has been limited mapping of these formations due to limited available geophysical log data. Although the primary depocenter of the Norphlet Formation (based on available data) is in Alabama and Mississippi, it is known to be present in Texas. It is overlain by Smackover Formation and underlain by Louann Salt. The Norphlet is dominated by alluvial-fan, wadi-, playa-, and eolian deposits (Budd, 1981). The depositional environment initially controls porosity and permeability. Aeolian deposits have the best porosity and permeability values. Diagenetic processes modify the porosity of the Norphlet Formation. Quartz cementation above 200°F (93°C) reduced porosity. Chlorite grain coating at places preserved the porosity of the Norphlet formation (Dixon, et al., 1989). The porosity of the Norphlet formation is 10 to 26 percent, and permeability varies between 0.1 and 650 millidarcy, depending on the facies (Godo, 2019). Due to its deposition in a sabkha environment and stratigraphic position above the salt, the salinity is very high and can reach about 240,000 parts per million of total dissolved solids (Godo, 2019). Several normal faults are present in the Norphlet formation, which may provide the high heat flow required for geothermal development.

The saturating fluids in the Smackover and Norphlet formations have variable hydrogen sulfide ("H<sub>2</sub>S") concentrations, which is essential to consider in reservoir evaluation and economics. H<sub>2</sub>S is toxic and can corrode

metal pipes. Several Smackover and Norphlet oil fields produce sour gas, and H<sub>2</sub>S concentration increases with increasing temperature (greater than 175°C or 347°F) in certain fields due to thermochemical sulfate reduction (McBride, et al., 1987; Claypool & Mancini, 1989; Shew, 1992). The H<sub>2</sub>S concentrations range from 25 percent to 42 percent.

### **5. Estimated Thermal Resource in the Gulf Coast**

The thermal resource base of the Gulf Coast is estimated to be 46,000 exajoules, and the methane volume entrained in the brine is 23,700 x 10<sup>12</sup> standard cubic feet, with a thermal equivalent of 25,000 exajoules (White & Williams, 1975), considering only Tertiary rocks. Wallace, et al. (1979) extended this study to the underlying Cretaceous rocks and estimated thermal energy of 110,000 exajoules, including onshore and offshore geopressured areas. This estimate does not include energy stored in methane. Esposito and Augustine (2012) at the National Renewable Energy Laboratory ("NREL") reassessed the potential of onshore geopressured geothermal energy from the Gulf Coast. They identified five major geopressured-geothermal formations in Texas: lower Wilcox, lower Frio, Vicksburg-Jackson, lower Claiborne, and upper Claiborne. They also concluded that the Vicksburg-Jackson in south Texas has high quality geothermal resources because of thick sandstone and high temperatures. However, this study was done at a high level and does not provide enough granularity. The reservoir properties used in this study are average estimates of the entire formation in the entire study area. Based on petrophysical measurements of core, Vicksburg has very low permeability in south Texas, in the range of 0.2 to 0.7 millidarcy, in the lower Gulf Coast (Swanson, et al., 1976; Rich & Kozik, 1971; Loucks, 1978). The above discussion relates primarily to conventional hydrothermal development. The Vicksburg-Jackson, lower Claiborne, and the upper Claiborne formations all may work well as targets for development if Closed Loop Geothermal Systems are used.

### **6. Type of Potential Geothermal Development in the Gulf Coast**

The upper and middle Gulf Coast can support Conventional Hydrothermal System development based on the available reservoir property information. These reservoirs will support conventional in-situ formation fluid-production-



based geothermal, and ‘geothermal anywhere’ concepts like Engineered and Advanced Geothermal Systems focused on high temperature rock. On the other hand, the lower Gulf Coast region of south Texas seems favorable for unconventional ‘geothermal anywhere’ type development, which can include drilling multilaterals and multi-stage fracturing (referred to as Next Generation EGS in this Report), since high porosity and permeability, required for Conventional Hydrothermal System development, are generally not present or are very restricted. These features elevate risk for conventional projects.

## 7. Stress Direction and Seismicity in the Gulf Coast

The present day principal maximum horizontal stress (“SHmax”) direction in the Gulf Coast is northeast to southwest, with minor stress field rotations locally (Snee & Zoback, 2018). Generally, the direction of hydraulic fractures tends to parallel SHmax, if these sections are hydraulically fractured for geothermal resources. The growth of the vertical hydraulic fracture depends on the contrast of SHmin between different beds. If the height of these fractures is high, they can inadvertently intersect other unfavorable zones rather than creating a desired fracture network to enhance fluid flow through these rocks.

There are no known occurrences of present day tectonic activity in this region, however, induced seismicity has been found to correlate with hydraulic fracturing of the Eagle Ford Shale in the Gulf Coast (Fasola, et al., 2019). This seismicity is somewhat in contrast to induced seismicity mainly related to saltwater disposal in the Permian Basin. Many Eagle Ford region earthquakes are distributed linearly along the Karnes fault zone and North Live Oak fault zone (Li, et al., 2021). Li, et al. (2021) also show several faults that have not been mapped previously. The depth range of these earthquake clusters varies between 2 to 10 kilometers in depth. Figure 4.20 shows the location of faults and recent earthquakes in the Eagle Ford play in south Texas.

If the development plan of geothermal resources in the Gulf Coast includes modern techniques, such as multi-stage fracturing along multi-laterals, induced seismicity must be monitored closely. This is because the strike of the growth faults is mostly along a northeast to southwest direction (Figure 4.18), which is parallel or subparallel to

the present day SHmax. Also, the sand wedges, which are potential geothermal reservoirs, were deposited towards the downthrown side of the growth faults. The thickness of these sand packages decreases away from the faults towards the southeast basinal side. Therefore, hydraulic fracturing sites targeting these reservoirs are likely to be close to the faults, some of which may be critically stressed, and need to be appropriately instrumented and monitored as the circulating fluids could enhance fault slip potential. This seismic potential affects most of the reservoirs of the Gulf Coast region.

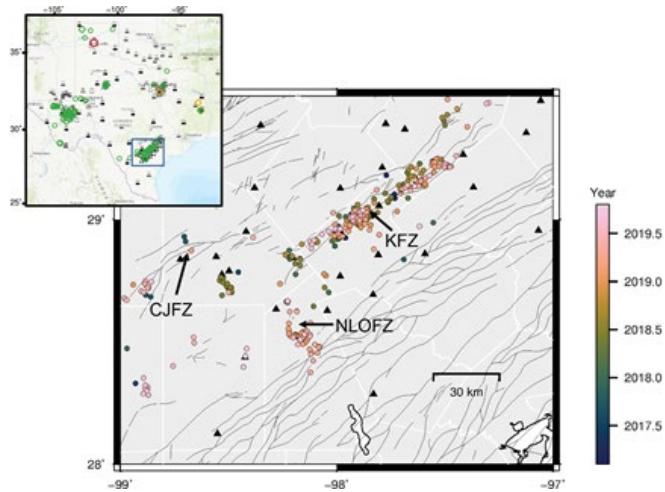


Figure 4.20. Map of the Eagle Ford Shale play, with locations of broadband seismic stations (in black triangles), earthquake locations (in colored circles), and previously mapped faults (in black lines) [after Li, et al., 2021]. Faults are interpreted by Ewing, et al. (1990). There are different fault zones in the area, including the Charlotte–Jourdanton fault zone (CJFZ), the Karnes fault zone (KFZ), and the North Live Oak fault zone (NLOFZ). Source: Adapted from Li, et al., 2021 and Ewing, et al., 1990.

## 8. Pleasant Bayou Test Wells in the Gulf Coast

The University of Texas at Austin, Bureau of Economic Geology (“Bureau” or BEG) was involved in drilling two pilot test wells (Pleasant Bayou 1 and 2) in Brazoria County, located between Houston and Galveston. Pleasant Bayou Well No. 1 was drilled in 1978 and plugged back and completed as a brine disposal well because of hole instability problems. The Pleasant Bayou Well No. 2 was offset 500 feet (152.4 meters) from the No. 1 well, drilled to 16,500 feet, and completed in 1979 (Riney, 1991). Well



No. 2 targeted the lower Frio Formation C-zone; the total thickness at the wellbore of this zone is composed of 125 feet (38.1 meters) of sandstone. Thick sandstones in this well have a porosity of about 18 percent. The well is bound on the southwest by large growth faults, which create compartments (Hamlin & Tyler, 1988). Based on the local geology interpreted from seismic and wireline data, there is also a possibility of many small scale faults and fault splays from the large growth fault in this region.

The initial pressure and temperature recorded at 14,560 feet (4,438 meters) was 11,116 pounds per square inch and 156°C (306°F). The well produced 20,000 barrels per day of water for a total of about 3.7 x 106 barrels from 1981 to 1983. With regard to energy output, the well produced approximately 0.5 megawatts electric from heat and one megawatt electric from co-produced gas (Riney, 1991). The produced brine was principally a sodium ("NaCl") solution with substantial calcium and ions, including potassium and magnesium. The salinity was 130,000 parts per million total dissolved solids.

## **9. Jackson County in the Gulf Coast**

Jackson County sits approximately in the middle of the Gulf Coast region inland from Matagorda Bay, approximately 100 miles (160 kilometers) southwest from Houston, and 110 miles (177 kilometers) northeast of Corpus Christi. With the central proximity of the county, Jackson County was chosen for our review as an example county for the Gulf Coastal zone, with the goal of gaining a greater understanding of the geothermal resources outside of the Eagle Ford Shale play. This study was accomplished as part of the University of Texas Geothermal Entrepreneurship Organization project ("GEO") funded by DOE (Batir & Richards, 2020; 2021).

The previous geothermal resources mapping of Jackson County was completed as part of Blackwell, et al. (2011a), heat flow maps and temperature-at-depth maps (Blackwell, et al., 2011b), the 2010 Interstate 35 East project (Blackwell, et al., 2010), and was originally part of the 2004 Geothermal Map of North America (Blackwell & Richards, 2004a; 2004b). Therefore, it has been a decade since the last review of geothermal resources in this area. Currently available data includes a BHT dataset accessible through the National Geothermal Data System ("NGDS") Borehole Observation file updated from recently drilled oil and gas well logs.

The previous mapping efforts used a thermal conductivity model for the Gulf Coastal region based on low thermal conductance in young unconsolidated sediments that increased conductance as the geology became older and further away from the shore (Blackwell & Richards, 2004a). The most recent 2020 (Batir & Richards, 2020; 2021) assessment incorporated the Pitman and Rowan (2012) thermal conductivity values assigned to Gulf Coast formations, although their work is based on research in Louisiana. There are some differences between the Gulf Coast depositional settings along the Gulf Coast from the speed of deposition to proximity to the shoreline at the time. Still, it was determined that when the formation descriptions were the same, these mineral-based thermal conductivity values by Pitman and Rowan (2012) were an improvement over a generalized model previously used. McKenna and Sharp (1989) measured thermal conductivities in South Texas were also used as a second boundary condition. As discussed earlier in the Chapter, the lack of thermal conductivity sample analyses for rocks in Texas is a limitation currently for the accurate mapping of the geothermal resources in Texas.

Using the oil and gas temperature data, there was an increase in data sites from 80 wells in 2011 (Blackwell, et al., 2011b) to 215 wells in the 2020 (Batir & Richards, 2020) project. The additional BHT data are distributed similarly over the county to the original 80 well sites allowing for an infilling of data. The SMU-Harrison correction was applied to the raw BHT data (Blackwell & Richards 2004). Combined with the more detailed thermal conductivity and stratigraphic column for the county, these data allowed for an update in the Jackson County heat flow map (Figure 4.21).

There are similar trends between the 2020 and the 2011 heat flow maps, going from higher heat flow in the northwest portion of the county and decreasing slightly to the southeast. With the additional data, the spatial resolution of the mapping increased between the 2011 and the 2020 datasets that produced a different pattern, yet the general trends are consistent. The county heat flow in the 2020 map ranges from 65 to 80 milliwatts per square meter, and the 2011 map is from 50 to 65 milliwatts per square meter. The new BHT data include an increased gradient that supports the increase in heat flow, although the prominent increase is more directly tied to the more representative thermal conductivity values.



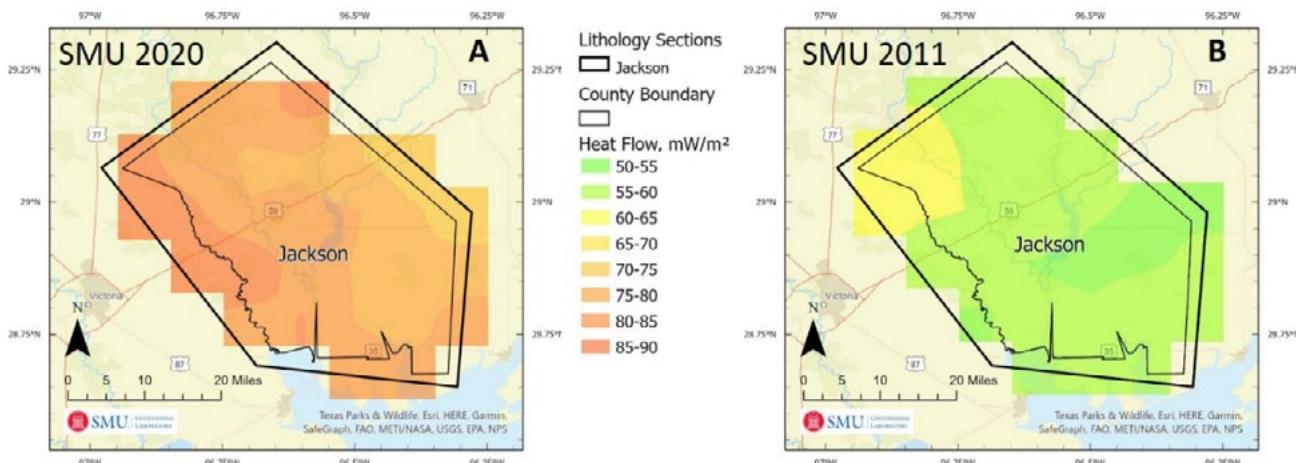


Figure 4.21. A comparison of heat flow maps for Jackson County with the most recent one in 2020 (Batir and Richards) using an updated thermal conductivity model and more BHT data points than the 2011 Blackwell, et al. map (this is a subset of the U.S heat flow map). Sources: Batir and Richards, 2020 and Blackwell, et al., 2011.

As part of the calculations for the temperatures-at-depth, especially those depths beyond any measured BHT, the radiogenic heat production of the sediments and basement rock is used as one of the parameters (Batir & Richards 2020). A maximum depth of 8 miles (13 kilometers) usually defines the thickness of the sedimentary formations; deeper than that is considered basement (igneous or metamorphic rock types). The sedimentary section in Jackson County is determined by geophysical studies to be as deep as 9.3 miles (15 kilometers). Therefore, Batir and Richards (2020) updated their basement thickness models for Jackson and Webb Counties. In doing so, the radiogenic heat production values improved the accuracy and resolution of the resulting deep temperatures.

Using the updated temperatures, radiogenic heat production, thermal conductivity, and detailed stratigraphic column, the temperatures were calculated at 6.2 miles (ten kilometers). Figures 4.22, 4.23, 4.24 are the maps of the temperatures at 3.5 kilometers, five kilometers, and 10 kilometers (11,480, 16,400, 32,800 feet, respectively).

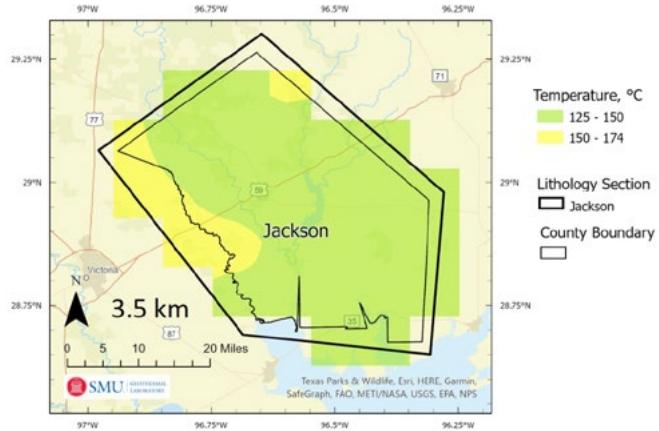
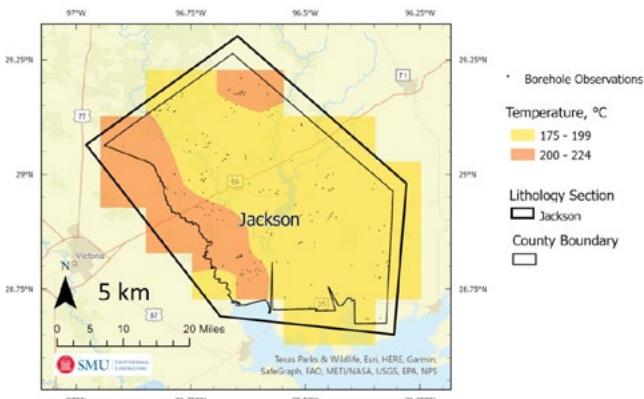
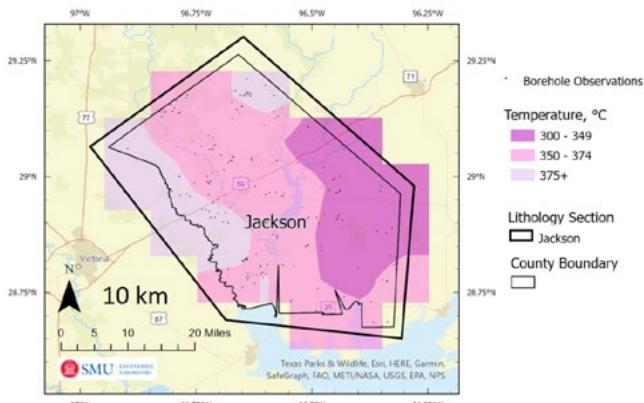


Figure 4.22. Map of temperatures below Jackson County at a depth of 3.5 km (11,480 ft). The temperatures range from  $125^{\circ}\text{C}$  to over  $150^{\circ}\text{C}$  ( $257^{\circ}\text{F}$  to  $302^{\circ}\text{F}$ ), with the warmer temperatures in the northwest portion of the county. At this depth, approximately one third of the BHT sites are drilled to or deeper than this depth and were therefore used in the calculation. Source: Adapted after Batir and Richards 2020; 2021.





**Figure 4.23.** Map of temperatures below Jackson County at a depth of 5.0 km (16,400 ft). The temperatures range from 175 °C to over 200 °C (347 to 392 °F), with the warmer temperatures in the northwest portion of the county. At this depth, there are 8 wells drilled near or deeper than this depth used in the calculation, with temperatures ranging from 180 to 220 °C (356 to 428 °F). Source: Adapted after Batir and Richards 2020; 2021.



**Figure 4.24.** Map of temperatures below Jackson County at a depth of 10 km (32,800 ft). The temperatures range from 300 °C to over 375 °C (572 to 707 °F). The warmer temperatures continue to be towards the northwest, somewhat following the increased thickness in sediments to the southeast being younger and cooler. At this depth, the temperatures are all extrapolated with no direct measurements. Source: Adapted after Batir and Richards 2020; 2021.

Jackson County is not in the middle of a highly active oil and gas play, such as the Eagle Ford or Barnett Shale play, yet the use of the existing oil and gas well data and past research of the geology and geophysics shows how the geothermal resource can be determined and that there are high temperatures available for resource use in all types of geothermal projects.

## IX. East Texas

The boundaries for East, North, South Texas, and the Gulf Coast can be overlapping depending on how they are defined. The I-35 report (Blackwell et al., 2010; Richards & Blackwell, 2012) discusses the four areas as they sit along or are east of Interstate 35 from the Mexican border to Oklahoma (Figure 4.14). For this study, the focus has been based on geological regions, and as such, the geology of East Texas is known for the “tight” formations (little fluid content) and impacted by deep salt structures, causing the formations to dip in different directions relative to the nearby salt structures as they moved upward, creating local faults and anticlines (Figure 4.25). The deep Jurassic Louann Salt is hypothesized to have been deposited on a flat surface in the Gulf Coast of the East Texas Basin (Figure 4.26). The basin filled over millions of years in sequences of deep water and shallow water environments. Deposits of shales and mudstones formed during the shallow water periods, while during transgressive, deep water events, sandstones to limestones were formed (Granata, 1960). The shoreline of East Texas Basin moved inward and outward, depositing shale-sand sequences to produce groups of thick formations such as the Cotton Valley Group, Nueva Leon Group, and Trinity Group. The Cotton Valley Group thickness is typically between 2,400 to 3,700 meters (8,000 to 12,000 feet) and at drill depths of 2,400 to 3,000 meters (about 8,000 to 10,000 feet).

Along the eastern border of Texas is the Sabine Uplift, which contains basement rocks that differ in radiogenic heat production from the rest of the Gulf Coast and East Texas basement. The uplift is considered a mid-rift high caused by an area of stability with less subsidence relative to the East Texas and South Louisiana rift basins (Granata, 1960). The results are major transform faults bounding the Sabine Uplift on its northeast and southwest sides. As additional Laramide compression caused folding and faulting, a restraining side-step formed northeast to southwest as a sheer fault system in the area of East Texas (Adams, 2009).



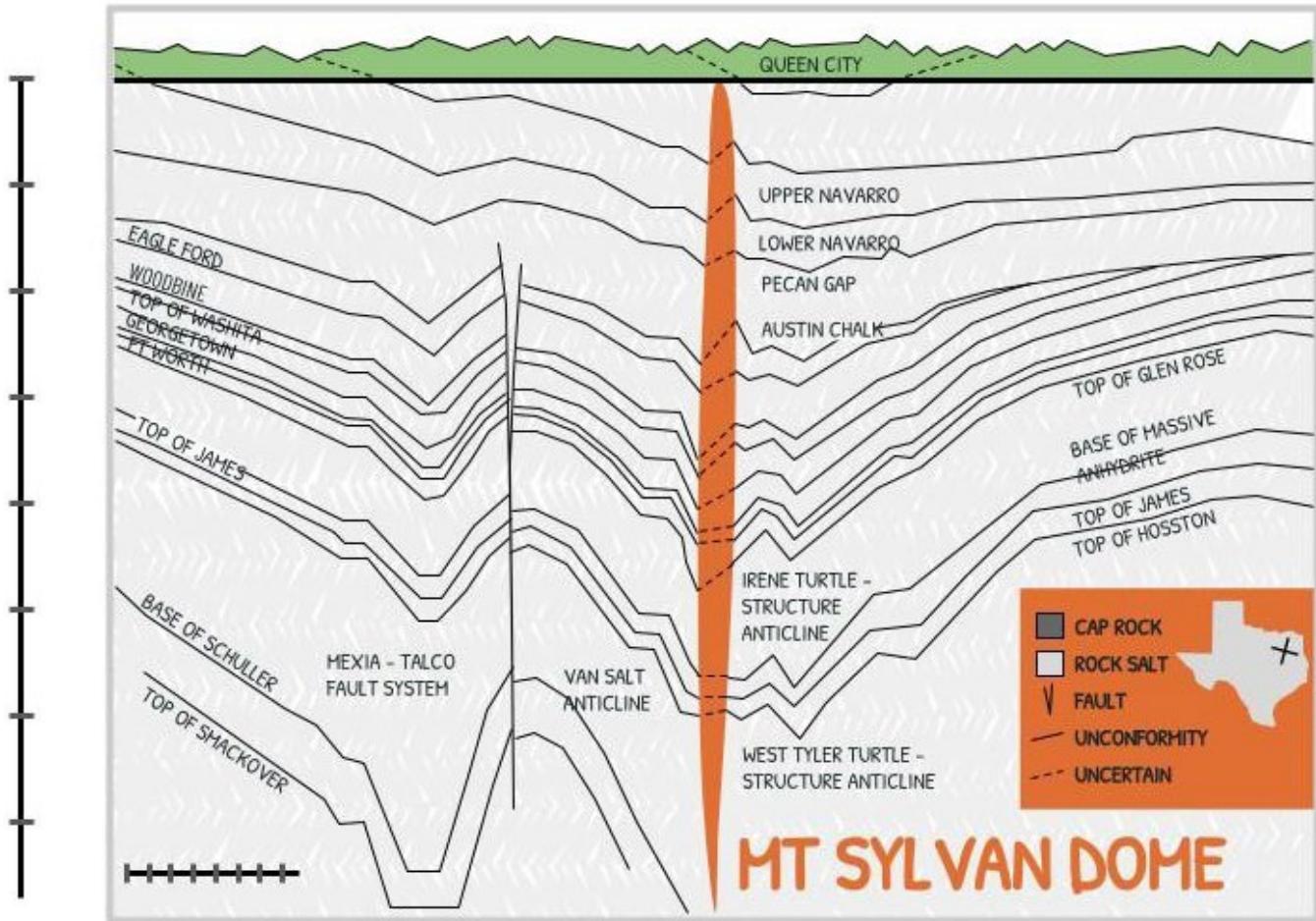


Figure 4.25. Structural cross-section across the East Texas Basin. Source: Adapted from Wood and Guevara, 1981.



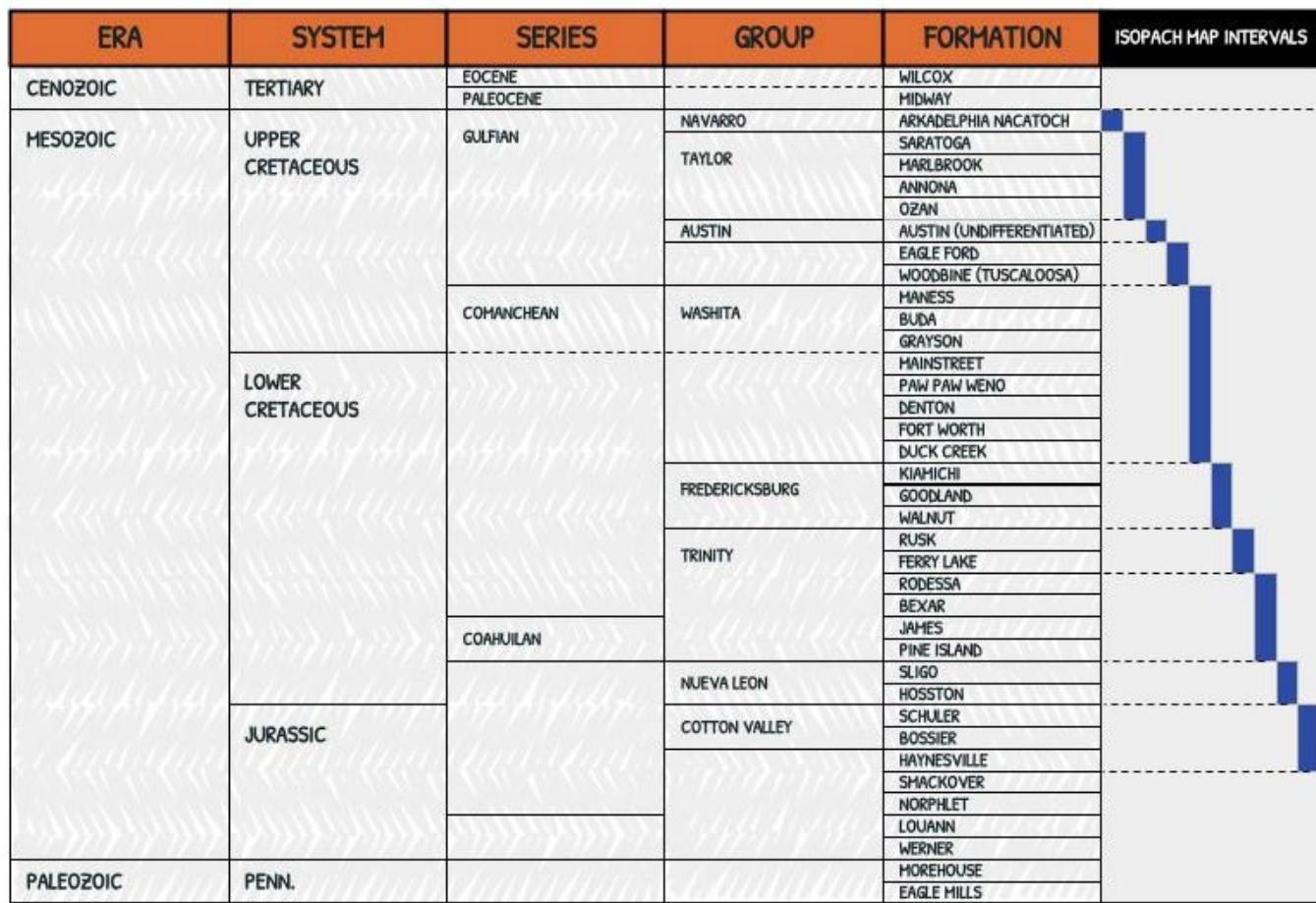


Figure 4.26. Stratigraphic column of the East Texas Basin. Source: Adapted from Granata, 1960.

### A. East Texas Geothermal Resources

The geothermal resources within East Texas were discussed as part of the Gulf Coast Geothermal-Geopressure studies (John, et al., 1988). The area's first regional heat flow mapping was part of the 1992 Geothermal Map of North America (Blackwell, et al., 1990). The heat flow was calculated to be between 50 to 60 milliwatts per square meter, considered similar to the central United States heat flow. The 2004 Geothermal Map of North America (Blackwell & Richards, 2004) shows this region, highlighting the use of oil and gas well BHT data with a thermal conductivity model based on sediment thickness and age, such that the thick young sediments were assigned a low thermal conductivity (about 1.4 watts per meter-Kelvin). More recently, with the addition of oil and gas BHT data, the heat flow in the area was re-evaluated at 60 to 80 milliwatts per square

meter and displayed a variability not previously realized. This new outcome highlights the value of updating assessments based on new data availability. Generally, specific research studies in East Texas show a trend of decreasing heat flow the further the resource is from the Sabine Uplift.

Differences in the predictions of heat flow between the original assessments and modern assessments highlight the importance of thermal conductivity measurements. The one set of k measurements for East Texas are from Fairway Field and discussed below. The regional gradient map (Figure. 4.27) shows the current BHT locations within the NGDS are the area's primary source of saved BHT data. Counties with additional BHT locations since the Blackwell, et al. (2011a) and the Richards and Blackwell (2012) maps are emphasized by their thicker borders and discussed in the next Section.



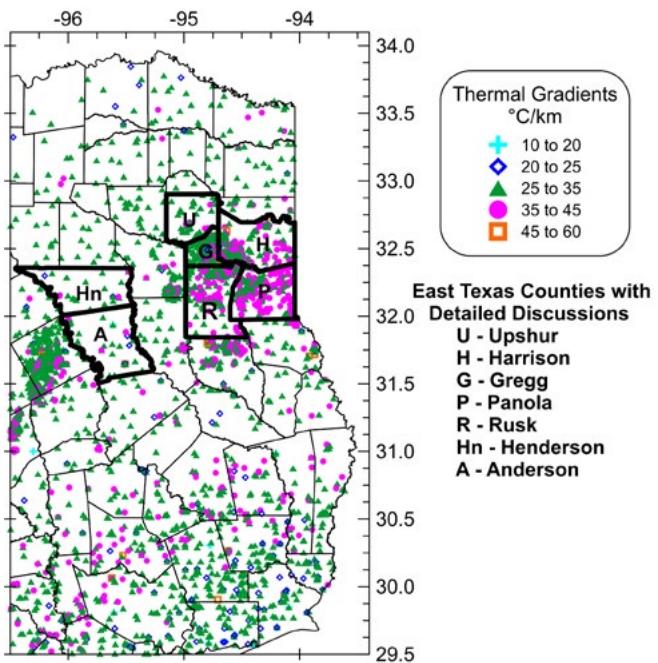


Figure 4.27. East Texas Bottom-hole Temperature Well Sites in the National Geothermal Data System.

The thermal gradients are one component of the heat flow calculation. Thickly bordered counties are discussed in this section. Pink circles and orange squares are sites with higher than the regional gradients. The deepest BHT data are plotted on top if more than one for the same site or close to each other. Source: Future of Geothermal Energy in Texas, 2023.

East Texas is a large and somewhat heterogeneous region, so we will examine some representative areas in greater detail. Studies to be discussed in this Section include the Richards and Blackwell (2012) I-35 corridor study of the entire eastern Texas region, as well as Kweik, et al. (2014) and Kweik (2014), which focused on the oil and gas Fairway Field in Henderson and Anderson Counties. The Batir, et al. (2018) study of the Longview area included Gregg, Rusk, Panola, and Harrison Counties. Lastly, the most recent review of Upshur County geothermal resources was completed for a private company by Batir and Richards (2020, unpublished report).

### **1. Detailed Review of Fairway Field: Henderson and Anderson Counties**

The Fairway oil field is located in East Texas near the town of Poynter, bordering Henderson and Anderson Counties. The field produced oil continuously for over 60 years (Webster, et al., 2018) (Figure 4.27). Hunt Oil Company

granted access to the SMU Geothermal Laboratory for Kweik to review the field, which has over 2,900 open-hole well logs and pressure surveys, for his Master's research project (Kweik, et al., 2014; Kweik, 2014). These data comprise open-hole (BHT and closed (shut-in) temperature logs, pressure logs, fluid production, and injection data. Taken together, these data provide an opportunity to analyze temperature variations associated with fluid migration and field development over time.

The density of data within the field allowed for a review of time sequence trends and the ability to determine a weighted average for parameters based on hundreds of wells. The field averaged temperature gradient of 35°C per kilometer (1.92°F per feet), the field average thermal conductivity of 1.98 watts per meter-Kelvin, and the conductive heat flow value is  $69 \pm 6$  milliwatts per square meter. The porosity ranges from 7.2 percent to 10.8 percent. The permeability varies between formations and across the field from eight millidarcy to 43.7 millidarcy.

An unexpected result in this field was the increase in reservoir temperatures of more than 10°C (20°F) over more than 50 years. The structure of Fairway Field is of a dome (turtle structure), allowing for the higher temperatures deeper to flow up as fluids are extracted, and pressures changed over the 50 years of production. This pattern represents an influx of heat over this time rather than a decrease, highlighting the ability to bring warmer temperatures into production over the life of a field. The availability of pressure-survey temperature data and fluid data provides a unique understanding of such dynamic geothermal resources (Kweik, et al., 2014; Kweik, 2014).

Fairway Field illustrates how sedimentary basins have considerable potential for geothermal development. In this field, the James Limestone formation is the primary source for fluid production from 1960 to 2012. As mentioned above, the temperatures increased in this field over the 50 years of operation. The increase in temperature caused the "heat loss" to become a negative number. A "heat loss" of  $-1.7 \times 10^{17}$  joules was calculated (Kweik, et al., 2014).

As part of this project, core samples of the James Limestone were analyzed for thermal conductivity, resulting in an averaged value of 2.60 watts per meter-Kelvin for this formation (Table 4.2). The detailed core



Table 4.2. Thermal conductivity and porosity values for James Limestone cores from seven wells across the field at various depths; Source: Adapted after Kweik, et al., 2014; Kweik, 2014.

Well #	Depth, m (feet)	Porosity %	Sample Plug Orientation To Lamination	Divided Bar Thermal Conductivity (Wm <sup>-1</sup> K <sup>-1</sup> )
647-3	3000 (9,842)	9.11	Parallel	2.42
649-3	3008 (9,868)	6.67	Parallel	2.95
746-3	3012 (9,880)	0.54	Perpendicular	2.45
452-2	3027 (9,930)	0.00	Parallel	2.50
747-2	3042 (9,978)	4.55	Perpendicular	2.78
548-3	3052 (10,009)	16.56	Parallel	2.20
149-2	3055 (10,021)	7.11	Parallel	2.83
Average Thermal Conductivity for James Limestone				2.6 ± 0.4

analysis across the 45 square miles(115 square kilometers) highlights the amount of variation in thermal conductivity and porosity that can occur even within one field (Kweik, 2014). For some rock types, the thermal conductivity changes with the direction of the bedding being analyzed. This difference is referred to as anisotropy. From the results of the James Limestone, thermal conductivity varies inconsistently with the change in bedding direction.

## 2. Detailed Review of Sabine Uplift: Rusk, Gregg, Harrison, and Upshur Counties

The Eastman Chemical plant, southeast of Longview, Texas, was the central point for a study to evaluate a Deep Direct Use ("DDU") application of geothermal energy to improve the efficiency of a gas power plant (Turchi, et al., 2020). The warm geothermal resource was modeled for its ability to produce supercooled fluids for turbine inlet cooling. Normally geothermal fluids are used to generate electricity from the extracted heat. For the Eastman Chemical plant projects, the geothermal heat energy was used to drive a chiller process that instead made supercooled fluids (4°C or 39°F) to be stored in an on-site tank. These fluids were for inlet cooling of the gas plant, when the outside air temperature was at least 16°C

(60°F) or hotter, to increase the efficiency of the plant. The Eastman Chemical company provided their time and data for this DOE Geothermal Technologies Office study conducted by the National Renewable Energy Laboratory, SMU Geothermal Laboratory, and TAS Energy (Batir, et al., 2018; Turchi, et al., 2020).

Examination of the geothermal resources focused on depths of the Lower Cretaceous Trinity Group (Travis Peak / Hosston, James, Pettet / Sligo) between approximately 5,576 to 8,856 feet (1,700 to 2,700 meters) and the Upper Jurassic Cotton Valley Group (Schuler and Bossier), approximately 8,200 to 10,988 feet (2,500 to 3,350 meters) for the application. Below the Cotton Valley Group are the Haynesville and/or Smackover Formations, which are expected to be above 150°C (300°F) below depths of 11,480 feet (3.5 kilometers) in Rusk, Harrison, and Gregg Counties, and less than 150°C in Upshur County (Figures 4.26 and 4.28).

The recent geothermal resource mapping differs from previous research in the area by the SMU Geothermal Laboratory as part of the Geothermal Map of North America (Blackwell & Richards, 2004) and the Geothermal Map of the United States (Blackwell, et al., 1990). The past two projects used a model for thermal conductivity



values based primarily on the age and thickness of the sedimentary basin. This model meant increased thermal conductivities moving from south to north across the Gulf Coastal Plain and East Texas.

The DDU study provided the ability to review the local detailed stratigraphic column and assign thermal conductivity values based on well location, formation thickness, and on mineralogy related to those in Louisiana (Pitman & Rowan, 2012). The Pitman and Rowan (2012) report determined thermal conductivities based on rock mineralogy for each formation, instead of from core samples on a divided bar. The minerals within the formations are similar, yet as discussed above in Fairway Field, it is expected that there are formation changes both laterally and vertically over a region that are not possible to take into consideration without more thermal conductivity sample analyses.

As site heat flow values are based on thermal conductivity and local temperature gradient, the variation in BHT data is a significant component in the heat flow value. Therefore, large error bars ( $\pm 25^{\circ}\text{C}$  or  $\pm 77^{\circ}\text{F}$ ) become the most significant error component in all future calculations. To account for the potential for BHT error, data are examined initially both as raw data for outliers and then mapped. The mapping process uses a gridding method capable of removing data that are more than two standard deviations from the surrounding values. As the amount of data points increases, more points can be averaged as a smoothing method to arrive at an improved value.

By incorporating the Pittman and Rowan (2012) thermal conductivity values for each formation, the overall heat flow values increased by approximately 5 to 10 milliwatts per meter squared over the previously calculated heat flow values in the Blackwell and Richards (2004) and Blackwell, et al. (2011) maps. Within the 12.4 mile (20 kilometer) radius near the city of Longview, heat flow varies from 65 to 95 milliwatts per meter squared (Figure 4.29), which is a higher typical variability than in regional mapping where the data are smoothed. Usual differences are approximately 10 to 20 milliwatts per meter squared. In Figure 4.29, the heat flow values show the general trend of hotter resources to the southeast in Rusk, Gregg, and Harrison counties.

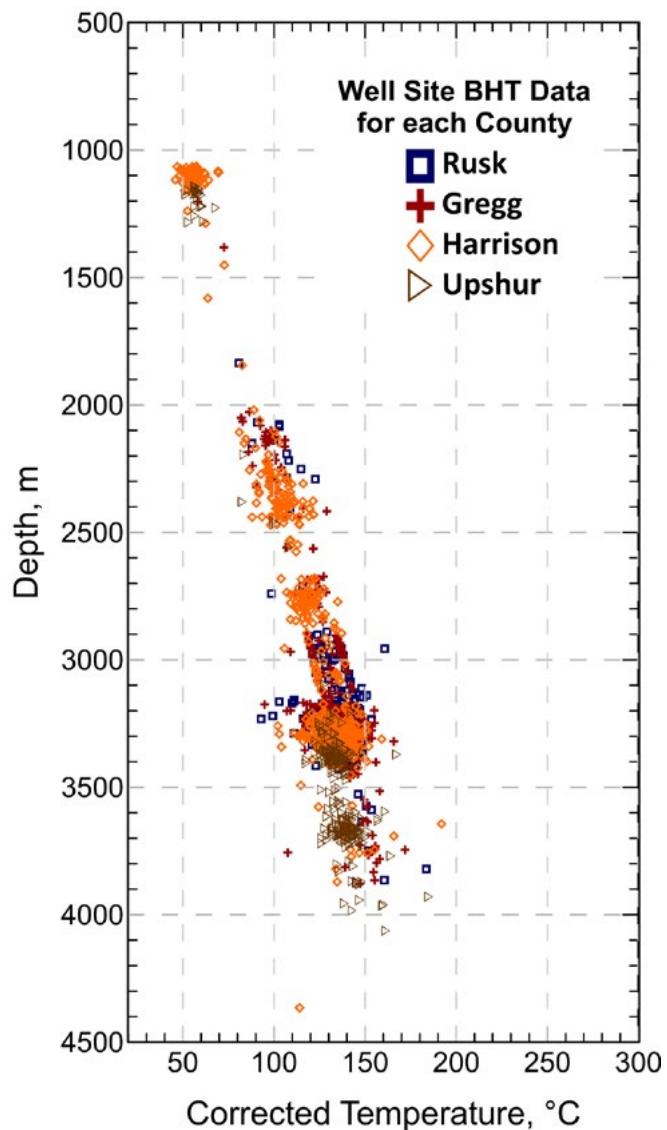


Figure 4.28. East Texas Corrected Temperatures for Upshur, Gregg, Rusk, and Harrison Counties.

The well temperatures in Upshur County are primarily the deepest, yet approximately the same temperatures as the wells 500 to 1000 meters shallower in the other counties to the southeast and closer to the Sabine Uplift. Source: Future of Geothermal Energy in Texas, 2023.

A heat flow of 55 to 65 milliwatts per meter squared is considered normal for the Central United States, therefore, there is more stored thermal energy in the East Texas basins than in many portions of the Central United States. This increase in heat is related to the sediments acting like a protective layer or a thermal blanket above the more radiogenically active basement rock of the Sabine Uplift.



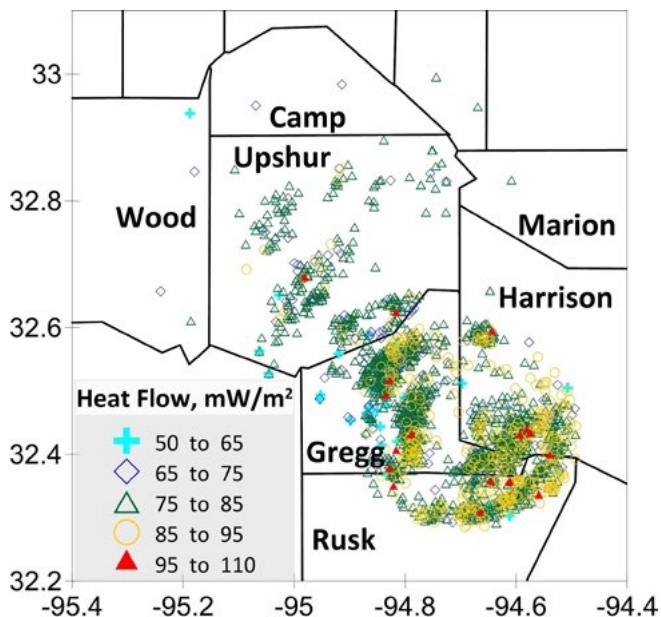


Figure 4.29. East Texas Updated Heat Flow. The heat flow trends warmer to the southeast towards the Sabine Uplift, which is located along the border of Texas and Louisiana. Sources: Batir and Richards, 2018 and Batir and Richards, unpublished 2020.

Another way to look at the available geothermal resources is using the Heat-in-Place or heat density calculations to provide the total thermal energy stored within a defined 3D volume. The denser the heat, the hotter it is within that area of rock. The DDU study (Batir, et al. 2018; Turchi, et al., 2020) follows the methodology of Zafar and Cutright (2014), who used the 3-D model to calculate the amount of heat being stored. For this study, the Travis Peak Formation was chosen because of the direct-use project constraints for production from wells. The Travis Peak thickness component and the temperatures through the formation are shown as the heat indicator (Figure 4.30). The top of the Travis Peak Formation lies between 6,560 to 7,872 feet (2,000 to 2,700 meters) below sea level, trending locally deeper to the northeast. On average, the Travis Peak is 1,804 feet (550 meters) thick, yet can vary from 984 to over 1,968 feet (300 to over 600 meters) in thickness. The calculated amount of heat stored ranges from 150 to over 275 megajoules per meter cubed as the thermal gradient and thickness of formation change, thus creating variations in the mapped heat density. There are no major faults mapped within the 12.4 miles (20 kilometers) area of this study, so the possibility of fault-driven fluids is unlikely.

The heat density map for the Travis Peak formation highlights the potential for geothermal resources to be variable within sedimentary formations. For the geothermal industry, this variability within sedimentary geothermal resources could be identified in a similar manner to the historic hydrothermal systems of the western United States. Although oil and gas fields are large geographic areas, there is usually an ideal location for drilling that can be identified to maximize production and profit.

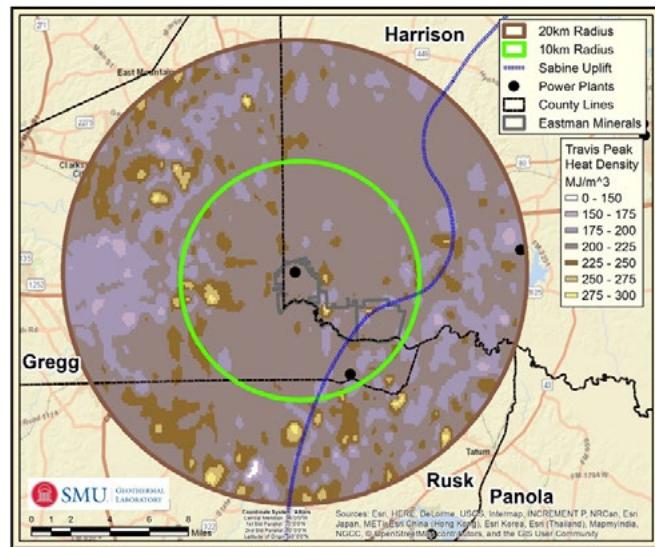


Figure 4.30. The Heat Density or Heat-in-Place Map of the Travis Peak Formation. This map represents the stored thermal resource and shows the local variations using the most advanced methods for calculation. The western edge of the Sabine Uplift is shown as a blue line on the eastern side of the map. Source: Adapted after Batir, et al. 2018 and Turchi, et al., 2020.

To better understand how much energy is stored within the Travis Peak formation, illustrated in this 6.2 mile (20 kilometer) circle in Figure 4.30, one megajoule is equal to the energy consumed in 0.278 kilowatt hour. Figure 4.30 uses megajoules per meter cubed units. Based on the volume of a cylinder,  $3.1416 \times 10 \text{ square kilometers} \times 0.550 \text{ kilometer}$  (the average thickness) =  $172.8 \text{ cubed kilometers}$  or  $172.8 \times 10^9 \text{ cubed meters}$ . Using an average heat density for Travis Peak of 200 megajoules per meter cubed, there are  $345.6 \times 10^{11} \text{ megajoules per meter cubed}$  within the 6.2 miles (20 kilometer) cylinder of Travis Peak rocks and fluids. Not all of the heat will be extractable; usually about 1 to 10 percent of the resource. If 1 percent is used, then  $345.6 \times 10^9 \text{ megajoules per meter cubed}$



cubed of energy is available. The equivalent of  $345.6 \times 10^9$  megajoules per meter cubed times 0.278 kilowatt-hour =  $96 \times 10^9$  kilowatt-hours. If the average home uses 10,632 kilowatt-hours per year (EIA, 2022), approximately 500,000 homes could be powered for over 18 years based on this stored heat. Thus, more than enough energy is stored within this formation to meet the residential power demand within this 6.2 mile (20 kilometer) circle.

Upshur County has three northeast to southwest oil and gas trends providing well data for initial geothermal resource analysis. As with most of Texas, the number of existing drilled wells is 4,193 in Upshur County (Batir & Richards, 2020), far greater than the current 313 BHT extracted from well log headers in the dataset (Figures 4.28 and 4.31). The available well data follow the three drilling trends. The grid size for the Upshur project maps is set to  $0.05^\circ$  latitude/longitude to include at least one data point within each grid cell and smooth the gradients. This grid size is similar to the size used in the Geothermal

Map of North America (Blackwell & Richards, 2004a,b) and the Geothermal Map of the United States (Blackwell, et al, 2011a).

In general, as shown by the 11,480 feet (3.5 kilometers) temperature gradients (Figure 4.31), Upshur County is consistent in thermal gradient with a small heat flux of about  $1.76$  to  $1.82^\circ\text{F}$  per 100 feet ( $32$  to  $33^\circ\text{C}$  per kilometer). Of interest in this figure are the deep salt intrusions having little to no direct impact on the thermal picture at the 11,480 feet (3.5 kilometers) or even deeper at 18,040 feet (5.5 kilometers) (Batir & Richards, 2020 unpublished report). The average temperature at 14,760 feet (4.5 kilometers) is  $160^\circ\text{C}$  ( $320^\circ\text{F}$ ), although the deepest BHT measurement is 4.1 kilometer. Upshur County is an example of a county with lower heat flow, yet temperatures are able to sustain geothermal development, especially with the ability to mix geothermal resources with other renewable energy sources, such as solar and biomass.

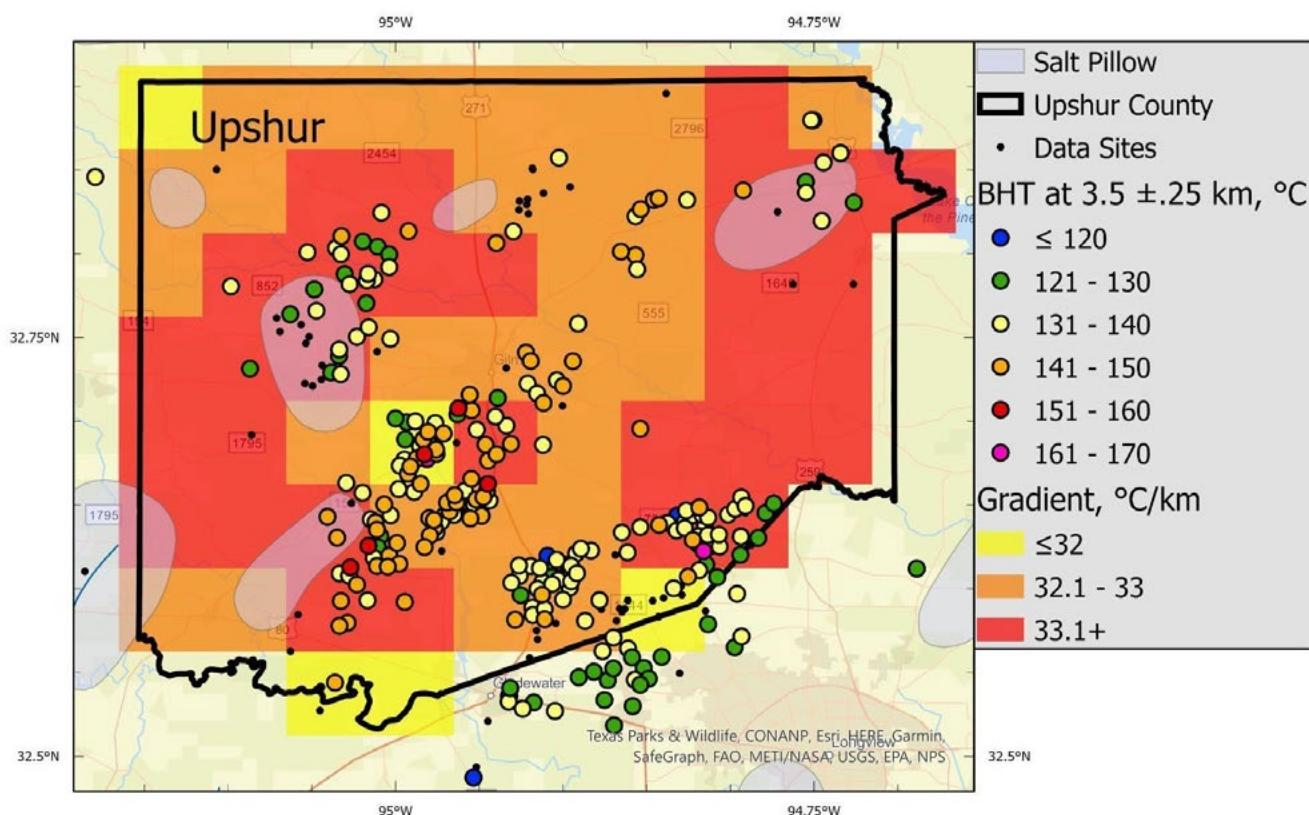


Figure 4.31. Map of 3.5 kilometers Corrected Well Temperatures and Gradients for Upshur County. The average temperature at this depth is  $136 \pm 7^\circ\text{C}$ . BHT measurements in this depth are between  $115^\circ\text{C}$  to  $170^\circ\text{C}$ , although the highest grid value is  $144^\circ\text{C}$  because of averaging within the cell. 274 wells penetrate the 3.25 to 3.75 kilometer depth range. Source: Adapted after Batir and Richards (2020).



## X. Permian Basin (West Texas):

The stratigraphic column of Upshur County follows the same general formations shown in Figure 4.26. Using the correlation between the Pittman and Rowan (2012) mineralogy for these formations, the well averaged thermal conductivity varies between 2.38 and 2.42 watts per meter Kelvin. The base of the sediment thickness is determined to be between 13,740 to 13,900 feet (4.19 to 4.24 kilometers).

The northern counties of East Texas are currently mapped similarly to Upshur County resources and not expected to change compared to the temperature-at-depth maps from 2011 (Blackwell, et al., 2011b) (Figures 4.5 through 4.7).

The Permian Basin of West Texas and south to east New Mexico (Figure 4.32) is the most important onshore sedimentary basin in the United States in terms of energy resources production. The basin has been producing hydrocarbons from multiple formations for over a century, resulting in one of the most extensive datasets for subsurface characterization and energy exploration, including geothermal energy. With changes in the energy business trends over the years, the Permian Basin has always been a top choice of onshore operators for resource exploration and development due to discovery thinking, new technologies, and favorable rock properties in the subsurface. The thickness of the sedimentary strata in the basin is more than 26,000 feet (7,925 meters), containing multiple reservoirs of varying sizes for geothermal resource development.

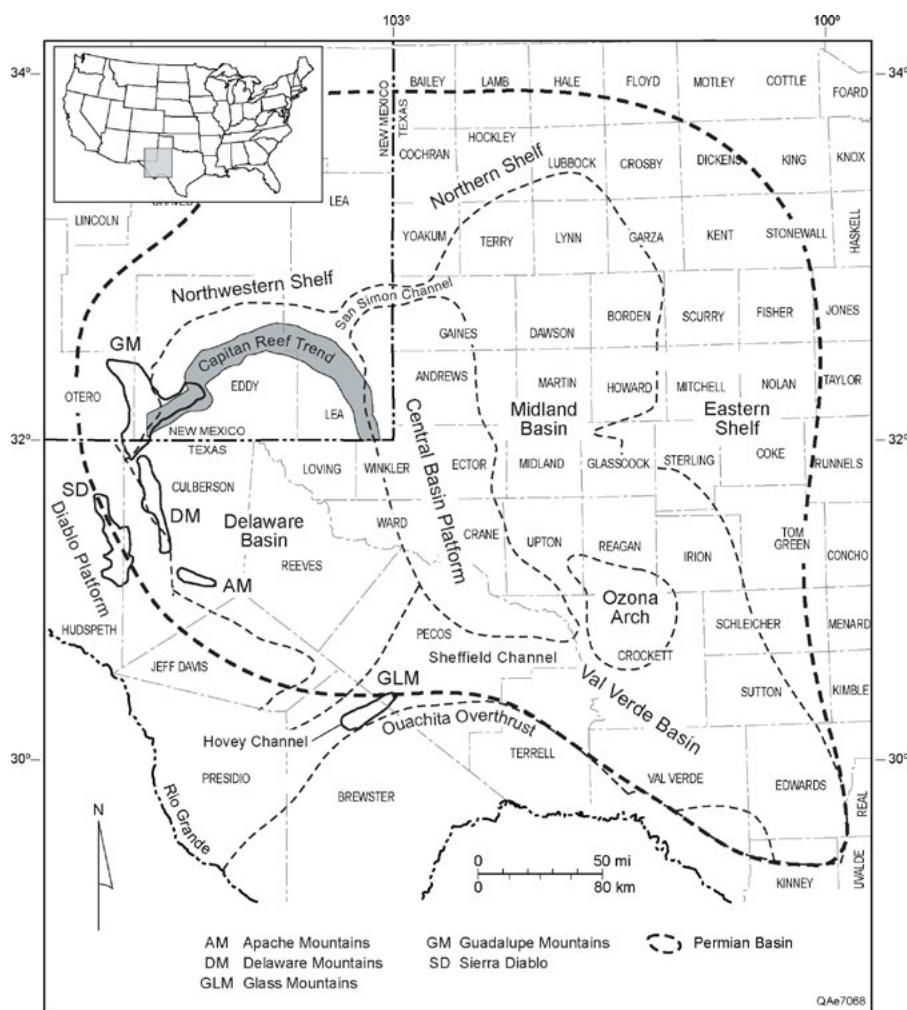
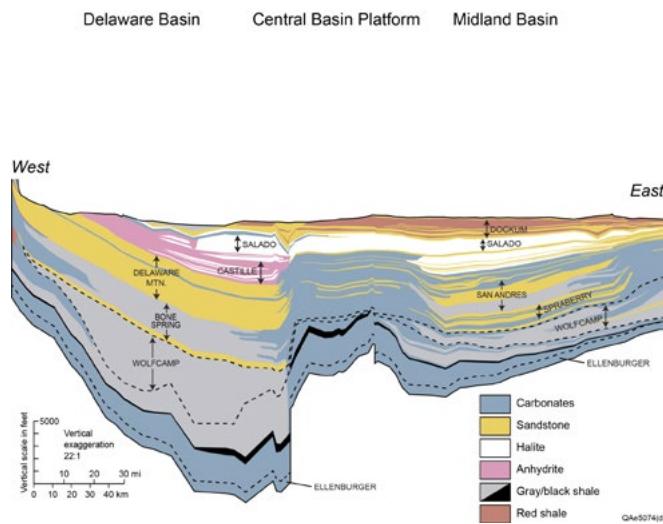


Figure 4.32. Location of the Permian Basin and sub-basins in west Texas and southeastern New Mexico, United States. Source: Dutton, et al., 2004.



The Permian Basin started from an ancient broad, shallow, gently dipping depression known as the Tobosa Basin. The Tobosa Basin records clastic and carbonate sediments from the Cambrian through Mississippian. The Tobosa Basin went through tectonic evolution due to the collision of the North American Craton with South America from Early Pennsylvanian through Early Permian, which resulted in the development of the deep Delaware Basin and Midland Basin, separated by the shallow Central Basin Platform (Figure 4.33). Vast deposits of clastics deposited in the deep basins and carbonates deposited on the shelves resulted in a mixed carbonate-siliciclastic pattern (Figure 4.33). Figure 4.34 shows the stratigraphy of the formations in the Permian Basin. Polyphase fault systems developed in the Permian Basin, which also involved reactivation of basement-rooted faults. Major faulting, folding, subsidence, tilting, and uplift of the basin reshaped the basin geometry and deposition of sediment.



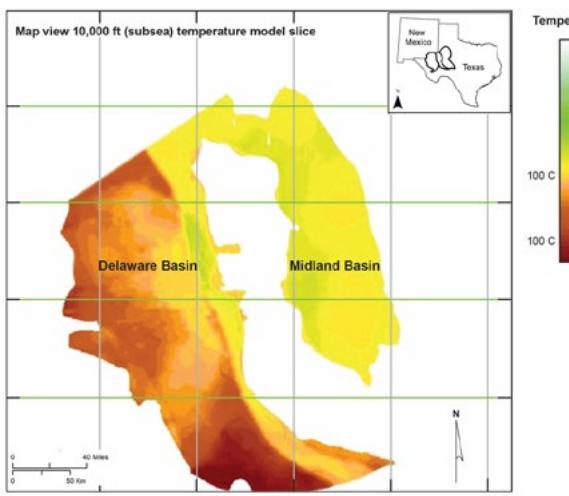
**Figure 4.33.** The east to west cross section of the Permian Basin and current trends of operation, including conventional, unconventional reservoirs, saltwater disposal, produced water, and enhanced oil recovery Source: Adapted after Scanlon, et al., 2017. Permission received from the American Chemical Society. Further permissions related to the material excerpted should be directed to the American Chemical Society.

The Greater Permian Basin's Delaware and Val Verde basins are deep and have a relatively high geothermal gradient. Keay, et al. (2021) generated a basin-wide temperature model and opined that depths deeper than 10,000 feet (3,048 meters) in both Delaware and Midland basins mostly correspond to temperatures over 100°C, which is suitable for low-enthalpy geothermal systems (Figure 4.35). Figure 4.36 shows a generalized geothermal gradient from a well across multiple formations in the Delaware Basin. Heat flow data in the Permian Basin are sparse. Blackwell, et al. (2011) reported average heat flow in Crockett County 57 milliwatts per meter squared with a standard deviation of  $\pm 13$  milliwatts per meter squared.

System	Epoch/Series/Stage	Age (Ma)	U.S. Epoch/Series/Stage	W-NW Shelf New Mexico	Delaware Basin	NW Shelf Texas	Central Basin Platform	Midland Basin
	Gzhelian	299	Virgilian	Cisco	Cisco	Cisco	Cisco/Cline	
	Kasimovian	303	Missourian	Canyon	Canyon	Canyon	Canyon	
	Moscovian	307	Desmoinesian	Strawn	Strawn	Strawn	Strawn	
	Bashkirian	315	Atokan	Atoka	Atoka	Atoka	Atoka	Atoka/Bend
			Morrowan	Morrow	Morrow			
CARBONIFEROUS	Serpukhovian	323	Chesterian	Barnett	Barnett	Barnett	Barnett	Barnett
	Visean	331	Meramecian					
	Tournaisian	347	Osagean	Mississippian Limestone				
	Kinderhookian	359	Famennian	Woodford	Woodford	Woodford	Woodford	Woodford
		372	Frasnian					
		382	Givetian					
DEVONIAN	Eifelian	388	Emrian					
	Pragian	393						
	Lochkovian	408						
	Pridoli	411						
	Ludlow	419						
	Wenlock	423						
SILURIAN	Llandovery	427	Western	Fasken	Wishen	Western	Western	Western
		433		Wink	Wink	Wink	Wink	Wink
		444						
		458		Fusselman	Fusselman	Fusselman	Fusselman	Fusselman
		470		Montoya	Montoya	Montoya	Montoya	Montoya
		485		Simpson Group				
ORDOVICIAN	Early							
	Middle							
	Late							
				Ellenburger	Ellenburger	Ellenburger	Ellenburger	Ellenburger
CAMBRIAN				Bliss	Bliss	Bliss	Bliss	Wilbems
								Moore Hollow
								Riley
					Nondeposition		Unnamed interval	

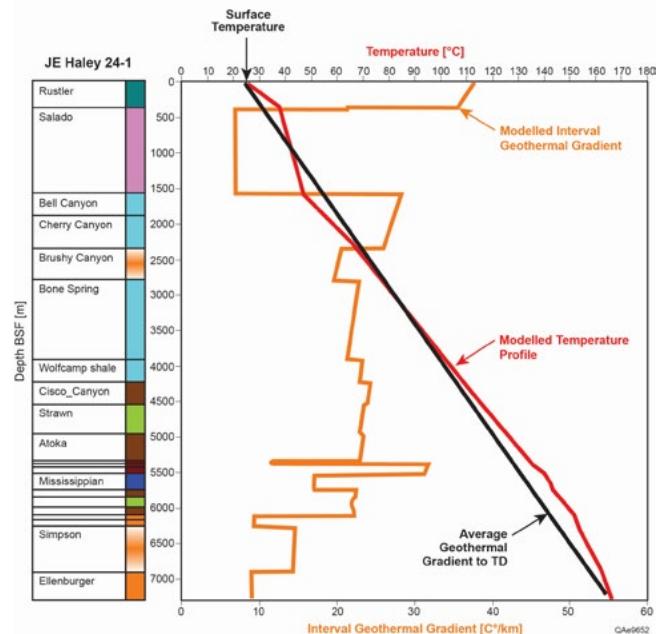
**Figure 4.34.** Cambrian-Carboniferous stratigraphy of the Permian Basin, deemed feasible for deep geothermal resources. Sources: Adapted after Ruppel, 2019; Ogg, et al., 2016; Kerans and Kempter, 2002; Kerans, et al., 2014; Hurd, et al., 2016; Nestell, et al., 2019.





**Figure 4.35.** Map view of the Permian Basin temperature model at a depth of 10,000 feet (3,048 meters) subsea. Warm colors indicate high temperatures. An approximate scale bar along with an inset map of the Permian Basin in West Texas and New Mexico is shown. Source: Adapted after Keay, et al., 2021

Deep formations in the Permian Basin are overpressured (Wallace, et al., 1978; Rittenhouse, et al., 2016; Lou, et al., 1994). Overpressure may be one of the critical success factors for producing hot brine from the subsurface for geothermal energy production. In the Delaware Basin, especially in the eastern margin of the basin, the third Bone Spring, Wolfcamp, Barnett, and Woodford shale formations are overpressured, with pore pressure often exceeding 0.7 pounds per square inch per feet, which is generally considered as the start of "hard overpressure." This overpressure might have been generated due to a combination of multiple factors in this basin, including disequilibrium compaction, clay diagenesis, hydrocarbon generation, and tectonism. The temperature gradient across the overpressure zone in the eastern Delaware Basin is  $25.1^{\circ}\text{C}$  per kilometer, compared to the basin's average geothermal gradient of  $21^{\circ}\text{C}$  per kilometer (Wallace, et al., 1978). Temperatures at the top and bottom of the overpressure system are about  $80^{\circ}\text{C}$  and  $115^{\circ}\text{C}$ , respectively (Figure 4.36). Below the Woodford, formations have mostly normal pore pressure gradients, however, local variations can exist. Wallace, et al. (1978) stated that the Permian, Mississippian, Devonian, and Ordovician sequences are overpressured in the Delaware Basin.



**Figure 4.36.** Geothermal gradient and temperature profile as a function of depth from a well covering the entire sedimentary strata in the Delaware Basin. Source: Adapted from Deighton, 2015.

#### A. Potential Geothermal Reservoirs and Reservoir Properties

Based on the available data, the Cambrian-Carboniferous strata in the Permian Basin is considered feasible for deep geothermal resource development. We remove the potential of tight mudrocks, such as Wolfcamp and Bone Spring, from current conventional geothermal consideration since they have very low porosity of about four to eight percent, ultra-low permeability, and other operational constraints, which will be discussed later. Nonetheless these might be attractive targets for Advanced Geothermal Systems, like Closed Loop Systems. The Wolfcamp Formation has high temperature as well as high overpressure in some places, which could be utilized for unconventional geothermal concepts like Engineered and Advanced Geothermal Systems. In addition, the Wolfcamp shale produces voluminous water. These waters could be injected into the deeper reservoirs with favorable reservoir quality, from which hot water could be flowed back to produce geothermal energy. This will be explored later in this Chapter.



## **1. Ellenburger**

The Ordovician-aged Ellenburger is the deepest and laterally most extensive carbonate formation with proven reservoir quality in the Permian Basin. The temperature in the Ellenburger can vary from 99 to 170°C (210 to 337°F) (Wallace, et al., 1978; Erdlac, 2006; Kosters, et al., 1990). A significant drop in sea level at the end of Ellenburger deposition resulted in subaerial exposure and widespread karstification and reservoir development (Kerans, 1990). The pore network of the Ellenburger is affected due to dolomitization, karsting, and tectonic fracturing. The upper and lower sections of the Ellenburger have high reservoir quality due to fracture density, breccia, and vugs, compared to the middle section, which is cemented (Sanchez, et al., 2019). In Ellenburger carbonates, matrix porosity is less than 5 percent, consisting of common matrix pore types such as interparticle, moldic, inter-crystalline, or micropores. In general, porosity in the Ellenburger ranges between 2 percent and 20 percent and permeability between 0.1 and 100 millidarcy (Loucks & Kerans, 2019). Although matrix porosity may be low, fractures increase permeability significantly, up to 2,250 millidarcy or more.

## **2. Simpson Group**

Overlying the Ellenburger, the Simpson Group clastic reservoirs are composed of highly mature quartz sandstones having primary interparticle porosity (Schutter, et al., 1992). The Simpson Group is thick in the Delaware Basin, and it is locally porous and permeable. The presence of carbonate cement is one of the factors occluding pores and reducing permeability. Average porosity in the Simpson Group varies from 7 percent to 16 percent in different fields (Tyler, 1991), and permeability ranges between 45 and 164 millidarcy (Galloway, et al., 1983; Wojcik, 1990).

## **3. Fusselman Formation**

The Ordovician-Silurian-aged Fusselman Formation consists of shallow water carbonate platform deposits. It has undergone a variable degree of diagenesis due to episodic sea-level fall. Karst features are also found in this formation. Some of the major Fusselman reservoirs are typically fault-bounded on the Central Basin Platform, and adjacent to part of the Midland Basin (Ruppel, 2019). In general, porosity in this formation varies from 3

percent to 12 percent, whereas permeability is generally between 0.001 and 10 millidarcy (Ruppel, et al., 2019; Kosters, et al., 1990). Apart from the karst, vugs, and fractures, permeability is very low in these reservoirs. The temperature across this formation is generally above 93°C (200°F) (Kosters, et al., 1990).

## **4. Thirtyone Formation**

The Devonian-aged Thirtyone Formation is another potential geothermal reservoir in the Permian Basin. These rocks include deepwater cherts, shallow water carbonates, and siliceous ramp limestones (Ruppel, et al., 2019). Each of these facies has significantly different reservoir characteristics that need to be considered while developing geothermal resources. Both carbonates and chert deposits of the Thirtyone Formation have undergone significant alteration since deposition. Chert facies have undergone both early and late episodes of diagenesis that have played important roles in reservoir development. Complete alteration to chert and quartz is likely to result in porosity loss, whereas slower rates favored retention of matrix microporosity. Carbonate dissolution is apparent near the top of the Thirtyone section and along major fault zones. Porosity in the Thirtyone Formation varies from less than 2 percent to 25 percent, with permeability ranging between 10 and 20 millidarcy (Ruppel, et al., 2019). It is highly heterogeneous due to a varying degree of diagenesis and fracturing. Several faults and fault splays intersect these reservoirs, some of which might also act as flow barriers.

Apart from the above deep formations, the Atoka, Strawn, and Cisco formations are potential geothermal targets. These formations are overpressured, especially in the eastern portion of the Delaware Basin. Similar to other carbonate formations, these rocks have undergone diagenesis, which has enhanced their reservoir quality in places.

A recent high level well screening by TGS, a global geophysical services company, showed that there are a few 100 wells and nearby areas that are ripe for repurposing for geothermal development in the Permian Basin (Keay, et al., 2021). They mainly used two criteria for screening: depth about 10,000 feet subsea (about 3,048 meters), implying higher temperature and flow rate (greater than 2,000 barrels per day). These wells contain injectors, shut-ins, and wells near the end of hydrocarbon



production life (based on decline curve analysis). Many of these wells are towards the eastern margin of the Delaware Basin and western margin of the Midland Basin. However, further analysis is needed, as some of the stratigraphic horizons, for example, the Wolfcamp, analyzed by Keay, et al. (2021), are not suitable for conventional geothermal development due to its ultra-low permeability.

The potential for induced seismicity is another major factor, especially in the southwest of the Delaware Basin and towards the western margin of the Midland Basin, for example, Martin County. This area has experienced several instances of elevated seismicity. The injection of voluminous amounts of water for geothermal development can increase the pore pressure and reduce effective stress, and thereby cause existing critically stressed faults to slip.

Formation water salinity is another uncertainty in these tight formations. Formation water salinity varies significantly in many deep formations in the Permian Basin, including Bone Spring and Wolfcamp formations. Their salinity varies from about 15,000 to 175,000 parts per million due to water mixing from different sources, including connate water, smectite-to-illite transition, and fluid migration from evaporitic sequences along faults and fractures (Nicot, et al., 2020). Salinity close to 15,000 parts per million is an indication of brackish water. This salinity may become an environmental concern, but is also a chemical engineering factor in developing a geothermal plant. Another potential issue in developing geothermal in the shale formations may be the lack of interest among operators to change focus and convert some of their main revenue producing reservoirs and wells to geothermal. Most of the revenue for shale operators in the Permian Basin comes from the Bone Spring, Wolfcamp, and Spraberry plays.

Many recent wells in the Permian Basin target tight formations, including Spraberry, Bone Spring, and Wolfcamp, and some shallower formations, with minimal targeting of deep formations. However, existing deep wells that are either shut-in or near the end of hydrocarbon production life can be converted to geothermal energy production. Water produced from the hydrocarbon producing Bone Spring, Spraberry, and Wolfcamp can be injected back into the deep reservoir for heat production. This reuse would increase the asset life and provide a transparent and predictable

path to the energy transition. However, a thorough analysis is needed to determine whether this is possible economically and at scale, and what other resources can be combined for geothermal resources in the oilfield to work economically. A few oil and gas wells here and there in the basin converted to low temperature geothermal wells will neither help reduce carbon emissions, nor provide required electricity to the power grid cheaply. Co-production options (discussed elsewhere in this Report) might provide a multi-revenue stream option that is more economically viable and scalable.

## B. Stress Direction and Seismicity in the Permian Basin

Several recent studies have found a strong correlation between saltwater disposal, hydraulic fracturing, and increased seismicity in the Permian Basin (Frohlich, 2012; Lomax & Savvaidis, 2019; Skoumal & Trugman, 2021; Savvaidis, et al., 2019). Some of these earthquakes have a magnitude over 3.0 (Figure 4.37). Due to decades of fluid injection and withdrawal, the state of stress in the basin has evolved. Snee and Zoback (2018) studied the state of stress in the Permian Basin. In the Midland Basin and Central Basin Platform, the direction of the SHmax is approximately east to west, whereas, in the Delaware Basin, SHmax orientation changes progressively from being nearly north to south in the north, to east southeast to west northwest in the south, including the western Val Verde Basin (Snee & Zoback, 2018). Critically stressed faults that are parallel to the SHmax may be prone to slip due to fluid injection.

The current faulting regime in the Midland Basin varies from normal to strike-slip, whereas in the Delaware Basin, it is primarily normal faults. This trend has implications on potential geothermal resource development strategies in the basin depending on the engineering approach. Because water injection will increase the vertical stress in this area, which is already in the normal fault regime, the concern is that the injection may enhance the chance of fault slip. Based on recent studies, some earthquakes in the Permian Basin occur at a greater depth close to the Ellenburger, rather than the shallow Delaware Mountain Group, which is the primary salt water injection zone. Water injection into deep reservoirs such as Ellenburger, which contains high fracture density and vugs, may transmit fluid down to the basement and facilitate pressure build up and fault slip, resulting in induced seismicity.



Therefore, future geothermal sites in the Permian Basin will need to be appropriately planned, instrumented and

monitored, and Next Generation concepts like Closed Loop Systems should be considered.

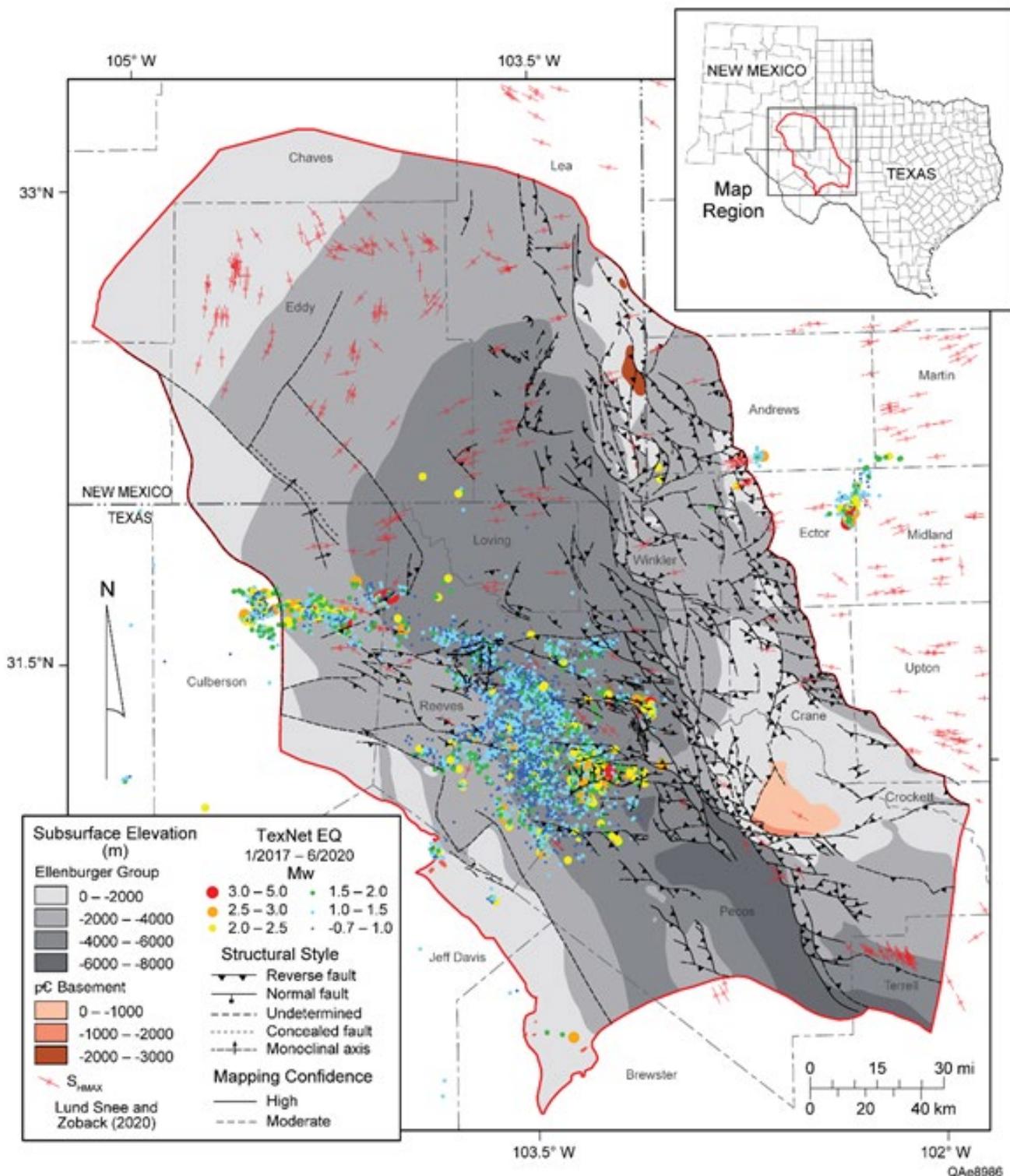


Figure 4.37. The location of interpreted faults and earthquake locations and magnitude in the Permian Basin, focusing on the Delaware Basin. The earthquake locations are analyzed by TexNet, UT Austin.

Sources: Adapted after Horne, et al., 2021.



## **1. Detailed Review of Crockett County**

Crockett County has many oil and gas wells, with the county's southern portion containing more well sites with temperature data available within the NGDS than in the north. It was studied in 2020 as part of the Texas Geothermal Entrepreneurship Organization Project to review a county that included the University of Texas Lands property as a prospect for geothermal development. Crockett County also was chosen for a detailed review because of its location within the Permian Basin, providing a large number of new well BHT data in the last 20 years (Batir & Richards, 2020; 2021).

The updates for Crockett County from the 2011 maps (Blackwell, et al., 2011b) to the 2020 maps (Batir & Richards, 2020; 2021) included an increase of locations from 65 in 2011 to 3,487 sites in 2020. As some of the well sites included more than one temperature-at-depth, there were a total of 3,503 temperatures used (Batir & Richards, 2020; 2021). Most of the new data are from the BEG-NGDS Borehole Observation file. The rest of the data are from the 2014 SMU BHT Heat Flow data file (Figure 4.38). The wells are drilled primarily between 6,560 feet and 9,840 feet (two and three kilometers), yet the deepest wells are at approximately 15,740 feet (4.8 kilometers), and they approximately average 170°C (338°F).

Within the BEG Borehole Observation file is a category of SMU Regional Heat Flow data. The data are not included in the SMU 2014 NGDS dataset, and Bureau does not have records as to their origination. One possible source is the work of Erdlac (2006) on the Permian Basin, since this dataset is primarily from wells in the early 2000s, and his report shows plots with large numbers of wells for Crockett County. There is a trend of high gradients with temperatures at 1.9 miles (3 kilometers) greater than 284°F (140°C), that were reviewed through the Texas Railroad Commission online data portal. Not all sites included a well log. Those that did were the same or very similar to the dataset temperature at depth. Only a few were not accurate. The increase in BHT values for the newest well logs brings up the potential that those wells drilled most recently are drilled more quickly and, therefore, will have different drilling impacts on the recorded temperature than those from the last century. For this work, a consistent SMU-Harrison Correction (Blackwell, et al., 1990; Richards & Blackwell, 2021) was applied to all well sites, but further research on drilling

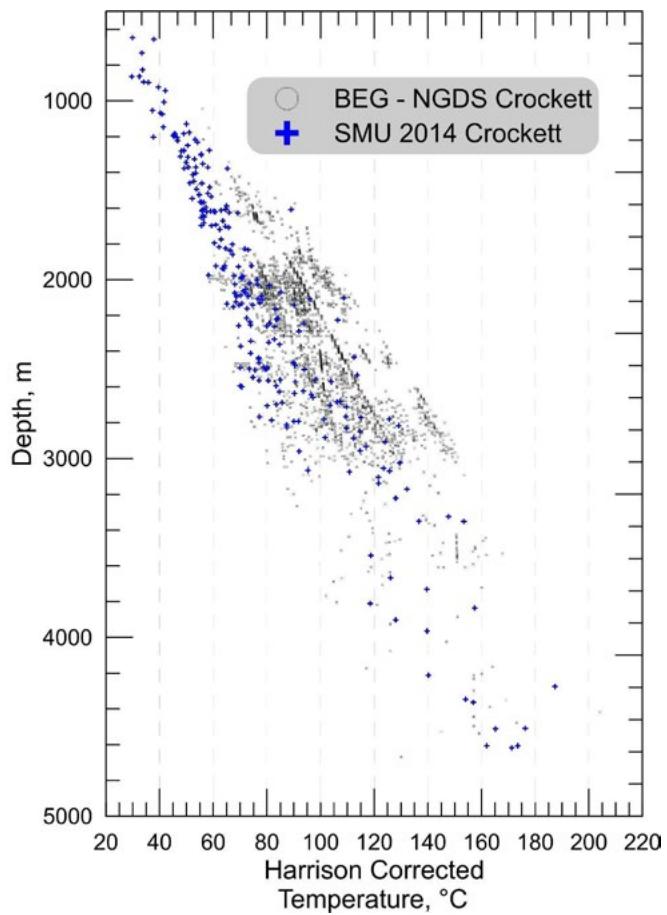


Figure 4.38. Temperature-depth data for Crockett County highlights the immense amount of new data in the NGDS uploaded from the Bureau. The Bureau data (gray circle) also trend warmer than the older SMU BHT data (blue plus). Source: Future of Geothermal Energy in Texas, 2023.

impacts of modern wellbores and surrounding formations will most likely change how raw BHT values are corrected for an in-situ setting.

Using the Crockett County BHT data, thermal conductivity values related to those used in the 2011 Blackwell, et al. maps, and two new detailed stratigraphic columns completed as part of the 2020 Batir and Richards study (Batir & Richards, 2020; 2021), an updated heat flow map was produced (Figure 4.39). Comparing the 2020 Batir and Richards map with the 2011 Blackwell, et al. map shows the increased detail possible with additional data. As mentioned above, there is a group of data that are higher gradients than previously known. These data result in the mapped heat flow increasing from a high of 65 to 70 milliwatts per meter squared in 2011 to 80 to 90 milliwatts per meter squared in 2020. The location of University Lands, which are State lands that generate



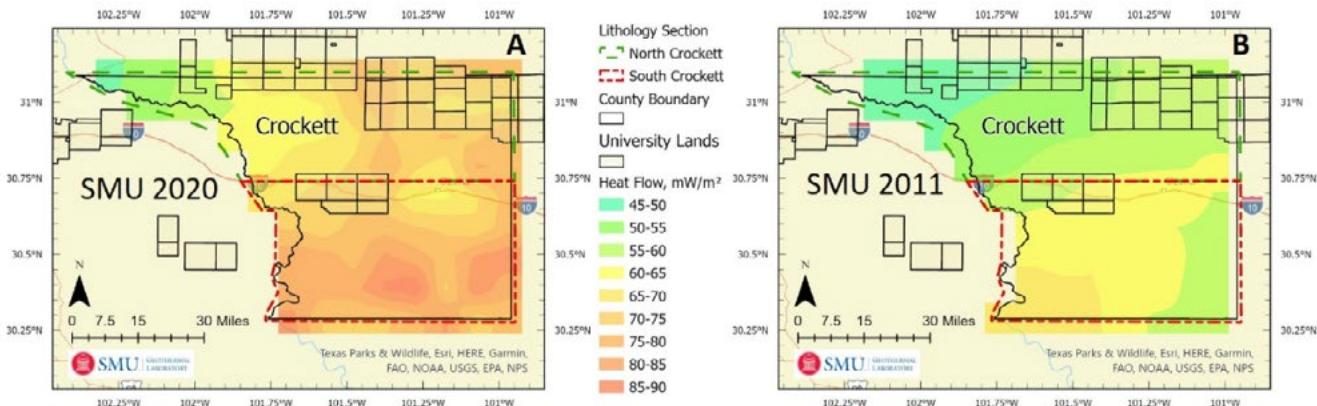


Figure 4.39. The comparison of SMU heat flow maps for Crockett County. (A) the results of detailed geology mapping using 3487 sites by Batir and Richards (2020), and (B) the SMU 2011 subset of U.S. heat flow map by Blackwell, et al. (2011a) with only 65 sites. Sources: Batir and Richards, 2020 and Blackwell, et al., 2011a.

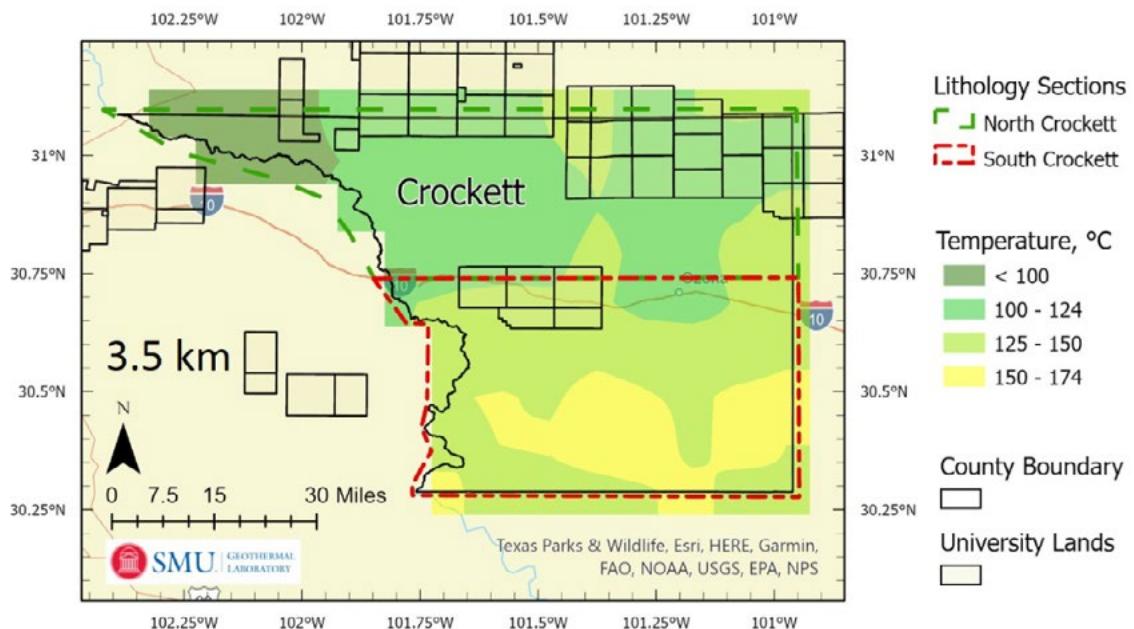


Figure 4.40. The SMU 2020 Crockett County Temperatures-at-Depth Map for 3.5 kilometers. The temperatures range from a low of less than 100°C (212°F) in the far northwest corner to over 150°C (302°F) in the southeast corner. Source: Batir and Richards, 2020.

revenue for the Permanent University Fund in Texas, are depicted as boxes in the eastern and central portion of the county, which includes higher heat flow values that may lead to developable geothermal resources. Geothermal development potential on University Lands is considered in further depth in [Chapter 13, State Stakeholders Implications and Opportunities](#) of this Report. Figures 4.40, 4.41, and 4.42 are the temperatures-at-depth maps for Crockett County at depths of 11,480 feet, 16,400 feet, and 32,800 feet (3.5 kilometers, 5.0 kilometers, and 10 kilometers) that use the latest heat flow values

as the foundation for the deeper depth temperatures. The highest temperatures at the respective depths are in the southern and eastern portions of the county. Temperatures do not reach 150°C (302°F) on University Lands until 3.4 miles (5.5 kilometers) depth, although there are areas at 125 to 150°C (257 to 302°F) at 11,480 feet (3.5 kilometers) depth.



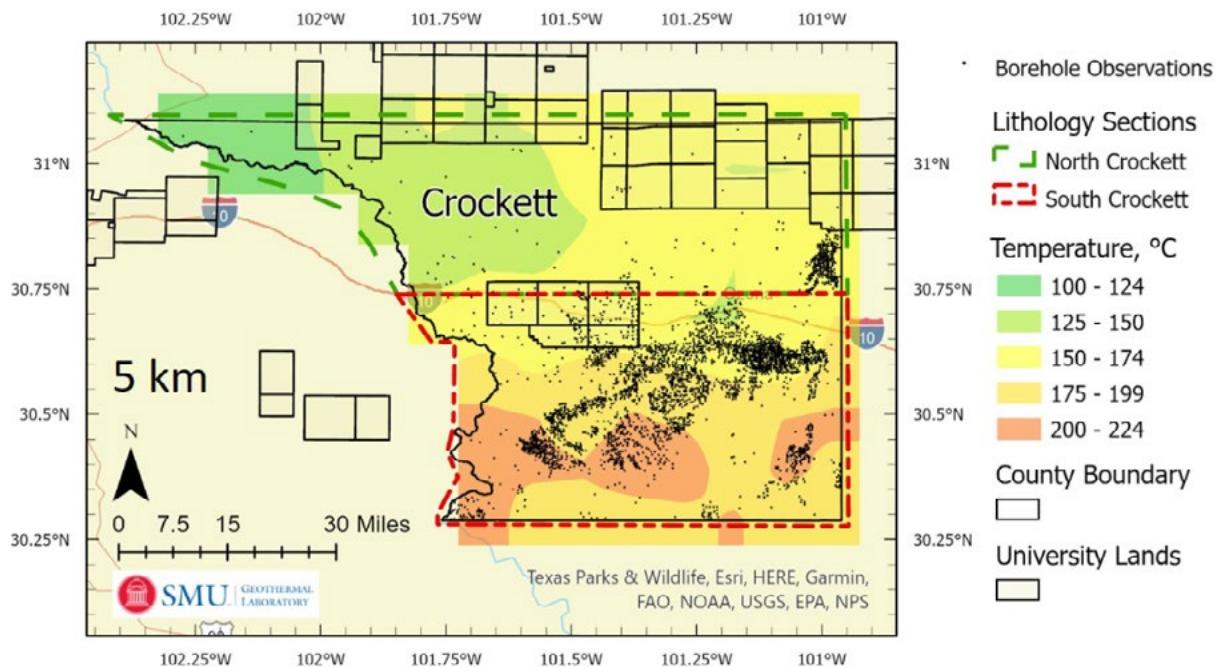


Figure 4.41. The SMU 2020 Crockett County Temperatures-at-Depth Map for five kilometers depth. This map includes the data sites used in the mapping of the temperatures. At this depth, the temperatures range from less than 125°C (257°F) in the northwest quadrant to over 200°C (392°F) in the southern portion of the map. The University Lands resource temperatures at this depth are approximately 150°C (302°F).

Source: Batir and Richards, 2020.

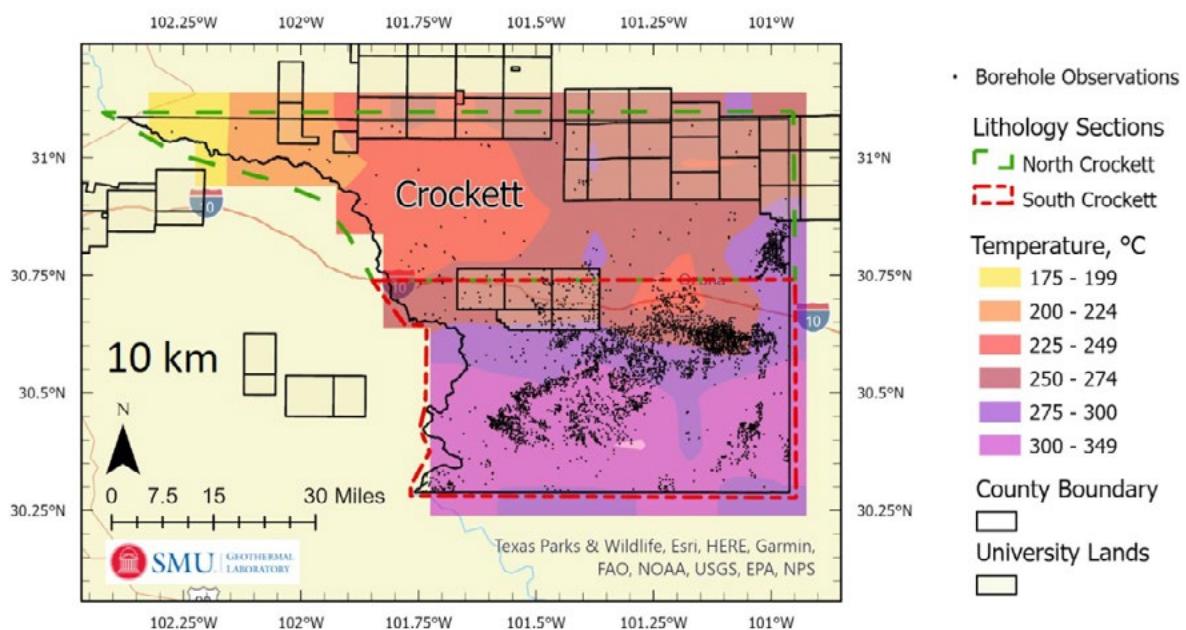


Figure 4.42. The SMU 2020 Crockett County Temperatures-at-Depth Map for ten kilometer depth. This map includes the data sites used in the mapping of the temperatures. At this depth, the temperatures range from less than 200°C (392°F) in the northwest quadrant to over 300°C (572°F) in the southern portion of the map. The University Lands resource temperatures at this depth are approximately 250°C (482°F). Source: Batir and Richards, 2020.



Crockett County is considered part of the Permian Basin and "cold" in terms of geothermal resources. The Heat Flow Map of Texas (Figure 4.4) at the beginning of this Chapter shows this area as blues and greens. The geothermal resources in Crockett County have not changed since the 1990 Geothermal Map of North America (Blackwell, et al., 1990) was produced; instead, our data and knowledge of the geology has grown, allowing for more detailed and accurate mapping of the geothermal resources below Texas.

### **1. Detailed Review of Webb County**

Webb County is dense with oil and gas wells, and much of the related data are in the NGDS. It was studied in 2020 as part of the Texas Geothermal Entrepreneurship Organization Project to improve one county in three regions as an example of changes where many additional BHT sites are newly available (Batir & Richards, 2020; 2021). Webb County is part of the heat flow transition zone from the lower heat flow in Permian Basin to the north, and the higher heat flow in South Texas and the Gulf Coast regions to the south and east. From the previous mapping by Blackwell, et al. (2011a,b), the southern portion of this county, along with Zapata and Starr Counties to the south, had higher temperatures at depth than the surrounding area. These counties are also along the U.S. and Mexico border, therefore, geothermal resources are interesting because developers may qualify for unique funding opportunities.

The updates for Webb County from the 2011 maps to the 2020 maps included an increase for well sites from 387 in 2011 to 1,708 sites in 2020. As some of the well sites included more than one temperature-at-depth, there were a total of 2,087 temperatures used (Batir & Richards, 2020; 2021). The results of the update showed a consistent pattern with the previous mapping efforts that included the addition of more refined sub-county details and an increase overall in temperatures deeper than 2.2 miles (3.5 kilometers).

Besides the additional temperature data, the 2020 studies (Batir & Richards, 2020; 2021) increased the detail for the geology via stratigraphic columns by dividing the county into four different lithology sections that roughly follow the Cretaceous continental shelf edge and the

related sediment influx that defined local depositional environments. The rocks in Webb county are older to the north, with younger sediments to the southeast. Complicating the geology are the growth faults in the deeper structures of the southern portion of the county that thrust the sedimentary formations higher in succession across the county. This change in stratigraphy was also enhanced by a change in thermal conductivity, from a simple model used in 2011 (Blackwell, et al., 1990; Blackwell & Richards, 2004) to assign thermal conductivity values based on related geology from McKenna and Sharp (1998), and a study of the same formations, though the location of this study was Louisiana (Pitman & Rowan, 2012).

The increased volume of temperature data and improved thermal conductivity values make a noticeable change in the resulting heat flow map when compared between the 2020 and 2011 maps (Figure 4.43). The previous heat flow averaged between 60 and 70 milliwatts per meter squared, and the 2020 calculated heat increases to a low of 70 milliwatts per meter squared and a high of 100 milliwatts per meter squared. These changes also impact the temperatures-at-depth, with more data measured at 2.2 miles (3.5 kilometers) and the improved geological relevancy of the deeper calculated temperatures at 4 miles to 6.2 miles (6.5 kilometers and 10 kilometers) (Figures 4.44 through 4.46) (Batir & Richards, 2020; 2021).

The new temperatures-at-depth are generally coldest to the northwest and hottest in the southeastern portion of the county. The 6.2 miles (10 kilometers) map shown in Figure 4.46 includes the well site locations for all the maps, highlighting the data density in the oil and gas fields with few-to-no points in the northwest portion of the county. Although the temperatures are also coldest in this few-to-no data area, geology trends do not indicate a reason for higher temperatures if more well-site data were available. At 2.2 miles (3.5 kilometers) depth, the temperatures are between 125°C and 175°C (257°F and 347°F). At 4 miles (6.5 kilometers) is where the source of the values change from measured BHT values to calculated between 200°C and 300°C (392°F and 572°F). By 6.2 miles (ten kilometers), the calculated temperatures are expected to be at least 300°C to over 375°C (572°F to over 707°F).



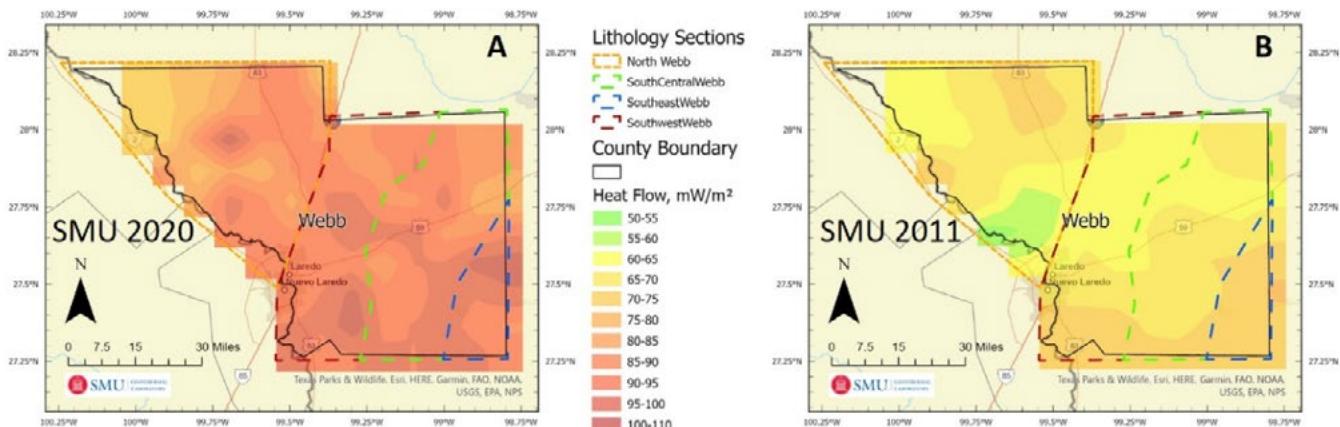


Figure 4.43. Webb County heat flow comparison between the Batir and Richards (2020) detailed study and the Blackwell, et al. (2011) generalized mapping as part of a national map. (A) SMU 2020 assessment. (B) SMU 2011 subset of U.S. heat flow map. The dashed lines divide the county into four sub-county stratigraphic columns used for the 2020 thermal conductivity determinations. Source: Adapted from Batir and Richards, 2020.

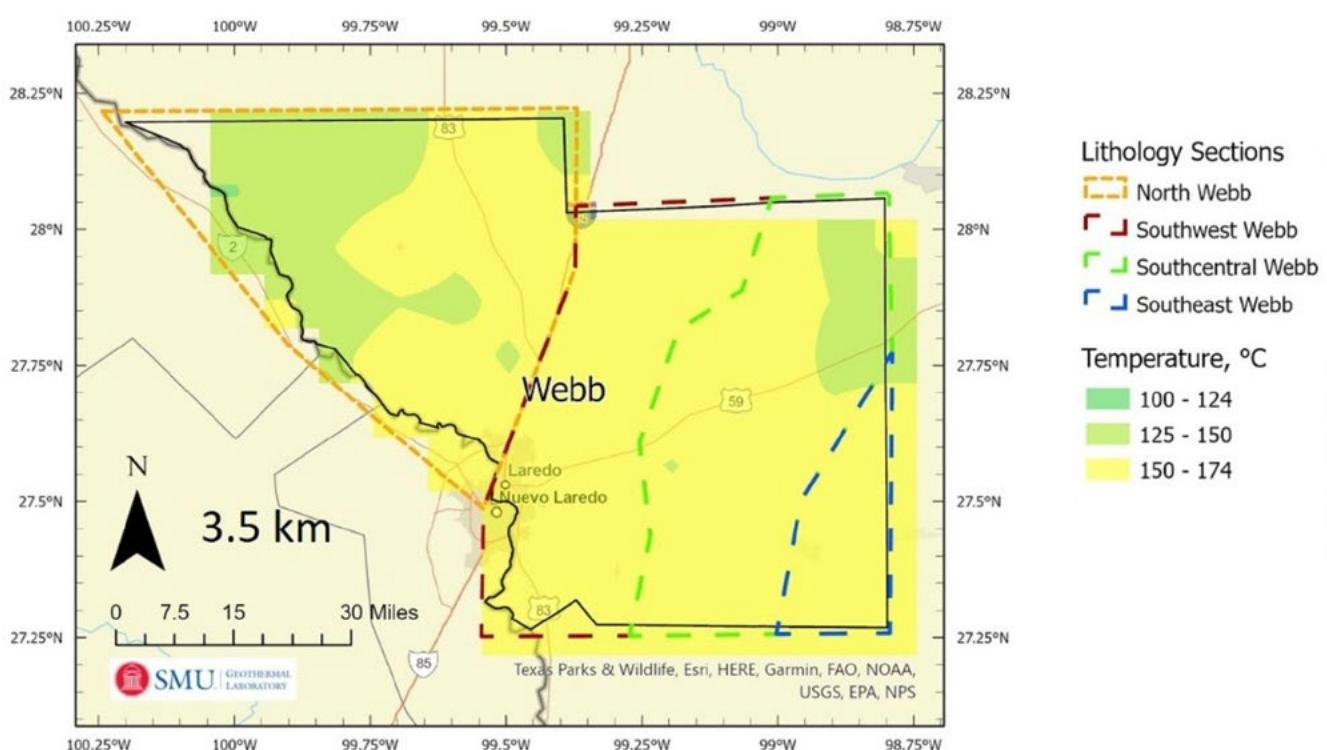


Figure 4.44. Webb County temperatures at 3.5 kilometers depth based on oil and gas well data and the lithology sections used for detailed thermal conductivity values. Source: Adapted from Batir and Richards, 2020.



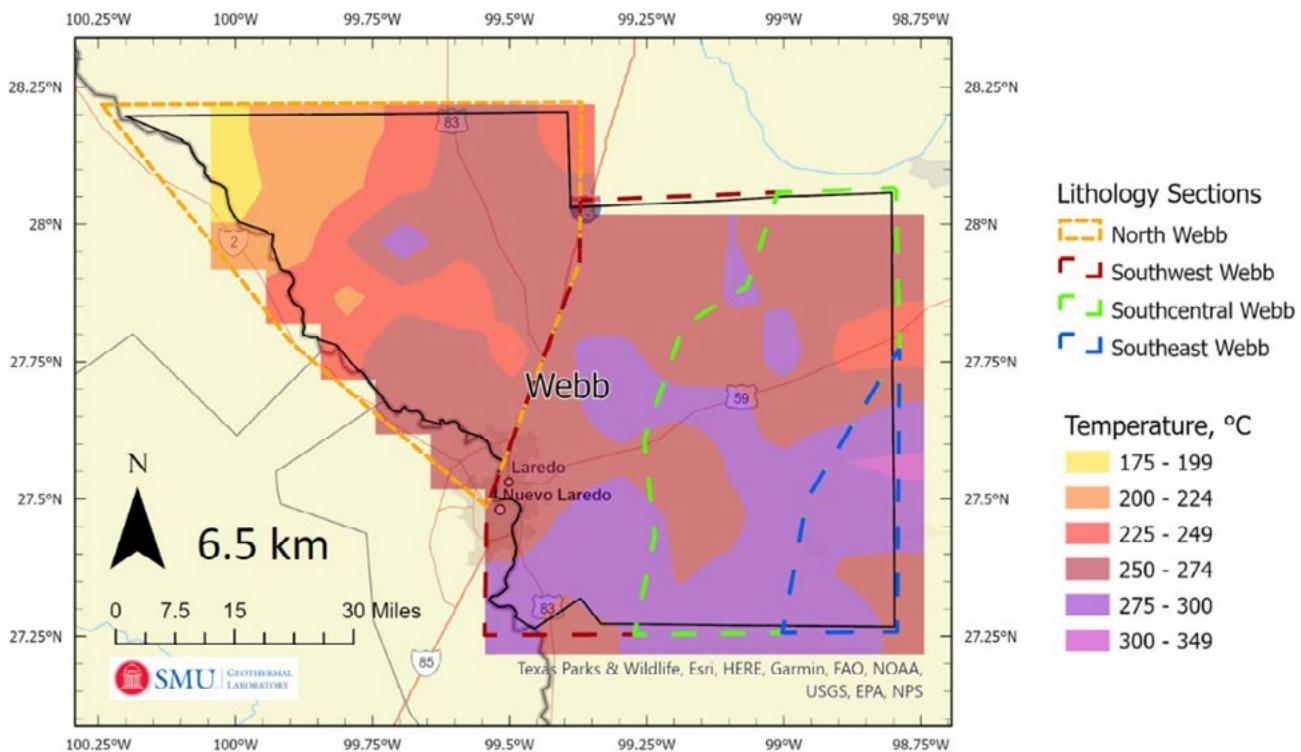


Figure 4.45. Webb County temperatures at 6.5 kilometers depth based on oil and gas well data and the lithology sections used for detailed thermal conductivity values. Source: Adapted from Batir and Richards, 2020.

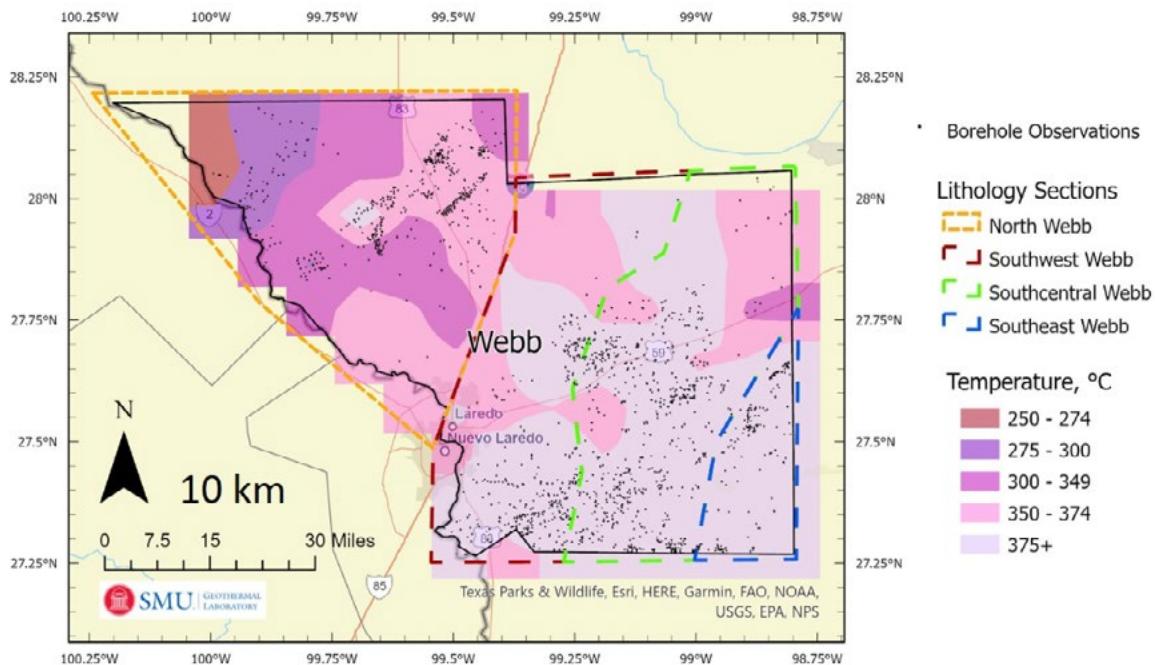


Figure 4.46. Webb County temperatures at ten kilometers depth based on oil and gas well sites that are typically less than 4.0 kilometers in depth (shown here as Borehole Observations) and the lithology sections used for detailed thermal conductivity values. Source: Adapted from Batir and Richards, 2020.



Webb County, and its related region of South Texas, have some of the highest potentials for geothermal resources based on the current oil and gas data. The deep sedimentary formations allow for an average of 7.4 kilometers of sediments in this region, with the deepest sediments to the southeastern portion of the county. As shown by the increase in data volume between the 2011 and 2020 maps, with each assessment and improved data resolution, the geothermal resources are better defined with more variability and reliability, yet with trends expected to be similar to those of the oil and gas fields.

## XI. Anadarko Basin (North Texas)

The Anadarko Basin is primarily located in Oklahoma and extends to the northern Texas Panhandle (Figure 4.47). The Anadarko Basin is considered one of the deepest foreland Paleozoic basins in the North American craton. The basin is bound by different structural highs, including the Amarillo-Wichita uplift (south), Nemaha uplift (east), and Cimarron Arch (west) (Johnson, 1989). Most of the published studies cover the Oklahoma portion of the basin. There are very few studies in Anadarko of North Texas (Kosters, et al., 1990). The present day Anadarko Basin started from its predecessor, the Oklahoma Basin. The Oklahoma Basin started as a broad embayment, which received a thick sequence of carbonates interbedded with shale and sandstone (Johnson, et al., 1988). The Oklahoma Basin underwent an orogenic episode during the Pennsylvanian period. The Oklahoma Basin was fragmented into multiple uplifts and major basins during this time, including the Anadarko Basin. The basin subsided throughout the Pennsylvanian-Permian period and continued to receive voluminous sediment. The late epeirogenic history of the basin is characterized by the Permian carbonates, red beds, and evaporites.

Based on the limited data, the heat flow decreases to the southeast of the basin in Oklahoma (Carter, et al., 1998; Gallardo & Blackwell, 1999; Frone, 2014). The western and northern portions of the basin have higher heat flow (between 54 and 62 milliwatts per meter squared) than the southern portion of the basin (between 39 and 47 milliwatts per meter squared) in Oklahoma. Figure 4.48 shows a temperature profile along with the depth in a deep well. Similar to the other basins in Texas, some areas in the Anadarko Basin are overpressured, especially southwest Oklahoma (Lee & Deming, 2002) and some

areas are underpressured. The pressure variation in the basin is related to two distinct geologic events, rapid burial and uplift/erosion. Based on the U.S. Geological Survey report (Nelson & Gianoutsos, 2011), a portion of North Texas Anadarko Basin (away from the Oklahoma border) is underpressured, however, a few places, such as Collingsworth and Wheeler Counties close to the Oklahoma border, might be overpressured. This border region is where the Anadarko Basin is deepest. There is not enough published pressure data in this specific area to draw meaningful conclusions for the North Texas Anadarko Basin. More formation-by-formation study is needed in the Anadarko Basin in north Texas.

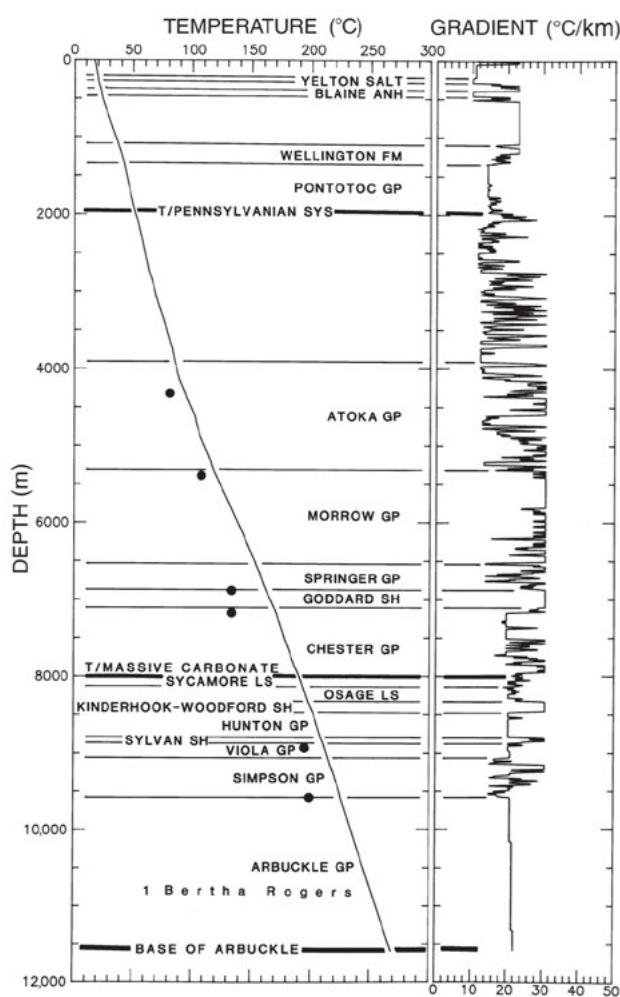


Figure 4.47. The location of the Anadarko Basin, along with prominent structural features. Source: Johnson et al., 1989; Gallardo and Blackwell, 1999.

Used with permission of Geological Society of America from *Sedimentary cover, North American Craton, U.S. Sloss, L., D-2, 1988*; permission conveyed through Copyright Clearance Center, Inc.



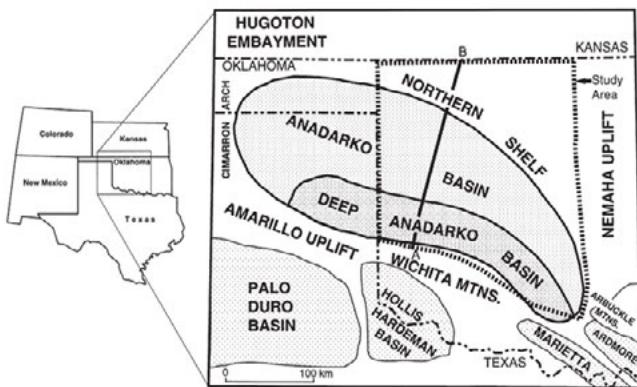


Figure 4.48: Calculated temperature-depth and gradient-depth model for a representative deep-basin well, along with the formations (Lone Star 1 Bertha Rogers well, Washita County, Oklahoma). Large dots are bottom-hole temperatures at well total depth. Source: Gallardo and Blackwell, 1999.

The Cambro-Ordovician Arbuckle Group is the deepest reservoir in the basin. The Arbuckle and its equivalents are all composed of very thick carbonate successions that are often dolomitized. The Arbuckle Group is fractured and contains vugs, similar to Ellenburger in the Permian Basin. Based on a study by NRG Associates (1986), porosity in the Arbuckle varies with depth, for example, 12.5 percent, 7 percent, and 6.2 percent at depths of 6,000 feet (1,829 meters), 7,664 feet (2,336 meters), and 18,240 feet (5,560 meters), respectively, which is indicative of an increasing degree of cementation. Based on the published data, horizontal matrix permeability varies from less than 0.16 millidarcy to 309 millidarcy, whereas vertical matrix permeability varies from less than 0.16 millidarcy to 197 millidarcy (Morgan & Murray, 2015). The presence of fractures enhances permeability greatly. Figure 4.49 shows the geothermal gradient in the Arbuckle is about 22°C per kilometer, and extrapolated temperature is about 250°C (482°F) at about 11,000 feet (3,353 meters) in one borehole location.

Overlying the Arbuckle Group, the Mid-Ordovician Simpson Group is also a potential geothermal reservoir composed of limestones, sandstones, and shales. The porosity of this group ranges between 10 to 18 percent over a depth of 3,500 feet (1,067 meters) to 11,000 feet (3,353 meters) (Ball, et al., 1991). Permeabilities vary between 15 and 300 millidarcy with an average of 120 millidarcy over the same depth range (Harrison & Routh, 1981). The Simpson Group has a temperature of about 200°C (392°F) at about 9,600 ft (2,926 meters) (Figure 4.49). The overlying Viola Group

is generally a tight carbonate section, however, locally dolomitized sections have good reservoir quality (Adler, et al., 1971). Other potential reservoirs include the Hunton, Meramec, and Morrow Groups, where temperatures are high enough to produce productively hot brine.

The Granite Wash is another potential geothermal reservoir straddling the Oklahoma and Texas border on the northern flank of the Amarillo-Wichita uplift, and occurs beneath Hemphill, Roberts, and Wheeler Counties in Texas. The Granite Wash is primarily composed of arkosic sandstones and conglomerates with low porosity (1 to 16 percent, average 8 percent) and permeability generally less than 0.1 millidarcy (Mitchell, 2014; Wei & Xu, 2016). However, there are prospective sections consisting of chert (Morrowan Granite Wash) and carbonate (Atokan Granite Wash). This reservoir is both structurally and stratigraphically complex due to its position near the Amarillo-Wichita uplift area. Since 2008, several horizontal oil and gas wells have been drilled in the deep Granite Wash play (9,000 to 15,000 feet or 2,743 to 4,572 meters), which has enabled a better understanding of the Granite Wash. The Stiles Ranch field in Wheeler County of North Texas is an example. The deep wells offer an opportunity to attain high temperatures and are also targets for repurposing depleted wells into geothermal wells. However, because of the lack of published studies, there is a need for detailed research on the subsurface in North Texas focused on geothermal energy potential.

Induced seismicity is a concern in the Anadarko Basin. There are some major faults along northwest to southeast in north Texas. The present day principal maximum horizontal stress direction is also along northwest to southeast (Lund Snee & Zoback, 2020). Therefore, water injection into deep reservoirs close to faults may result in fault slip and earthquakes. However, this should not be a significant concern for Advanced Geothermal Systems, like Closed Loop Geothermal Systems.

## XII. Other Settings

### A. The Llano Uplift

The Llano Uplift is a unique geologic province in Texas, depicted in the Central Texas Uplift in Figure 4.1. It is an area of approximately 62 by 37 miles (100 by 60 kilometers) of igneous and metamorphic rocks at the surface. The only other region like it is in far West Texas.



The uplift is a window into a rather complex mixture of ancient rocks that were part of the core of a mountain chain of Precambrian age, which is greater than one billion years old (Mosher, et al., 2008). It consists primarily of igneous and metamorphic basement rocks that have been uplifted relative to their surroundings due to several periods of tectonic activity starting in the Precambrian (Ewing, 2016). For the purposes here, the main point of the geology is that it consists of “hard” rocks instead of the general “soft” rock (sedimentary) geology of most of the rest of Texas. The “hard” rocks make deep drilling slower, more difficult, and therefore more expensive in this setting. The nature of these rocks and their history also means there is no petroleum in the uplift region. In turn, this results in a complete lack of wells in the region, other than shallow water wells. The well data map of Texas (Figure 4.3) is the empty region west of Austin and the Hill Country.

The lack of data does not prevent building a reasonable picture of the thermal state of the crust. The regions around the uplift, characterized by much better temperature data, are relatively stable and have constant crustal heat flow in the 35 to 45 milliwatts per square meter range. Given the lack of geologically recent activity in the Llano uplift, it is reasonable to expect to find a similar 35 to 45 milliwatts per square meter heat flow throughout the uplift. The uplift rocks are very low permeability, thus, there is no thermal disturbance due to fluid movement in the crust. Finally, reasonable thermal conductivity measurements are available for the rock types in the region. Combining the data allows for a reasonable determination of the temperature at depth model, as shown in Figures 4.5 through 4.7 at the beginning of this Chapter.

From the heat flow and temperature at depth maps, it is evident that the uplift is one of the cooler regions of Texas, as shown in Figures 4.4 through 4.7. Even at 6.2 miles (10 kilometers) depth, the temperatures are between the 150 and 175°C (302 and 347°F) range. While these temperatures might be a reasonable target for certain geothermal technologies, they are less attractive compared to other areas of Texas. The depths and hard rock in the Llano Uplift will result in more expensive drilling, and the region will benefit from the development of cheaper methods to drill hard rock.

## B. El Paso – The Edge of the Basin & Range

The far west of Texas, around El Paso, is on the edge of the Basin and Range province. This is a region of ongoing crustal extension. This crustal extension results in a thinner crust. Since the temperature boundary conditions on the top and bottom of the crust are unchanged, the thermal gradient must increase. The temperature maps for Texas (Figures 4.5 through 4.7) show that the highest temperatures in Texas underlie this region and may exceed 350°C (662°F) at 6.2 miles (ten kilometers) depth.

Besides the high background temperatures due to thin crust, the Basin and Range province is characterized by deep extensional faulting. This faulting, in many parts of the Basin and Range, creates permeable pathways. Water heated by deep circulation into the crust along those pathways can rapidly flow to the surface, creating exploitable Conventional Hydrothermal Systems. While there are no producing geothermal systems in this region, there have been exploration projects on Fort Bliss, a large military base that stretches from Texas into New Mexico, with the latest announced in 2020 (Richter, 2020).

Historically, the region has not been of interest to the oil industry, and is thus sparsely drilled (Figure 4.3), but there have been some geothermal exploration programs because of the known high heat flow in the area. Most of the drilling and data is relatively shallow and is indicative mainly of shallow fluid flow; there have been deep wells of around 3,280 feet (one kilometer) that reached temperatures of 93°C (200°F) (Lear, et al., 2016). Taking an average surface temperature of 18°C (64°F) results in a gradient of 75°C per kilometer (4.1°F per 100 feet). While this measurement is possibly elevated due to fluid convection, it still indicates significant temperatures in the shallow to intermediate subsurface.

As high as any in Texas, these temperatures clearly make this region a high priority for further geothermal exploration and development. However, the current data is relatively sparse. Texas’ other “hot” regions, the Gulf Coast and East Texas, have rich data sets that quantitatively delineate the resource at the region to county scale. The relative lack of data in Texas’ Basin and Range region means that the apparent high temperatures are not well constrained. In other western states, the Basin and Range is the site of most U.S. hydrothermal geothermal systems (by number, not generation capacity),



but there are no known hydrothermal systems in the Texas zone. It is estimated that there are three to five times as many undiscovered Blind Hydrothermal Systems ("BHS") in the western United States (BHS are Conventional Hydrothermal Systems with no surface manifestations). By extension, there may be multiple BHS to be discovered in the Texas Basin and Range region.

Thus, the Basin and Range region of Texas appears to have significant geothermal potential both for the development of Conventional and Next Generation Geothermal Systems. A more precise and certain thermal picture of the area is needed. A program of intermediate-depth drilling across the region is called for to define the thermal picture of the region. Confidence in the regional temperature landscape would, in turn, spur site-specific exploration and investment in geothermal projects.

### C. Central Texas/Edwards Plateau

The Central Texas Hill Country was a region of Cretaceous age limestones when much of Texas was covered by shallow seas. The region is bounded on the south and east by the Balcones Fault Zone, which forms the boundary with the coastal plains, and extends west to the Llano Uplift, surrounding it. West of the Llano Uplift, the limestones continue as the Edwards Plateau. These areas have experienced limited petroleum exploration except in the far west of the region, where it grades into the Permian Basin. Like the Llano Uplift, a reasonable picture of the thermal condition of the subsurface of Central Texas and the Edwards Plateau is possible but is not well constrained.

As shown in Figures 4.5 through 4.7, this region is relatively cool. Unlike the Llano Uplift, however, the rocks, limestones, are considered "soft" rocks. Thus, while the temperatures are not any hotter than in the adjacent Llano area, the cost of reaching the same depths is much less. This makes the region an easier geothermal exploration target than the Llano Uplift. Also, like the basin and Range, data is relatively sparse and would benefit from a systematic data collection program.

## XIII. Conclusion

Texas has an immense resource at hand in the form of accessible heat for geothermal energy production - thousands of times our current energy usage in Texas. Texas also has a wide variety of geologic/geophysical settings, thus there is no "one size fits all" approach to understanding and assessing the geothermal potential of Texas. This variation and complexity in the geologic and geophysical setting will require thoughtful research and planning as entities seek to develop geothermal resources in the State.

This Chapter provides a solid starting point for project planning and understanding the general conditions in an area or region. Site specific analysis is still needed to reduce risk and better understand this natural and reoccurring exploitable resource in Texas. The Lone Star State is unique to possess substantial information about the subsurface, although more of this data needs to be analyzed with a view toward geothermal development. Where there has not been oil and gas development (see Figure 4.3), our knowledge of the subsurface is weak. These sparsely drilled areas include most of the population centers outside of the Gulf Coast. **Of significant note, where we have taken deeper dives at the county scale in this Report, we find that the subsurface heat resource is better than previously estimated in the most recent mapping of the Texas heat resource, last conducted in 2011.** This is due to more refined approaches, a large increase in well drilling and available data since 2011, and a comprehensive update of county level mapping in Texas.

Going forward, government, industry, and academic cooperation and coordination is needed to fill in the gaps in our knowledge of the Texan subsurface, and provide a foundation for accelerating geothermal development. Texas has everything needed to help launch the future of geothermal, including the resource, and can lead the world in the Geothermal Anywhere movement.



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## Conflict of Interest Disclosure

**Ken Wisian** serves as an Associate Director of The Bureau of Economic Geology, Jackson School of Geoscience at the University of Texas at Austin, and is compensated for this work. His main area of research for 30 plus years is in geothermal systems. Outside of this role, Ken Wisian 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.

**Shuvajit Bhattacharya** serves as a Research Associate at Bureau of Economic Geology, The University of Texas at Austin, and is compensated for this work. His main research expertise are in petrophysics, seismic interpretation, and integrated subsurface characterization. He has contributed to the regional geology and formation characteristics of the Gulf Coast, Permian Basin (West Texas), and Anadarko Basin (North Texas) portion of this chapter. Outside of this role, Shuvajit Bhattacharya certifies that he has no affiliation, 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.

**Maria Richards** serves as the Coordinator of the SMU Geothermal Laboratory in the Roy M. Huffington Department of Earth Sciences, and is compensated for this work. Her main area of research for 26 years is in geothermal resource exploration. Outside of this role, Maria Richards certifies that she has no affiliation, 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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## Chapter 5

# The Oil and Gas Industry Role: Technology Transfer, Development, Acceleration, and Scale

R. Schulz, S. Livescu

**All geothermal technologies will realize near term benefits from oil and gas technology spillover, providing quick wins and achievable learnings projected to deliver 20 to 43 percent in cost savings, depending on the type of geothermal technology.**

## I. Introduction

There are a number of synergies between geothermal technologies and the skills, expertise, technologies, and resources of the oil and gas industry. In this Chapter, we examine the role of the oil and gas industry in Texas, with its supportive policy and regulatory regime for subsurface energy extraction, and a broad social license for drilling operations, to accelerate the development and deployment of geothermal technologies and projects. While the oil and gas industry has been hesitant historically to invest in conventional geothermal technologies, as appropriate locations to develop them are increasingly scarce and geographically limited, the oil and gas industry could play a particularly important role in advancing new, more globally scalable applications that could expand the resource base of geothermal energy into sedimentary basins and Hot Dry Rock (“HDR”) applications.

However, to spur significant increases in the scale and pace of geothermal development, and encourage engagement of the oil and gas industry in these concepts, it is essential to demonstrate a pathway toward cost reduction to show investors and other stakeholders that geothermal can be a competitively priced energy source.

This Chapter reviews the current range of surface and subsurface geothermal technologies, and their strengths and limitations, with a focus on supply and demand in Texas. A technology roadmap is introduced, applicable across all geothermal technologies, to provide a framework to describe technology maturity and potential market viability (elements to support markets with sufficient supply and demand to warrant major investor interest). We consider the key levers and opportunities to



the lower cost of geothermal technologies, applying three main types of learning, including: (1) spillover from the oil and gas industry, (2) economies of scale, and (3) learning by research and development, and predict potential cost reductions that can be achieved across multiple geothermal technologies. We conclude by examining the role of collaboration models to address gaps in innovation, and the need for new business models within oil and gas to accelerate the pace of industry engagement in geothermal.

## II. Background

Geothermal energy uses the heat generated in the Earth's subsurface, either through Direct Use concepts (as discussed in detail in [Chapter 2, Direct Use Applications](#)), or for electricity generation, as was discussed in [Chapter 1, Geothermal Electricity Production](#). Geothermal heat in the form of natural hot springs has been used by humans for millennia, and the first electricity generation from conventional hydrothermal reservoirs dates back to the early 1900s (IRENA, 2021a). Geothermal heating and cooling for buildings and industrial applications has grown since 2015 by 72 percent, to about one exajoule per year predominantly in the United States, Europe, and China (Lund & Toth, 2020). Geothermal energy for electricity generation has grown more slowly, due to limited conventional resources, generating about 94 terawatt hours, with capacity additions largely in Indonesia, Kenya, Philippines, Turkey, and the United States (IEA, 2020b).

Geothermal and upstream oil and gas developments have many overlapping features. Both require a detailed understanding of the subsurface, the drilling and completion of wells, the ability to understand and predict fluid flows in the subsurface, the handling of fluids for flow assurance, and for some applications, management of large-scale projects. Due to the nascent nature of scalable geothermal technologies, there is significant potential to increase performance (e.g., efficiency, reliability, expansion to lower quality reservoirs), and to lower costs.

Technologies that share similar ancestry, such as geothermal and upstream oil and gas, may have the potential to achieve this radical, 'step change' style innovation by building on one another's strengths and resources (Arthur, 2009). For example, offshore wind, through its similarity to the oil and gas industry's geotechnical, logistics, and project management

requirements, relies on strong spillover potential from the oil and gas industry (IEA, 2019). The potential technology spillover between geothermal and upstream oil and gas could be greater than examples like offshore wind, due to the greater number of transferable disciplines between the two. Transferable skills from oil and gas to geothermal are broad, and include resource characterization and exploration, drilling and completions, operations and maintenance, and risk management and mitigation.

There are, however, a number of differences between geothermal and the upstream oil and gas industry, including the types of reservoirs, volumes of fluids produced, temperature variations, fundamental customer base, and the underlying business model. Unlike upstream oil and gas, which produces a commodity that is transported for local or global use, Direct Use geothermal delivers solutions for distributed customers at their location, specific to their needs. In the case of geothermal electricity generation, projects require a new supply chain that is very different from the oil and gas industry. Instead of barrels, pipelines, refineries, trains, and ships, projects require utility grid connections, enabling power markets, electricity off-takers, and power purchase agreements. "Operating" a geothermal project, unlike oil and gas production, requires entities to become utilities. This is a concept that is met with varying levels of unease by oil and gas entities, particularly within the "parent" of major international oil companies, as it represents a fundamental shift in business model that is difficult to enact on a company-wide level while beholden to shareholder pressures.

We will consider in Section III of this Chapter how transfer of existing technologies from the upstream oil and gas industry might impact geothermal cost in the coming decades. We will then consider how a shift in thinking and business model approaches within the oil and gas industry may ease the transition of oil and gas entities into the geothermal space.

## III. Technology Transfer from Oil and Gas to Geothermal

Texas industry and academia have helped to expand the frontiers of oil and gas production, and boost the efficiency of extraction. For example, the unconventional oil and gas revolution began in the 1990s with Mitchell Energy's focus on the Barnett Shale in Texas, and as unconventional



drilling techniques were applied in the Permian basin, production has increased substantially. Today, Texas is the fourth largest oil producing entity in the world (EIA, 2021; Rystad Energy, 2021). As the world increasingly looks to transition to clean energy, geothermal, and its synergies with the oil and gas sector, has become a natural focus area for the oil and gas industry.

There are many examples of technology transfer between the two industries. For example, the first polycrystalline diamond cutter ("PDC") bits, now responsible for more than 90 percent of oil and gas well lengths drilled globally, were designed for geothermal use in the 1970s, and first tested in a petroleum well in South Texas (Scott, 2021). In the last two years, a Texas based collaboration led by NOV and Texas A&M, performing work at the United States Department of Energy's Frontier Observatory for Research in Geothermal Energy ("FORGE"), utilized PDC bits alongside oil and gas optimization technologies and workflows, achieving double the expected rates of penetration through hard, granitic rock at over 230°C (446°F) bottom hole temperature (Sugiura, et al., 2021).

#### A. What is Needed From Oil and Gas if Geothermal Deployment is to Accelerate

In this Chapter, we focus on potential contributions from the oil and gas industry to support geothermal and, in turn, what key features the oil and gas industry would need to see to warrant increasing support for geothermal technology development. To this end, technology roadmaps are a visualization tool used in strategic planning that highlight the key challenges to achieving market penetration for a given technology (IEA, 2014; Amer & Daim, 2010). They help to provide a framework to link the current business environment with a vision of the future. Geothermal projects, particularly Deep Direct Use ("DDU") and power projects, can require substantial early investment and carry high exploration risks. To warrant this level of investment, there must be a vision for how to reduce early exploration risks and/or achieve larger supply and market demand for geothermal technologies.

Most geothermal capacity today consists of shallow wells between 164 to less than 3,280 feet (50 to less than 1000 meters) for Direct Use heat or Conventional Hydrothermal Systems utilized to generate electricity. Unconventional well technology allows for more efficient approaches to Direct Use heat and cooling, and there is

limited additional global capacity available to expand conventional hydrothermal resources. Changing the conceptual design and applications around Direct Use for heating and cooling, and expanding power generation capabilities into sedimentary basins and other Hot Dry Rock plays would substantially broaden the potential market for geothermal operators.

According to over 20 interviews with leaders of geothermal companies and geothermal experts conducted for this Chapter (see [Appendix A](#) of this Chapter for the list of participants), each geothermal technology that exists today, particularly the emerging scalable concepts like Closed Loop Geothermal Systems and Engineered Geothermal Systems, differs in its level of maturity in the field, and what improvements are needed to achieve greater deployment at scale (Visser, et al., 2019). Some geothermal technologies, such as Direct Use heating and cooling, satisfy these conditions for their current limited market penetration, but do not satisfy these conditions for an accelerated or broader scale up.

To deploy commercially at scale, geothermal technologies need to satisfy the following conditions:



**Possess adequate heat transfer from the subsurface to Working Fluids:** Rock is a low conduction medium. When heat is taken out in the form of hot fluid transfer, the rock must be sufficiently conductive or, more often, utilize natural convective processes in the subsurface to maintain a continuous heat-exchange process.



**Present long-term, sustained operability:** Technologies must be able to demonstrate long-term operability at a reasonable cost.



**Offer sufficient resource to scale:** The technology must have sufficient supply to be deployed across multiple markets, or it may be unable to achieve economies of scale across supply chains and operations.





**Demonstrate credible, competitive costs** to an acceptable market range.



**Find a viable market with demonstrated demand:** There must be local demand for the energy source in question.

Other factors are also important. For example, social acceptance (social license to operate), and a supportive policy environment are essential to reduce non-technical risks that can cause project delays or cancellations. Supportive public acceptance and policy environments lower risk perceptions for financiers due to more reliable timeframes for permitting or tax support mechanisms. Streamlined permitting timeframes, for example, can positively impact project valuations (Neupane & Adhikari, 2022). A detailed analysis of the impact policies have on the geothermal industry can be found in [Chapter 12, Policy, Advocacy, and Regulatory Considerations in Texas](#).

For this Report, we focus on the potential role for deployment in Texas, which tends to view oil and gas activities and its contributions to the economy in a positive light, and which may allow for more field-testing opportunities for geothermal technologies than in other regions or countries. Texas also has a supportive policy and regulatory environment, and centuries of relevant subsurface jurisprudence to draw from, allowing operators, investors and insurers increased confidence in the stability of their investments. In many states and countries, geothermal energy faces an uncertain policy and high-risk and regulatory framework, providing little incentive for geothermal deployment.

## IV. Overview of Geothermal Technologies

Geothermal technologies differ in their function (heating and cooling, or power generation), the type of resource they utilize, the maturity of the technology, and the resources needed to extract or transfer heat. The geothermal technologies described in [Chapter 1, Geothermal and Electricity Production](#) and [Chapter 2, Directuse Applications](#) can be divided into four categories: Conventional Hydrothermal Systems ("CHS"), Direct Use heating and cooling systems ("DHCS"), Engineered or Enhanced Geothermal Systems ("EGS"), and Advanced Geothermal Systems, which we use interchangeably in this Report with Closed-Loop Geothermal Systems ("CLGS"). Each holds opportunities for technology transfer from the oil and gas industry, along with key barriers and gaps that need to be addressed.

### A. Conventional Hydrothermal Systems ("CHS")

CHS reservoirs are found at major tectonic plate boundaries, and have minimal global footprint. CHS uses steam or hot water produced from the subsurface to run a turbine to produce electricity. This is generally done "Open to Reservoir," where reservoir fluids may deliver subsurface gasses to the surface, including unwanted or hazardous gasses such as carbon dioxide ("CO<sub>2</sub>") and hydrogen sulfide ("H<sub>2</sub>S"), though this is highly dependent on the nature of each geothermal reservoir and associated fluids. Projects are ongoing to capture and store produced CO<sub>2</sub> from CHS reservoirs (Carbfix, 2021).

In 2005, Chevron became the largest geothermal operator globally, primarily due to ownership of CHS projects acquired following its purchase of Unocal. This engagement ended with the divestment of the business unit in 2016. Since 2016, oil and gas industry investments in the CHS space remained limited, until more recent investments by Chevron Technology Ventures, and Baker Hughes into Baseload Capital, for example. Despite limited industry investment, oil and gas industry practices, including standardized reporting across the industry, and project development, may help to bridge stranded markets, reduce costs, and allow access to funding and insurance for projects.



CHS	Adequate heat transfer	Long-term, sustained operability	Sufficient resource to scale	Demonstrate credible, competitive costs	Viable market, demonstrated demand
	YES	YES	NO	POTENTIAL	CASE BY CASE

Figure 5.1. CHS resources roadmap. Color-coding indicates the relative maturity of each condition. Red indicates the condition has been tested and is not satisfied. Green indicates the condition has been testified and is fully satisfied. Blue indicates the condition has not yet been met (in testing or to be tested). Gray indicates markets are on a local, case by case basis. Source: *The Future of Geothermal Energy in Texas, 2023*.

While CHS is a mature technology, the lack of a broad, global resource base has deterred substantial interest and investment by the oil and gas industry, though as we will explore in further detail in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#), this trend may be changing.

### B. District Use Heating and Cooling Systems (“DHCS”)

Geothermal DHCS utilizes the subsurface (generally in very shallow low-temperature sedimentary basins) to store and source fluids to be used in commercial and residential buildings, agriculture, aquaculture, or other light industries for heating and cooling. DHCS operates in a “Closed to Reservoir” configuration, with no or nearly unmeasurable direct emissions, and at temperatures too low to support production of electricity. There are also Open to Reservoir DHCS technologies.

Direct Use heating and cooling systems are also referred to by a variety of other terms, including thermal energy networks, and many others. DHCS is a mature technology that can further benefit from oil and gas industry practices to reduce costs and expand resource access. For example, DHCS applications have traditionally required a large surface footprint. The use of directional drilling technologies and new well designs from the oil and gas sector has significantly reduced required surface area by up to a factor of 100, by drilling directionally from a single, small surface well pad (Thierry, et al., 2021). By monitoring heat exchange and surface heating needs closely, fluids can be directed appropriately in the subsurface to optimize heating and cooling exchange. DHCS may further benefit from increased social awareness and policy support to reduce cost burdens and increase access for consumers, new funding mechanisms such as leasing approaches that have been successful in residential solar, and inclusion in building codes in commercial settings.



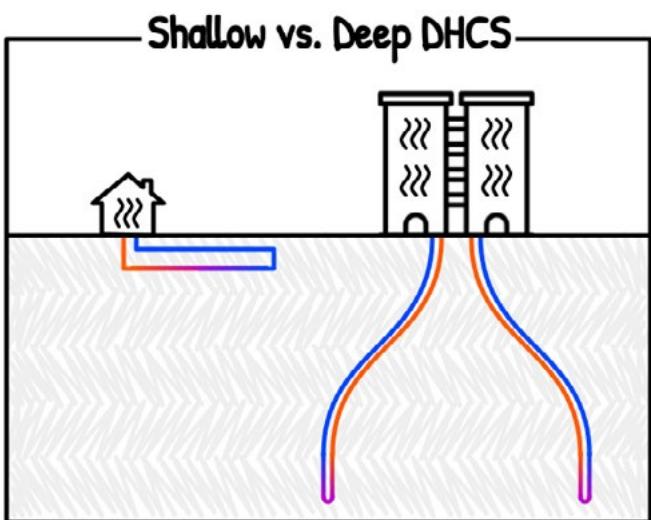


Figure 5.2. Shallow, residential scale DHCS compared with a Deep DHCS concept, pursued by oil and gas entities, to reduce surface footprint and service larger buildings. Source: *Future of Geothermal in Texas, 2023*.

As will be explored in further detail in [Chapter 9, The Texas Startup and Innovation Ecosystem](#), a significant number of entrepreneurs and investors have entered the DHCS market. This includes non-petroleum investors such as Breakthrough Energy, Lennar Home Construction,

Comcast Ventures, Bedrock Energy, and Google Ventures (through Dandelion Energy) in the United States, and several oil and gas related entities, such as Schlumberger's Celsius Energy (France and Massachusetts), Causeway GT (Ireland and Texas), and Eden Geothermal (United Kingdom) (Thierry, et al., 2021; Schlumberger, 2021; O'Halloran, 2021; Shieber, 2021; Lundin, 2019). Additionally, Shell and Energie Beheer Netherlands drilled 1.7 mile (2.7 km deep) depth DHCS wells in the Netherlands. A further exploration license has been granted to Shell and D4 to provide 200 megawatts thermal of geothermal heating (DHC News, 2021; Ottevanger, 2021).

Companies researching DHCS applications at greater depths tend to use existing oil and gas assets, including data or wells to estimate or test heat potential, reducing exploration risk and costs. Networked or district DHCS concepts, despite the advantage of a larger resource base, have seen limited growth due to higher initial capital costs, and in many domains, higher regulatory burden. While operating costs are low, the relatively high upfront cost to install a Deep Direct Use ("DDU") heating and cooling system deters many potential customers (Laterman, 2019).

DHCS	Adequate heat transfer	Long-term, sustained operability	Sufficient resource to scale	Demonstrate credible, competitive costs	Viable market, demonstrated demand
	YES	YES	YES	POTENTIAL	TBD

Figure 5.3. DHCS resources roadmap. DHCS is a mature technology but costs could be reduced and resources expanded through the application of oil and gas practices and assets. Source: *Future of Geothermal Energy in Texas, 2023*.



## C. Engineered or Enhanced Geothermal Systems (“EGS”)

EGS targets hot metamorphic or sedimentary rock. Sedimentary basins comprise about 16 percent of the earth's surface, and thus are significantly more abundant than CHS resources (Neupane & Adhikari, 2022; Geiser, et al., 2016). EGS utilize either natural or hydraulically-stimulated fractures to create an underground reservoir. Fluid, usually water, is injected into the hot, fractured reservoir, and produced from nearby wells to generate electricity. As discussed in other Chapters of this Report, CO<sub>2</sub> is being experimented with as a viable Working Fluid to replace water in some EGS concepts due to its lower critical point compared to water.

Sufficient, long-term reservoir flow can be challenging in EGS concepts, and finding (or creating) sufficient porosity and permeability in deep, hot rocks requires significant resources, energy, and cost. However, the recent tight oil and shale gas boom, with its origins in the State of Texas under George Mitchell's efforts to produce gas economically out of the Barnett Shale, has undergone several rounds of technological innovation over the past three decades. Many of these advances could be applied

to reduce drilling times and costs of EGS. Horizontal drilling techniques have largely not been applied in EGS projects to date, but could provide a boost to efficiency, while well completion advances, particularly multi-zone completions and operational efficiencies achieved during tight oil and shale gas activities, could be applied to increase the productivity of EGS systems (Gradl, 2018). In this report, we refer to these potential improvements to EGS as a result of the application of oil and gas technologies “Next Generation EGS.”

A number of entrepreneurs have made strides into EGS, pursuing Next Generation EGS concepts to improve performance and efficiency. Current investors in EGS trials include the U.S. Department of Energy, Breakthrough Energy, Google Ventures, and drilling rig companies Helmerich & Payne (through Fervo Energy), Patterson UTI, and Chesapeake Energy (through Criterion Energy Partners) (Patterson-UTI, 2022; Terrell, 2021; Tiernan, 2021). The United Kingdom has at least two active EGS start-ups, United Downs (Geothermal Engineering Ltd (“GEL”)) and Eden Geothermal, both funded by a mixture of public and private funding (Eden Geothermal, 2021; GEL, 2021). Additionally, well testing at United Downs

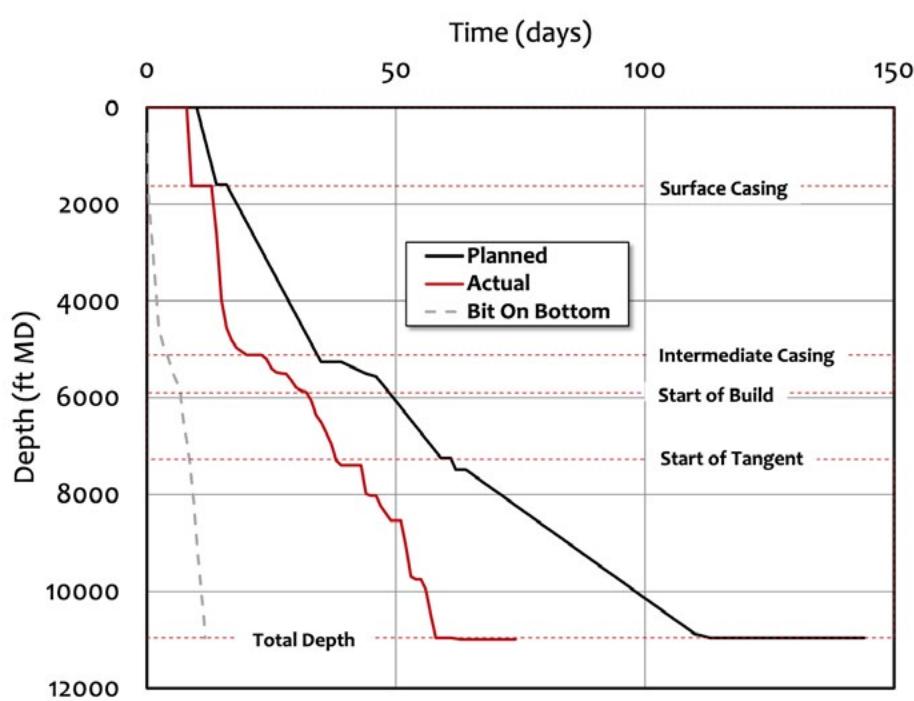


Figure 5.4. Days versus depth for Well 16A(78)-32. Recent oil and gas technology and practices from the shale boom can provide a step-change in performance as highlighted in drilling results at the United States Department of Energy Utah FORGE site. With oil and gas industry crossover, the first well in the campaign achieved best-in-class performance. Source: Winkler & Swearingen, 2021.



EGS	Adequate heat transfer	Long-term, sustained operability	Sufficient resource to scale	Demonstrate credible, competitive costs	Viable market, demonstrated demand
YES	NOT VIABLE TO DATE	POTENTIAL	NOT VIABLE TO DATE	TBD	

Figure 5.5. EGS resources roadmap. EGS physics and resource base are promising but field trials to date have been unable to achieve long-term commercial rates to demonstrate operability. Source: Future of Geothermal Energy in Texas, 2023.

recorded the highest lithium concentration ever tested in geothermal brines, and GEL announced it will produce 4,000 tons of lithium annually from its next sites starting in 2026 (Richter, 2021). Lithium is a critical mineral used in batteries, and the IEA estimates that lithium demand for clean energy technologies will grow by more than 13-fold by 2030 in a Net Zero Emissions by 2050 Scenario (IEA, 2022).

The oil and gas industry has largely shied away from EGS, and in particular from Traditional EGS concepts thus far, due to both technical and non-technical risk perception. As we've seen with recent investments, and will explore in further detail in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#), there appears to be more interest from industry in engaging in Next Generation EGS concepts. Historically, the oil and gas industry backed some of the field trials in EGS (e.g., Woodside's Habanero and Cooper Basin), but companies largely exited after a number of failures requiring re-drills, without achieving consistent commercial rates (Hogarth & Holl, 2017; Breede, et al., 2013). The high cost, operational difficulties in producing and injecting in very tight EGS reservoirs, and induced seismicity risks have dissuaded widespread oil and gas entity engagement in EGS to date. Supporting technologies that demonstrate EGS can operate long-

term at commercial rates, drive down costs, and manage seismicity concerns would encourage investment into the technology.

#### D. Advanced Geothermal Systems (“AGS”)

AGS are next generation geothermal technologies, which primarily operate in a Closed to Reservoir configuration. SuperHot Rock (“SHR”) systems are also sometimes grouped into AGS. For this Section, we focus on Closed-Loop Geothermal Systems (“CLGS”), which covers a range of Closed or partially Closed to Reservoir concepts for electricity generation, including Hybrid Geothermal Systems. The CLGS approach, if successful, would allow geothermal to achieve no/low greenhouse gas emissions, and also allow use of more efficient engineered Working Fluids, which will be discussed in greater detail later in this Chapter. Similar to CHS and EGS, waste heat can be used similarly as an adjunct value chain.

CLGS trials largely rely on thermal conduction in rock (a poor conductor) from long wellbores, whereas CHS relies on convection to support heat transfer. The oil and gas industry and customers looking for reliable, off-grid, baseload power, including the U.S. Department of Defense (“DOD”) and several municipalities in Texas, are watching



CLGS	Adequate heat transfer	Long-term, sustained operability	Sufficient resource to scale	Demonstrate credible, competitive costs	Viable market, demonstrated demand

Figure 5.6. CLGS resources roadmap. CLGS are in the early demonstration phase but current views on ease-of-operations and large resource base are encouraging entrepreneurs and investors. Source: Future of Geothermal Energy in Texas, 2023.

current field trials in Texas and elsewhere with interest (Hayes, 2021; Sage Geosystems, 2021). In contrast to ESG and CHS, oil and gas majors have already made some steps into CLGS, and as we will see in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#), have indicated significant enthusiasm for the concept. Chevron and BP invested in Eavor, which is field trialing in Canada and Germany, while Nabors has invested in Sage Geosystems, which is field trialing in Texas (Laureman, 2021; Veazey, 2021), and more recently, Baker Hughes invested in Greenfire, which is field trialing in California.

Recent well engineering advances are under investigation that may allow the creation of deeper and larger underground well networks to increase efficiencies gained from unconventional oil and gas drilling, helping to improve economics to allow sufficient upscaling of the technology (van Oort, et. al., 2021; Eavor, 2022). Sage Geosystems, for example, is trialing a hybrid closed-loop system in South Texas that uses hydraulic fracturing to allow more fluid movement around the wellbore to improve heat exchange. With success, CLGS could provide an opportunity for geothermal to scale to sedimentary basins with significantly less risk of induced seismicity,

and without the scaling and corrosion risks seen in CHS and EGS reservoirs.

## V. Geothermal Power Plant Types and the Efficiency Evolution

Hot geothermal liquids such as water and steam are converted into electricity using a variety of processes, with higher enthalpy (generally higher temperature) geothermal fluids driving higher efficiencies (O'Sullivan & O'Sullivan, 2016). Geothermal energy is always "on," and combined with high overall plant uptime, this results in high capacity factors (the percentage of time that a plant is generating electricity) of between 60-90 percent for individual plants, and a global average of just under 85 percent in 2020 (IRENA, 2021b). Capacity factors are, however, highly influenced by declining reservoir pressure and operations. Operations and maintenance ("O&M") costs can be low for new plants, but may rise substantially, particularly if new wells need to be drilled to maintain pressure.



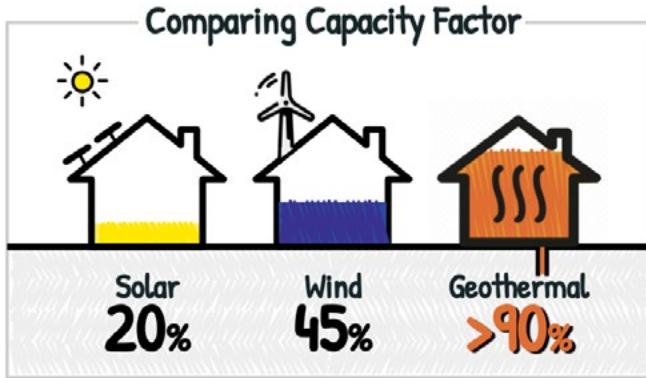


Figure 5.7. Capacity factor comparison for renewable energy technologies. Capacity factor is the percentage of time that a plant is generating electricity. Source: Adapted from EIA, 2014.

Geothermal power plants have low conversion efficiencies compared to other thermal power plants (Moon & Zarrouk, 2012; Gisler & Miller, 2021). Conversion efficiency, as defined by Moon and Zarrouk (2012), is the ratio of net electric power generated (megawatts electric) to the geothermal heat produced/extracted from the reservoir (megawatts thermal). Geothermal power plants have conversion efficiencies that range from one to 21 percent, with a global average of about 12 percent (IRENA, 2021b). One major limitation of geothermal power production is the low turbine efficiencies achievable with current technologies. Additionally, over time, scale and corrosion from geothermal brines can impact operability and plant efficiency, resulting in higher O&M costs. This presents a significant opportunity for innovation, and new ways of doing to increase the economic attractiveness of geothermal projects across technologies, entirely outside of subsurface considerations.

The efficiency of a geothermal power plant depends first on the enthalpy and heat transfer capabilities of the working fluid driving the turbines. Historically, dry steam plants, where steam from geothermal wells directly drives a turbine to generate electricity, usually above 225°C (437°F) bottom-hole temperature, comprise most of the historical power generation capacity in the United States (Robins, et al., 2021). Dry steam plants have relatively high efficiencies of around 12 to 21 percent (Moon & Zarrouk, 2012). In comparison, coal plants reach about 600°C (1,112°F) and, depending on technology, have efficiencies of about 35 to 45 percent (Carbon Brief, 2020).

In the last twenty years, flash steam plants have become common as higher temperature CHS resources become

more scarce. Flash steam plants use hot geothermal fluids greater than 182°C (360°F) pumped into a surface tank, with vapor from the rapid expansion of fluids into the tank (flashing) driving a turbine (Harvey & Wallace, 2016). The pressure drop can encourage silica scale to occur on the inside of piping, acting as an insulator and reducing efficiencies. With additional cost, flash plants can be constructed and run with multiple stages to increase heat recovery and plant efficiency.

Binary plants (also called Organic Rankine Cycle, or "ORC" systems have become the most common type of new plant installed in the United States, and are used for lower enthalpy fluids with temperatures ranging from about 90°C to 180°C (194°F to 356°F) (Robins, et al., 2021; Hijriawan, et al., 2019; El Haj, et al., 2017). Geothermal fluids are pumped into a heat exchanger, where they heat and flash a secondary organic working fluid (e.g., isopentane, pentafluoropropane), which in turn drives a turbine. For low grade heat applications, Hartulistiyoso, et al. found optimal plant efficiency of around seven percent using more commonly available working fluids (Hartulistiyoso, et al., 2020).

Innovation in geothermal power plants and system Working Fluids may be a key lever to improve economics and expand the resource base for new geothermal technologies. Recently, companies have utilized hybrid systems combining other power sources (fossil fuel or renewables) with geothermal to help increase the overall efficiencies of the power production system (Robins, et al., 2021). Innovations in Working Fluids may play a key role in increasing geothermal efficiencies, and expanding applicability to lower enthalpy ranges (Song, et al., 2020). For instance, the Southwest Research Institute in San Antonio, Texas has designed a supercritical carbon dioxide ("sCO<sub>2</sub>") turbine in partnership with Sage Geosystems that could achieve an efficiency greater than 20 percent in reservoirs at approximately 175°C (347°F), and around 3.7 miles (six kilometers) in depth (Nielson, 2021). The system is set to perform an initial field test on a well drilled in South Texas in a sedimentary basin in 2023.

There has also been increasing interest amongst oil and gas entities in the promise of direct heat to electron transfer, or Thermo-Electric Generation ("TEG") as a potential generation solution for not only geothermal wells, but also electricity production from waste industrial heat generally. TEG concepts are further from commercial



viability than other generation contenders, however, and rely on significant amounts of rare earth metals, creating a potential challenge to reaching commercial scale (Elghool, et al., 2017).

## VI. The Role of the Oil and Gas Industry

As discussed, geothermal has strong potential crossovers with the oil and gas industry, as both industries strive to characterize and predict fluid flows from the subsurface, use wells to access resources, handle facility and fluid production at the surface, and execute large-scale projects. Value could be quickly gained by the geothermal industry in application of some of the processes, technologies, and assets from the oil and gas industry. Spillover processes and technologies may prove critical to lower cost and improve efficiencies (summarized in the Cost and Technology Improvements Section of this Chapter and [Appendix B](#)). Importantly also, the oil and gas industry can provide the needed funding, in-kind and operational support, and even lease holdings for geothermal field trials.

The oil and gas industry has created a number of design and resource standards that allow the industry and other stakeholders, such as financiers, insurers, and governments, to characterize projects and their risks. The Petroleum Resources Management System, developed by several oil and gas industry organizations, is the widely held standard for resource reporting to the U.S. Securities and Exchange Commission (USSEC, 2017; USSEC, 2008). The American Petroleum Institute ("API") has created a number of standards for oil and gas well operations and construction that are used as global references (API, 2021).

These standards serve to create a common language, from drilling wells, to building plants, to estimating reserves. They serve to communicate processes, to allow for a quicker spread of knowledge and practices across industry, and to gain support from a wider group of experts, investors, insurers, and regulators. Entrepreneurs from oil and gas entering the geothermal domain have encountered difficulties gaining financing and insurance without these standards, and without clear regulations. For geothermal operations in sedimentary basins, new standards and regulations may be needed to communicate resource and reserve profiles, establish viability of long-term production, and to facilitate a

streamlined well and project permitting process. These key standards would support fledgling companies to communicate project opportunities and risks in a common manner, allowing more reliable access to financing and expanding the reach of geothermal.



Figure 5.8. Thermal imaging of a reservoir flow test showing high temperature fluid flowing through the piping and tank system at the DEEP Earth Energy sedimentary geothermal pilot project in Saskatchewan, Canada. The DEEP project is an example of how oil and gas methods and technology transfer can enable new concepts and capabilities in geothermal. Photo credit: DEEP Earth Energy

A demonstrable demand for geothermal energy is needed to justify increases in policy support and investment in geothermal field trials. There are several technologies that may allow for larger markets, but the oil and gas industry currently keeps the notion of a CHS market in mind when assessing geothermal potential. The growth of DHCS applications, and field trials of EGS and AGS, could help the oil and gas industry further diversify into clean energy, as geothermal provides investment opportunities with strong overlap in upstream skills and assets, and supports employment transition opportunities for oil and gas workers. Governments, both Federal and State, can incentivize geothermal development by insuring projects, or by providing grants or concessional loans to "first of a kind" demonstration projects. These types of incentives are considered in further detail in [Chapter 12, Policy, Advocacy, and Regulatory Considerations in Texas](#).

Texas is one of the preeminent locations globally for describing and exploiting subsurface resources. It



provides a unique opportunity to drive geothermal innovation forward given its people, assets, institutions, and supportive social and policy environments. Texas research institutions and universities across the State have contributed significantly to the advancement of the oil and gas industry, and developed world leading expertise in geoscience and petroleum engineering. Texas has over 1.3 million wells drilled, with hundreds of thousands of well logs, drilling and completion reports, seismic, core data, and other information that can fast track subsurface exploration and derisk early project costs (TWDB, 2022). For example, existing wells can provide an opportunity to confirm temperatures and reservoir quality in untested formations. The temperature range of the Texas Gulf Coast fits well for testing new concepts for DHCS, EGS and AGS. Perhaps most uniquely, the supportive social and policy environment allows for a natural fit for entrepreneurs looking to test geothermal innovation in a supportive community.

### A. Learning, Technology Transfer and Cost Reduction

The assets, workforce, and subsurface conditions of the State of Texas provide a unique opportunity to test the physics and commerciality of geothermal concepts. Equally important is the ability to demonstrate a pathway to lower costs to highlight to investors and other stakeholders that geothermal can be a competitively priced energy source. Given uncertainty on the timescales of actual implementation in the field, it is important to look at the key levers and opportunities to lower costs from existing assets and ways of working from the oil and gas industry, economies of scale, and benefits of further research.

#### 1. Learning

The rate and nature of technological change and cost reductions are critical assumptions for the assessments of a technology's long-term suitability to provide energy at an affordable price. Historically, for power production technologies, costs for technologies decrease as experience accumulates (McDonald & Schrattenholzer, 2001). Yeh and Rubin summarize a broader scope of contributions to learning, including spillover effects, learning by research and development ("R&D") and economies of scale, as well as a series of factors behind apparent cost increases, for example, in early

development due to "first generation" technology costs (Yeh & Rubin, 2012).

**This Chapter applies three main types of learning that can reduce future costs in geothermal, including:** (i) spillover from the oil and gas industry, (ii) economies of scale, and (iii) learning by R&D. Learning by R&D is further split into technologies known to be trialing now (within the next one to two years), and those that require further funding (Table 5.1).

Learning-by-doing, where cost improvements are created by experience, helping to deliver increasing cost efficiencies, are not explicitly modeled to avoid double-counting efficiencies gained by spillover or economies of scale. The methodology employed in this Chapter includes learning-by-doing within the umbrella of economies of scale learning. Cost increases during first technology trials, initial scale-up, troubleshooting, or increases in supply chain costs, are also not explicitly modeled (although these may play a role in the future). The learning curve here adapts that from Yeh and Rubin, but uses spillover and economies of scale in place of learning-by-doing.

$$Y = (Y_{\text{pre-dev}} + Y_{\text{dev}} + Y_{\text{misc}}) * (1 - (b_{\text{og}} + b_{\text{eos}} + b_{\text{rd}})) [1]$$

**Where:**

- $Y$  = levelized cost of electricity (or heat) at time  $T_1$ , see below
- $Y_{\text{pre-dev}}$  = contribution of pre-development (exploration) costs to levelized cost of electricity (or heat) at time To
- $Y_{\text{dev}}$  = contribution of development costs to levelized cost of electricity (or heat) at time To
- $Y_{\text{misc}}$  = contribution of miscellaneous costs to levelized cost of electricity (or heat) at time To
- $B_{\text{og}}$  = learning curve cost reduction resulting from oil and gas spillover
- $B_{\text{eos}}$  = learning curve cost reduction resulting from achieving economies of scale
- $B_{\text{rd}}$  = learning curve cost reduction resulting from research and development technology efficiencies

Types of learning are assumed to occur in different time intervals as technologies mature through their technology roadmaps (Table 5.1). Where applicable, oil and gas spillover is assumed to occur in the short-term,



with quick and efficient crossover from the oil and gas industry. Economies of scale are assumed to take a minimum of five years for initial effects to be seen, as all technologies, despite maturity or resource base, require a further social license to operate, and supporting policy environments to allow scale-up. In many cases, these technologies of scale are facilitated by oil and gas spillover (e.g., multi-well pad efficiencies).

For technologies that are trialing now, it is assumed it will take at about five years for trials to be conducted, assessed, and re-deployed at some minimal scale. For technologies that are funded now, it is assumed that a minimum of about ten years is needed to research, build benchtop models, build field prototypes, and further deploy at scale.

Cumulative investment or stock of oil and gas spillover, economies of scale, and R&D are assumed to be maximized during the time intervals to allow for a best-case learnings transfer. Critical to this assumption is that global learnings of deployment across all technologies would be shared efficiently, and not just those occurring within the State of Texas. To do this effectively involves the interplay of companies, industry organizations, countries, and other entities. This is explored in more detail in the Collaboration and Innovation Models Section of this Chapter below (IEA, 2020a; 2020b; 2020c).

- LCOE [\$/MWh] =  $[\sum(\text{Capital}_t + \text{O\&M}_t + \text{Fuel}_t + \text{Carbon}_t + D_t) * (1+r)^{-t}] / \sum \text{MWh} (1+r)^{-t}$  [2]
- MWh = The amount of electricity produced annually in MWh;
- $(1+r)^{-t}$  = The real discount rate corresponding to the cost of capital;
- $\text{Capital}_t$  = Total capital construction costs in year t;
- $\text{O\&M}_t$  = Operation and maintenance costs in year t;
- $\text{Fuel}_t$  = Fuel costs in year t;
- $\text{Carbon}_t$  = Carbon costs in year t;
- $D_t$  = Decommissioning and waste management costs in year t.

In a geothermal power example, Y represents the leveled cost of electricity (or heat) per kilowatt-hour (or megawatt-hour) generated ("LCOE(H)"). LCOE(H) can also be expressed directly as the net present value of fixed and variable costs needed to produce a unit of energy, typically a kilowatt or megawatt hour (IRENA, 2017; IEA, 2020).

Geothermal technologies are compared based on their current leveled cost of electricity (or heat) generation and future ability to drive down costs. The IEA's Levelized Cost of Electricity ("LCOE") model is used to calculate break-even LCOEs. Assumptions used in the LCOE model are noted in [Appendix B](#), and the cost basis for each technology, before application of learning curves, are shown in Table 5.2.

**Table 5.1. Types of learning applied and their applicable time intervals. Source: Future of Geothermal Energy in Texas, 2023.**

Types of Learning	Description	Time Interval (Years)
Oil and Gas Spillover	Application of current technologies and practices. CLGS cost estimates already contain spillover assumptions	0 to 5
Economies of Scale	Applied dependent on achieving technology roadmap elements to enable manufacturing style projects: establishing physics, operability, social acceptance, demand, supportive regulatory environment	5 to 20+
Learning by R&D: Trialing Now	Adopt and adapt R&D, e.g., new working turbine Working Fluids/supercritical CO <sub>2</sub> turbines for concentrated solar power and novel subsurface well networks	5 to 20+
Learning by R&D: Funding Now	R&D funding and deployment increase well flow rates and/or to access higher temperature and difficult to drill reservoirs	10 to 20+
Learning by Doing	Applied on basis of overall technology learnings based on cumulative experience	Ongoing



Table 5.2. Geothermal technology initial capital cost basis. Estimates were assessed using the range of temperatures found across Texas up to about 6.5 kilometers (about 4 miles), or up to about 225°C (440°F). NREL's Annual Technology Baseline assumes the use of flash plants are valid above 200°C (392°F). Sources: Beckers & Johnson, 2022; NREL, 2022; Beckers, et al., 2021; Flowers, 2021; NREL, 2021; IEA, 2020; IRENA, 2017; Mattson & Neupane, 2017; Rubin, et al., 2015.

Geothermal Technology	Cost Range (2020 U.S. Dollar per kilowatt)	Comment
CHS	4 120 – 5 870	Cost range based on U.S.-based experience
DHCS or TEN	1 400 – 1 900	
EGS	27 330 – 65 000	Cost range reflects NREL guidance spanning flash and binary power plants. In Texas, binary power plants may be likely given subsurface temperature gradients.
CLGS	5 750 – 14 375	Compared to other geothermal technologies, initial costs from CLGS sources contained some assumed oil and gas spillover.

Table 5.3. Project cost phasing by geothermal technology. Note: Annual operations and maintenance costs are assumed to be 2.5 percent of total project costs. Source: IRENA, 2017; IEA, 2020b.

Project Cost Phase	CHS	DHCS	EGS	CLGS
Pre-Development Survey, Exploration, Appraisal Resource & Fluid Characterization	10%	10%	10%	10%
Development	85%	80%	86%	86%
Development well costs Drilling Completions Power plant & steam gathering system Infrastructure & interconnection	24% 24% 20% 20%	20% 24% 16% 16%	40% 24% 39% 39%	40% 24% 16% 7%
Miscellaneous	7%	60%	7%	7%
	4%	10%	4%	4%

## 2. Technology Capital Costs

Learning parameters are applied separately to the different technologies, assets, and practices used to develop a geothermal project. The costs incurred at each project development phase are therefore estimated on the basis of reported phasing and geothermal and petroleum well cost comparisons (IEA, 2021; Thierry, et al., 2021; GTO, 2019; Nyberg & Howell, 2019; Gul & Aslanoglu, 2018; Lukawski, 2016; Kipsang, 2015; Lukawski, 2014; Mansure & Blankenship, 2013; Gehring & Loksha, 2012).

Well completion costs are not separately split out for CHS and DHCS, as they are currently a minor component of cost. For electricity generation technologies, binary ("ORC") power plants are assumed given the temperatures and depths for Texas geothermal power resources (about 175°C or 347°F) (Blackwell, et al., 2011). Miscellaneous includes insurance and other project management costs.



### 3. Transferable Practices, Technologies, Assets and Ways of Working

Each project phase is further segmented into individual technology, practices, or assets, and assigned to one of the potential learning cost reduction parameters (see [Appendix B](#) for overview and sources). In addition, we estimate the range of cost reduction that could be realized for each technology based on cost savings achieved by the unconventional petroleum industry over the last three decades, industry interviews, and additional available literature (Jacobs, 2021; IEA, 2020b; IEA, 2020c; El Haj Assad, et al., 2017; Lowry, et al., 2017; EIA, 2016; Patel, et al., 2016; Rubin, et al., 2015; Scott, 2015; Augustine, 2011; Mansure, et al., 2006; Kotter, 1996).

Three scenarios were developed for each element based on a low, medium, or high range of cost reduction achievable. Not all oil and gas industry technologies or practices have been assessed. The deployment of

geothermal technologies may benefit from practices not described here, whereas those discussed may not reach full potential.

### 4. Modeling Results

The cost reductions for the four geothermal technologies (CHS, DHCS, EGS, AGS) depend on their current maturity, level of incorporation of current spillover technologies, ability to scale, and applicable R&D technologies as outlined in [Appendix B](#). The breakdown of the impact of different learning types, and the associated phasing of capital, is shown in Figures 5.7 to 15.3. Figures 5.7 to 5.9 indicate the range and midpoint of LCOE (or "LCOH") achievable using the cumulative contributions from each of the three learning factors discussed above. Figures 5.10 to 5.13 highlight the phasing of capital cost savings resulting from the learning types discussed in this Chapter.

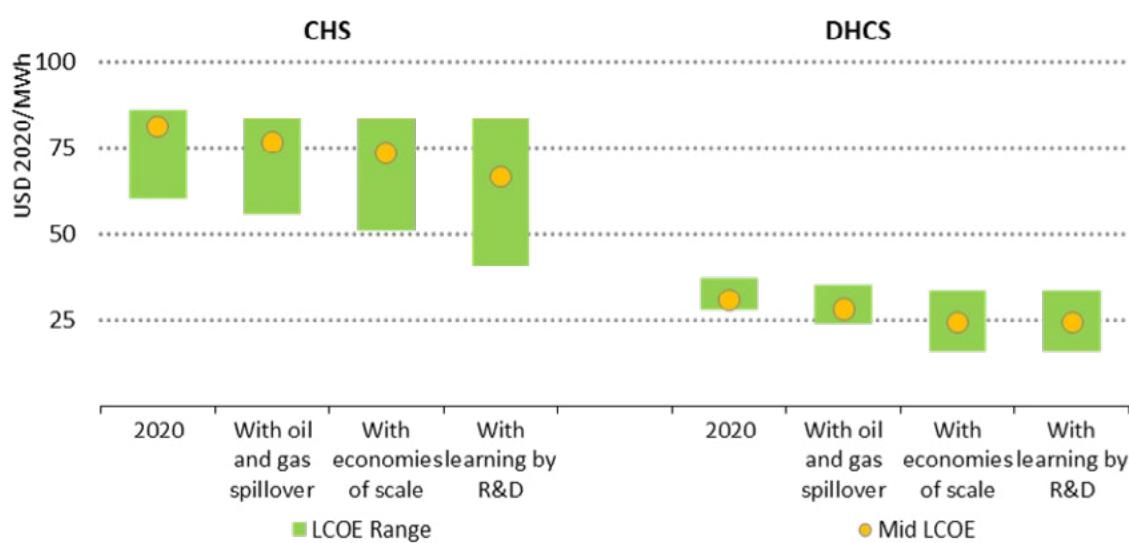


Figure 5.9. LCOE and LCOH ranges for DHCS and CHS, with cumulative reductions from learning factors.  
Source: *Future of Geothermal Energy in Texas, 2023*.



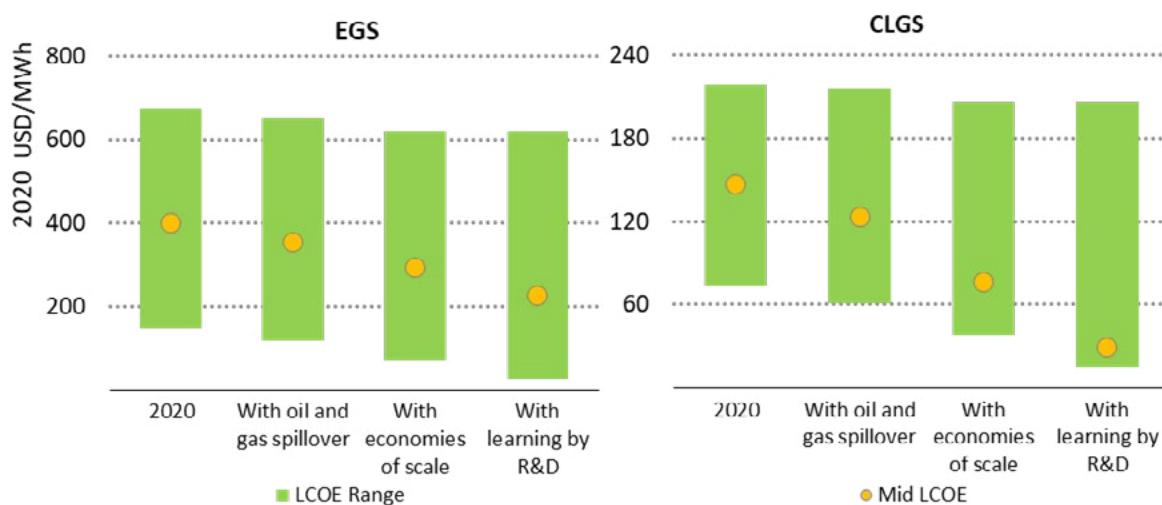


Figure 5.10. LCOE ranges for EGS and CLG, with cumulative reductions from learning factors. Source: *Future of Geothermal Energy in Texas, 2023*.

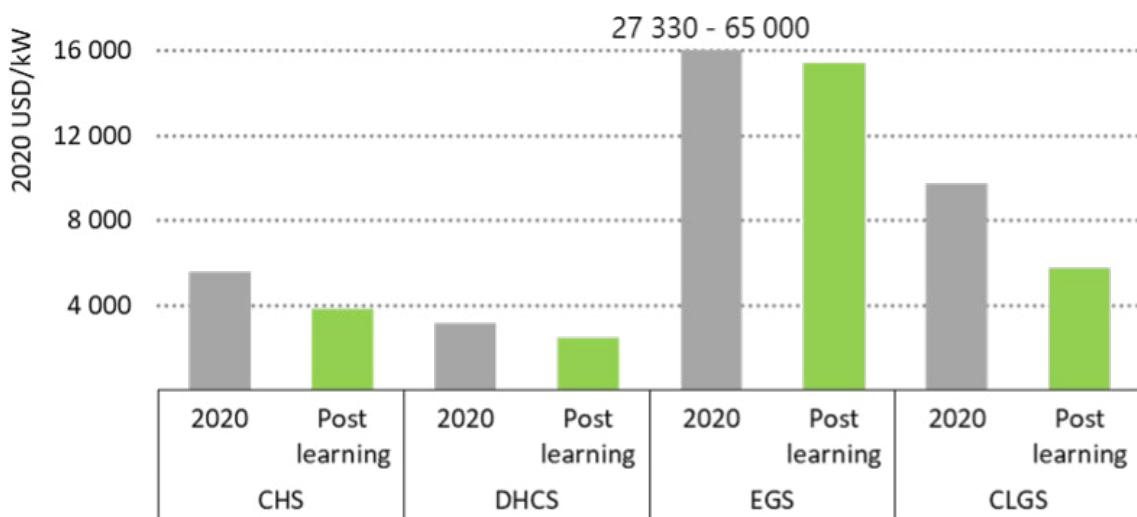


Figure 5.11. Mid-case capital costs by technology type before and after learning. Source: *Future of Geothermal Energy in Texas, 2023*.



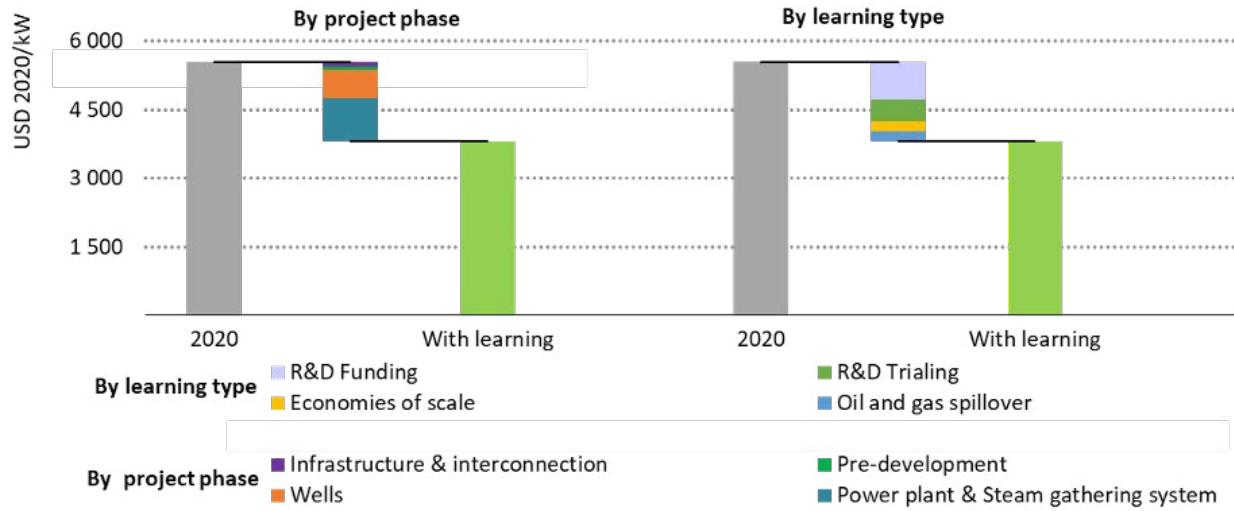


Figure 5.12. Reduction in mid-case capital costs by project phase and learning type for CHS. Source: *Future of Geothermal Energy in Texas, 2023*.

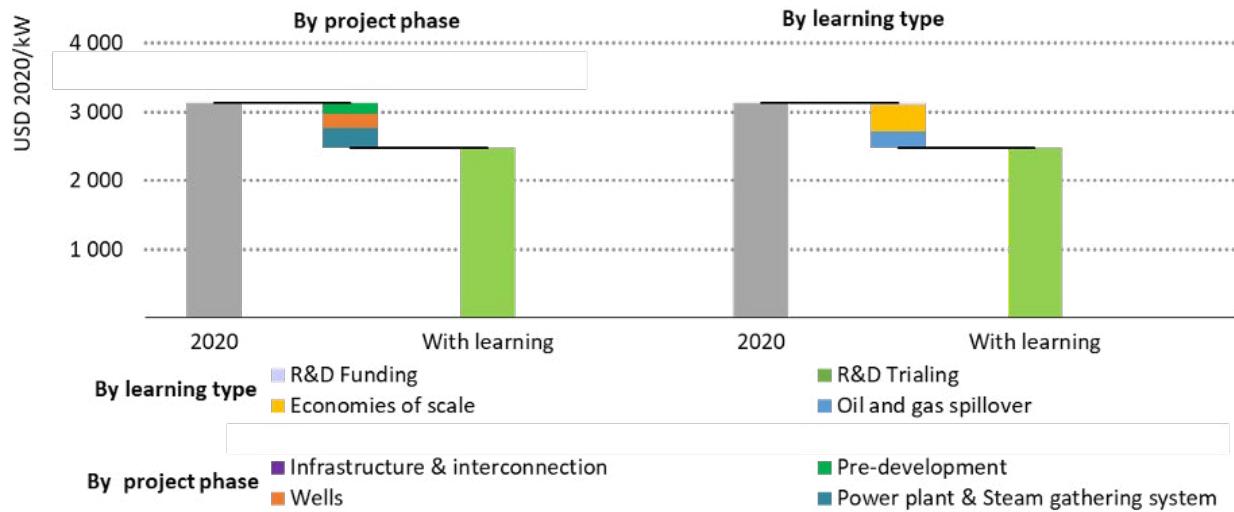


Figure 5.13. Reduction in mid-case capital costs by project phase and learning type for DHCS. Source: *Future of Geothermal Energy in Texas, 2023*.



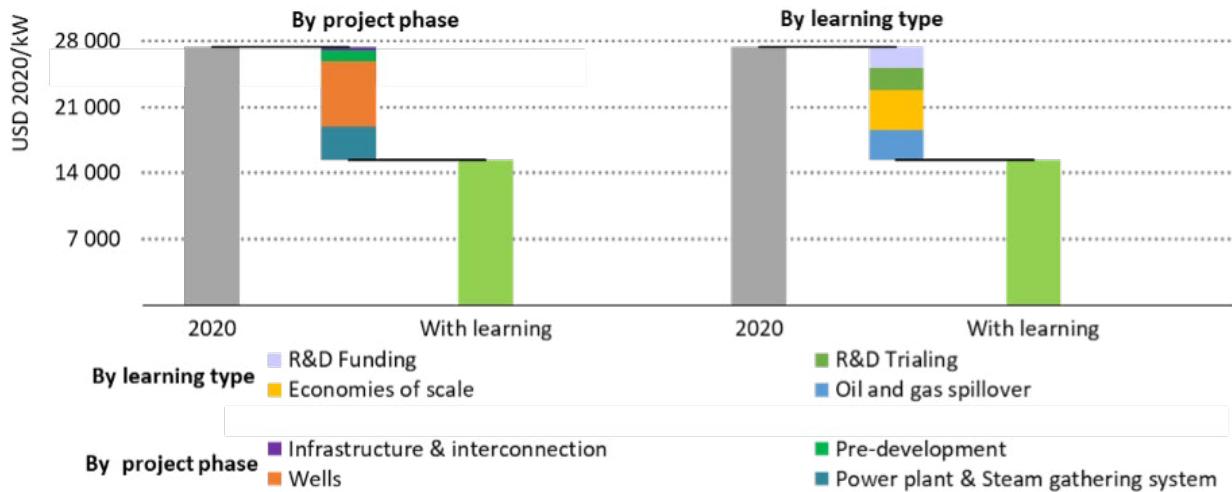


Figure 5.14. Reduction in mid-case capital costs by project phase and learning type for EGS. Source: *Future of Geothermal Energy in Texas, 2023*.

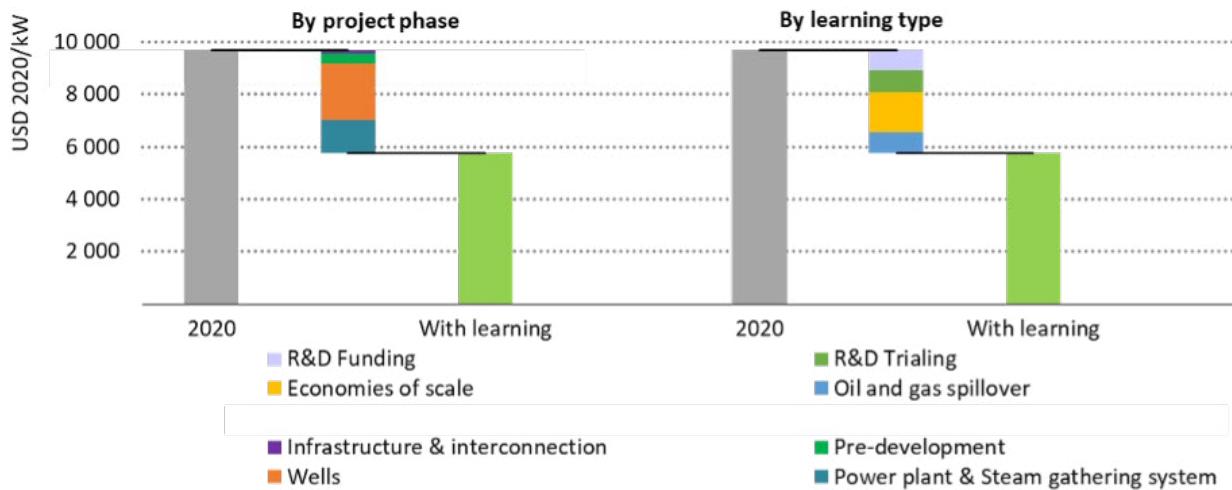


Figure 5.15. Reduction in mid-case capital costs by project phase and learning type for AGS. Source: *Future of Geothermal Energy in Texas, 2023*.



## **5. Discussion**

Potential efficiency gains and cost reductions, largely against the backdrop of recent learnings from unconventional oil and gas technologies and practices, may provide LCOE(H) reductions of six to 25 percent across the range of geothermal technologies. Potential cost reductions are possible, and in some cases significant, even among mature technologies such as shallow DHCS and CHS. All technologies could see a near term benefit from oil and gas spillover that provides quick wins and achievable learnings. The full extent of learnings, projected to be between 20 to 43 percent, will depend on the level of investment support into demonstration and deployment projects, as well as early phase R&D funding. Early support of geothermal in Texas may allow the technologies time to trial and mature with success, allowing for first mover advantage in a new industry, and effective transitioning of people and resources in the 2030s and beyond.

### **B. Conventional Hydrothermal Systems**

CHS has no market, per se, in Texas, but in areas outside of Texas, some cost improvement can be expected with a concerted effort to transfer learnings between the geothermal and oil and gas industries. The transfer of oil and gas practices, including reporting methodologies and drilling efficiencies may function to decrease the cost of CHS by an estimated six percent. The limited supply of CHS resources reduces the impact of economies of scale, but further use of multi-well drilling, and replicated topside designs could serve to reduce costs by another three percent. Spillover from research and development investments to improve EGS and AGS economics, particularly to improve turbine efficiencies or access higher heat, may in turn improve CHS, resulting in a further nine percent reduction in cost.

### **C. Direct Use Heating and Cooling Systems**

DHCS is the only geothermal technology with relatively wide social acceptance that may allow, given supportive policies and market demand, relatively fast cost reductions from both spillover and economies of scale. For DHCS, oil and gas spillover would allow for a nearly ten percent near-term cost reduction, while economies of scale can reduce costs by over 20 percent. Additionally,

other non-financial benefits, such as reduced surface area usage for development, may be attractive for many customers. The use of existing wells and data may allow significant cost reductions for most of the pre-development costs and risks.

### **D. Engineered (or Enhanced) Geothermal Systems**

The range of EGS cost estimates is wide due to technology immaturity, and the range of Texas subsurface temperatures. In practice, this range will reduce once concepts are piloted in Texas, but this serves to highlight the level of technology uncertainty. EGS cost reductions get help from oil and gas spillover, resulting in over 11 percent reduction in costs, with upside enabling reductions of over 50 percent if the technology can reliably achieve commercial rates. R&D funding and learning are essential to driving EGS subsurface, well, reservoir, production, and plant efficiency levels to be competitive with other thermal power generation technologies (reaching around \$60 USD per megawatt hour in a high learning case). EGS needs to be aggressively pushed in all areas of learning to achieve cost-competitive LCOEs, and relies heavily on early oil and gas spillover.

### **E. AGS (or Closed Loop Geothermal Systems)**

AGS cost estimates carry some embedded oil and gas cost carryover assumptions, helping them start at a lower point than EGS, albeit with high uncertainty. In turn, AGS enjoys less impact from oil and gas spillover, and most near-term learning improvements rest on building economies of scale, which account for nearly 60 percent of cost improvements. Operators may experience cost increases as they trial the technology, and begin to troubleshoot surface and subsurface issues. AGS cost estimates approach \$29 USD per megawatt hour with the combination of oil and gas spillover, economies of scale, and success with learning by trialing.

### **F. Emerging Technologies**

R&D on the benchtop and in the field are essential to further drive down geothermal power generation costs. There are several technologies that could reduce costs across most geothermal concepts, including improved turbine efficiencies (and trialing engineered working fluids), accessing higher heat, enabling higher volume



rates (particularly supporting a larger onshore wellbore market, exploration of monobore well designs, or electrical-submersible pumps designed for geothermal applications), and enabling more connected subsurface wellbore designs. Some important elements not described well in literature are operational costs, and relatively high annual thermal degradation due to scaling that projects experience.

### **G. Oil and Gas Crossover is Key to Cost-Competitiveness**

The oil and gas industry could play several important roles in the growth of geothermal, including early adoption of industry practices, reducing exploration risk in sedimentary basins, providing funding and direct resource support, and providing a model for industry standards and best practices. For example, early crossover in DHCS has demonstrated new subsurface design approaches, and is deepening and expanding the resource base for DHCS. The Direct Use market shows clear capabilities to upscale with oil and gas spillover, providing benefits to the industry in the form of smaller surface footprints, and enhanced control and efficiency on integrated subsurface and surface flows. DHCS, with its achievable path to lower costs and its higher maturity, provides a clear case for investment and expansion in Texas and other regions.

In Texas, EGS and AGS have the potential to drive toward LCOEs competitive with gas, and some solar photovoltaic and onshore wind, but this is heavily dependent on oil and gas spillover, particularly from unconventional well engineering practices, to drive improved efficiencies. EGS needs to demonstrate capabilities to develop and operate reservoirs reliably. AGS needs to demonstrate successful application of the physics of the technology in the subsurface, and demonstrate long-term operability. These challenges will need funding from the oil and gas sector and other private and public actors in the next few years for piloting, troubleshooting, iteration, and continued learning.

## **VII. Collaboration and Innovation Models**

The above analysis suggests that there are pathways forward to lower and more competitive geothermal costs

for electricity and heat generation. But the success of this model depends on building collaborations and further innovation in R&D, increasing social awareness and acceptance, developing stronger policy environments, and encouraging demand. Collaboration platforms may be a key way to accelerate action on all of these fronts. In this Section, we will consider collaboration models that have functioned successfully amongst private entities, and oil and gas industry entities in particular. [Chapter 12, Policy, Familiarization, and Regulatory Considerations](#) in this Report considers models for State policy recommendations to support the geothermal industry in Texas.

The drivers for a collaboration platform in the case of geothermal, are enabling enhanced and faster creativity in research, accelerating development and deployment realms, and fostering social acceptance. Collaborative platforms can provide the means and mechanisms to bring together actors from complementary disciplines, sectors, and communication realms (Winickoff, et al., 2021). Winickoff, et al. (2021) describe the cases of the National Nanotechnology Coordinated Infrastructure (“NNCI”) and the field of engineering biology that use social engagement to prevent miscommunication around the technologies, and raise public awareness and acceptance.

### **A. Private Consortia**

Historically, the oil and gas industry has used collaboration initiatives, such as Deepstar, to foster innovation in deepwater reservoirs (Deepstar, 2021). Initiated in 1991, and until recently administered by Chevron, Deepstar managed a project portfolio intended to reduce costs and risks associated with producing oil and gas from deepwater reservoirs. Geothermal innovation similarly requires the convergence of disciplines across subsurface, surface, and digital domains, as well as power markets, grid infrastructure, and other emerging areas of technology that are less familiar to the oil and gas industry. Additionally, compared with deepwater drilling, social acceptance has moved from a rig hundreds of miles offshore, to a technology that may be located in view of someone’s backyard, building a marked contrast in social engagement needs. Oil and gas industry perspectives about working within private consortia are considered in detail in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#).



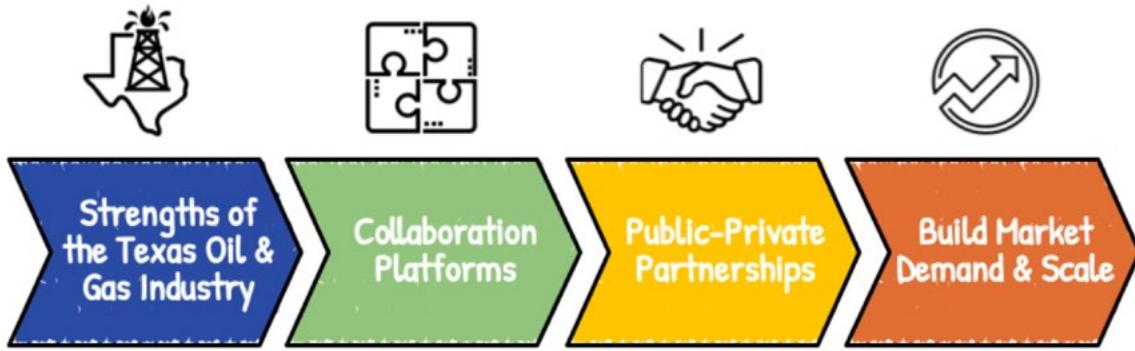


Figure 5.16. Texas as a basis for geothermal growth in conjunction with collaboration platforms and public-private partnerships to build further market demand. Texas' people, assets and supportive policy regime can facilitate geothermal market demand, enhanced by the use of collaboration platforms and public-private partnerships to drive faster learnings, increase public engagement and enhance value creation for industry and investors. Source: *Future of Geothermal in Texas, 2023*.

### B. Public Private Partnerships

As discussed in further detail in [Chapter 12, Policy, Advocacy, and Regulatory Considerations in Texas](#) of this Report, the State of Texas has a history of novel private-public partnerships. For example, the NASA/Space-X partnership successfully increased efficiencies, and drove new innovations in a mature technology sector (Maney, 2015). For the public sector, these partnerships are key to driving efficiency gains, reducing life-cycle costs, and transferring risks. For the private sector, they can provide enhanced return on investment, help gain competitive advantages, and identify new resource or value streams. In the case of Space-X, the technologies needed to effectively and efficiently explore for geothermal bare strong resemblance to technologies needed to explore space or the deepest areas of our oceans. Knowledge and key actors may reside in enterprises such as NASA, the U.S. National Laboratories, or by bridging across to other sciences and art in order to create the connections and generate value needed. The subject of technology transfer between space, defense and geothermal is explored in depth in [Chapter 8, Other Strategic Considerations for Geothermal in Texas](#) of this Report.

## VIII. Conclusion

The oil and gas industry, particularly in Texas with its rich history in energy leadership, assets, resources, friendly policy environment, and social acceptance of subsurface

energy production, could play a critical role in enabling efficiency gains, lowering costs, and demonstrating key elements of geothermal technologies. Next generation geothermal concepts need to prove that they can expand into sedimentary basins to create larger market opportunities, with a roadmap to achieve competitive economics. To achieve this, the geothermal and oil and gas industries should support innovative demonstration projects through direct investment, and using current assets (e.g., seismic and well data, wells, leases, and people). Government, both State and Federal, in turn, can incentivize geothermal projects by insuring or covering a part of drilling costs or by providing grants or concessional loans for first of a kind geothermal projects.

This support could accelerate oil and gas learnings spillover, drive project cost reductions of around five to ten percent, and enable additional economies of scale cost reductions of eight to 30 percent (and perhaps up to 50 percent in some cases). R&D support for benchtop and field trials is also essential to boost innovation and market potential. Industry organizations can enable faster dissemination of best practices, lessons learned, and the development of standards to allow communication of key project parameters and risks to stakeholders. Critical to all elements are new collaboration models for geothermal to enable cross-sector innovation, and increase public awareness to support social acceptance and market demand.



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## Conflict of Interest Disclosure

**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.

**Silviu Livescu** serves as a faculty member in the Petroleum and Geosystems Engineering Department and a co-principal investigator for the HotRock Industry Affiliates Program, both at the University of Texas at Austin, and is compensated for this work. He is also a co-founder of Bedrock Energy, a geothermal heating and cooling startup, and the editor-in-chief of Elsevier's Geoenergy Science and Engineering. Outside of these roles, Silviu Livescu 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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## Chapter 5 Appendix A

The authors of the Future of Geothermal Energy in Texas report are grateful for the participation and insight provided by the following individuals. Thank you for taking the time to share your knowledge and experiences about the learning spillover effects from the oil and gas industry to the geothermal industry that will impact Texas and the globe. Data collected from all participants has been aggregated and anonymized to capture and disseminate trends, views, and perspectives.

### INTERVIEW PARTICIPANTS (listed in alphabetical order)

- Marit Brommer, Executive Director, International Geothermal Association
- Rob Crossley, Senior Petroleum Geologist, CGG
- Nick Cameron, Solutions Senior Delivery Manager, bp
- John Clegg, Chief Technology Officer, Hephae Technology
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- Jordan Nielsen, Engineer, Southwest Research Institute
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- Vikram Rao, Executive Director, Research Triangle Energy Consortium
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- Cindy Taff, Chief Executive Officer, Sage Geosystems
- Jeroen van Duin, General Manager Geothermal, Shell
- Eric van Oort, Professor of Petroleum Engineering, University of Texas, Austin



## Chapter 5 Appendix B

### Transferable practices, technologies, assets and ways of working

Each project phase is segmented into learning types, broken into applicable petroleum technology, practices or assets, and assigned a potential learning cost reduction parameter that varies for a given geothermal technology based on applicability (Table 5.4). We estimate the range of cost reduction that could be realized for each technology, practice or asset based on existing literature and industry interviews. A range (low-medium-high) was developed for each element based on potentially achievable learning. Not all technologies have been assessed. Additional technologies may play important roles in the future. Alternatively, others may not reach the full potential described.

**Table 5.4. Technologies, practices and assets characterized and used to assess geothermal learning curve potentials. Source: Future of Geothermal Energy in Texas, 2023**

Type of Learning	Project Phase	Technology, Practice, or Asset	Cost or productivity improvement range	Low	Mid	High									
Oil and Gas Spillover	Pre-Development	Basin modeling	0 to 70%	0%	0%	0%	20%	40%	70%	0%	30%	50%	0%	30%	70%
Oil and Gas Spillover	Pre-Development	Existing wells and data (well logs, seismic, reports, core)													
Oil and Gas Spillover	Drilling	Drilling efficiency processes	5 to 19%	5%	8%	10%	5%	10%	19%	5%	10%	19%	5%	10%	19%
Oil and Gas Spillover	Drilling	Real-time operating centres													
Oil and Gas Spillover	Drilling	Measuring While Drilling (<200 degC)													
Oil and Gas Spillover	Drilling	Directional well-drilling	5 to 12%	5%	8%	12%	5%	8%	12%	5%	8%	12%	0%	0%	0%
Oil and Gas Spillover	Drilling	Horizontal well-drilling	10 to 20%	10%	15%	20%	10%	15%	20%	10%	15%	20%	0%	5%	10%
Oil and Gas Spillover	Drilling	Multi-lateral wells	Not characterized												
Oil and Gas Spillover	Drilling	Expandable tubulars casing	Not characterized												
Oil and Gas Spillover	Completions	Hydraulic fracturing	0 to 40%	0%	0%	0%	0%	0%	0%	0%	15%	40%	0%	10%	15%
Oil and Gas Spillover	Completions	Multi-zone completions: Plug and perf(orate), sliding sleeves													
Economies of Scale	Development Well Costs	Multi-well pad designs	0 to 30%	0%	5%	10%	5%	15%	30%	5%	20%	30%	5%	20%	30%
Economies of Scale	Completions	Zipper frac operations	0 to 20%	0%	0%	0%	0%	0%	0%	5%	10%	20%	5%	10%	20%
Economies of Scale	Completions	Wellbore clean-out/ drill out	0 to 5%	0%	0%	0%	0%	0%	0%	10%	2%	5%	1%	2%	5%
Economies of Scale	Power plant & Steam gathering system	Modular or replication-focused developments	0 to 40%	0%	5%	10%	5%	15%	40%	5%	15%	40%	5%	15%	40%
R&D Funding	Pre-Development	Seismic acquisition (Broadband)	0 to 20%	0%	10%	20%	0%	10%	20%	0%	10%	20%	0%	10%	20%
R&D Funding	Pre-Development	Seismic processing and interpretation													

Table 5.4. (Continued)

R&D Trialing R&D Funding "	Development	Advanced turbineworking fluids, e.g. supercritical CO <sub>2</sub> ; other	Estimated 0 to 20%	0%	10%	20%	0%	0%	0%	0%	10%	20%	0%	10%	20%
R&D Funding	Development	>200 degC drilling and completion technologies (examples below)	Estimated 0 to 20%	0%	8%	15%	0%	0%	0%	0%	8%	15%	0%	8%	15%
R&D Funding	Development	Measuring While Drilling (>200 degC)	Not characterized												
R&D Funding	Development	High-temperature packers	Not characterized												
R&D Funding	Development	Cementing - high temperature, self sealing	Not characterized												
R&D Funding	Development	Geochemical interactions and scaling reduction	Not characterized												
R&D Funding	Development	Electric Submersible Pump (>175 degC)	Not characterized												
R&D Funding	Development	Onshore large wellbore-sizes	Estimated 0 to 20%	0%	8%	15%	0%	0%	0%	0%	8%	15%	0%	8%	15%
R&D Funding	Development	Reservoir models; Heat, fluid and sweep	Not characterized												
R&D Funding	Development	Reactive transport modeling	Not characterized												
R&D Funding	Pre-Development	In-site stress modeling	Not characterized												
Oil and Gas Spillover	Development	Standardised operational reporting	Applied under drilling efficiency												
Oil and Gas Spillover	Development	Standardised operational reporting	Applied under drilling efficiency												
Oil and Gas Spillover	Miscellaneous	Standardised reserves reporting	Not characterized												
Oil and Gas Spillover	Operations	Digitalisation and integrated systems engineering	2 to 7%	2%	5%	7%	2%	5%	7%	2%	5%	7%	2%	5%	7%
Oil and Gas Spillover	Operations	Additive manufacturing	0 to 5% reduction operational costs	0%	2%	5%	0%	0%	0%	0%	2%	5%	0%	2%	5%

Table 5.5. LCOE calculation key input parameters. Source: Future of Geothermal Energy in Texas, 2023.

Key LCOE input parameters	CHS	DHCS	EGS	CLGS
Annual degradation(%)	0.002			
Capacity factor assumption	Uniform			
Capacity factor(%)	0.83	0.95	0.83	0.83
Project start year	2019			
Development duration(years)	4	1	4	4
Construction duration(years)	4	1 to 2	4	4
Operating life(years)	30			
Operation start year	2027			
Decommissioning costs	5% of total project costs			
Energy revenue escalation rate	2% annually			
Operations and maintenance costs	5% of total project costs, annually			
Ratio of debt (e.g., bank loans) in financing for capital expenditures and refurbishment	Development: 10%, Construction and Operations: 40%			
Cost of debt	3.5%			
Return on equity	8.5%			
Debt term (years)	20			
Debt service coverage ratio	1.30			
Currency for inputs	United States Dollars			
Inflation rate	2.50%			
Central government tax rate	21%			
Local government tax rate	0%			
Depreciation style	Straight-line			





## Chapter 6

# Oil and Gas Industry Engagement in Geothermal: The Data

J. Beard, K. Wisian, S. Livescu, B. Jones

***Publicly available data does not capture the flurry of innovation and engagement in the oil and gas industry for geothermal currently, as many entities have not yet made their strategies and activities public. By analyzing the geothermal interests of fifteen oil and gas majors, both trends and pathways forward emerge.***

### I. Introduction:

The research and analysis in this Report is based on the foundational principle that Texas, as the global epicenter of the oil and gas industry, is uniquely positioned to lead in building the future of geothermal energy, and presumes that the oil and gas industry will be a willing and engaged partner in that leadership. However, if you search the news for evidence of oil and gas engagement in geothermal, aside from a few scattered articles and press

releases, a majority released over the past year, there is scant evidence of significant industry-wide engagement and enthusiasm for geothermal. Why is that? Simply put, a majority of entities, many who have built geothermal strategies, hired internal geothermal teams, funded internal research and development, and are planning geothermal pilots and projects, have not announced their activities publicly.



Some entities report that they plan to make geothermal a part of shareholder and board discussions in 2023, while others state that they are taking their time to consider their public relations strategies for geothermal, or are waiting to review data from pilot projects before announcing their engagements publicly. Either way, with the authors of this Chapter having been frequently engaged with oil and gas industry entities about the opportunity in geothermal since as early as 2017, we note that the accelerating engagement, emerging vision statements, rapidly expanding teams, innovative solutions, internal and external investments, and growing confidence amongst players in this space is a trend that Texas, and indeed the world, should not ignore.

For an industry that is famous for its measured, conservative approaches to new business models, and perhaps equally famous for taking its time to make consequential strategic decisions, the fact that within the past four years, entities have gone from zero or almost zero engagement, to a growing consensus that geothermal is globally scalable, and the challenges solvable by industry in the near term, is extraordinary. As you'll see in the data below, **almost 70 percent of entities interviewed for this Chapter reported that there are no technology challenges associated with geothermal that the oil and gas industry cannot solve.**

In a divergence from the typical format of a formal reporting of research results, a personal story of an author may help shed light on the driving force behind this Chapter. In 2021, Chapter co-author Jamie Beard performed a TED talk entitled "The Untapped Energy Source That Could Power the Planet" to an audience that was not entirely warm to the idea of the oil and gas industry leading the future in any way, much less a way that would preserve the status quo of drilling and subsurface energy extraction. After her talk ended, she spent the rest of the conference exchanging with often irate audience members, many who did not believe that the oil and gas industry would take the geothermal opportunity seriously, or have the capability of enabling global scale for geothermal, even if we could get past the clearly present issues of polarization and mistrust. One man stated in exasperation at the end of a particularly heated discussion, "We've heard it all before from big oil – and by the way – you don't know them. You are going to find yourself disappointed."

As he walked away, Jamie remembers thinking "I do know them." Indeed, she had been collaborating actively with "them" for years, and was privy to the accelerating energy in the industry for geothermal. In fact, it was the weight of the industry, the technical competence, and the confident voices of industry veterans that provided the foundation for her to get up on the stage and say the things she did in her talk. But it also occurred to her that there was no publicly available data to backup all that she was seeing and hearing from industry about geothermal. This Chapter is an attempt to address that need, to serve as a stopgap until more entities are ready to begin discussing their plans and strategies with the world.

## II. Research Objective and Methodology

In this research, fifteen oil and gas industry majors were identified to be interviewed anonymously about their engagement in geothermal. Entities were chosen based on authors' knowledge of entity engagement in the space, and assuring a diverse sample size that represented 1) different sectors of the industry, including operators, oil field service companies, drilling contractors, and tool makers/suppliers, 2) varying entity sizes, and 3) varying regions globally in which the entities operate. All entities agreed to provide data about their interests and engagement in geothermal anonymously to authors, and that data would be analyzed and shared in aggregate format, with no attribution to any particular entity. Interviews took place virtually over a period of months in 2022, and were attended by oil and gas entity teams, and a combination of one and three authors of this Chapter, depending on the schedules of the authors.

Authors note that the fifteen entities interviewed are not an exhaustive list of oil and gas industry entities engaged in geothermal. In fact, since a majority of the interviews for the Chapter concluded, several additional majors have entered the space, some with now public presence. The subset of entities interviewed represents a snapshot across a diverse set of entities so we might view and act on emerging trends, and is not an attempt at a wholly inclusive list.



Table. 6.1. Companies interviewed for this research analyzing oil and gas industry engagement in geothermal. Entities interviewed are listed in alphabetical order by column. Source: *Future of Geothermal Energy in Texas, 2023*.

International Oil Company	Independent Operator	Oilfield Service	Drilling Contractor	Supplier/Tools
bp	Calpine Corporation	Baker Hughes	Helmerich & Payne, Inc.	NOV Inc.
Chevron Corporation	Chesapeake Energy Corporation	Weatherford International	Nabors Industries Ltd.	
Repsol S.A.	Continental Resources, Inc.			
Shell	Ecopetrol S.A.			
TotalEnergies SE	Murphy Oil Corporation			

Note that while we have separated entities by industry sector for illustrative purposes above, we will not maintain this separation in the presentation of the data, as all responses have been aggregated across all entities to preserve anonymity.

### III. Research Outcomes

Questions were asked to participating entities across five themes, 1) timing of engagement and strategy, 2) types of geothermal technologies, concepts, and resources of interest, 3) ability of industry to address challenges in geothermal, 4) pilots and research and development ("R&D"), and 5) collaboration and consortia.

Responses were then aggregated and organized into the graphical representations below. Specific questions asked of the entities are listed in the headings preceding each graphic. Where the answer to a question was not binary, or required explanation from the entity, details are provided in narrative format to give further context to the data or outcome. We have also noted below where trends emerged in the data that were not well captured by the graphical representations.

#### A. What Year Did Your Entity Begin Engaging in Geothermal?

For the purpose of this question, "engage" was defined to mean significant and sustained interest sufficient to justify the application of resources to geothermal, either

through the funding of internal R&D and/or teams, or external investment in ventures and/or pilots.

One entity reported sustained engagement since the 1980's, which is represented in the graphic (but beginning in 2010 for the sake of brevity). Three entities reported that they had some engagement in geothermal historically, one as early as the 1960s, either through investments made in projects, or tools/services they provided to the geothermal industry, but that interest had waned before picking up pace significantly over the past few years. These more sporadic periods of prior engagement are not represented in the graphic.

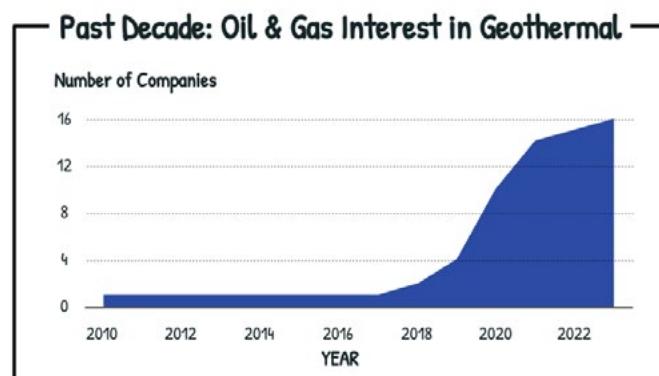


Figure 6.1. Oil and gas entity engagement in geothermal over the past decade. Source: *Future of Geothermal Energy in Texas, 2023*.



The graphic demonstrates an increase in engagement since 2018, increasingly rapidly beginning in approximately 2020 to present. Reasons provided by entities for their recent increased engagement in geothermal varied, and included increased bandwidth in internal teams as a result of the COVID driven industry downturn, corporate commitments to emissions reductions and/or carbon neutrality, participation in or attendance of the PIVOT conference series (PIVOT, 2022b) which increased awareness of the sector, societal and institutional investor pressure with regard to Environmental, Social and Governance (“ESG”) concerns, alignment with existing or planned investments in green hydrogen and/or carbon capture, utilization, and storage (“CCUS”), or combinations of these factors.

Entities broadly agreed that geothermal is a rational part of their larger diversification strategies due to the significant skills and expertise overlap between industry and geothermal. About half of entities reported that their engagement began as a “grassroots” movement, which gained traction and worked its way into upper level management, or in the case of two entities, presentations to the Board. Others reported that the inquiries came from the “top down” after either institutional investors or major shareholders posed questions about geothermal to the C-suite, or an executive became interested in the topic.

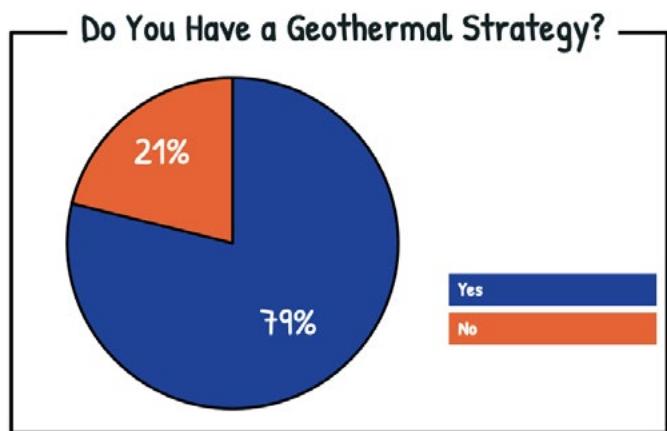


Figure 6.2. Oil and gas entities with a geothermal strategy, either adopted or in development.  
Source: Future of Geothermal Energy in Texas, 2023.

### B. Do You Have a Geothermal Strategy in Place?

For the purpose of this question, “geothermal strategy” is defined as an opportunity or market analysis, plan for engagement, business model, investment strategy,

or any other internal strategic document focused on geothermal, either adopted or in development currently.

79 percent of companies interviewed have some form of geothermal strategy. Of the entities who answered “no” (21 percent), 75 percent of them reported that the purpose behind the formation of their internal geothermal team was to explore the need for such a document and/or create one. Of the entities who answered “yes” (79 percent), more than 60 percent of them reported that their strategy document has led to either an investment in a geothermal pilot or startup, or the publication of a report and/or marketing materials focused on geothermal over the past two years.

### C. Which Concepts, Resource Types, Technologies, and Trends are Oil and Gas Entities Engaging With in Geothermal?

For this next series of questions, we asked entities to answer “yes,” “no,” or “maybe” to indicate their level of interest and/or engagement in a variety of geothermal concepts, resource types, and technologies. Interest and/or engagement was defined for the purpose of this Section as sustained interest or inquiry that may lead to engagement by the entity in this technology focus area. An answer of “maybe” was appropriate in this series of questions where an entity was marginally interested in the topic, but did not consider it within their primary areas of interest or expertise, or viewed the concept as sufficiently flawed as to diminish their interest in the topic. Nuances like these in the data will be explored, as applicable, after each graphic.

This Section is divided into the following groups, 1) types of geothermal technologies, 2) type of geothermal resource, 3) types of technologies and methodologies transferrable to geothermal from oil and gas, and 4) emerging trends. Details on these four topics are explored further in Chapter 1, Geothermal and Electricity Production.

#### 1. Geothermal Technologies

The following geothermal technologies are explored in the Section below: 1) Traditional Engineered Geothermal Systems, 2) Next Generation Engineered Geothermal Systems, 3) Advanced Geothermal Systems/Closed Loop Geothermal Systems, 4) Direct Use Heating and Cooling Systems, 5) Oil and Gas Well Reuse, and 6) Hybrid Geothermal Systems.



### a. Traditional Engineered Geothermal Systems

For the purpose of this Section, Traditional Engineered Geothermal Systems ("Traditional EGS") are defined as an Open to Reservoir Scalable Geothermal concept that utilizes hydraulic fracturing to engineer or enhance a subsurface reservoir for the purpose of producing geothermal heat or electricity, but that does not utilize advanced directional drilling and/or frac'ing techniques, such as horizontal drilling and multi-stage fracturing.

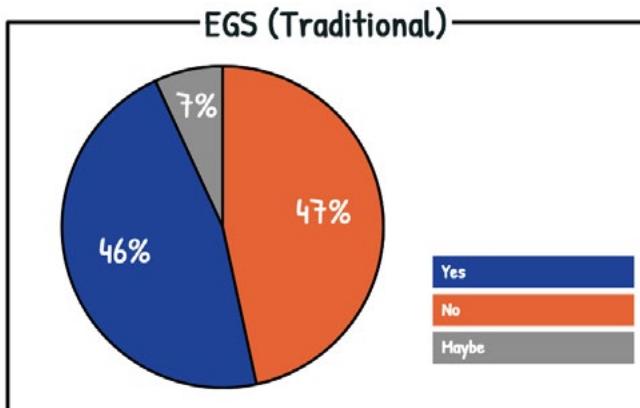


Figure 6.3. Oil and gas entities engaged or interested in Traditional Engineered Geothermal Systems ("EGS"). Source: *Future of Geothermal Energy in Texas, 2023*.

Of the 47 percent of the entities who answered "no," 70 percent expressed doubt about the technical feasibility, likelihood of success, and/or operations and maintenance challenges associated with Traditional EGS concepts, while 30 percent expressed that they did not consider it to be within their primary areas of interest or expertise.

### b. Next Generation Engineered Geothermal Systems

For the purpose of this Section, Next Generation Engineered Geothermal Systems ("Next Gen EGS") are defined as an Open to Reservoir Scalable Geothermal concept that utilizes hydraulic fracturing to engineer or enhance a subsurface reservoir for the purpose of producing geothermal heat or electricity, that incorporates advanced directional drilling and/or frac'ing techniques, including but not limited to, horizontal drilling and multi-stage fracturing.

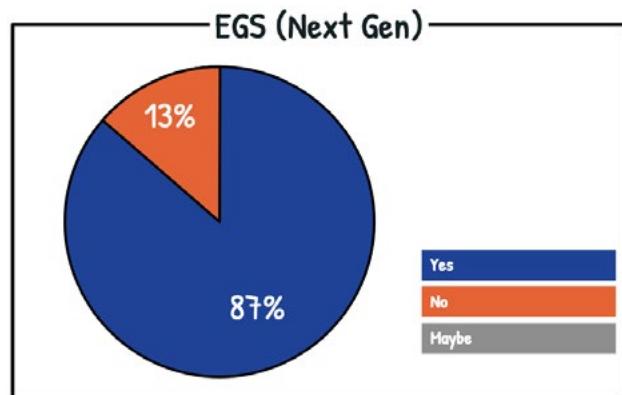


Figure 6.4. Oil and gas entities engaged or interested in Next Generation Engineered Geothermal Systems ("EGS"). Source: *Future of Geothermal Energy in Texas, 2023*.

Noteworthy here is the level of agreement amongst entities (87 percent) that EGS concepts need to evolve and utilize cutting-edge technologies to increase the likelihood of success of EGS projects. Also notable is that at least one entity stated that while it did not consider Traditional EGS to be within its area of expertise, it believed it had contributions to make in the Next Generation EGS space.

### c. Advanced Geothermal Systems/Closed Loop Geothermal Systems

For the purpose of this Section, Advanced Geothermal Systems/Closed Loop Geothermal Systems ("AGS") are defined as a Closed to Reservoir Scalable Geothermal concept that can take a variety of configurations, but that rely primarily on conduction for heat exchange between the subsurface and the well.

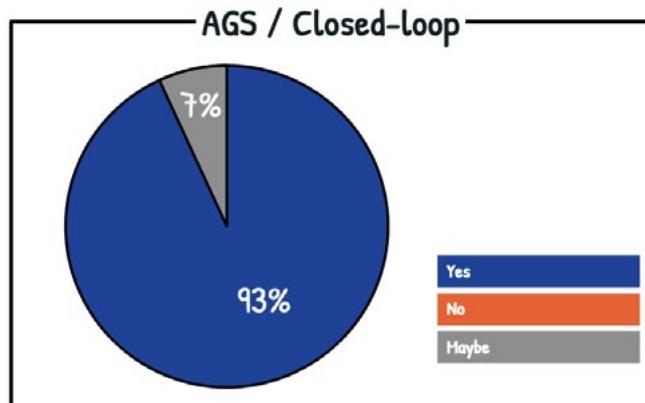


Figure 6.5. Oil and gas entities engaged or interested in Advanced Geothermal or Closed-Loop Systems ("AGS"). Source: *Future of Geothermal Energy in Texas, 2023*.



93 percent of all entities responded "yes" to a level of interest and/or engagement in AGS. Several entities responding "yes" reported that their interest in this concept surrounds the potential for use of novel engineered Working Fluids, or supercritical carbon dioxide ("sCO<sub>2</sub>"), to harvest heat at lower temperatures than water requires. Others noted that they are most interested in pursuing AGS in deeper, higher temperature reservoirs, with three mentioning SuperHot Rock (considered separately below) in particular. A smaller proportion of entities described their interest in the context of oil and gas Well Reuse, and the production of heat from such wells for Direct Use (also considered separately below). Authors note that this is an area of increasing and enthusiastic industry interest that is remarkably out of step with current funding and support for geothermal on the Federal level, and an area where the State of Texas could lead with supportive policies and incentives.

#### d. Direct Use Heating and Cooling

For the purpose of this Section, Direct Use was defined broadly to include both shallow heating and cooling projects, and deeper, higher temperature commercial and industrial heat projects.

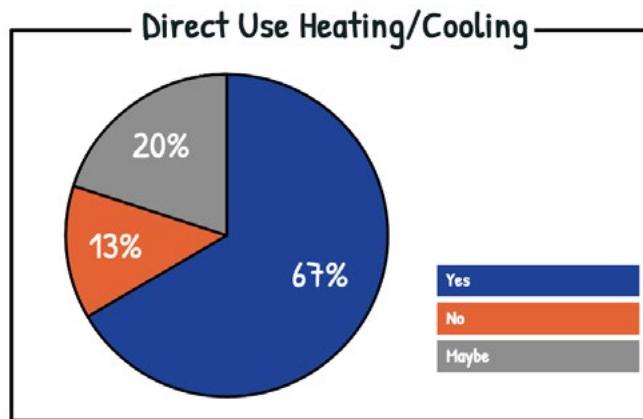


Figure 6.6. Oil and gas entities engaged or interested in Direct Use Heating and Cooling ("DU"). Source: Future of Geothermal Energy in Texas, 2023.

Of the 67 percent of entities responding "yes," almost 50 percent referred to oil and gas Well Reuse as a potentially viable source of Direct Use heat, with the caveat that currently co-located off-takers for the heat may be rare at the most promising sites in Texas due to remote well locations, but that there could be opportunities to

build industry on the best sites, for instance, bitcoin mining or data centers. Several of these entities also pointed to the opportunity of geothermal Direct Use to decarbonize industrial heat needs along the Texas Gulf Coast. In particular, two entities who answered "yes" pointed to Deep Direct Use ("DDU") for large-scale commercial buildings as a potentially viable model for oil and gas companies to pursue in Direct Use that would utilize existing skill sets. At least two entities expressed their interest in Direct Use as contingent upon a viable geothermal power project, with waste heat from the plant utilized for other purposes. These entities therefore would not seek to develop a stand alone Direct Use project, but may be interested in utilizing waste heat from a power project for other purposes.

Entities answering "no" or "maybe" failed to see a viable business model for oil and gas entities in drilling and developing heating and cooling projects, particularly shallow and low-temperature projects, or did not consider Direct Use to be within their area of expertise.

#### e. Oil and Gas Well Reuse

For the purpose of this Section, Oil and Gas Well Reuse is defined as any concept that uses an existing hydrocarbon well for a geothermal purpose, whether that be through full geothermal conversion, or co-production concepts that harvest both hydrocarbons and heat.

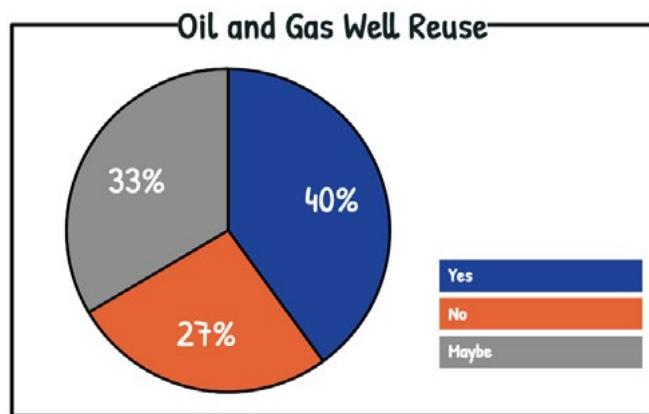


Figure 6.7. Oil and gas entities engaged or interested in Oil and Gas Well Reuse. Source: Future of Geothermal Energy in Texas, 2023.

The entities were not in agreement on the potential for the reuse of oil and gas wells, with only 40 percent



responding “yes.” Several of the entities answering “yes” pointed to the potential for decarbonization of on-site oil and gas operations using co-produced heat from hydrocarbon wells. One entity noted that this potential will be limited by the speed and scale of oil and gas operation electrification, and also by the efficiency of power production equipment like Organic Rankine Cycle (“ORC”) turbines. Others referred back to their Direct Use answers, and noted that oil and gas wells are likely not well suited for power production, but may provide a viable source of Direct Use heat if there are nearby or co-located off-takers. Several entities answering “yes” or “maybe” expressed that existing wells may be an inexpensive pathway to pilot new geothermal concepts in terms of the subsurface information they provide and reduced drilling costs associated with the pilot, but may not be appropriate to convert into operating geothermal assets long term.

Entities answering “no” and “maybe” pointed to challenges such as well integrity, limited flow rates due to the smaller casing sizes used in oil and gas, legal and liability uncertainty, remote location of wells, insufficient temperatures to support project viability, and the potential for unintended hydrocarbon production in situations of full well conversion.

#### f. Hybrid Geothermal Systems

For the purpose of this Section, Hybrid Geothermal System is defined as combinations of two more technologies or concepts, with at least one of them being geothermal, such as more than one geothermal concept (AGS/EGS, for example) combined into one system, or geothermal coupled with technologies such as hydrogen or lithium production, subsurface energy storage, et al.

Of the 67 percent of the entities who responded “yes,” they did so with enthusiasm, expressing that hybrid systems are likely to improve project economics, and have helped them align geothermal with other strategic investments of their entities, CCUS being an example that was raised by several entities.

Entities who answered “maybe” and “no” were more doubtful that hybrid concepts would benefit projects, instead expressing the concern that hybrid concepts would introduce additional risks to projects, and may complicate diligence and financing due to additional complexity. One entity expressed a view in the middle

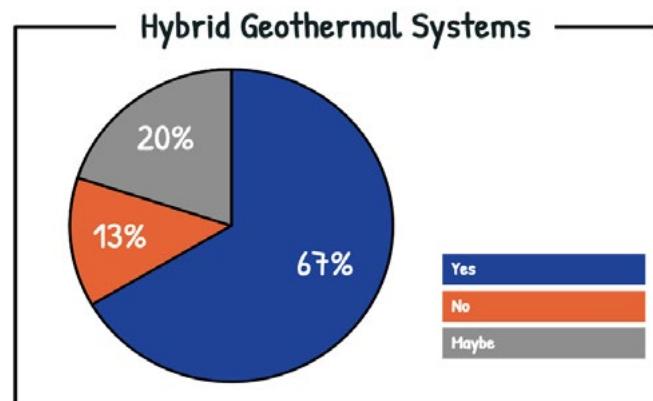


Figure 6.8. Oil and gas entities engaged or interested in Hybrid Geothermal Systems. Source: *Future of Geothermal Energy in Texas, 2023*.

of these two positions, stating that they believe adding a hybrid component to a geothermal project may help the economics of otherwise marginal projects, but for projects not on the margin, it would be easier to pursue geothermal as a stand alone project.

#### 2. Type of Formation/Resource Targeted

As discussed in detail in [Chapter 1, Geothermal and Electricity Production](#) and [Chapter 4, The Texas Geothermal Resource](#), there are several geothermal resource types in Texas where geothermal projects are likely to be developed over the coming years, with sedimentary formations and Blind Hydrothermal Systems being the largest and nearest term opportunity, and deeper SuperHot resources coming later when enabled by technological advancements. In this Section, we asked entities for their opinions and levels of excitement about these Texas present resources, and also about another geothermal resource type, Hydrothermal, which is not present in Texas, but that oil and gas entities have begun to engage in outside of the State.

##### a. Hydrothermal

For the purpose of this Section, Hydrothermal resources, also referred to as Conventional Hydrothermal Systems (“CHS”) elsewhere in this Report, are defined as geothermal resources having a combination of sufficient naturally occurring porosity in the subsurface, sufficient heat transfer into the system, and the natural presence of water in the subsurface, together producing a near surface developable resource.



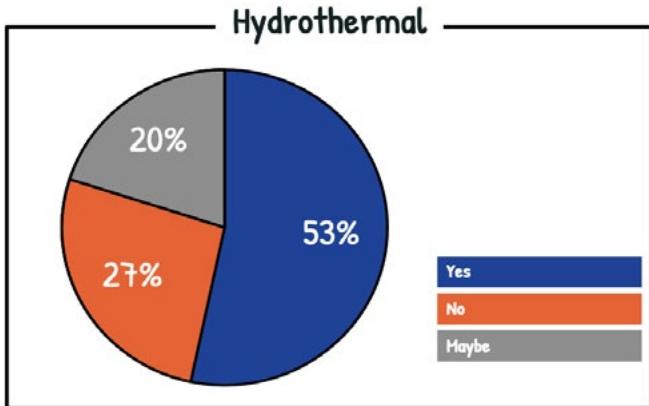


Figure 6.9. Oil and gas entities engaged or interested in Conventional Hydrothermal Systems (“CHS”). Source: *Future of Geothermal Energy in Texas, 2023*.

There are no CHS present in Texas, however, we included the resource in our interview because a number of oil and gas entities have begun to engage in hydrothermal projects in various locations globally, and we hoped to offer some color about why some entities have chosen that path.

Hydrothermal, similar to Traditional EGS, tends to be a divisive topic where there is little agreement amongst oil and gas entities about the viability of the global hydrothermal opportunity. If you are not in the oil and gas industry and immersed in these discussions, you might wonder what all the fuss is about. Hydrothermal makes up a majority of the geothermal developed in the world today, and is ubiquitous in geothermal famous places in the world, such as Iceland. But due to a history of oil and gas consideration, analysis, and investment/divestment in the space, it is a subject of debate and a source of bias against geothermal in the industry.

On the one hand, some entities view hydrothermal as globally insignificant, geographically limited, and a niche opportunity, where there is little room for innovation and scale, and where development is limited by the location of the resource, which tends to be in remote regions of the world. This sentiment is fairly summarized in an interview in 2020 between one of this Chapter’s co-author, Jamie Beard, and Vik Rao, former CTO of Halliburton, now Executive Director of the Research Triangle Energy Consortium. The article was published by HeatBeat and aptly named “I Hated Geothermal, Then I Realized It Is Now Scalable” (HeatBeat, 2020). This issue was also explored by a panel of experts at the PIVOT2022 conference, with

a more hopeful outlook about the prospect of oil and gas entities engaging in the hydrothermal space (PIVOT, 2022a).

For the entities who answered “no” or “maybe” to this question, many of their comments echoed the themes in the above article, with one interviewee stating that oil and gas would achieve a faster and more impactful learning curve going after the larger and more scalable prize in geothermal, which is Hot Dry Rock, or “geothermal anywhere.” Others opined that the oil and gas industry would have little to contribute, aside from perhaps pre-project subsurface characterization, to the already mature and technologically enabled hydrothermal landscape.

On the other hand, more than half of interviewed entities expressed not only interest, but active engagement in hydrothermal exploration and projects. Some of these projects have been announced publicly since interviews were conducted, including projects and partnerships being pursued by Repsol, Chevron, Ecopetrol, and Shell, discussed in further detail elsewhere in this Report, while others are set to be announced in 2023. Entities interested in hydrothermal made the case generally that hydrothermal offers a straightforward avenue to “ease” into geothermal, to collect data and learnings in the field with relatively low risk, to get geothermal electrons onto the grid, make the business case and gain further traction for geothermal within their entities, and offers an opportunity to work with traditional geothermal industry players and exchange learnings and knowledge.

A majority of supporting entities readily agreed that hydrothermal is a geographically limited resource that has its fair share of challenges (resource decline over time, and exploration risk were raised by more than one entity), but argued that there is a sufficient development runway for hydrothermal globally for industry to engage, learn, and then move on to more complex and technically difficult projects, like EGS and AGS. One entity argued that in order to pursue geothermal, their team had to demonstrate a viable business case out of the gate to their management, and hydrothermal was the only avenue currently, out of all geothermal concepts, where they were able to do that.



## b. Blind Hydrothermal and Sedimentary Resources

For the purpose of this Section, sedimentary geothermal resources are defined as any concept intended to harvest heat and/or power from sedimentary basins, and Blind Hydrothermal Systems are defined similarly, but include the natural presence of sufficient amounts of water in the sedimentary formation for geothermal production. Due to their similar nature geologically, and often close proximity to one another geographically, we grouped these two dominant Texas sedimentary geothermal resources together into one inquiry.

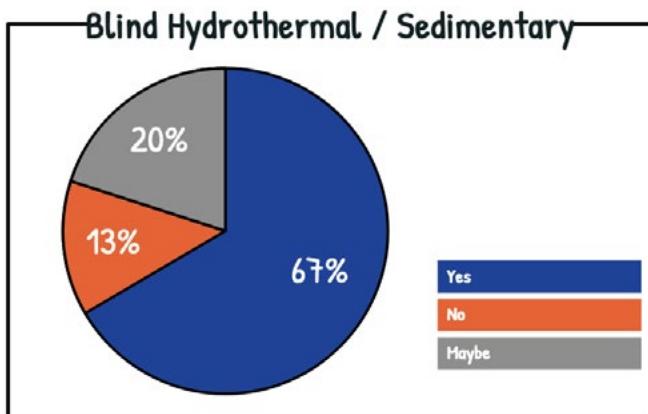


Figure 6.10. Oil and gas entities engaged or interested in Blind Hydrothermal/Sedimentary Resources. Source: *Future of Geothermal Energy in Texas, 2023*.

67 percent of the entities responded "yes," with several entities having made, or were in the process of making at the time of the interview, investments in startups working in this area. At least two entities expressed enthusiasm for the contributions their entities may make in the characterization of sedimentary and Blind Hydrothermal Systems, with one entity expressing that they are actively working on this internally. Notably, several entities who responded "no" to hydrothermal, responded "yes" to blind hydrothermal, noting that blind hydrothermal is a global frontier that is not yet well defined, and may be a significant resource that oil and gas could not only help explore for and characterize, but also develop.

Because sedimentary basins tend to be low to mid-enthalpy resources, engineered Working Fluids or sCO<sub>2</sub>, which have lower supercritical points than water, were raised by more than one entity as potential avenues forward when discussing methods for developing

sedimentary basins. One entity expressed concern about the price of purchasing CO<sub>2</sub>, noting that currently CO<sub>2</sub> is mined and sufficiently costly to ruin the economics of a project, and that until CO<sub>2</sub> is either free, or entities get paid to sequester it in systems, it is not a realistic Working Fluid medium at scale. Entities who answered "maybe" expressed doubt about the economic viability of sedimentary resources, aside from potentially Direct Use heat applications, given their lower temperatures compared to basement formations.

## c. SuperHot Rock

For the purpose of this Section, SuperHot Rock is defined as any concept intended to harvest heat and/or power from geothermal resources that are at or exceed the supercritical point of water at about 373°C (about 707°F). Developing these resources will require deeper drilling into harder rock types, under more extreme temperatures and pressures than other geothermal resource types. At the time the interviews took place, several interviewees had made, or were in the process of making, investments in startups pursuing SuperHot Rock resources.

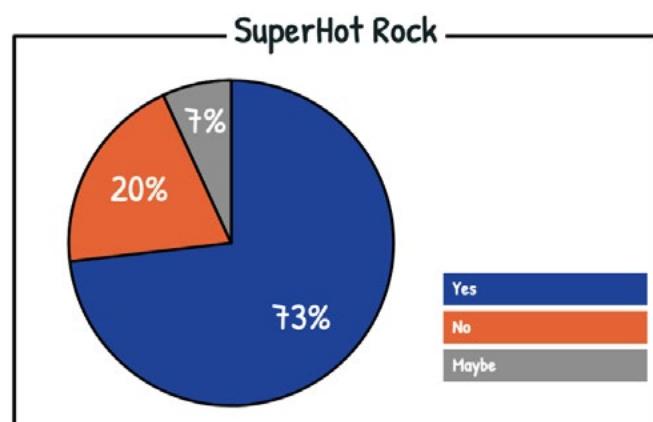


Figure 6.11. Oil and gas entities engaged or interested in SuperHot Rock ("SHR"). Source: *Future of Geothermal Energy in Texas, 2023*.

73 percent of entities responded "yes" to a level of interest and/or engagement in SuperHot Rock resources. Given that oil and gas tends to be a conservative industry that learns incrementally, the level of enthusiasm for SuperHot Rock within oil and gas entities is surprising. As will be discussed further in the Challenges Section below, several entities expressed that SuperHot Rock related challenges are the most significant and onerous in geothermal, but all entities who expressed this concern also expressed



confidence that the industry can and would overcome them. At least two entities expressed interest in utilizing SuperHot resources for coal plant conversion projects, and those who answered “yes” generally agreed that efficiently accessing SuperHot resources would likely solve efficiency and cost challenges associated with geothermal projects. Conversations with interviewees about SuperHot resources tended to be dominated by discussions about drilling, technology gaps, and required R&D. We will reserve those discussions for their respective Sections below.

### **3. Technologies and Methodologies**

In the next series of questions, we asked entities about their engagement in the transfer of various technologies from oil and gas to geothermal, and about the development of new technologies specifically to support their engagement in geothermal.

#### **a. Resource Characterization**

For the purpose of this Section, Resource Characterization is defined in a micro sense as local, project specific subsurface analysis performed for the purpose of project siting, risk assessment, and risk mitigation. In a macro sense, Resource Characterization is defined as the process of utilizing oil and gas data, and exploration technologies and/or techniques to map or predict the presence and depth of geothermal resources globally.

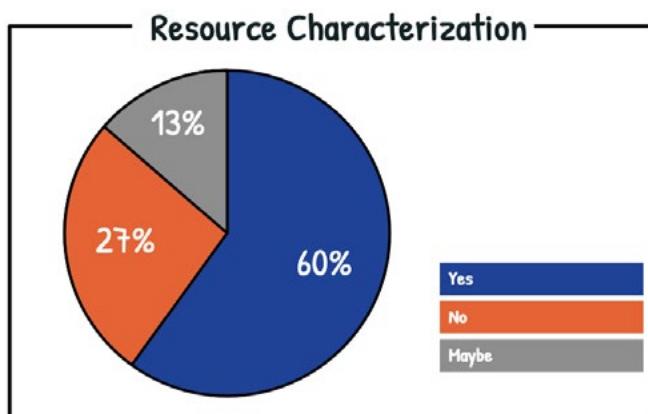


Figure 6.12. Oil and gas entities engaged or interested in Resource Characterization. Source: *Future of Geothermal Energy in Texas, 2023*.

Different entity types engaged with this question in different ways. Of the 60 percent of entities who answered “yes,” the majority tended to be operators,

though that was not always the case. Within the category of “yes” answers, entities taking a more global approach to Resource Characterization tended to be International Oil Companies (“IOCs”), while Independents tended to view their contribution to Resource Characterization as regional or project specific. Amongst IOCs, several entities referred specifically to global characterization of Blind Hydrothermal Systems, depth to basement rock, and SuperHot anomalies. Amongst entities who answered “yes,” there was little doubt about the value of their data and capabilities in this area, and the transferability of oil and gas exploration technologies and techniques into the geothermal realm.

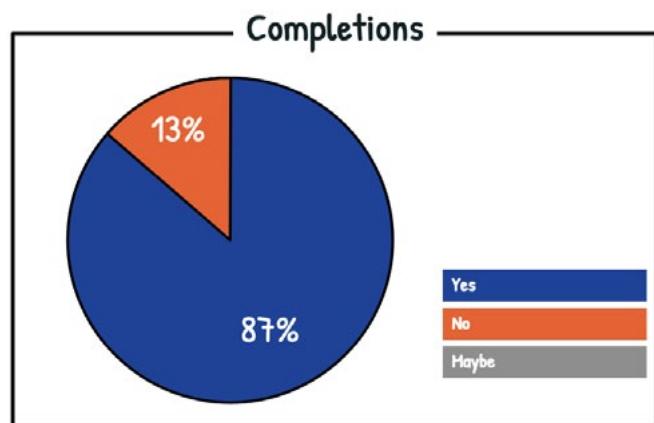


Figure 6.13. Oil and gas entities engaged or interested in Completions Technologies and Techniques. Source: *Future of Geothermal Energy in Texas, 2023*.

Oilfield service companies, drilling contractors, and suppliers tended to answer this question as “no” or “maybe,” though several answered “yes.” For those who answered “yes,” they viewed some of their existing technologies that they deploy in oil and gas as likely to make significant contributions in the realm of characterization. Entities who answered “no” felt that resource characterization was simply not within their area of expertise.

#### **b. Completions**

For the purpose of this Section, Completions are defined as preparing a geothermal well for operation after the drilling process is completed. Across geothermal technologies, Completions can involve different technologies and techniques, with EGS involving hydraulic fracturing, for instance, and AGS involving novel casing and cementing procedures.



87 percent of entities answered "yes," suggesting that Completions is an area where significant leaps forward can be made through the transfer of oil and gas technologies, methods, and techniques into geothermal. At least two entities expressed concern that this is a technology area where existing geothermal methods are "decades behind" oil and gas.

While the entities answering "yes" tended to agree that the application of advanced stimulation techniques, like multi-stage fracturing, provided low hanging fruit to advance EGS Completions, there was less consensus amongst entities about the future of AGS Completions. At least one entity expressed the view that AGS Completions are likely to be "significantly more technically complex" than is currently acknowledged when AGS concepts are discussed publicly. Another entity expressed that in the context of AGS, innovations like new valve configurations will likely be needed to increase the commercial viability of AGS.

At least two entities expressed concern about the number of unknowns in the realm of completions for SuperHot Rock concepts, noting that we currently have sparse operational understanding of the mechanical behavior and evolution over time of rock and fractures at SuperHot temperatures and pressures, and that currently available Completion technologies in industry, with cements being a frequently mentioned example, are not well suited for reliable, long term performance at these higher temperatures and stresses. Nevertheless, entities expressed general enthusiasm for taking on these challenges, suggesting that even where concerns were raised, that the challenges were likely not insurmountable for the oil and gas industry.

### c. Drilling Technologies

For the purpose of this Section, Drilling Technologies is defined to include 1) the application of existing oil and gas drilling technologies and techniques to geothermal applications, 2) the adaptation of existing oil and gas drilling technologies and techniques to perform better in geothermal drilling applications, and 3) next generation, energy based drilling technologies, such as plasma, laser, particle, and millimeter wave. Across these three drilling categories, 80 percent of entities reported engagement in this topic through either ongoing internal R&D, field trials of newly developed technologies, or investments in startups pursuing drilling technologies.

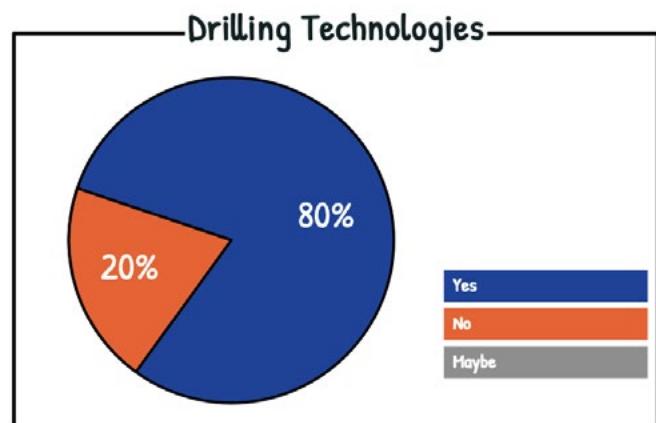


Figure 6.14. Oil and gas entities engaged or interested in Drilling Technologies. Source: Future of Geothermal Energy in Texas, 2023.

Of the entities who answered "yes," all, with the exception of two entities, expressed at least some engagement across all three drilling technology types. Also amongst entities who answered "yes," operators tended to report engagement in this space through partnerships and/or investments, while oilfield service, drilling contractors and suppliers tended to report direct engagement through internal R&D, field trials, and investments. Approximately half of entities answering "yes" across all entity types expressed a desire to attempt existing oil and gas tool adaptation before investing heavily in next generation drilling technologies, noting that some existing off the shelf technologies from oil and gas were just beginning to be utilized in the geothermal space with significant impact.

While almost all entities who answered "yes" to this question reported engagement across all three drilling technology types, of the three, next generation drilling technologies enjoyed the least amount of consensus. At least two entities reported prior significant internal investments in next generation drilling technologies, with disappointing results. Others expressed operational concerns with the deployment of next generation technologies, including issues such as inadequate power supply both on the rig, and downhole to operate the technologies, the need for rig and workflow redesign to accommodate the technologies, and the potential for workforce safety hazards. At least two entities raised the next generation tool power supply concern as significant, noting that without significant advances in downhole power supply methods, such as wired pipe, next generation technologies will fail to launch.



When discussing integration of next generation drilling technologies into oil and gas rigs and workflows, at least two entities used the term “Rig of the Future” specifically to describe their engagement in this space, and at least one entity stated that the goal of their pending investment in a startup pursuing next generation drilling technologies was to further their internal goal of pursuing Rig of the Future designs.

100 percent of entities who answered “no” to this question were operators, with at least one expressing the potential of partnering in this area in the future, but no current substantive engagement.

#### d. Operations and Maintenance Innovations and Technologies

For the purpose of this Section, Operations and Maintenance is defined to mean any technology or method applied to achieve operation of a geothermal power or heat operation, including both the subsurface and surface. This definition opened up several interesting lines of discussion with entities about their future business models in geothermal, which we will attempt to capture in the comments below.

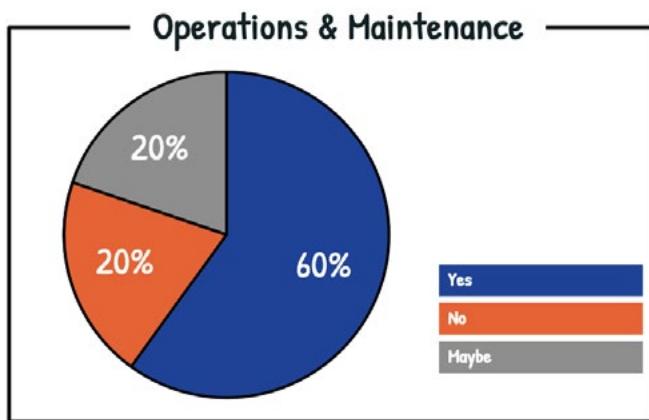


Figure 6.15. Oil and gas entities engaged or interested in Operations and Maintenance (“O&M”).  
Source: *Future of Geothermal Energy in Texas, 2023*.

Overall amongst interviewees, there was a good deal of consensus regarding the need for entities to continue to engage in geothermal projects after the well and project construction phase, and into operational years, with 60 percent answering “yes.” With regard to the subsurface, there was also general consensus about why this continuing engagement would be required. EGS, AGS, and

Hybrid Geothermal Systems will require close monitoring of the subsurface and system to assure that operational challenges like fracture evolution, short circuiting, scaling, well integrity, et al. are mitigated and managed if they do occur. Scalable geothermal projects of all types are also likely to require constant monitoring for induced seismicity for the lifetime of the project. It was how the entities intended to engage in projects that entered into their operational phases where differences emerged.

During discussions of operations and maintenance, the question frequently arose of who the owner and operator of our hypothetical geothermal projects was. Some entities view themselves firmly as service providers, contractors and/or suppliers, and therefore were likely to answer “maybe” to this question, responding that they’d assist if contracted to do so by an operator. Among the entities who answered “yes,” however, entities were split about what role they intended to play. At least five entities entertained the idea of their entity taking on the role of owner/operator of geothermal projects, with at least three entities noting that this role was central to their geothermal strategy. Interestingly, not all of these three entities are operators currently in the oil and gas industry.

Further, operators tended to take the view that if their entities successfully operate wind and solar projects, technologies that were firmly outside of their wheelhouse before decades of investment in the renewables space, why wouldn’t they then take the same view for geothermal projects, which are firmly within the wheelhouse of parent companies. One entity noted that there were unique challenges associated with convincing the parent company of any oil and gas major to operate a project that produces electrons, as opposed to hydrocarbons, noting that it was an entirely different business model and way of thinking, something that parent entities are not accustomed to. Another entity observed that the existence of “New Energies” arms of oil and gas majors has the consequence of siloing employees who understand the business of “selling electrons” away from employees in the parent, who understand the business of exploring for and producing energy from the subsurface. “Geothermal is both subsurface and electrons, and we aren’t currently built to navigate that from a business model standpoint,” the interviewee noted. This pain point in industry is significant, and the subject of [Chapter 7, The Geothermal Business Model & the Oil and Gas Industry](#).



With the exception of only a few interviewees, entities who answered “yes” tended to agree as a general rule that the oil and gas industry would likely need to vertically integrate further through joint venturing or acquisitions in order to fill expertise gaps associated with plant operations on the surface. Several interviewees who answered “yes” took the view that either through mergers, investments, and/or acquisitions, both executed and planned, they have positioned themselves to take a system-wide (meaning both surface and subsurface) approach to geothermal, which may position them to seamlessly own/operate geothermal projects in the future.

#### e. Surface Plant Innovations

For the purpose of this Section, Surface Plant Innovations are defined to mean any part of a geothermal power or heat operation that does not pertain to the subsurface. This includes equipment like turbomachinery for power production, heat and power technologies, modular plant designs, cooling technologies, grid interconnects, and related infrastructure.

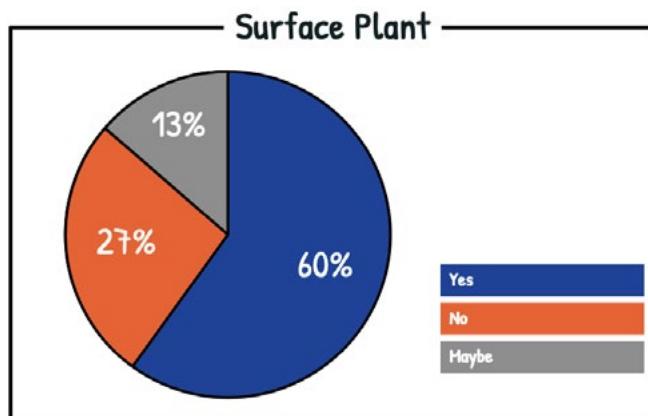


Figure 6.16. Oil and gas entities engaged or interested in Surface Plant Innovations. Source: *Future of Geothermal Energy in Texas, 2023*.

The data that emerged from this question, with the exception of one entity, matched almost entirely, with data from the prior question about operations and maintenance. Consistent with the prior data, operators tended to be more enthusiastic about engaging in the development of surface innovations, but not all of the 60 percent of entities who answered “yes” were operators. The development of sCO<sub>2</sub> and organic engineered Working Fluid driven turbines were mentioned by several entities as areas of particular interest, as were the application of thermoelectric generators (“TEGs”) in the

geothermal context. Amongst entities who answered “no” or “maybe,” at least two entities noted that this is an area that they may pursue in the future with the help of strategic partners.

#### f. Technologies to Monitor and/or Mitigate Induced Seismicity Risk

For the purpose of this Section, technologies to monitor and/or mitigate induced seismicity risk are defined to include technologies deployed in all phases of project development and operation, including during site assessment, drilling and construction, and during operations and maintenance.

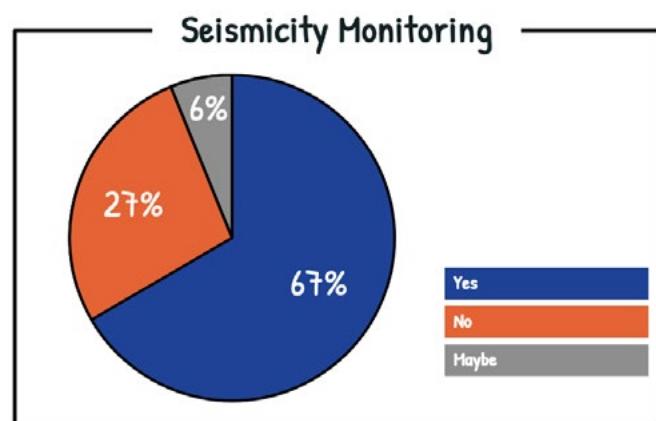


Figure 6.17. Oil and gas entities engaged or interested in Seismicity Monitoring. Source: *Future of Geothermal Energy in Texas, 2023*.

As a general rule, most entities, including those who answered “no,” expressed that this is an important topic for geothermal, and that oil and gas expertise in this area developed as a result of wastewater disposal in unconventional, would be directly applicable and impactful as scalable geothermal concepts are deployed across different regions and geologies. Entities who expressed the most enthusiasm for making investments in this space tended to be operators. While oilfield service, drilling contractors, and suppliers were more likely to answer “no” or “maybe” to this question, several expressed excitement about the application of relevant existing technologies within their portfolios into geothermal projects to monitor seismicity.



#### 4. Emerging Trends

Authors note emerging trends within the oil and gas industry, namely automation and digitization to increase efficiency and/or optimize in the oil and gas context, appear to be a given amongst entities to apply in the geothermal context, right out of the gate. In the context of automation, and in particular rig automation, one entity noted that while pursued for efficiency and workforce risk mitigation purposes in oil and gas (meaning the potential for a shortage of rig workers in the future), rig automation would have the significant and added bonus in the geothermal context of insulating workers from the environmental, health, and safety hazards of working with hot and supercritical fluids on the rig floor, and reducing the cost of downtime.

Digitization was another area where interviewees expressed significant enthusiasm, with several stating that massive efforts at data collection, standardization, and sharing from geothermal operations, paired with AI/machine learning and predictive analytics could do as much to advance geothermal as the development of new drilling technologies. One interviewee stated "Oil and gas is where it is today because of data sharing and standardization. Geothermal does not have that currently." Digital twinning of geothermal systems and operations was another frequently mentioned example, with entities broadly agreeing that these methods are now bearing fruit in the oil and gas industry, and should be quickly transferred into geothermal.



Figure 6.18. An example of oil and gas rig automation. In 2022, NABORS and ExxonMobil announced the oil and gas industry's first fully automated land rig, which included a first of its kind robotics module. Rig floor automation may improve worker safety and process consistency in both the oil and gas, and geothermal contexts.

Source: NABORS, 2022.

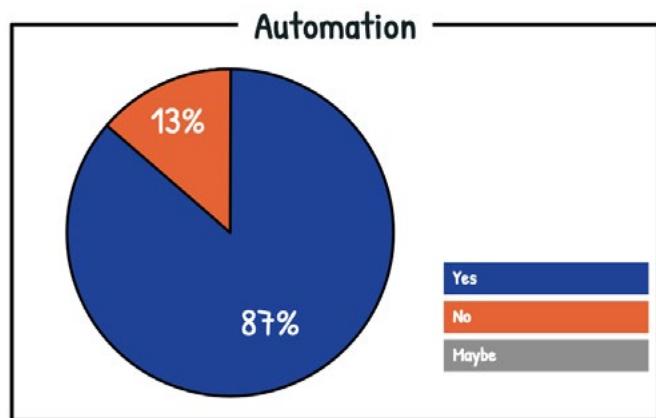


Figure 6.19. Oil and gas entities engaged or interested in applying Automation technologies to geothermal. Source: *Future of Geothermal Energy in Texas, 2023*.

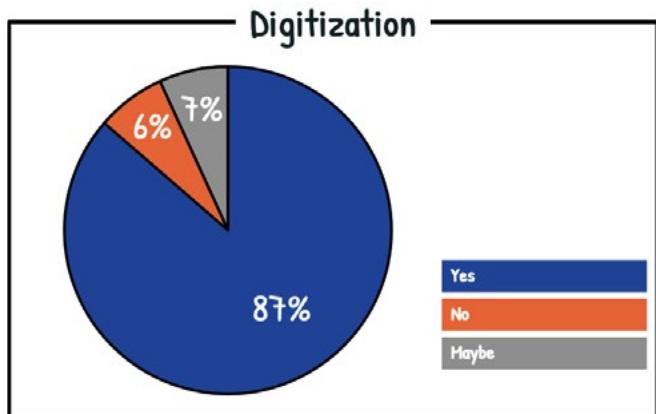


Figure 6.20. Oil and gas entities engaged or interested in applying Digitization technologies to geothermal. Source: *Future of Geothermal Energy in Texas, 2023*.

#### D. Geothermal Challenges and the Oil and Gas Industry

We asked interviewees about their views on both technical and non-technical challenges associated with achieving fast global scale for geothermal. In the first question, we asked entities if there are technical challenges associated with geothermal that the oil and gas industry will not be able to solve. 67 percent responded "no," with few hesitating in offering this answer. For at least one entity who expressed that they were "unsure," challenges associated with SuperHot Rock were given as an example of a potentially difficult set of challenges. Another entity agreed that currently available technologies would pose major challenges in the SuperHot context, but noted that with focused R&D, they may be overcome.

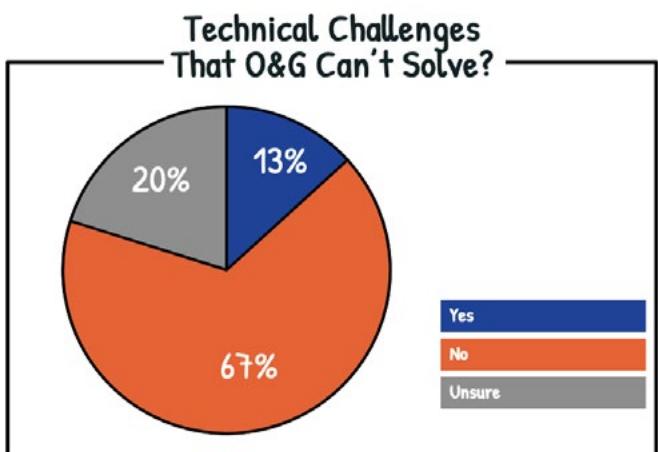


Figure 6.21. Oil and gas entity responses when asked if there were technical geothermal challenges that the oil and gas industry could not solve. Source: *Future of Geothermal Energy in Texas, 2023*.

All entities who believed that there were indeed geothermal related technical challenges that oil and gas would not be able to solve, expanded that surface equipment such as ORC turbines and other turbomachinery, are an essential component to the success of geothermal. Entities offered that current surface technologies are inefficient, that little innovation in this space is ongoing, and that this is an area that is outside of the expertise of most oil and gas entities. These entities took the position that if geothermal fails to launch, it will be the result of poor performance of equipment on the surface, and failure to innovate in this area.

In the second question, we asked entities if there were non-technical challenges associated with geothermal that the oil and gas industry will not be able to solve. Many more entities expressed that there were indeed non-technical challenges that were unsolvable by industry, as compared to unsolvable technical challenges. Non-engineering challenges of concern to entities, in order of most frequently raised, were 1) policy, regulatory, and permitting issues, 2) legal uncertainty, 3) social license issues, and 4) lack of funding for pilots and essential research.

Of the entities who answered that they were “unsure,” or that there were no unsolvable non-technical challenges, they broadly acknowledged that policy, regulatory, and permitting challenges exist, particularly on Federal land in the United States, but noted that development can be pursued on state and/or private land in jurisdictions who

are accustomed to working with the oil and gas industry. Texas was given by at least two entities as an example of such a jurisdiction. At least one entity noted with regard to policy, regulatory, and permitting challenges, that while there is currently no effective Federal geothermal lobby, that should not be considered a challenge that oil and gas cannot overcome – rather – the oil and gas lobby could begin to do this work on behalf of the industry for geothermal, and that State specific advocacy groups would be well positioned to tackle State level challenges.

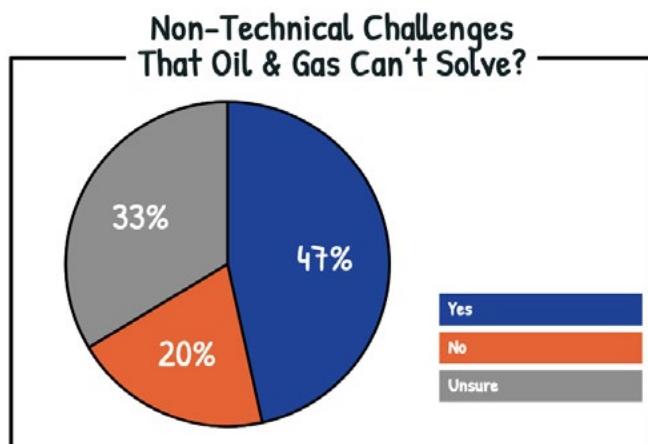


Figure 6.22. Oil and gas entity responses when asked if there were non-technical geothermal challenges that the oil and gas industry could not solve. Source: *Future of Geothermal Energy in Texas, 2023*.

With regard to the ability of industry to address social license to operate issues, one entity noted that if development in particular locations or States becomes too contentious, industry can adjust to develop in areas where communities are accustomed to working with industry in the oil and gas context. The interviewee noted that there will be no shortage of demand for small footprint, firm, green energy in the future, and that industry will simply “go where we are wanted” until the world begins to view geothermal development as a valuable and desirable community asset.

Finally, with regard to concern for lack of funding for essential R&D and pilot projects as raised by at least two entities, these are challenges that both industry and startup teams are facing, and are considered in further detail below, and in [Chapter 9, The Texas Startup and Innovation Ecosystem](#).



## E. Pilots and R&D

Entities were asked the hypothetical question of how they would spend a budget of \$100 million to have the greatest impact and near term benefit for the growth of geothermal. 87 percent percent of entities chose to spend more than 80 percent of their \$100 million on pilots and field deployments. This reflects a consistent theme that was repeated by entities many times during the interview process, that field deployment and iterative learning is essential, was the foundational principle that enabled the shale boom, and that for geothermal to succeed, teams must have sufficient funds to try new things (and sometimes fail) in the field, iterate, and try again.

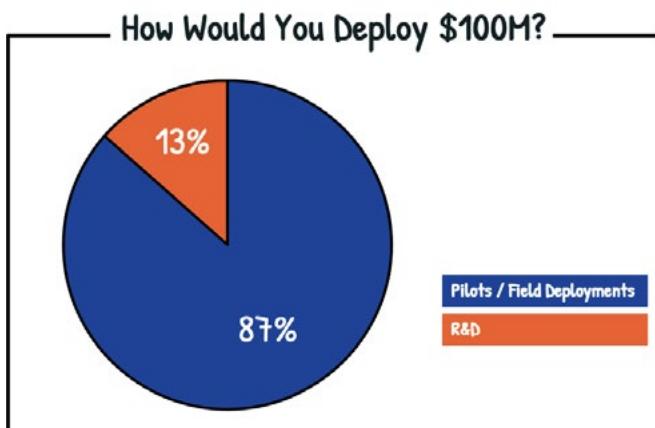


Figure 6.23. Oil and gas entity responses when asked how they would deploy \$100 million dollars in funding for geothermal. Source: Future of Geothermal Energy in Texas, 2023.

Of teams who chose to spend a majority of their funding on pilots and field deployments:

- Three would pursue a sedimentary geothermal pilot;
- Two would pursue a combined heat and power pilot;
- Two would pursue a blind hydrothermal pilot;
- Two would pursue a geothermal + CCUS hybrid system pilot;
- One would pursue a coal plant conversion pilot;
- One would pursue a SuperHot pilot;
- One would pursue an offshore geothermal pilot; and
- One would pursue a hydrothermal revitalization pilot.

Teams generally expressed the desire to fund a series of iterative wells within one technology type, and in one location, as opposed to pursuing multiple unrelated pilots.

Entities who expressed an interest in funding R&D stated the desire to put more than 80 percent of their funds toward 1) high-temperature electronics, including sensor technologies, and 2) next generation drilling technologies.

100 percent of entities acknowledged that at least some R&D will be needed to address technical challenges. Several noted that oil and gas entities are already working on the R&D challenges that they believe are key to growing geothermal, including high-temperature completions technologies, like cements and fluids. Two areas of R&D were raised consistently by entities as areas of research that may be outside of the areas of expertise of their entities, or that no one entity may be incentivized to invest heavily in. These include surface technologies like ORCs, turbomachinery driven directly by sCO<sub>2</sub> or engineered Working Fluids, and/or thermoelectric generation ("TEGs"), and materials science research into high-temperature materials such as elastomers, coatings, insulators, electronics and sensor technologies.

We next asked entities if they believe that materials R&D is essential to addressing challenges associated with the growth and development of geothermal. Entities were split approximately 50/50 on this topic between "yes" and 'unsure.'

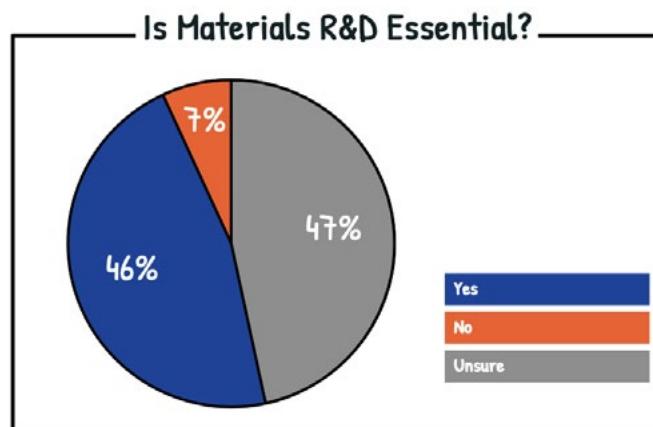


Figure 6.24. Oil and gas entity responses when asked if materials research and development is essential to addressing geothermal challenges. Source: Future of Geothermal Energy in Texas, 2023.

Entities who answered "yes" most frequently referred to SuperHot Rock challenges as likely to require significant



R&D dollars in materials, with entities raising the issues of corrosion, scaling, and a host of unknowns that will arise when working with supercritical fluids. Entities noted that supercritical water and/or brines are likely to pose a different set of technology challenges compared with sCO<sub>2</sub> and engineered Working Fluids, but a majority of interviewees agreed that the higher the temperature, the greater the set of unknowns in terms of technology solutions and needs, and the more likely that materials R&D will be needed. One entity noted that drilling and exploration at the temperatures associated with SuperHot projects are not entirely unknown to oil and gas, offering deepwater offshore exploration wells as an example of projects that exceeded 300°C (572°F). The interviewee continued by noting that these deepwater wells were among the most complex and expensive ever drilled, and had the prize of decades of oil and gas production behind them to justify the investment. Thus, he noted, while industry could technically drill SuperHot projects today, the end does not currently justify the means in terms of cost. The interviewee noted that this is where materials R&D may become relevant, in reducing the cost of drilling these complex wells.

"Unsure" entities generally did not disagree that materials R&D was needed and would be helpful in growth geothermal, but instead took the position that there may be other ways to achieve the same result using more incremental approaches, existing technology adaptations, and innovative methods to achieve a similar result without the need to develop new materials. One example that was raised by an entity that might, for example, negate the need for the temperature hardening of all tools downhole is to increase the pumping capabilities of rigs to achieve increased circulation, utilize technologies that allow for continuous circulation, and aggressively cool, or even refrigerate fluids at the surface. These methods, he noted, may keep the tools cool enough to reliably drill deeper and hotter projects with conventional oil and gas technologies.

To a majority of entities who were "unsure," they generally agreed that before significant dollars are invested in materials science, much of which could take a decade or more before becoming commercially viable, there needs to be a cost/benefits analysis of other ways to achieve a similar result with adaptations to existing tools, technologies and techniques.

100 percent of interviewees who answered "no" on this question felt certain that adaptation of existing technologies would be sufficient to overcome challenges without significant materials R&D investment.

#### F. Industry Collaboration and Consortia

The last set of questions focused on the idea, often originating from governments and funding entities, that some form of organized industry collaboration, or a consortium model, may be a key avenue to enabling accelerated progress of the industry as a whole in addressing geothermal challenges. Data collected from responses suggests that while the idea sounds good on paper, the devil lies in the details.

93 percent of interviewed entities expressed support for the idea that combined industry effort in the form of cross-entity collaboration would be helpful in addressing geothermal challenges. However, when we asked follow up questions about what that collaboration might look like, responses got more nuanced.

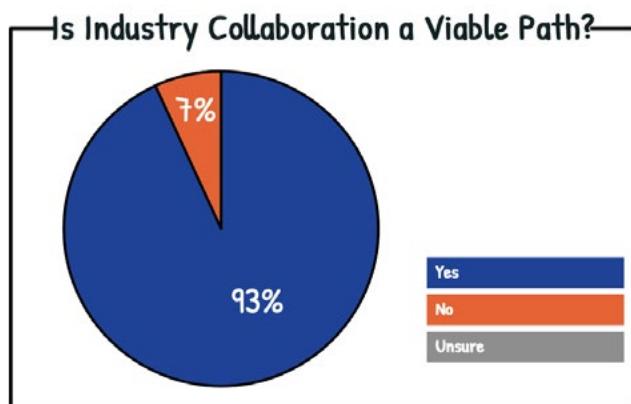


Figure 6.25. Oil and gas entity responses when asked if industry collaboration is a viable path to address geothermal challenges. Source: Future of Geothermal Energy in Texas, 2023.

When asked what types of information entities would find most helpful to share amongst a consortium of entities, there was a fair deal of disagreement, with some saying that only data that would help with industry-wide standardization would be acceptable, while others expressed interest in limited data sharing of the outcomes of consortium member pilots. Others expressed that the purpose of such an effort should be shared R&D, with the group benefitting from advancements as a whole, but



entities disagreed about how intellectual property would be handled in such an arrangement, and several entities expressed that intellectual property was a sticking point for their entities in entering and considering such arrangements. Though all entities were asked, few were able to offer concrete examples of R&D focused industry consortia that they believe were highly effective at achieving the goals they set out to achieve.

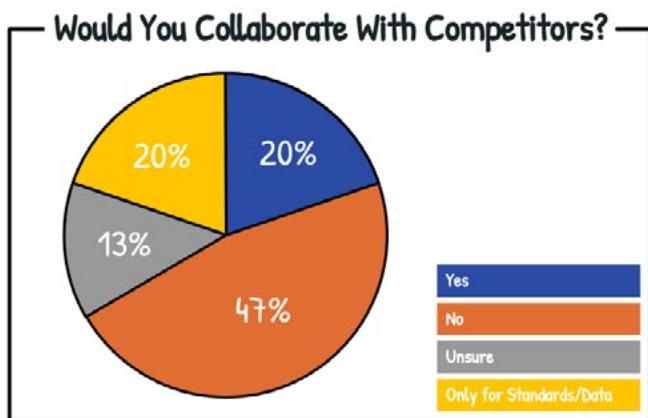


Figure 6.26. Oil and gas entity responses when asked if entities would be willing to collaborate with competitors in an industry consortium.  
Source: *Future of Geothermal Energy in Texas, 2023*.

Generally, responses to this question were consistent based on industry entity type. For instance, operators generally agreed that R&D focused consortia arrangements can be successful, even when the consortia includes competitors. One entity stated “operators are just better at this.” Other entity types, including oil field service, drilling contractors, and suppliers were much more hesitant generally to consider a consortium model that would include competitors. In fact, those entities were much more likely to take the position that a small group of existing and complementary partners,

including trusted and existing customer/service provider relationships, was a much more effective strategy for collaboration, or that it is best to let entities compete than to try to collaborate with competitors.

An example of this complementary partnership approach to collaboration is the recently launched “Wells2Watts” consortium, which is a partnership between Baker Hughes, Continental Resources, INPEX, and Chesapeake Energy. A first of its kind amongst oil and gas industry entities for geothermal, the goal of the partnership is to progress technologies that will support oil and gas Well Reuse, as well as non-productive geothermal well revitalization. The consortium will work with geothermal startup Greenfire Energy on the use of AGS/Closed Loop Geothermal Systems in the Well Reuse context (Baker Hughes, 2022).

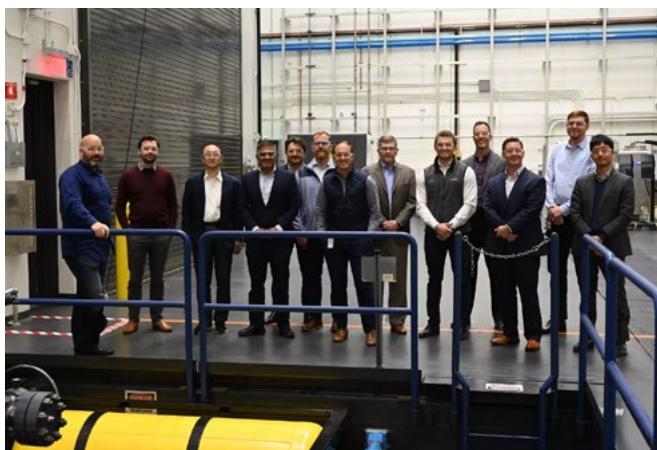


Figure 6.27. The Wells2Watts consortium team at their laboratory test well at the Oklahoma State University Hamm Institute of American Energy in Oklahoma City, Oklahoma. Source: *Baker Hughes, 2022*.



## IV. Conclusion

Over the past few years, largely behind the scenes, oil and gas entities have been building visions, ideating, planning investments and pilots, funding R&D, building teams and strategies, and otherwise entertaining their level of engagement in building the future of geothermal. This behind the scenes activity has begun to show up publicly in occasional press releases and headlines, and in industry panels at the PIVOT - From Hydrocarbons to Heat conference, but these public glimpses of industry activity only scratch the surface of industry engagement (PIVOT, 2022c; 2022d). If we look closely at the data reported by industry about their areas of interest in geothermal, we can see clear trends. One is belief across entities that application of modern technologies from industry to

geothermal will have a substantive and positive impact on project outcomes. Another is a forward looking view of what concepts might bear fruit for industry, including "bold" concepts that have failed to get traction within traditional geothermal and government spaces, like AGS/Closed Loop, and SuperHot Rock.

Finally, the view of nearly 70 percent of interviewed entities that there is not a single technical challenge associated with geothermal that industry cannot solve is headline worthy. Rarely in such a conservative industry, in response to a speculative question, do we see such a consensus. That traction and consensus is what can propel Texas into a global leadership role in geothermal, led by its oil and gas industry.



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## Conflict of Interest Disclosure

**Jamie Beard** serves as Executive Director of Project InnerSpace, a 501(c)(3) organization that works on issues within the subject matter of this manuscript, and is compensated for this work. She further serves in a non-compensated role as a founding member of the board of the Texas Geothermal Industry Alliance. Outside of these roles, Jamie Beard certifies that she has no affiliations, including but not limited to 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.

**Ken Wisian** serves as an Associate Director of The Bureau of Economic Geology, Jackson School of Geoscience at the University of Texas at Austin, and is compensated for this work. His main area of research for 30 plus years in geothermal systems. Outside of this role, Ken Wisian 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.

**Silviu Livescu** serves as a faculty member in the Petroleum and Geosystems Engineering Department and a co-principal investigator for the HotRock Industry Affiliates Program, both at the University of Texas at Austin, and is compensated for this work. He is also a co-founder of Bedrock Energy, a geothermal heating and cooling startup, and the editor-in-chief of Elsevier's Geoenergy Science and Engineering. Outside of these roles, Silviu Livescu 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.

**Bryant Jones** serves as the Head of Education and Policy at Project InnerSpace, a 501(c)(3) organization that works on issues within the subject matter of this manuscript, and is compensated for this work. He is also a full-time Ph.D. candidate at Boise State University where he researches at the nexus of policy studies, science and technology studies, and energy transition studies. Outside of this role, Bryant Jones 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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## Chapter 6 Appendix A

The authors of the Future of Geothermal Energy in Texas report are grateful for the participation and insight provided by the following individuals. Thank you for taking the time to share your knowledge and experiences about the oil and gas industry engagement in the geothermal industry in Texas and from around the globe. Data collected from all participants has been aggregated and anonymized to capture and disseminate trends, views, and perspectives.

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## Chapter 7

# The Geothermal Business Model & the Oil and Gas Industry Challenges and Opportunities

T. Lines

*Combining robust State leadership and the resources of the oil and gas industry, an aggressive, but technically feasible target for geothermal development in Texas would be to supply the equivalent of all fossil-fuel generated electrical energy and Direct Use heat to industry and buildings, by drilling 60,000 geothermal wells, the equivalent of four years of oil and gas drilling in the State. By committing to an aggressive program of geothermal research and development, drilling, and development 'at home,' Texas' legacy industries and highly skilled workforce will be superbly qualified to deploy geothermal at scale in Texas, and then across the globe.*

## I. Introduction

In this Chapter we consider whether and how the structures and commercial practices of the oil and gas industry would benefit the geothermal industry, and the potential financial advantage to geothermal of the Inflation Reduction Act ("IRA"), and future carbon costs.

We present and analyze the forward prices of the primary fuels with which geothermal energy needs to compete, and provide powerful justification for premium pricing against intermittent renewables and fossil fuels. We

propose a geothermal business model, and estimate the potential impact of exponential growth of geothermal development, utilizing the resources and scale of the oil and gas industry as it exists today, both globally and in Texas.

The challenge and novelty of geothermal from a business model perspective lies in the fact that it is both more expensive per megawatt electric to develop than wind



and solar, and has some of the subsurface risks of oil and gas developments. Investors in commercial wind and solar projects, constructed at scales of many tens of megawatts capacity, receive rates of return of less than ten percent, and even less than five percent in some cases. These investments are perceived as low risk, with predictable returns over a contracted project lifetime. In most cases, when geothermal electric power is competing with gas, wind, and solar, it is offered similar energy prices, which yield project returns of six to eight percent, occasionally less than ten percent (refer to Section VI of this Chapter for quantification of heat, electricity, and storage energy prices in Texas). This reflects the low value that utility buyers assign to geothermal energy's competitive advantage: clean baseload power. Geothermal is available 24/7/365, is low- or non-carbon emitting, and can provide both heat and electrical energy (Dhar, et al., 2020; Bošnjaković, et al., 2019).

However, as Texas increasingly transitions from fossil fuel energy to other forms of energy, this firm and "clean baseload" competitive advantage, even at current capital expenditures per kilowatt hour, becomes a dominant factor in decision-making. The profound implications of this for the electricity sector in Texas are examined in detail in Section VI of this Chapter.

The potential for premium pricing of geothermal energy can be revealed by segmenting the geothermal market by customer need, and designing business models to target those segments. Some examples discussed in this Chapter are:

- Energy-intensive industries and individual plants that use liquid fuels instead of, or as well as, gas. Section VI.1 compares energy costs by fuel type and lists target industries by the quality of heat they require;
- Customers for whom supply interruption has unusually serious consequences, for instance, the Department of Defense has announced it regards the development of geothermal energy supply within or near the boundaries of its bases as its "number one energy objective," expressing that geothermal could satisfy its requirement for energy resilience. This topic is considered in further detail in [Chapter 8, Other Strategic Considerations for Geothermal in Texas](#) of this Report. Other potential customers are those who require uninterrupted electricity supplies, and may currently satisfy this requirement with back-up diesel

generation – hospitals, for example, and indeed some of the industries referred to in Section VI.1;

- A related niche is the roughly ten percent of Texas customers who are not connected to the Electric Reliability Council of Texas ("ERCOT"), and not thereby benefiting from its enormous economies of scale;
- Ancillary services for ERCOT, such as maintaining frequency after a disturbance to the grid, and offline capacity that can provide power within ten minutes. The prices for these services are currently based on the marginal costs of gas and coal. However, battery storage is rapidly becoming the major player in this niche. Refer to Section VI.3 for more on this topic.

In Sections VII and VIII, we gaze into the future, to envision scenarios where geothermal achieves significant global scale over the coming decades, and the impacts of that scale on the global and Texas energy mix, both heat and power.

## II. The Outstanding Success of the Texas Oil and Gas Industry

The case for oil and gas expertise, innovation, and technology substantively impacting a growing, but nascent, geothermal energy industry appears to be compelling. But will existing oil and gas business models be able to cross over into geothermal as smoothly as the technologies, workforce, and learning? In this Section we describe and analyze the structure and practices of the hydrocarbon industry, and consider whether transferring "lessons learned" could benefit the nascent Texan geothermal sector.

In 2021, there were over 5,000 active oil and gas operators in Texas, with production ranging from 475,000 barrels per day, to 30 barrels per day; two billion cubic feet per day, to ten million cubic feet per day; and from 10,000 leases, to one lease (RCC, 2021). The largest oil producer contributed only ten percent of the total liquids production, and 40 companies 75 percent (of 4.7 million barrels per day). The largest gas producer contributed only seven percent of the total gas production, and 117 companies 75 percent (of 29 billion cubic feet per day). The Herfindahl-Hirschman Index ("HHI") is a commonly accepted measure of market concentration, with 1,500-2,500 being described by the U.S. Department of Justice as moderately concentrated; greater than 2,500 highly concentrated; and zero, the (theoretically) most competitive marketplace (DOJ, 2018).



The Texas oil and gas production industry has an HHI of less than 200. On this measure, it is a very diverse market. It is also influential, contributing 5.6 percent of global liquids, and 7.2 percent of global gas production in 2021 (WECS, 2021).

The ownership structure of the more than 5,000 companies is also diverse, consisting of the major oil companies ("Majors"), independent oil companies, listed vehicles, private equity firms, royalty funds, hedge funds, limited liability partnerships, limited partnerships, individual and family farms, families, high-net worth individuals, cooperatives, collectives, and others.

Oil and gas assets at every stage of exploration, development, and production are frequently and easily traded. In addition to large transactions facilitated by investment banks and broker-dealers, there are hybrid-online auction houses such as the Oil & Gas Clearing House, which has conducted on average 1,000 transactions per 16,000 properties across North America over the last 30 years (OGCH, 2022).

Buyers, sellers, and lenders generally agree on a reduced set of metrics that facilitate rapid decisions on whether to transact, principally including:

- Acreage;
- Current production;
- Forward commodity prices for future cash flow calculations, and;
- Proved developed producing ("PDP"), proved developed not-producing, and undeveloped reserves (and sometimes probable reserves), reported by an independent expert in compliance with an internationally recognised standard. The three standards commonly used in North America are those of: the Society of Petroleum Engineers ("SPE PRMS 2018"); the U.S. Securities and Exchange Commission ("SEC"); and the Canadian Oil & Gas Evaluation Handbook ("COGEH"). The wide acceptance and understanding of these standards is pivotal to the efficiency of the mergers and acquisitions ("M&A") marketplace.

The volume of transactions is sufficiently high that metrics such as dollars per acre, dollars per barrels per day, dollars per PDP reserves, dollars per proven reserves, dollars per proven and probable reserves, and discount factor for pre-tax net present value valuation (currently around 18 to 20 percent for PDP reserves) are routinely collated and accepted by buyers and sellers as the basis for rapid rough valuations – sufficient to establish whether the two parties are close enough to deal. Detailed information on all oil and gas drilling and production is freely available from the Texas Railroad Commission ("RRC"), and can be used to sense-check sellers' claims and third party reports (RCC, 2022).

The market for oil and gas debt is highly competitive and sophisticated, with reserves-based lending widely available, as well as the more usual revolving credit, bond, and mezzanine instruments. Most usually, third party reports of PDP reserves are the foundation for lending, but weight is also given to probable producing, drilled uncompleted wells ("DUC"), and proved undeveloped reserves. 48 to 60 month tenors are common.

In summary, the oil and gas transaction process is so efficient that industry players can enter and exit assets at every stage of the value chain, and borrow against production as well as balance sheets. The consequence of this is that investors can choose in which segment of the risk over return they wish to participate, then attempt to add or extract value, and be reasonably sure they have a viable exit. It also enables non-industry players to participate when assets are de-risked<sup>1</sup>, for example, shale wells on their hyperbolic decline curves are attractive to pension funds needing to match long term assets to liabilities.

In addition to attracting investors with varying appetites for risk over reward, the confidence that assets can be readily monetised attracts a wide variety of (usually undercapitalised) expert teams to seek highly speculative assets and plays, do intellectual work to delineate them and prepare them commercially, and then farm them out to better capitalized entities to add further information and development (such as drilling wells) who, in turn, may farm out to other entities to develop and produce (and so on, until mature production and end of field life enhancement over extension).

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<sup>1</sup>In particular de-risking future production profiles. Oil prices can be hedged for up to ten years.



### III. A Comparison Between the U.S. Oil & Gas and Geothermal Industries

#### A. Geothermal Industry Structure in the United States

##### 1. Geothermal Exploration and Production Companies

The structure of the geothermal exploration and production industry in the United States, and to a large extent globally, is of vertically integrated entities undertaking cradle-to-grave projects. Current U.S. geothermal power generation nameplate capacity is approximately 3.6 gigawatts from around 95 power plants, of which more than 90 percent are in California and Nevada, and the balance in Alaska, Hawaii, Idaho, New Mexico, Oregon, and Utah (Robins, et al., 2021). Three new plants in Nevada and two in California are near commissioning status (Robins, et al., 2021).

Table 7.1 identifies the 15 most significant geothermal production companies delivering this electrical power.

The geothermal industry is much more concentrated than the oil and gas industry. Table 7.1 also presents the ownership of each geothermal entity, a variety of listed companies, private equity, not-for-profit, and municipalities & public utilities. This variety provides industry resilience and a wide potential spectrum of risk/return profiles.

With a few exceptions,<sup>2</sup> geothermal exploration and production companies own 100 percent of the working interest in their producing plants, in contrast to the oil and gas industry, where multiple and sophisticated ownership structures enable different investors to choose their risk/return exposure within the overall project return. The understanding and execution of these techniques would greatly benefit investor risk management within the geothermal industry.

These 15 companies have by far the most expertise within the United States in exploring and producing geothermal energy, and the growth of geothermal power and Direct Use heat production in Texas would greatly benefit from their partnering with oil and gas operating companies, technology startups, and oilfield service companies.

Table 7.1. U.S. geothermal power generation operating companies (including lithium co-production companies). Source: *Individual company websites*.

Geothermal Operating Company	Ownership
CalEnergy Operating Corp	BHE Minerals, Berkshire Hathaway: NYSE BRK.A
Controlled Thermal Resources (inc. Lithium)	Private Equity
EnergySource	Private Equity
EnergySource Minerals (Lithium)	Private Equity
Calpine Corporation	NYSE Ticker: CPN
GE Renewable Energy (Battery Storage for geothermal)	NYSE Ticker: GE
Northern California Power Agency	Municipalities and utilities
Silicon Valley Power	Not for Profit Municipal Electric Utility
U.S. Renewables Group	Private Equity
Coso	Atlantica Sustainable Infrastructure Private Equity
Cyrq	Macquarie Infrastructure & Real Assets (MIRA)
Enel	Borsa Italiana, Ticker: ENEL
Open Mountain Energy /Kaishan Compressor Company	Private Equity; JV Kaishan, China
Ormat Technologies Inc	NYSE Ticker: ORA
Pacificorp	OTCMKTS: PPWLO
Terra-Gen Power LLC	Private Equity

<sup>2</sup>Notably the JV between Calpine, NCPA, SVP & USRG for The Geysers GPP; and CalEnergy & EnergySource for Imperial Valley GPP (including lithium).



## B. Transactions

Table 7.2 presents the principal U.S. geothermal transactions in the last few years, a stark contrast to the average 16,000 oil and gas transactions per year over the last 30 years. Transactions that transfer ownership of operating companies are the most common, followed by transfers of packages of producing assets, with some exploration upside. Compared to oil and gas, there is an absence of farm-outs, Drillco agreements, overriding royalty interest and net profit interest agreements, mezzanine with warrants, sales to pension funds, and insurance companies.

The adoption of these more sophisticated and flexible finance solutions from oil and gas could increase deal flow, and hence price discovery and a common language of current asset valuations.

In contrast to the oil and gas industry, there is no commonly accepted geothermal resources determination standard in the United States (although the United Nations ([unece.org](http://unece.org)) Resource Classification system is being adopted by some countries), and there are rather few independent experts to provide an unbiased opinion. The effect of this is to increase uncertainty in the range of recoverable volume and the value of a geothermal asset. This greater uncertainty is perceived as greater investor risk, and so buyers and equity and debt investors require a greater return to compensate (i.e., the cost of capital increases simply because there is no accepted resource determination standard). Its absence also increases transaction costs, since investment banks, lending banks, and stock exchanges instead adopt bespoke and in-house methods, hindering the growth of a cost-competitive third party valuation sector.

Table 7.2. Recent acquisitions of U.S. geothermal companies and assets. Sources: *Individual company websites*.

Date	Asset/Company	Geothermal Megawatts Electric	Buyer	Seller	Consideration (dollars in millions)
Apr-17	Wabuska Geothermal Project, NV	Four wells, 5,000 acres	Open Mountain Energy	Homestretch Geothermal	Not disclosed
Jul-17	Rye Patch-Humboldt House Geothermal Project, NV	Nine wells & surface facilities + 9,000 acres	Open Mountain Energy	Presco Energy LLC	Three + royalties
Jan-18	U.S. Geothermal Inc: ID, OR, NV	45	Ormat Technologies Inc (ORA)	JCP Investment Management, and other shareholders	110
Mar-19	Assets in UT & NV	98 <sup>3</sup>	Enel Green Power	GE Capital's Energy Financial Services (50/50 JV with Enel	265
Nov-20	Hudson Ranch one geothermal power station Salton Sea, CA	55	Macquarie Infrastructure & Real Assets (MIRA)	Mercury, New Zealand	27
Mar-21	Cyrg Energy LLC: UT, NV, NM	121	Subsidiary of MIRA	Tenor CM and LSV	Not disclosed
Mar-21	Coso Geothermal Power Holdings, LLC: CA	135	U.S.-based Atlantica Sustainable Infrastructure	Bardin Hill IP, Avenue Cap, Corre Partners Mgt, Voya Financial.	170
Jul-21	TG Geothermal Portfolio, LLC: NV	68 plus Coyote Canyon Greenfield	Ormat Technologies Inc (ORA)	Terra-Gen	171

<sup>3</sup>Plus 550 megawatts of wind & 2.4 megawatts of solar.



### C. Comparative Risk and Reward

The listed companies, private equity, not-for-profit, municipalities, and public utilities in Table 7.1 have different stakeholder objectives and costs of capital. Retaining a similar mix for future geothermal projects could facilitate a sustainable capital structure implemented at scale, especially if initially supported by Federal and Texas State tax incentives, and research grants. (In Section V and VI, the benefits of current tax incentives and also potential cap and trade schemes are also discussed).

Experienced oil and gas investors would naturally compare all the relative risks of a geothermal investment with an oil and gas investment, to help determine their required return on equity or debt. Table 7.3 describes some of the risks associated with oil and gas and geothermal projects, and subjectively assigns a relative risk between the two. Table 7.3 suggests directionally that it would be rational for oil and gas investors to perceive similar risks from

the geothermal subsurface than oil and gas, but a much lower commodity price risk. Oil and gas price volatility is usually by far the most important sensitivity to future cash flow, followed by schedule, capital expenditures, and well deliverability. An exception to future cash flow would be a production sharing contract specifically designed to move commodity price risk over reward to the host government.

Although tradeable oil and gas futures and options offer a mitigation to oil and gas price volatility, these instruments also amplify the negative financial impact of project schedule overruns and lower than expected production. By contrast, the geothermal sales contract might typically be an electric and/or thermal power purchasing contract, which moves some or all the commodity price risk from the supplier to the final consumer. There is still a risk of negative financial impact from project schedule overruns and lower production than expected through the produce-or-pay clause.

Table 7.3. Comparison of risk registers for oil and gas and geothermal, and mitigations. Source: Future of Geothermal Energy in Texas, 2023.

Investor Perceived Risk	Oil & Gas	Geothermal	Mitigation of Geothermal Risk
Resource Classification and Categorisation	High	Higher	An investor-accepted resource standard. Investors require more exposure to projects and their outcomes
Plateau Phase of Production Profile	Medium	Medium / High	Hydrothermal has similar risks to oil and gas. Other extraction techniques (e.g., EGS, AGS, HDR, SHR) require more exposure to projects and their outcomes. Open loop behaves more like an oil field, plateau and then decline. Closed Loop like shale gas, sharp decline then plateau.
Decline Phase of Production Profile	Medium	Low	O&G: Usually uneconomic after ~20-30 years on decline, with ever decreasing net revenues pa. Geothermal: potentially economic after 30 years with similar net revenues each year. Differences between extraction techniques as above.
Well construction	Medium	Medium / High	Drilling, materials, and electronics technology development
Oil well re-use	Low / Medium	Low / Medium	Well understood work-flow
Surface facilities	Low	Low	
Project Schedule Overrun	Medium / High	Medium / High	Implementation of best practice / lessons learned. An increase in U.S.-manufactured (or world-wide) organic Rankine cycle and steam cycle power generation equipment.
Capital Cost Overrun	Medium / High	Medium / High	An increase in U.S.-manufactured organic Rankine cycle and steam cycle power generation equipment.
Opex Overrun	Low	Medium	More exposure to projects and their outcomes (e.g., actual frequency of workovers)
Unscheduled downtime	Low	Low	
Commodity Price Risk	High	Low	The PPA for electricity or heat provides similar protection as the traditional gas sales contract. But unscheduled downtime may invoke take-or-pay clawback. The price risk is moved from the supplier to the consumer.



Commodity price volatility and absolute prices, therefore, strongly influence the oil and gas equity returns required by investors in the United States. The response to this volatility is investment committees typically stipulate unlevered hurdle rates of return of at least 15 percent to much greater than 20 percent. These hurdle criteria have not changed much in the last decade.

There is no consensus yet within the investment market as to what might be a reasonable range of internal return for a geothermal project. Table 7.3 may suggest an equity rate of return between 12 percent and 15 percent, to reflect much lower commodity price risk, avoidance of hedging costs, and the potential for material upside from future carbon costs (refer Section VI of this Chapter). In a private conversation with the author, a fund manager indicated a 15 percent hurdle.

The objectives of other categories of investors such as not-for-profit corporations pursuing Environmental, Social, and Governance ("ESG") objectives; municipalities; and public utilities may emphasize non-financial factors more than private equity and listed companies. If a geothermal project were to satisfy these non-financial criteria, the equity hurdle rate of return required by these investors may be lower than the 12 to 15 percent suggested above.

Large Direct Use heat customers may also be a source of low costs of equity because their commercial interests are aligned with the geothermal heat provider. They may also have strong balance sheets suitable for raising low cost debt for geothermal development.

Texas has a number of important advantages that reduce the investor risks listed in Table 7.3, which may reduce investors' equity hurdle rate of return compared with the 12-15 percent estimated above:

- There is very detailed, electronically searchable subsurface information and well flow rate information on approximately 250,000 producing wells and 150,000 abandoned/suspended wells (Source RRC);
- The reservoir performance of producing and abandoned oil and gas fields is very well understood;
- Suspended oil and gas wells close to customers may be converted to geothermal production at much lower cost than drilling new wells (albeit much less productive). However, repurposing O&G wells can be

very expensive and it might be cheaper to redrill fit for purpose. The final casing string dictates the hole diameter and therefore production flow is often a limiting factor;

- Some areas of Texas have high geothermal gradients, potentially reducing well depths to commercially useful heat resources. This depends on conductivity of the target formation and aquifer dynamics;
- Permitting and bureaucracy are very efficient, reducing time to first production and revenue;
- Industry accounts for over 50 percent of Texas energy consumption, and Texas City is in an area of high geothermal gradients;
- Texas has multiple energy-intensive plants whose owners may be willing to co-invest in geothermal supply at competitive equity rates of return since they are commercially aligned with the geothermal operator. Their strong balance sheets could reduce the cost of debt.

These advantages might suggest an equity rate of return of between ten percent and 12 percent, where investors can be satisfied by abundant historical data that subsurface resource determination and production profile uncertainty is low, and schedule overrun risks are low.

#### **D. Geothermal Business Models for Major International Oil Companies**

There is compelling reason to believe that the transfer of oil and gas skills, expertise, and technological innovation into geothermal will drive down geothermal energy costs. This expertise and technology transfer can occur through the work of research organizations pursuing research and development ("R&D") in the geothermal sector. It can also be accomplished through oil and gas executives and technologists working within commercial entities aimed at advancing geothermal energy development.

International oil companies ("IOC") and national oil companies ("NOC") have extremely varied historical involvement in geothermal, as is discussed in detail in [Chapter 1, Geothermal and Electricity Production](#) and [Chapter 5, The Oil and Gas Industry Role](#) of this Report. They are currently diverse in their participation in the various emerging geothermal technologies, and in



the current wave of new technology and development projects. This data is set out in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#) of this Report. Of the European IOCs, Shell is active publicly, with its ongoing Direct Use projects in the Netherlands, and an announced conventional hydrothermal project in Canada. The venture capital arms of bp and Chevron have invested in the startup Eavor, and reportedly have additional investments under consideration. Chevron had a conventional geothermal business before divesting it, and has re-engaged more recently with joint venture investments, including one announced in December, 2022 with Baseload Capital (Chevron, 2022). Notably, Chevron was also recently announced as a finalist candidate for development of a geothermal project in Sonoma, California (SCP, 2022).

In China, Sinopec's joint venture with Icelandic firm Arctic Green is the largest geothermal district heating company in the world, with over two million customers saving 16 million tonnes of carbon dioxide by December 2022. Sinopec-Arctic Green has drilled 800 geothermal wells in 750 "heat centrals" in 70 cities. Its geothermal energy is cost-competitive with coal and gas, and its well costs are about 25 percent of similar European wells (Arctic Green, 2022). In Indonesia, the national oil and the national gas companies (Pertamina Oil Company and PT PLN Gas Company) and one national geothermal company (PT Geo Dipa Energi) have developed the majority of the country's 2.3 gigawatts-electric, with plans to reach 7.2 gigawatts by 2025, with \$15 billion in investment. By contrast in the Philippines, geothermal development and production is ultimately owned by a \$20 billion listed conglomerate.

In Europe, IOCs like Equinor, bp, Total, and Shell are accelerating their involvement in offshore wind. The attractions of this sector include the major offshore project aspect of wind farm development with overlapping expertise to offshore oil and gas development, as well as the billions of dollars per gigawatt scale of the capital investment and power capacity. However, this sector is now highly competitive, with reported unlevered project IRRs in low single digits.

## E. Oil Field Service Companies and Geothermal

Global energy and oilfield service companies ("OSCs") such as Halliburton, Schlumberger, Baker Hughes, and Weatherford have long been engaged in geothermal development, recognizing the opportunity for their

products and services to fit that market just as well as they fit oil and gas. These companies have played a key role in the technology development trajectory of oil and gas, and it is these technologies and learnings that will drive the cost reductions considered earlier in this Chapter in geothermal. Smaller energy service companies, including contractors and suppliers, may be able to directly apply their products and services to geothermal applications, or be able to make slight adjustments in their strategy and adaptations to their technologies to make that offer, all within the bounds of their existing business model. Perspectives of the various entity types within oil and gas about these prospects are considered in depth in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#).

However, the affordability of oilfield services and materials (i.e., drilling and completions spreads, logging, PDC bits, casing) for geothermal development is especially challenging when oil and gas prices cause an excess of demand over supply. While overall volumes of geothermal activity are insignificant compared with oil and gas, OSCs can, and do, discount their prices to retain/build market share in geothermal. But a massive increase in geothermal activity in Texas would result in supply-constrained OSC decision-makers having to choose how to react, and the implications on their future cash flow and shareholder value / share price.

Indeed a significant market response to this dilemma is recent equity investment by OSCs in geothermal startups with the potential to scale and produce demand for their rigs and equipment to drill geothermal projects. Helmerich & Payne, Patterson UTI, and Nabors Industries are actively pursuing this strategy. Furthermore, drilling contractors are themselves investing in research and development to develop new geothermal drilling technologies and methods, which these companies are incorporating into "rig of the future" designs through in-kind partnership with geothermal entities.

## F. Startups Leading the Way

There is indeed a trend of oil and gas personnel turning up on geothermal projects, and to that end, the fastest moving entities involving oil and gas expertise in geothermal currently are startups. In 2019, the Geothermal Entrepreneurship Organization ("GEO") launched at the University of Texas at Austin, with the goal of recruiting oil and gas workforce and researchers into geothermal



entrepreneurship. From that initiative launched Sage Geosystems and a myriad of other startups, many with oil and gas teams, including veteran managers and high level executives from the biggest oil and gas companies in the world. This pattern is understandable. The oil and gas industry is moving slowly toward geothermal, while entrepreneurial oil and gas veterans are eager to move quickly to apply their skills and knowledge to this field. The startup ecosystem does not demand project deployment at scale, nor does it have the restrictions of rigid business models and the constraints of long-standing corporate culture. This unleashing of oil and gas expertise and problem solving onto geothermal challenges has resulted in startups quickly becoming the vehicle for innovation and technology transfer from oil and gas into geothermal.

Over the past 18 months, more geothermal startups have launched than in the past ten years combined. Texas based teams are leading the way in this accelerating growth. It seems likely that it will be startups that will replicate the ground-breaking work of George Mitchell in the geothermal context, by deploying new concepts in the field, quickly learning, advancing through iteration, and de-risking concepts sufficiently to ready them for scale. Startups will run the sprint, while the slower, larger industry entities ready themselves to engage when concepts mature. The geothermal innovation ecosystem in Texas is explored in further detail in [Chapter 9, The Texas Startup and Innovation Ecosystem](#) of this Report.

## G. Trading Assets

The limited pool size<sup>4</sup> of geothermal companies (Table 7.1) restricts the breadth and depth of subject matter expertise available for the full cycle, from exploration to mature production, and the volume of risk capital available for research, demonstration, and development. The introduction of this Chapter illustrates the importance of an efficient, low cost mechanism for selling and buying interest in oil and gas assets as value is added to them. The same process of many small entities adding value and then selling out/down to larger entities who add more value would greatly benefit the geothermal industry, and is illustrated below.

- **Micro Operator** - Startup teams with expertise but limited capital to explore and prep a geothermal

asset for a farm-out, or develop a new technology or AI application, developing one asset (like a well) for megawatts electric;

- **Series A Capital** - Investors with a high risk and high return profile farm-in or take corporate equity to, for example, drill one or two appraisal wells and perhaps a trial production (e.g., venture capital firms and corporate venture fund);
- **Series B, C & D Funding** - Capital and organizational structure in exchange for ownership and equity;
- **Full Field and Technology Development** - Investors with the balance sheet and project management skills to drive the main development and technology implementation and deployment;
- **Operations and Harvesting** - Investors to take over the running of routine operations (e.g., through PE or corporate M&A).

## H. Comparison of Supply Chains

The geothermal supply chain has strong similarities to oil and gas for subsurface, and some surface, facilities. But, especially for electricity generation and battery storage, there are notable differences, among them Organic Rankine Cycle, Steam Cycle, and Emerging Turbomachinery driven plant surface facilities, high voltage grid connections, electricity off-takers, and power purchase agreements. For Direct Use heat production, there are some generally good analogs with oil and gas – for example export of superheated water/steam by insulated pipeline to customers up to a few miles from the heat source, can be achieved with oil and gas pipeline technology, and long term heat supply contracts have analogs with long term gas supply contracts.

Most of the manufacturing facilities for geothermal plant turbomachinery are overseas, particularly in China. There are U.S. manufacturers, but personal inquiries suggest that lead times for this equipment are over a year, and prices are not competitive with Chinese equipment. It is notable that one of the geothermal operating companies has a joint-venture with a Chinese equipment manufacturer: Open Mountain Energy and Kaishan Compressor Company. Kaishan has an office in Loxley, Alabama.

<sup>4</sup>Calpine (Energy Capital Partners): 725 megawatts; Ormat: 2,000 megawatts; CalEnergy (Berkshire Hathaway): 350 megawatts; Cyrg Energy: 121 megawatts; Hudson Ranch: 49 megawatts (Macquarie Infrastructure & Real Assets); Northern California Power Agency (NCPA): 220 megawatts; Terra-Gen: 87 megawatts.



Manufacturers in the United States will respond to demand, but the availability of surface plant equipment may prove to be a bottleneck to the rapid roll out of geothermal power generation. The Inflation Reduction Act (refer to Section V of this Chapter) requires minimum domestic content to gain full advantage from its investment tax credits and production tax credits.

### I. Insurance to De-risk Exploration and Appraisal

As the deployment of geothermal power accelerates this decade, innovative financial solutions will be required to manage this unique risk profile. The World Bank and European Commission have both used insurance instruments to mitigate the risk of geothermal wells not delivering the energy flow rate required for minimum profitable development. At least one private company, Parhelion, a risk insurance company based in the United

Kingdom, offers similar insurance products. Geothermal focused non-profit Project InnerSpace recently funded a team of insurance experts to design and build a bespoke insurance product aimed specifically at "first of a kind" geothermal deployments. That project launched in January 2023.

### IV. Fiscal matters: Implications of the Inflation Reduction Act for Geothermal Projects

The Inflation Reduction Act 2022 ("IRA") is poised to be a marketplace game changer for the energy industry in the United States, and possibly globally. The IRA extends to 2034 the time limit for production tax credits and investment tax credits for renewable energy projects that can be offset against taxation, and widens the definition

**Table 7.4. Illustration of benefit of investment tax credit on levelized cost of Direct Use heat ("LCOH"). Measurements in dollars per million British thermal units ("\$/MMBTU"). Sources: Compton, et al., 2022; Hartford, 2022; NLR, 2022; O'Neill, et al., 2022; Smith & Tassone, 2022.**

Tax Incentive	LCOH \$/MMBTU	Improvement in Competitiveness relative to zero percent
Investment Tax Credit: 0%	7.7	
Investment Tax Credit: 30%	6.6	14%
Investment Tax Credit: 50%	5.9	23%
<b>Illustrative Scenario</b>		
Reuse of two suspended frac'd horizontal sandstone and carbonate oil and gas wells on same pad		
15,000 barrels per day injector/producer pair		
Delivering 60 pounds per second of steam to industrial customer at average 110°C (230°F) for 30 years		
<b>Assumptions</b>		
Capital Expenditures \$8 million		
Operating expenditures \$1 million pa including pump electricity		
Combined IT Rate: 21%		
ORRI: 7.5%		
Investment Tax Credit is a percentage of capital expenditures, deducted from tax in the first year. It is carried forward as needed.		
<b>Cost of Capital assuming 2.5% long term inflation, 30% equity, 70% debt</b>		
<b>Equity: 15%</b>		
<b>Debt: 7%</b>		

<sup>5</sup>Calculations using TU Delft DoubletCalc 2D for produced temperature profiles, fed to NREL Geophires 2.0 bicyclic economic model to calculate LCOE and pump power (Reservoir Model 5, Economic Model 3).



of projects that are eligible (IRA, 2022). The legislation incentivises domestic content, apprenticeship training, and minimum wage rates, as well as developments on brownfield, extractive fossil fuel sites, abandoned coal mines, coal power generation sites, and in low income tribal land communities.

Table 7.4 presents an illustrative calculation of the levelized cost of heat for a project to re-use two horizontal oil wells as an injector / producer pair to deliver steam to a nearby industrial customer<sup>5</sup>. In most cases, such a geothermal project should qualify for a 30 percent

investment tax credit (refer to Table 7.5 and Table 7.6), decreasing the project's levelized cost of heat ("LCOH") by 14 percent in this example.

By fulfilling additional criteria, the investment tax credit can increase to 50 percent, decreasing LCOH by 23 percent in this example.

The example described in Table 7.4 was modeled using TU Delft DoubletCalc 2D for produced temperature profiles, which were input to the NREL Geophires 2.0 bicycle economic model to calculate LCOE and pump power (Beckers & McCabe, 2019; NLOG, 2016).

**Table 7.5. Summary of IRA benefits to renewables for 2024. Sources: Compton, et al., 2022; Hartford, 2022; NLR, 2022; O'Neill, et al., 2022; Smith & Tassone, 2022.**

Technology	Wind / Geothermal	Solar/Battery Charged by Solar	Standalone Battery
Credit	Section 45 ("S 45") Production Tax Credit ("PTC") or Section 48 Investment Tax Credit ("ITC")	S 45 PTC (solar only) or S 48 ITC (solar & battery)	S 48 ITC whether or not charged by ITC property
Credit Amount	\$27.50 per megawatt in 2022 adjusted for inflation (PTC). Note: the base amount unadjusted for inflation is \$15 per megawatt/hour	Ditto	N/A
	30% of the basis of energy property (ITC)	Ditto	30% of basis of the battery (ITC)
	Start of construction before Jan 1 2025	Ditto	Ditto
Wage and Apprenticeship Requirements	(i) Apply above one megawatt capacity (ii) Wage for duration of construction and entire ten year PTC and five year ITC recapture period (iii) Apprenticeship requirements must be met during construction period only (12.5% / 15% of total labor hours b4 /after end 2024) and all (sub)-contractors employ at least one apprentice if greater than four persons on a project)	Ditto	Ditto
Bonus Credits	Additional 10% for PTC and 10% of basis for ITC for each of the following criteria: (i) domestic content requirements are met (ii) located in an energy community or (iii) for ITC only: located in a low-income community on tribal land and less than 5 megawatts, and 1.8GH.hr pa	Ditto	Additional 10% of basis for ITC for each of the following criteria: (i) domestic content requirements are met (ii) located in an energy community
Direct pay	Not for a private company unless a cooperative engaged in furnishing electric energy to persons in rural areas	Ditto	Ditto
Transferable	Yes, for taxable years 2023 onwards	Ditto	Ditto



Table 7.6. Summary of IRA benefits to renewables for 2025 to 2034. Sources: Compton, et al., 2022; Hartford, 2022; NLR, 2022; O'Neill, et al., 2022; Smith & Tassone, 2022.

Technology	Any Clean-Energy Generating Facility with a GHG Emissions rate less than or equal to zero	Standalone Battery
CREDIT	Section 45Y (S 45Y") Production Tax Credit ("PTC" or Section 48E ("S 48E") Investment Tax Credit ("ITC"))	S 48E ITC whether or not charged by ITC property
CREDIT AMOUNT	Greater than or equal to \$26.0 per megawatt hour in 2025 adjusted for inflation (PTC)	N/A
	30% of the basis of energy property (ITC)	30% of the basis of the battery (ITC)
	Phasedown starting in 2034 earliest	Phasedown starting in 2034 earliest
WAGE AND APPRENTICESHIP REQUIREMENTS	(i) Apply above one megawatt capacity (ii) Wage for duration of construction and entire ten year PTC and five year ITC recapture period (iii) Apprenticeship requirements must be met during construction period only (ten to 15% of total labor hours depending on start date and all (sub)-contractors employ at least one apprentice if greater than or equal to four persons on a project)	Ditto
BONUS CREDITS	Additional 10% for PTC and 10% of basis for ITC for each of the following criteria: (i) domestic content requirements are met (ii) located in an energy community or (iii) for ITC only: located in a low-income community on tribal land and less than five megawatts, and 1.8GH.hr pa	Additional 10% of basis for ITC for each of the following criteria: (i) domestic content requirements are met (ii) located in an energy community
DIRECT PAY	2025-2032: Not for a private company unless a cooperative engaged in furnishing electric energy to persons in rural areas	Ditto
TRANSFERABLE	Yes	Ditto

Due to the time value of money, the LCOH could be reduced further if the geothermal operating company could offset other tax liabilities in the year the investment credit was awarded, rather than having to wait for the project itself to generate sufficient tax liabilities. It is also possible to sell the investment tax credit to third parties.

Tables 7.5 and 7.6 present a summary of the IRA benefits to renewables (including geothermal) for 2024, and 2025–2034 respectively, and the obligations to qualify for them. Table 7.7 presents a summary of the definitions used in the tables and the IRA. It also lists the References of this Chapter used to compile this Section, with special mention to MossAdams (with their disclaimer) for their excellent tabulation which Table 7.5 and Table 7.6 closely follow (O'Neill, et al., 2022).

## V. Implications of Carbon Costs for Geothermal Competitiveness

The Organization for Economic Co-operation and Development's ("OECD") 2021 analysis of U.S. effective carbon rates asserts that despite its lack of an explicit carbon tax, its fuel excise taxes and emissions trading system permit-pricing priced 37 percent of its carbon emissions from energy use, of which about five percent were priced above EUR 60 per tonne (OECD, 2022; OECD, 2021). The majority of unpriced emissions were from the electricity sector and the industrial sector.

On December 13, 2022, the European Union reached provisional agreement on its Carbon Border Adjustment Mechanism ("CBAM"). It bears similarities to California's



Table 7.7. Definitions and full references: IRA benefits to renewables for 2024 to 2034. Sources: Compton, et al., 2022; Hartford, 2022; NLR, 2022; O'Neill, et al., 2022; Smith & Tassone, 2022.

Domestic Content
Greater than 55% of components: steel, iron, manufactured products, are manufactured in the United States. (Details to be confirmed by relevant U.S. government agencies)
Energy Community
(i) Brownfield sites
(ii) Metropolitan or non-metropolitan area with direct employment or local tax revenue over an established percentage related to the extraction, processing, transport, or storage of coal, oil, or natural gas as well as an unemployment rate at or above the national average
(iii) Census tract or any adjoining tract in which a coal mine closed after December 31, 1999, or a coal fired electric power plant was retired after December 31, 2009
Technology Neutral (Clean Electricity Investment Credit and the Clean Electricity Production Credit)
Any electricity generating facility of a type that the Secretary of Treasury determines on an annual basis has an "anticipated greenhouse gas emissions rate" that is not greater than zero. The Clean Electricity Investment Credit will also apply to standalone battery storage technology.
Prevailing Wage Requirement as interpreted by the National Law Review (NLR, 2022)
"The new prevailing wage requirement is intended to ensure that laborers and mechanics employed by the project company and its contractors and subcontractors for the construction, alteration, or repair of qualifying projects are paid no less than prevailing rates for similar work in the locality where the facility is located. The prevailing rate will be determined by the most recent rates published by the U.S. Secretary of Labor. Prevailing wages for the area must be paid during construction and for the first five years of operation for repairs or alterations once the project is placed in service. Failure to satisfy the standard will result in a significant penalty, including an 80% reduction in the ITC (i.e., an ITC of 6%), remittance of the wage shortfall to the underpaid employee(s) and a \$5,000 penalty per failure. For intentional disregard of the requirement the penalty increases to three times the wage shortfall and \$10,000 penalty per employee. Projects under one megawatt (AC) are exempt from the requirement."
Apprenticeship Requirement as interpreted by the National Law Review (NLR, 2022)
"For projects with four or more employees, work on the project by contractors and subcontractors must be performed by qualified apprentices for the "applicable percentage" of the total number of labor hours. A qualified apprentice is an employee who participates in an apprenticeship program under the National Apprenticeship Act. The applicable percentage of labor hours phases in and is equal to 10% of the total labor hours for projects that begin construction in 2022, 12.5% for projects beginning construction in 2023, and 15% thereafter. Similar penalties to the prevailing wage penalties apply for failure to satisfy the apprenticeship requirement. A "good faith" exception applies where an employer attempts but cannot find apprentices in the project's locality. Projects under one megawatt (AC) are exempt from the requirement."

multi-sector Cap and Trade program and Auction of Emissions Allowances introduced in 2013, which imposed a three percent pa reducing cap on emissions for electric power plants and industrial plants emitting more than 25,000 tons partial pressure of carbon dioxide, since extended to fuel distributors (EU, 2022; Dumitru, 2021; CCI, 2020).

CBAM initially affects all imports to the European Union ("EU") of iron and steel, cement, fertilizers, aluminum, electricity, and hydrogen, as well as some precursors and downstream products. Indirect emissions are also

included. Reporting obligations apply from October 2023, and imported goods will require independent verification of carbon content. From 2026 and 2027, the verified carbon content will be the taxable base for an extension to the current EU Emissions Trading System ("ETS"), with new CBAM certificates auctioned. However, the EU tax is offset by carbon taxes from the exporting country, incentivising major exporting countries to introduce their own schemes rather than transferring tax receipts to the EU. In June 2021, Democrat Senators introduced a plan to tax iron, steel, and other imports from countries without ambitious climate laws (Friedman, 2021).



In May 2022, the seventh Western Climate Initiative auction ("WCI") settled at \$30.85 per ton of carbon dioxide emissions (Sutter, 2022), providing \$1.1 billion for the California Climate Investments fund, and \$300 million for the Quebec Electrification and Climate Change Fund. The December 15, 2022 trading close for the EU ETS Carbon Permits was EUR 85 per metric tonne.

Table 7.8 presents the U.S. Energy Information Administration ("EIA") carbon dioxide emissions coefficients, which show a significant emissions advantage of geothermal energy over competing fossil fuels (EIA, 2022a).<sup>6</sup> It also presents the dollars per million British thermal units cost on each primary energy supply, assuming (a) the May 2022 \$30.85 per ton WCI and (b) the December 2022 EUR 85 per metric tonne EU ETS.

It shows that under the WCI, geothermal energy would have a price advantage of \$1.4 per million British thermal units over Henry Hub Natural Gas ("HH NG") and greater than \$2 per million British thermal units over liquid fuels. Under the EU ETS, the advantage would be \$3.7 per million British thermal units over HH NG and greater than \$5.5 per million British thermal units over liquid fuels.

## VI. Competitive Analysis of Geothermal in Texas

As discussed in Section I of this Chapter and in [Chapter 1, Geothermal and Electricity Production](#) and [Chapter 2, Direct Use Applications](#) of this Report, multiple geothermal products, including electrical power, Direct Use heat for industry and space heating, and subsurface energy storage, have target markets in Texas. To win significant market share, geothermal energy needs to be price competitive, and Table 7.9 presents the forward commodity prices for the primary fossil fuels used in Texas by industry and commerce.

Factory-gate energy prices might additionally reflect pipeline/ tanker/ truck transportation fees; distribution hub costs; and local supply/demand adjustments, so Table 7.9 is simply indicative of the price-targets geothermal needs to achieve. And if carbon pricing evolves, either to avoid EU carbon import taxes, or if the WCI becomes more generally adopted, then geothermal energy's relative carbon cost savings in Table 7.8 could materially improve its competitiveness and attractiveness to customers.

**Table 7.8. Comparison of carbon dioxide emissions and carbon costs for fossil fuels and geothermal.** Primary energy source measurements are carbon dioxide per million British thermal units ("CO2/MMBTU"), dollars per ton of carbon dioxide ("\$/ton CO2"), and dollars per million British thermal units ("\$/MMBTU"). Source: EIA, 2022a.

Primary Energy Source	Henry Hub Natural Gas	Low Sulfur Gas oil (No 2 Heating oil)	Middle distillate/ residual fuel blends (No 4 Heating Oil)	Gulf Coast High Sulfur (3-3.5 percent) Fuel Oil (No 6 Heating Oil)	Coal/ Lignite Powder River Basin	Geothermal Steam
<b>Carbon Emissions (IEA)</b>						
Pounds CO2/ MMBTU	117	163	165	166	216	26
Ton CO2/ MMBTU	0.058	0.082	0.082	0.083	0.108	0.013
<b>Carbon Permit Price: California / Quebec Western Climate Initiative 7th Auction May 2022</b>						
Permit \$/ton CO2	30.9	30.9	30.9	30.9	30.9	30.9
Permit \$/MMBTU	1.8	2.5	2.5	2.6	3.3	0.4
<b>Carbon Permit Price: European Union ETS 15th Dec 2022</b>						
Permit \$/ton CO2	81.7	81.7	81.7	81.7	81.7	81.7
Permit \$/MMBTU	4.8	6.7	6.7	6.8	8.8	1.1

<sup>6</sup>However, the EIA's methodology, itself referring to the U.S. Environmental Protection Agency's inventory of U.S. greenhouse gas emissions and sinks, does not include the carbon content of the well and facilities construction.



Three geothermal applications relevant in Texas are explored below.

#### A. Direct Use Geothermal Heat

[Chapter 2, Direct Use Applications](#) of this Report described the opportunities for Direct Use geothermal to decarbonise residential and commercial heating and cooling, industrial processes, and other Direct Use heat use cases. Table 7.9 illustrates that liquid fuels are two to three times more expensive than gas per million British thermal units, suggesting that a focus on industries or plants that use liquid fuels may provide a business opportunity for geothermal heat. Because converting hot water to steam is energy intensive due the latent heat of evaporation, providing steam to almost any industrial process can materially reduce the liquid fuel consumption required to achieve the final process temperature (even very high temperature processes). Many of the energy-intensive industrial processes listed in Table 7.10 are operating in Texas (Bianchi, et al., 2019).

The Fuel Oil (also known as Heating Oil) classifications referred to in Table 7.9 are as follows with direct attributions to these references (Coker, 2022; EIA, 2022b; Holloway & Holloway, 2020):

- No. 2 Fuel Oil is used in atomizing burners for domestic heating and moderate capacity commercial and industrial burner units;
- No. 4 Fuel Oil is used extensively in large industrial and commercial burner installations that are not equipped with preheating facilities. (The classification also includes No. 4 (heavy) diesel fuel which is used for low- and medium-speed diesel engines); and
- No. 6 Fuel Oil is viscous and is used in industrial burners with pre-heating facilities.

To win significant Texas market share in the immediate future, geothermal Direct Use heat prices would need to be comparable to the prices of 24/7/365 fossil fuels in Table 7.9. **For example, for 2023 and 2024, a range of \$4.7 to \$5.8 per million British thermal units for gas and \$13.3 to \$13.8 per million British thermal units for No 4 Heating Oil to which the operating and ongoing capital expenditures costs of the gas and fuel oil plants would need to be added** (currency in U.S. dollars). As stated in the note to Table 7.9, factory-gate gas and No 4 Heating Oil prices might be higher to reflect pipeline, tanker, and truck transportation fees; distribution hub costs; and local supply and demand adjustment.

Table 7.9. Comparison of Nymex Energy Futures for Fossil Fuels (13th December 2022). Measurements are listed as million British thermal units per cubic foot ("MMBTU/ft<sup>3</sup>") and dollars per million British thermal units ("\$/MMBTU"). Source: Nymex, 2022.

Year	Henry Hub Natural Gas	Low Sulfur Gasoil (No 2 Heating oil)	Middle distillate/residual fuel blends (No 4 Heating Oil)	Gulf Coast High Sulfur (3-3.5 percent) Fuel Oil (No 6 Heating Oil)	WTI	Coal/Lignite Powder River Basin <sup>7</sup>
Gross Heating Value	0.001 MMBTU/ft <sup>3</sup>	1.04 MMBTU/ft <sup>3</sup>	1.08 MMBTU/ft <sup>3</sup>	1.12 MMBTU/ft <sup>3</sup>	1.01 MMBTU/ft <sup>3</sup>	0.74 MMBTU/ft <sup>3</sup>
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU
2023	\$5.8	\$18.7	\$13.8	\$9.0	\$13.4	\$3.01
2024	\$4.7	\$17.5	\$13.3	\$9.2	\$12.8	\$3.24
2025	\$4.6	\$16.9	N/A	N/A	\$12.1	\$3.47
2026	\$4.6	\$16.6	N/A	N/A	\$11.6	\$3.70

<sup>7</sup>Nymex delisted all U.S. thermal coal futures in January 2021 stating that open interest had fallen to zero. Therefore, these are internal forecasts based on a pro-rata increase in coal price from \$2.55/MMBTU 2020 to \$2.78/MMBTU in 2021 reported in ERCOT State of the Market.



To estimate a target for fossil-fuel competitive geothermal Direct Use heat prices further into the future, in Tables 7.11 and 7.12 we add, respectively the California Carbon Permit prices and EU Emissions Trading Scheme (“ETS”) carbon prices in Table 7.8 to the price of gas and fuel oil

in Table 7.9 to estimate carbon-adjusted Direct Use heat prices for gas and fuel oil. (This exercise assumes gas and fuel oil futures remain at 2023/2024 prices, to clarify the impact of the carbon pricing).

Table 7.10. Main processes and their temperature levels per industrial sector. Source: *Bianchi, et al.*

Industry/Temperature Level of Process	LT (less than 212°F)	MT (less than 212 to 570°F)	HT (greater than 570°F)
Iron and Steel			Blast furnace/basic oxygen furnace route
			Direct melting of scrap (electric arc furnace)
			Direct reduction
			Smelting reduction
Large combustion plants	Cogeneration/combined heat and power	Steam generation	Combined cycle plants
			Gasification/liquefaction
			General fuel heat conversion
			Steam generation
Petrochemicals			Distillation
			Catalytic Cracking
Large volume inorganic chemicals: ammonia, acids and fertilizers			Conventional steam reforming
			Sulfuric acid process
Large volume inorganic chemicals: solids and others		Sulfur burning	Sodium silicate plant
			Tank furnace process
Food and tobacco	Crude vegetable oil production from oilseeds	Solubilization/alkalizing	High-temperature frying
	Heat recovery from cooling systems	Utility processes	
Glass			Heating the furnaces primary melting
Organic fine chemicals	Process of energy supply		Co-incineration of liquid waste
			Thermal oxidation of VOCs
Nonferrous metals		Primary lead and secondary lead production	Smelting reduction
			Zinc sulfide (sphalerite)
Cement, lime, and magnesium oxide			Clinker burning
			Kiln firing



- Using the California carbon permit prices in Table 7.11 increases the target price for competitive geothermal Direct Use heat to **a range of \$6.1 to \$7.2 per million British thermal units for gas and \$15.5 to \$16.0 per million British thermal units for No 4 Heating Oil**, to which the factory-gate additional pricing and the operating and ongoing capital expenditures costs of the gas and fuel oil plants would need to be added.
- Using the EU ETS, carbon permit prices in Table 7.12 increases the target price for competitive geothermal Direct Use heat to **a range of \$8.4 to \$9.5 per MMBTU for gas and \$19.0 to \$19.5 per MMBTU for No 4 Heating Oil**, to which the factory-gate additional pricing and the operating and ongoing capital expenditure costs of the gas and fuel oil plants would need to be added.

Even further into the future, if Texas transitions away from gas and fuel oil through policy such as legislation, carbon taxes, or other mechanisms, renewable electric heating and nuclear combined heat and power would be key competitors to geothermal.

## B. Geothermal for Electricity Production

In 2021, gas and coal comprised 60 percent of generating capacity to the Texas power generation market (42 percent gas, 19 percent coal), as illustrated in Figure 7.1 (Potomac, 2022). ERCOT forecasts that in 2023, gas will remain at 42 percent, and coal will reduce to 11 percent. ERCOT controls the supply of approximately 90 percent of the State's total electricity demand (ERCOT, 2022). It centrally coordinates transactions between competitive wholesale power buyers and sellers, and manages the financial side of the energy market by collecting money from companies that consume power and paying the resources that produce the power (ERCOT, 2022). The other ten percent of electricity consumed in Texas includes cooperatives and commercial operators supplying micro-grids and small settlements, which may also be a target for geothermal. Table 7.13 presents the growth in installed power generation and energy consumption in recent years. The average capacity factor (i.e., the actual energy consumption divided by the

**Table 7.11. Carbon-adjusted Direct Use heat prices for gas and fuel oil using California Carbon Permit scheme. Measurements in dollars per million British thermal units ("\$/MMBTU"). Source: Future of Geothermal Energy in Texas, 2023.**

Year	Henry Hub NG	California Carbon Price (Relative to Geothermal)	California Carbon Adjusted Henry Hub NG price	Low Sulfur Gasoil (No 2 Heating oil)	California Carbon Price (Relative to Geothermal)	California Carbon Adjusted Low Sulfur Gasoil (No 2 heating oil)
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU
2023	\$5.8	\$1.4	\$7.2	\$18.7	\$2.1	\$20.8
2024	\$4.7	\$1.4	\$6.1	\$17.5	\$2.1	\$19.6
	Middle distillate/residual fuel blends (No 4 Heating Oil)	California Carbon Price (Relative to Geothermal)	California Carbon Adjusted Middle Distillate (No 4 Heating oil)	Gulf Coast High Sulfur (3-3.5%) Fuel Oil (No 6 Heating Oil)	California Carbon Price (Relative to Geothermal)	California Carbon Adjusted High Sulfur Fuel Oil (No 6 Heating oil)
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU
2023	\$13.8	\$2.1	\$16.0	\$9.0	\$2.2	\$11.1
2024	\$13.3	\$2.1	\$15.5	\$9.2	\$2.2	\$11.3



Table 7.12. Carbon-adjusted Direct Use heat prices for gas and fuel oil using EU Emissions Trading Scheme (ETS) Carbon Permit prices. Measurements in dollars per million British thermal units ("\$/MMBTU").  
Source: Future of Geothermal Energy in Texas, 2023.

Year	Henry Hub NG	EU Emissions Trading Scheme Carbon Price (Relative to Geothermal)	ETS Carbon Adjusted Henry Hub NG price	Low Sulfur Gasoil (No 2 Heating oil)	EU Emissions Trading Scheme Carbon Price (Relative to Geothermal)	ETS Carbon Adjusted Low Sulfur Gasoil (No 2 heating oil)
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU
2023	\$5.8	\$3.7	\$9.5	\$18.7	\$5.6	\$24.3
2024	\$4.7	\$3.7	\$8.4	\$17.5	\$5.6	\$23.1
<hr/>						
	Middle distillate/residual fuel blends (No 4 Heating Oil)	EU Emissions Trading Scheme Carbon Price (Relative to Geothermal)	ETS Carbon Adjusted Middle Distillate (No 4 heating oil)	Gulf Coast High Sulfur (3-3.5%) Fuel Oil (No 6 Heating Oil)	EU Emissions Trading Scheme Carbon Price (Relative to Geothermal)	ETS Carbon Adjusted High Sulfur Fuel Oil (No 6 heating oil)
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/MMBTU
2023	\$13.8	\$5.7	\$19.5	\$9.0	\$5.7	\$14.7
2024	\$13.3	\$5.7	\$19.0	\$9.2	\$5.7	\$14.9

theoretically achievable energy generated) is about 50 percent, but this would be a significant under-estimate for geothermal because wind and solar are not able to generate power 24/365.

Figure 7.2 (Potomac, 2022) illustrates the cumulative frequency of customer demand for power generation into which new geothermal power generation capacity needs to fit, either/and as baseload, middle order, peak or ancillary services, all of which are discussed below. Figure 7.2 shows that in 2021, demand was greater than 40 gigawatts for 5,631 hours or 64 percent of the year. A geothermal power plant operator may choose to offer its energy at a price that is likely to be called 64 percent of the year (the capacity factor of a power plant with an offer price to run at the 40 gigawatts electric margin). Or perhaps if a geothermal operator decided to compete with nuclear and coal as a baseload plant, operating for over 90 percent of the year (7,884 hours), it would have to offer its electricity at a price that would always be accepted at the ~35 gigawatts electric margin. Figure 7.3 shows the prices paid for electricity for a given number of hours on

the system, Figure 7.4 shows the prices at different times of the day and Figure 7.5 in different calendar months. There are many ways to compete and make profits on the ERCOT system.

**The challenge for the geothermal “new entrant” to the ERCOT system is what price (and therefore implied capacity factor) should it offer its electricity to achieve a return on investment at least equal to its cost of capital.**

Figure 7.5 also presents a number of other components that the final customer pays for. Amongst these are “ancillary services”, which can be extremely profitable to power plant operators. The geothermal opportunities to provide ancillary services are discussed in Subsection VI-C below.

Table 7.14 presents the average real time prices for electricity to ERCOT for the period 2014 to 2021. There is a strong correlation with the average gas price because gas has usually been the “price setter.” For much of the time gas supplies the marginal kilowatt hour which sets



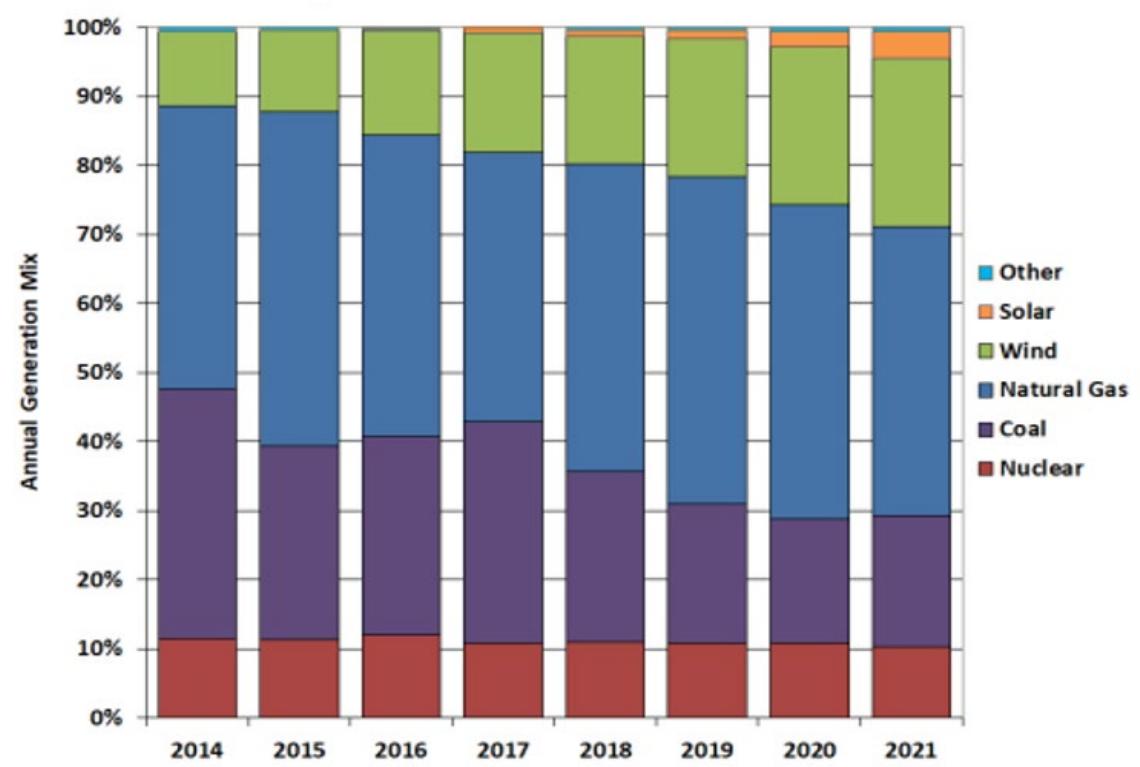


Figure 7.1. 2021 ERCOT generation mix maximum day demand in 2021 was 72.3 gigawatts and 80.0 gigawatts in 2022. Installed capacity in 2021 was 86 gigawatts and in 2022 92 gigawatts. Source: ERCOT, 2021, 2022.

the price. Gas is still the dominant price setter, except for some ancillary services where batteries have taken over (refer Subsection VI-C below). However, as ERCOT transitions away from gas and coal, prices will be set by other sources of supply. The candidates include wind, solar, battery storage, and nuclear. If geothermal were available to ERCOT at scale supplying electricity from base load to peak, and ancillary services, it would compete for this role (refer Subsection VI-D below).

Table 7.15 presents the settlement prices by fuel type in the ERCOT jurisdiction, again the 2021 prices are strongly influenced by Winter Storm Uri so they are also presented excluding this effect, so the 2020 and 2021 prices do provide a comparison.

In particular, ERCOT referenced data published by the Nuclear Energy Institute (“NEI”) for the average generating cost of nuclear power in 2020 & 2021 was approximately \$0.0307 per kilowatt electric hour and \$0.0293 per

Table 7.13. ERCOT installed generation capacity and energy consumption. Source: Future of Geothermal Energy in Texas, 2023.

Year	Installed Capacity	Consumption	Calc. Capacity Factor (Underestimate)
			Percent
			electric per hour
2020	82	382	52
2021	86	393	51
2022	92	TBA	TBA



kilowatt electric hour respectively, so prices in 2020 were lower than cost (NEI, 2022). According to the NEI, these generating costs include capital for upgrades related to license extensions of plants, uprates, and completed safety-related investments post-September 11th and post-Fukushima. So notably, the NEI does not mention amortization of initial construction cost or provision for decommissioning. Since geothermal energy is a potential

competitor to nuclear energy for the replacement of coal and gas base load supply, the Levelized Cost of Energy of new nuclear energy is of great significance. With regard to leveled cost calculation, the EIA estimates the capital expenditures for new brownfield nuclear power of about \$6,100 per kilowatt hour (EIA, 2020) for an average for 600 megawatt and 2,000 megawatt power plants.

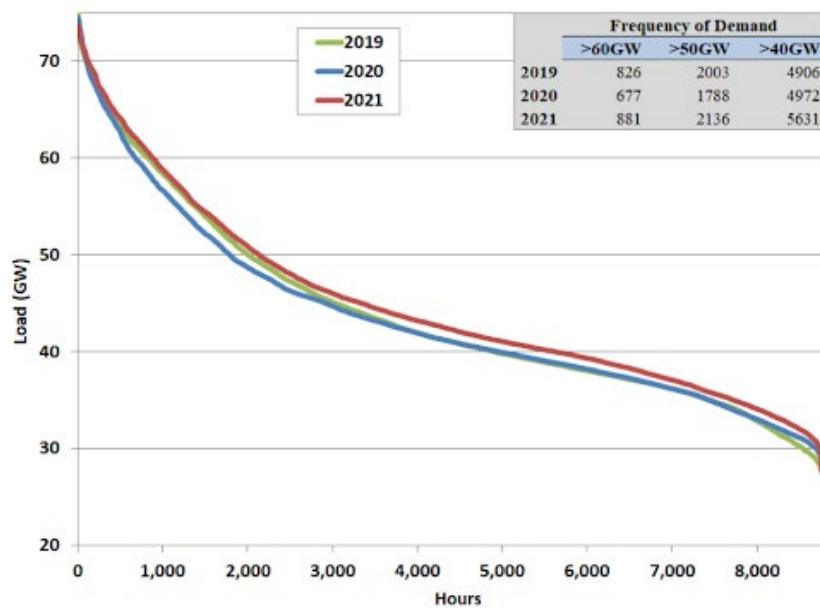


Figure 7.2. Frequency of Demand ERCOT. Source: ERCOT, 2022.

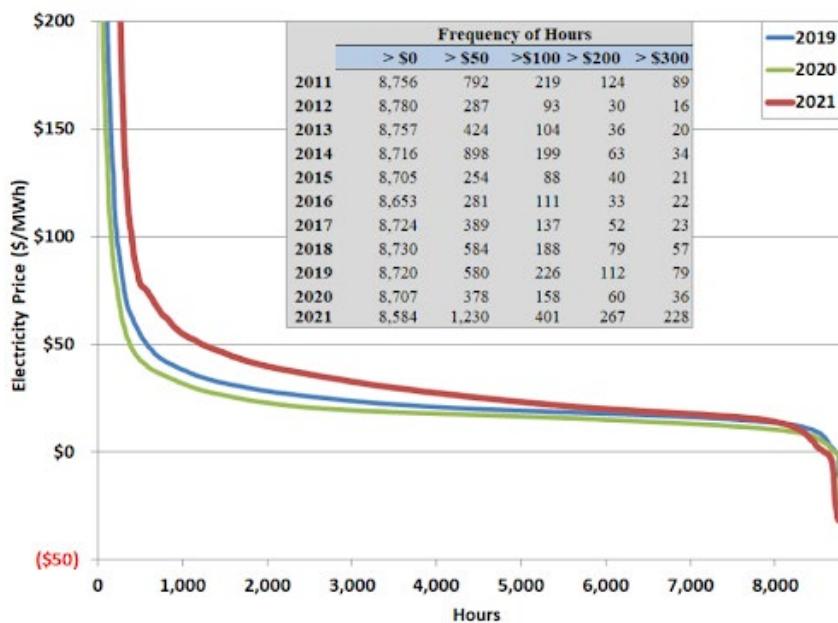


Figure 7.3. Frequency of Electricity Prices During 2021. Source: ERCOT, 2022.



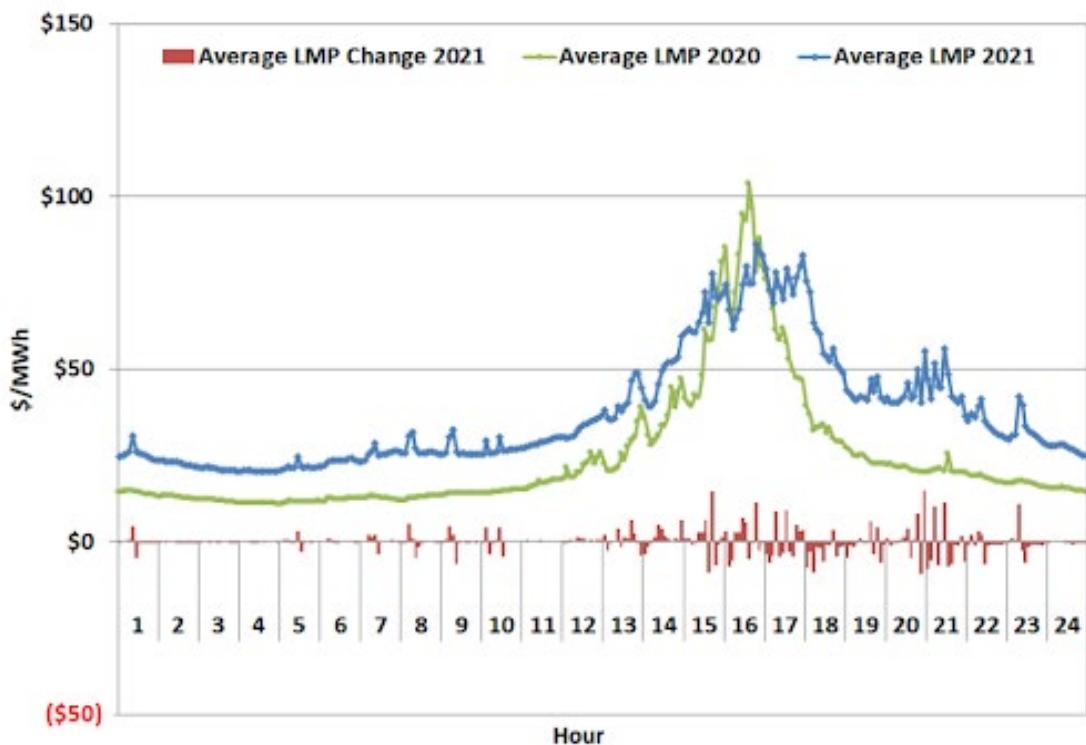


Figure 7.4. Price by Time of Day May to Sept 2021. Source: ERCOT, 2022.

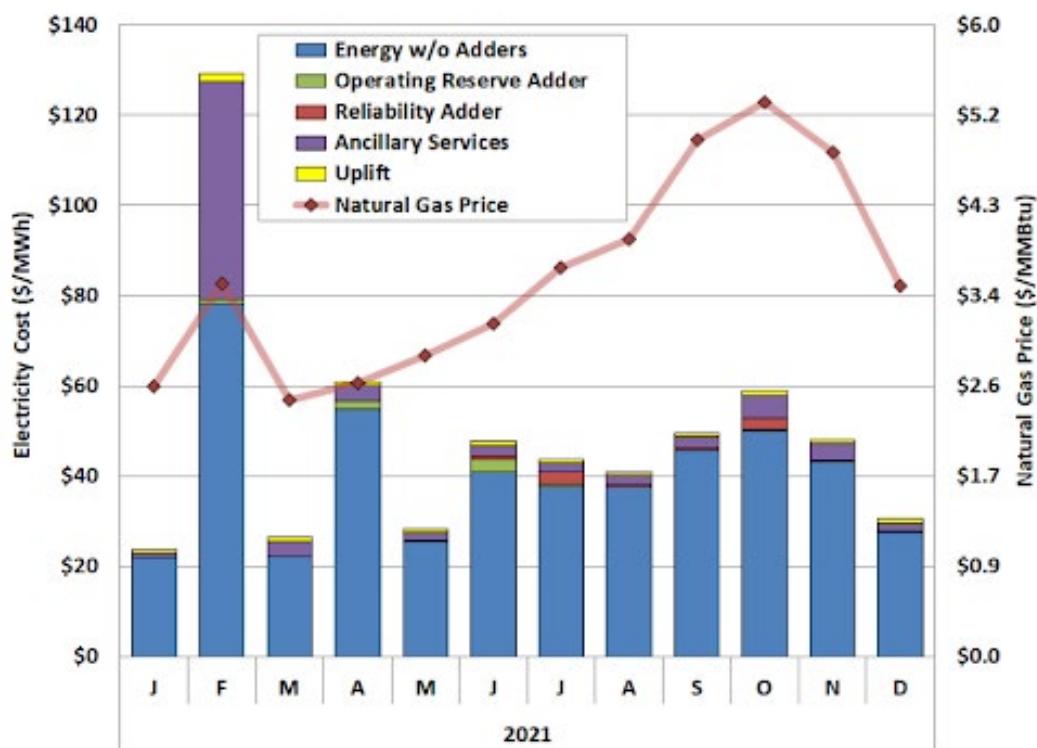


Figure 7.5. Prices by Month 2021 (without Uri). Source: ERCOT, 2.



Table 7.16 presents the Nymex electricity futures for ERCOT, for example, in Houston for 2023, and re-presents in the same units the Henry Hub Natural gas futures and the Powder Basin Coal price internal forecasts. The implied fuel-only generation cost from gas and coal are also presented in Table 7.16, using a typical energy conversion efficiency for a combined cycle gas turbine ("CCGT") gas plant to electricity (between 50 and 60 percent, assume 50 percent), and U.S. coal plant (average 33 percent, assume 30 percent) (DOE, 2022; Ray, 2015). For year-average 2023, the ERCOT Houston futures are \$0.021 per kilowatt hour off-peak and \$0.034 per kilowatt hour peak, the latter is similar to the implied fuel-only electricity cost derived from coal prices, and lower than from gas prices.

To win significant Texas market share in the immediate future, geothermal electricity prices would need to be comparable to the prices of 24/7/365 fossil fuels in Table 7.16. **This is a range of \$0.032 to \$0.039 per kilowatt-electric hour for 2023-2024, to which the operating and**

**ongoing capital expenditures costs of the gas and coal plants would need to be added.** However, geothermal electricity does offer advantages over both gas and coal which might justify a premium:

- Multi-year supply contracts remove customers' exposure to fossil fuel price volatility and hedging costs;
- Customers can realize a savings from future maintenance and replacement costs on gas boiler plants;
- Resilience from external outages for priority non-interruptible customers if located within or near customers' site limits, such as healthcare facilities and Department of Defense military installations; and
- Ramp up times for geothermal electricity generation may be comparable to or faster than CCGTs, and therefore have this additional advantage over thermal coal and nuclear plants, which have slower response times.

Table 7.14. Average annual real-time energy market prices. Measurements in per kilowatt electric hour ("\$/kW.hr") and dollars per million British thermal units ("\$/MMBTU"). Source: Potomac/ERCOT 2022.

Year	2014	2015	2016	2017	2018	2019	2020	2021	2021 w/o Uri
<b>ERCOT \$/kW.hr</b>	\$0.041	\$0.027	\$0.025	\$0.028	\$0.036	\$0.047	\$0.026	\$0.168	\$0.041
<b>Natural Gas \$/MMBTU</b>	\$4.32	\$2.57	\$2.45	\$2.98	\$3.22	\$2.47	\$1.99	\$7.30	\$3.62

Table 7.15. Comparison of settlement prices by fuel. Source: Potomac/ERCOT 2022.

Generation Type	Output-Weighted Price dollars per per kilowatt electric hour		
	2019	2020	2021(w Uri)
Coal	\$0.044	\$0.025	\$0.148
Combined Cycle	\$0.047	\$0.025	\$0.208
Gas Peakers	\$0.126	\$0.060	\$1.023
Gas Steam	\$0.135	\$0.042	\$0.405
Hydro	\$0.043	\$0.024	\$0.305
Nuclear	\$0.035	\$0.020	\$0.138
Power Storage	\$0.155	\$0.081	\$0.109
Private Network	\$0.046	\$0.024	\$0.177
Renewable	\$0.141	\$0.035	\$0.044
Solar	\$0.061	\$0.025	\$0.076
Wind	\$0.021	\$0.011	\$0.061



To estimate a target for fossil-fuel competitive geothermal electricity prices further into the future, in Tables 7.17 and 7.18 we add, respectively, the California Carbon Permit prices, and EU ETS carbon prices in Table 7.8 to the price of coal and gas in Tables 7.9 and 7.16, to estimate carbon-adjusted electricity prices for gas and coal. This exercise assumes gas and coal futures remain at 2023/2024 prices, to clarify the impact of the carbon pricing.

- Using the California carbon permit prices in Table 7.17 increases the target price for competitive geothermal to a **range of \$0.042 to \$0.070 per kilowatt-electric hour**, to which the operating and ongoing capital expenditures costs of the gas and coal plants would need to be added.
- Using the EU ETS carbon permit prices in Table 7.18 increases the target price for competitive geothermal to a **range of \$0.058 to \$0.125 per kilowatt-electric hour**, to which the operating and ongoing capital expenditure costs of the gas and coal plants would need to be added.

Even further into the future, if Texas transitions away from gas and coal (by legislation, carbon taxes, etc.), (i) nuclear, and (ii) wind+solar+storage will be key competitors to geothermal. This is analyzed below in Section D Geothermal vs. Nuclear vs. Wind+Solar+Storage.

As a sense check, Table 7.19 presents recent published power purchase agreements for approximately 100 megawatts electric of geothermal plants in the Western United States (Robins, et al., 2021), with contract prices all around \$0.07 per kilowatt-electric hour, perhaps reflecting a strategy to build baseload renewable electricity supply, albeit at a premium to fossil fuels. Twenty-eight States in the United States have adopted Renewable Portfolio Standards (“RPS”), which require that a specified percentage of the electricity utilities sell comes from renewable resources (NCSL, 2021). In Texas, the RPS applies to retail entities defined as: investor-owned utilities that have not unbundled, retail electric providers in deregulated areas, and municipal utilities and electric cooperatives that offer customer choice (NCCETC, 2022).

Consistent with the approach in Table 7.19, in Europe, both Croatia and Germany governments apply a premium to their power purchase agreements for geothermal. For Croatia, from 2020, Geothermal power plants between 0.5 megawatts and 20 megawatts are incentivized (Croatia Incentive, 2020). The German Renewable Energy Sources Act (“EEG”) offers a stable and transparent support scheme for electricity generation using geothermal resources. Under the EEG, the feed-in tariff for electricity generated by geothermal energy amounts to 25.20 cents per kilowatt hour (German Incentive, 2017).

Table 7.16. Comparison of Nymex Houston Electricity Futures with Henry Hub Natural Gas restated in comparable units. Measurements listed in table as dollars per kilowatt thermal hour (“\$/kWth.hr”). Peak contract assumes five megawatts x 16 Peak Hours for a total of 80 megawatt hours arithmetic average of all ERCOT Houston 345 kilovolt Hub real-time settlement point peak prices provided for the contract month (Monday-Friday). For off-peak contract assumptions in this table, the arithmetic average of all ERCOT Houston 345 kilovolts Hub real-time settlement point off-peak prices provided for the contract month. Sources: NYMEX, ERCOT, This Report.

Year	Ercot Houston 345 Kilovolt Hub 5 Megawatt Peak Futures	Ercot Houston 345 Kilovolt Hub 5 Megawatt Off-peak Futures	Henry Hub Natural Gas	Henry Hub Natural Gas Converted to Electricity at a CCGT Efficiency of 50 Percent	Coal/Lignite Powder River Basin	Coal/Lignite Powder River Basin Converted to Electricity at an Efficiency of 30 Percent
	\$/kWe.hr	\$/kWe.hr	\$/kWth.hr	\$/kWe.hr	\$/kWth.hr	\$/kWe.hr
2023	\$0.034	\$0.021	\$0.020	\$0.039	\$0.010	\$0.034
2024	N/A	N/A	\$0.016	\$0.032	\$0.011	\$0.037



Table 7.17. Carbon-adjusted fuel-only electricity prices for gas and coal using California Carbon Permit prices. Measurements in per kilowatt electric hour ("\$/kW.hr") and dollars per million British thermal units ("\$/MMBTU"). Source: *Future of Geothermal Energy in Texas*, 2023.

Year	Henry Hub NG	California Carbon Price (Relative to Geothermal)	California Carbon Adjusted Henry Hub NG price	California Carbon Adjusted Henry Hub NG price	Henry Hub NG converted to Electricity at a CCGT efficiency of 50%
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/kWth.hr	\$/kWe.hr
2023	\$5.8	\$1.4	\$7.2	\$0.024	\$0.049
2024	\$4.7	\$1.4	\$6.1	\$0.021	\$0.042
	Coal/ Lignite Powder River Basin	California Carbon Price (Relative to Geothermal)	California Carbon Adjusted Powder River Coal price	California Carbon Adjusted Powder River Coal price	Coal/Lignite Powder River Basin converted to electricity at an efficiency of 30%
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/kWth.hr	\$/kWe.hr
2023	\$3.01	2.9	\$5.95	\$0.020	\$0.068
2024	\$3.24	2.9	\$6.18	\$0.021	\$0.070

Table 7.18. Carbon-adjusted fuel-only electricity prices for gas and coal using EU Emissions Trading Scheme ("ETS") Carbon Permit prices. Measurements in per kilowatt electric hour ("\$/kW.hr") and dollars per million British thermal units ("\$/MMBTU"). Source: *Future of Geothermal Energy in Texas*, 2023.

Year	Henry Hub NG	EU Emissions Trading Scheme Carbon Price (Relative to Geothermal)	ETS Carbon Price-Adjusted Henry Hub NG price	ETS Carbon Price-Adjusted Henry Hub NG price	Henry Hub NG converted to Electricity at a CCGT efficiency of 50%
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/kWth.hr	\$/kWe.hr
2023	\$5.8	\$3.7	\$9.5	\$0.032	\$0.065
2024	\$4.7	\$3.7	\$8.4	\$0.029	\$0.058
	Coal/Lignite Powder River Basin	EU Emissions Trading Scheme Carbon Price (Relative to Geothermal)	ETS Carbon Price-Adjusted Powder River Coal price	ETS Carbon Price-Adjusted Powder River Coal price	Coal/Lignite Powder River Basin converted to electricity at an efficiency of 30%
	\$/MMBTU	\$/MMBTU	\$/MMBTU	\$/kWth.hr	\$/kWe.hr
2023	\$3.01	\$7.8	\$10.8	\$0.037	\$0.123
2024	\$3.24	\$7.8	\$11.0	\$0.038	\$0.125



### C. Geothermal for ERCOT Ancillary Services including Battery Storage

ERCOT has access to approximately two gigawatts of battery storage, which helps mitigate intra-day price volatility, and supplement coal and gas for ancillary services (Watson, 2022). It reports another 0.8 gigawatts of storage is pending full access to the grid. NREL forecasts capital expenditure ranges from \$1,240 to \$1,400 per kilowatt hour for utility scale 4-hour lithium battery storage in 2023 (in 2020 USD), and operating expenditures from \$31 to \$35 per kilowatt year (NREL, 2022). A recent report notes that capital expenditures may already be as low as \$1,000 per kilowatt hour (Murray, 2022). This compares with the International Renewable Energy Agency's reported range for geothermal electrical power 2020 of \$2,140-\$6,250 per kilowatt hour, average \$4,500 per kilowatt hour (IRENA, 2021), and the above mentioned EIA estimate for brownfield nuclear power of about \$6,100 per kilowatt hour (EIA, 2020).

Figure 7.6 illustrates ERCOT data presented by Enverus Intelligence Research ("EIR"), which presents the proportion of battery storage revenue earned from intra-day arbitrage of energy (orange) and ancillary services to stabilize the grid by adding generation on demand (green, Regulation Up), reducing generation on demand (red, Regulation Down), maintaining frequency after a perturbation to the grid (purple, Responsive Reserve), and offline capacity that can provide power within 10 minutes (light blue, Non-Spinning Reserve). Figure 7.6 shows that battery operators strongly prefer providing ancillary services. The reason is that profits from batteries supplying ancillary services in 2021, for example, were approximately \$150,000 per megawatt hour, compared

with \$40,000 per megawatt hour for intra-day arbitrage (EIR, 2022).

However, previously high prices for Regulation Up and Regulation Down roughly halved in 2022, to \$13 per megawatt hour and \$10 per megawatt hour respectively, because battery storage has now saturated these once highly profitable market niches where prices were previously set by the higher marginal costs of gas and coal. As more storage comes online in 2023, EIR forecasts that prices for Responsive Reserve and Non-Spinning Reserve will similarly fall, potentially halving gross profits for batteries from 2021 to 2023.

Geothermal reservoirs, particularly in sedimentary basins, have the technical capability for both short and long duration pumped storage capacity. With current and near-term technology, it is not cost-competitive with battery storage for the one to four hour period. However, Texas-based Sage Geosystems have demonstrated cost-competitiveness for durations longer than eight to 12 hours, offering a storage technology that could deliver daily, weekly, and seasonal storage capacity (Sage, 2022). Other Texas based entities, like Earthbridge Energy, are pursuing similar concepts. Further details about these projects can be explored in [Chapter 3, Other Geothermal Concepts with Unique Applications in Texas](#) of this Report. These capabilities could contribute to a cost effective transition from the current 60 percent fossil fuels in ERCOT's electricity mix, releasing gas for export. If the transition from fossil fuels is to be achieved by building out more intermittent renewables, the grid will require much greater levels of energy storage, and/or clean baseload capacity, to fulfill the energy supply and ancillary service role.

Table 7.19. Public power purchase agreements for geothermal power generation between November 2019 and September 2020. Source: *Robins, et al., 2021*.

Project	State	Size (megawatt electric)	Pricing (dollar per kilowatt electric hour)	Term (years)
Hell's Kitchen	California	40	0.074	25
Whitegrass	Nevada	3	0.0675	25
Star Peak	Nevada	12.5	0.07025	25
Casa Diablo	California	16	0.068	20
Puna	Hawaii	46	0.07	30



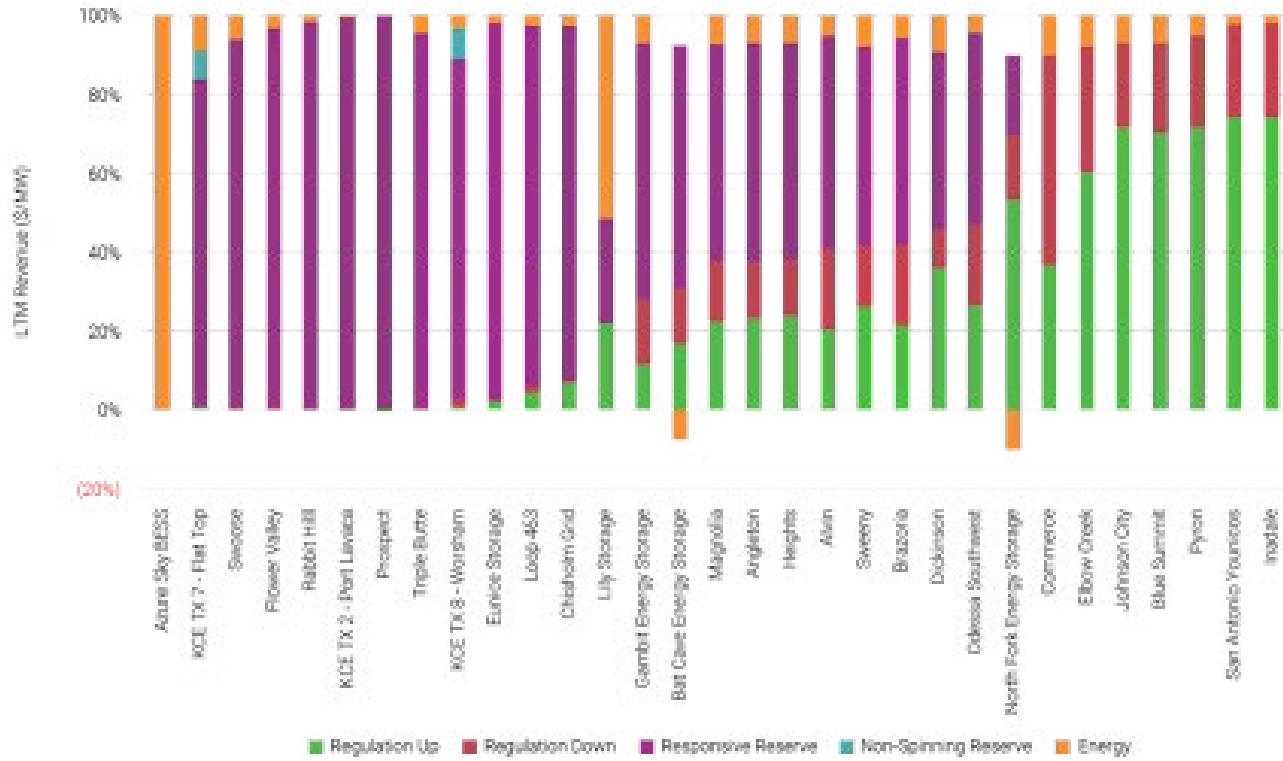


Figure 7.6. Proportion of battery storage revenue from price arbitrage ancillary services 2022.  
Source: ERCOT, 2022.

#### D. ERCOT's Future: Geothermal vs. Nuclear vs. Wind+Solar+Storage

Robert Mulloy of Calpine Corporation (though in a private capacity) has developed a model to understand the storage requirements required if ERCOT's fossil fuel energy were replaced with wind+solar+storage, or instead with nuclear (Curry, 2022a; Curry, 2022b). Figure 7.7 plots the actual electricity demand (called "Load" in the Figure) for ERCOT during the period August 1, 2022 and September 1, 2022 versus the currently installed aggregate wind and solar production of electricity. The difference was satisfied by ERCOT's fossil fuel, hydro, and nuclear mix.

Mulloy showed that increasing solar and wind by eight times would cover the fossil fuel shortfall, but require 900,000 megawatt hours of storage (Figure 7.8 refers), and would lose 37 terawatt hours of electricity to serve a total load of 63 terawatt hours (Figure 7.9). Mulloy calculated the same new wind+solar+storage capital expenditures

could build 90 gigawatts of new nuclear power, which would more than satisfy the shortfall at all times (Figure 7.10). He therefore concluded that additional nuclear capacity would be a cheaper solution despite the much higher capital cost per kilowatt of nuclear energy than wind+solar+storage because nuclear requires no storage.

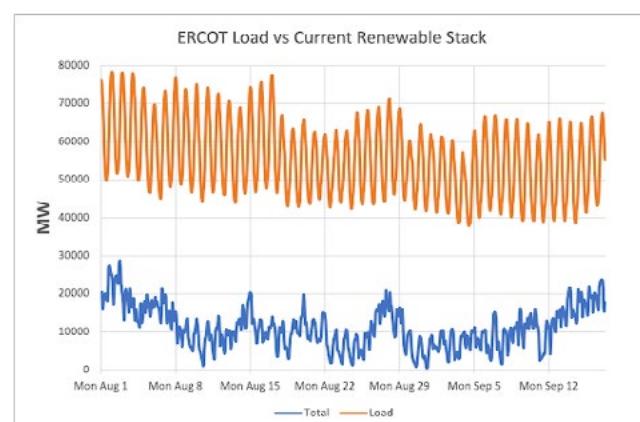


Figure 7.7. August through September 2022 actual demand vs wind and solar. Source: ERCOT, 2022.  
Source: ERCOT, 2022.



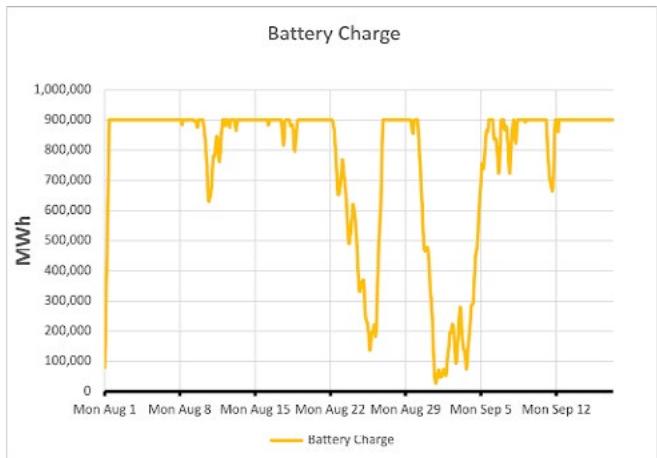


Figure 7.8. Battery capacity requirements for eight times solar and wind in ERCOT energy mix. Source: Interview with Mulloy, 2022.

Below we extend Mulloy's analysis to compare geothermal with nuclear:

- Geothermal capital expenditures are already cheaper than nuclear in dollars per megawatt electric;
- It has no long-term hazardous waste challenge;
- It does not need a critical or scarce raw materials;
- It is much quicker to permit and build, and as will be explored later in this Chapter;
- It may enjoy the speed and scale of the oil and gas industry behind it for rapid development.

With the rapid pace of innovation incentivised by the Federal government and the U.S. Department of Energy, geothermal energy's competitive advantage over nuclear will widen further. Like nuclear, geothermal has a much smaller footprint than wind and solar. Geothermal also enjoys more social license generally than nuclear, making near term development and scale a more realistic view than significant nuclear development.

To conclude this Section, at even its current price per kilowatt hour, geothermal energy is a strong contender for ERCOT's future energy mix, freeing Texas produced gas which currently services demand in Texas, for export elsewhere. These concepts are explored further in [Chapter 11, Geothermal, the Texas Grid, and Economic Considerations](#) of this Report. Geothermal is faster to implement than nuclear and currently typically cheaper per megawatt. If the grid were to be decarbonized and gas instead exported, Mulloy's excellent analysis therefore results in the following conclusion about the most cost-

effective replacement for the grid's fossil-fuel mix: geothermal would be cheaper than both new nuclear and new solar+wind+storage for base load supply, and could out-compete new solar+wind+storage for middle order and peaking supply, and some ancillary services.

## VII. The Impact of the Oil & Gas Industry Developing Geothermal at Scale

We have explored how the oil and gas industry business model differs from geothermal, and the challenges and creative ways of thinking that will need to occur within oil and gas companies to enable large-scale movements by industry into the space. If those barriers were addressed, however, and the oil and gas industry began developing geothermal projects at the scale at which it currently produces oil and gas projects, the impact globally could be quick and substantial.

In Subsection A, we compare the global scale of the oil and gas operations with geothermal; in Subsections B and C we quantify and justify the fundamental assumptions required for the electricity and Direct Use heat calculations respectively. Using these assumptions, we quantify the global opportunity in Subsection D and then customize and apply these findings to the Texas opportunity in Subsection E. In Subsection E, we also report the maximum geothermal capital cost that still achieves 12 percent investor return on equity (refer: Section III-C: 10 to 12 percent for Texas) at the Texas carbon-adjusted fossil fuel prices from Section VI. The aim of this "backwards economic calculation" is to quantify the capital cost target the Texas oil and gas industry must achieve to make geothermal projects investable.

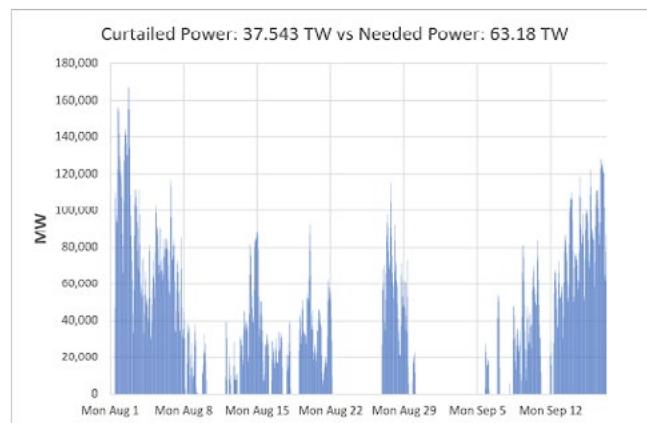


Figure 7.9. Wasted power associated with eight times that of solar and wind. Source: Interview with Mulloy, 2022.



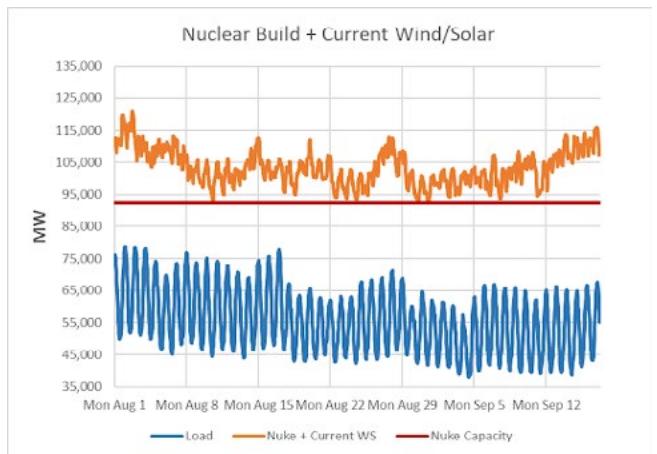


Figure 7.10. Replace fossil fuels with nuclear instead of wind. Source: Interview with Mulloy, 2022.

### **Firstly, we put the scale of the global geothermal challenge in perspective:**

Geothermal electricity projects vary in capacity from one megawatt electric to over one gigawatt electric. Globally, there are about 15.8 gigawatts geothermal electric in 2021, of which the United States has 3.7 gigawatts electric and Indonesia 2.3 gigawatts electric (IRENA, 2022). The U.S. EIA reported that global non-hydroelectric renewable electricity generation capacity in 2021 was 1.84 terawatts, which is about 23 percent of the total global electricity generation capacity of eight terawatts (EIA, 2022c). So currently, geothermal contributes less than one percent of global renewable electricity generation capacity and 0.2 percent of global electricity generation capacity. IEA (2022) reports that the global electricity consumption in 2021 was 82 exajoules (22,800 terawatt hours electric). 2020 geothermal electric energy production was 95 terawatt hours electric, about 0.4 percent of global electric energy production (Huttrer, 2021).

Geothermal Direct Use heat projects total about 30.2 gigawatts thermal globally excluding Geothermal Heat Pumps (Lund & Toth 2021), of which China has 14 gigawatts thermal, and Turkey 3.5 gigawatts thermal. In 2020, these 30.2 gigawatts produced 117 terawatt thermal hours (421 petajoules), implying a 44 percent capacity factor for geothermal Direct Use heat. The International Energy Agency ("IEA") 2022 World Energy Outlook reported that in 2020, final energy consumption for industry and buildings (and 'other') excluding electricity was 231,000 petajoules or approximately 64,000 terawatt-hours, so geothermal Direct Use heat contributes 0.2 percent of global Direct Use heat supply.

Note in the IEA Annex A energy consumption tables, geothermal Direct Use heat is classified under the term "Heat" (end use). In 2021, the Heat category consumed 13 exajoules (3,611 terawatt hours) so geothermal contributed only three percent. Refer to Appendix 7.4 for additional details.

Therefore, for geothermal to have a material impact on decarbonising global energy supply, a step change in technology development and investment is required on a scale similar to the United States transition from conventional hydrocarbon reservoir development to shale reservoir development (or indeed the Apollo program). The United States oil and gas industry has demonstrated its capability to rearrange geopolitics and make the U.S. the world's top producer of gas. With the support of Federal and State governments and major investment institutions, it is uniquely qualified to disrupt the current narrative about the world's future energy mix by developing geothermal energy at global scale.

#### **A. The Necessary Scale of Geothermal Development**

According to Rystad Energy, between 2015 and 2020, approximately 1,100 geothermal wells were drilled for electrical power generation globally, with an average of 180 wells per year during that period (Smith, 2021). The report goes on to predict growth in the sector of 500 wells per year by 2025, and nearly 700 by 2030. Refer to Figure 7.11.

Although Figure 7.11 represents a large percentage increase in geothermal well drilling to 2030, the actual well numbers are insignificant when compared to the oil and gas industry. For example, the Texas RCC reports that 16,500 wells were drilled/sidetracked/other-activities in Texas between January and November 2022, 13,700 in 2021, 20,150 in 2020, 17,700 in 2019. The recent high was 2014, 28,500 wells (RCC, 2022; 2021; 2020; 2018). Figure 7.12 (for the USA as a whole) shows 40,000-50,000 wells per year between 2006 and 2014, during the transition from conventional reservoir development to shale reservoir development. Figure 7.12 shows that the average drilled footage per well increased from 6,500 feet to 15,000 feet in 15 years. Indeed the doubling of wells drilled and of the lateral length per well, combined with five to ten fold increases in frac stages and fluid and proppant volumes/foot contributed to an exponential rise in U.S. shale oil and gas production over this period.



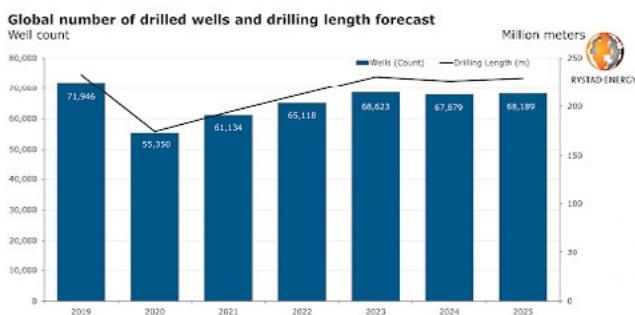


Figure 7.13. Global Number of Drilled Wells, 2019–2025. Source: Rystad, 2020.

Figure 7.13 shows that roughly 60,000 to 70,000 onshore oil and gas wells are forecast to be drilled each year globally, which by comparison with Figure 7.12 would be considerably lower than in the period 2006 to 2014.

**Since Texas typically drills 15,000 to 20,000 wells each year, Figure 7.13 shows that Texas accounts for almost a third of the total onshore oil and gas wells drilled/sidetracked in the world each year.**

So how much geothermal electricity and Direct Use heat could be produced if the oil and gas industry deployed a similar combination of rapid technology development and comparable well drilling to geothermal energy production? To explore this question, we offer a “back of the envelope” calculation of the potential for fast, disruptive, globally

relevant scale should the oil and gas industry develop geothermal energy technology and projects with the same focus and energy that transformed the United States oil and gas industry in less than 15 years.

Many emerging geothermal plant designs call for multiple wells to be pad drilled in a single location to contribute to a central power plant. For the purpose of this exercise, we have chosen well outputs that are at the lower end of values cited as potentially achievable in Texas by sources and interviewees for this Report. These conservative outputs may also be reasonable to expect when seeking to develop sub-optimal geothermal resources near the world’s population centers, for instance. We assume that it will take between now and 2030 for the oil and gas industry to fully engage in geothermal to sufficient levels to scale the industry, and that before 2030 (within eight years from this Report date) one or more geothermal concepts will be successfully demonstrated in the field and be ready for scale.

For the purpose of the global portion of this exercise (refer to Subsection D below), we assume global industry capacity approaching the Figure 7.13 forecast of 60,000 to 70,000 oil and gas wells. We also assume deployment of current oil and gas technologies (not new technological innovations). Assuming sufficient demand for geothermal energy globally, the global oil and gas industry could drill 50,000 geothermal wells to meet increasing geothermal

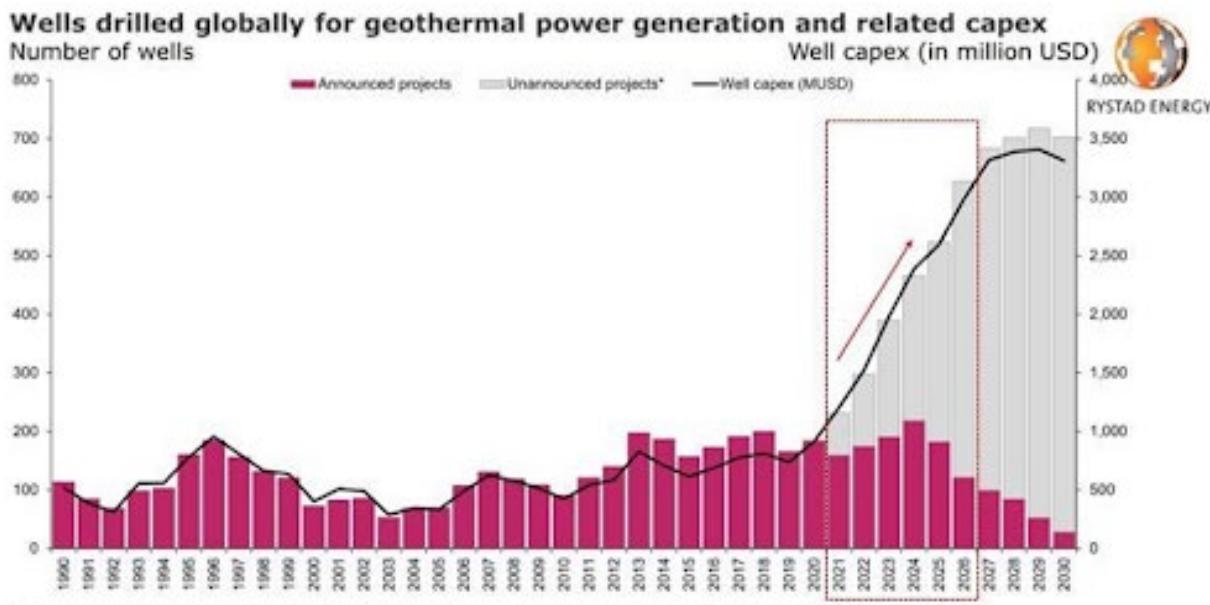


Figure 7.11. Geothermal wells drilled by year. Sources: Rystad Energy, 2021 and Smith, 2021.



Table 7.20. Number of wells drilled in Texas for years 2014 and 2019 through 2022. Source: RCC, 2022; 2021; 2020; 2018.

Number of Wells Drilled in Texas for Years 2014 and 2019 Through 2022					
Year	2022	2021	2020	2019	2014
No. of Wells	16,500	13,700	20,150	17,700	28,500

demand globally (from Figure 7.12, each year between 2012 and 2014, over 40,000 wells were drilled in the United States alone, a measure of potential capacity). The geopolitical implications of this are discussed at the end of this Chapter.

For the purpose of the Texas portion of this exercise (refer to Subsection E below), we assume 2014 industry capacity, during which Texas drilled 28,500 wells, approaching double the average for the last four years. We also assume deployment of current oil and gas technologies (not new technological innovations). Assuming sufficient demand for geothermal energy in Texas, the Texas oil and gas industry could, if profits justify, expand to drill 15,000 wells pa for geothermal, in addition to current oil and gas activity (note the total global figures include these Texas figures).

## B. Assumptions For the Global Geothermal Electrical Power Calculation

We assume each horizontal geothermal production well sustainably outputs three megawatts electric and requires one horizontal water injection well, the simplest currently widely applicable development concept. Variants include a single well alternating as an injector and producer ("huff & puff") and various Hybrid Geothermal Systems. As discussed elsewhere in this Report, 2.5 kilometer deep wells in Iceland typically produce over five megawatts electric, and the Iceland Deep Drilling Project and other technologies, such as plasma drilling, are aiming to develop 426°C (800°F) rock and produce greater than 30 megawatts electric per well. On the other hand, three megawatts electric is an aggressive target for wells outside of volcanic and subduction zones (and ultra-

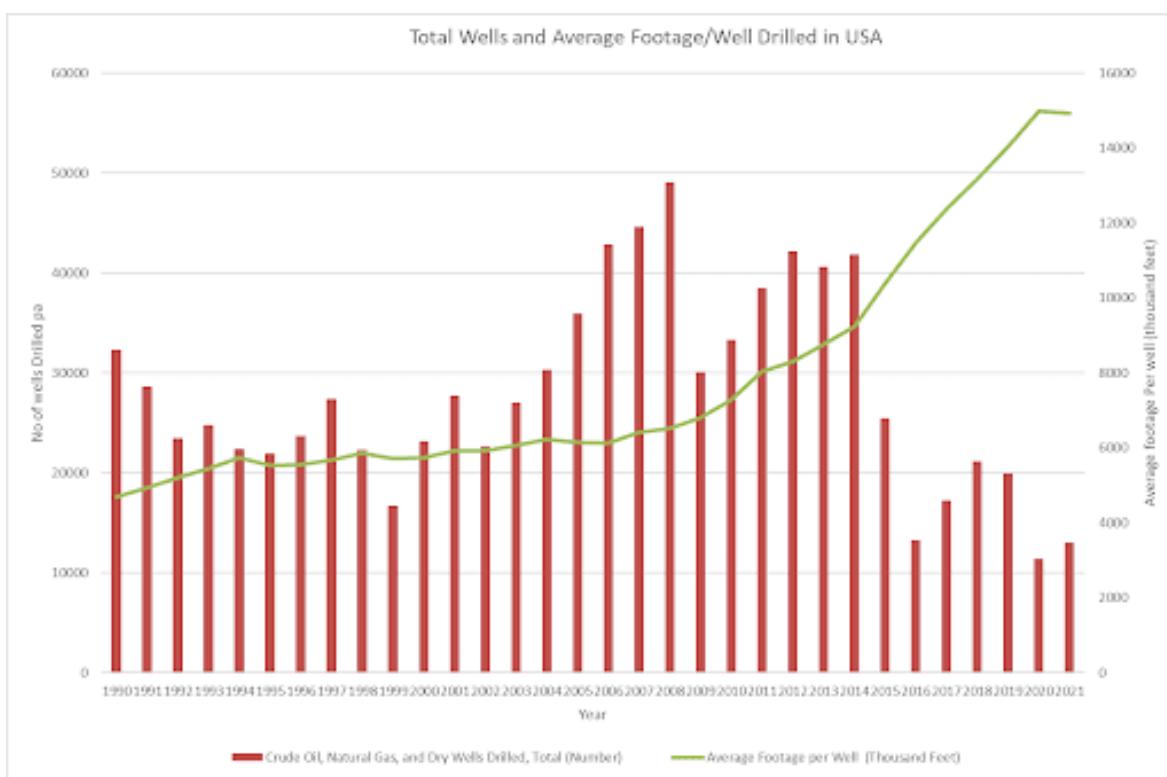


Figure 7.12. Total Wells and Average Footage Per Well drilled in the USA. Source: EIA, 2022.



deep wells), because of the inefficiencies associated with producing heat from a reservoir, and converting that heat into electricity, namely:

- The heat losses from the reservoir to the surface, and from the surface plant and equipment; the minimum temperature approaches of heat exchangers for binary circuits; and heat losses in the conversion plant itself;
- The pump energy required to lift fluid from the reservoir and inject fluid back into the reservoir;
- The second law of thermodynamics: the maximum efficiency for converting heat into work is  $\{1-T_{\text{cold}}/T_{\text{hot}}\}$  where T is in absolute temperature - after Carnot);
- The conversion plant design and fluid selection (Rankine, Brayton, Single Flash, Double Flash / organic fluid, water, sCO<sub>2</sub> etc);
- The mechanical and thermodynamic losses from rotating machinery in the conversion plant.

Figures 7.14 and 7.15 (Moon & Zarouk, referencing Lawless, 2010 and others) correlate actual plant power generation conversion efficiencies from 94 geothermal plants with their reservoir enthalpy (average: 12 percent, range: one percent to 21 percent). They show, for example, that for a reservoir at 200°C (392°F) and reservoir enthalpy at 850 kilojoules per kilogram, or 366 British thermal units per pound), that the conversion efficiency of thermal reservoir energy (strictly **enthalpy**) to exported electricity is approximately nine percent. Their findings, whilst based on thermodynamics, are *derived from actual plant data*. The tables suggest that a flow rate of 25,000 barrels per day (100 pounds per second) water from a 200°C (392°F) reservoir would be required to export three megawatts electric from the geothermal plant. As a sense check, NREL's Geophires 2.0 open-source simulation tool with the following assumptions: 201°C (395°F) reservoir, 71°C (160°F) injection temperature, 25,000 barrels per day (100 pounds per second) flow rate (amongst others) yields maximum gross electrical power generation of 3.6 megawatts electric offset by pumping power for lifting and injection of one megawatt electric. Of note, over the course of 30 years, in this particular reservoir simulation, the gross power declined to 2.6 megawatts electric because the rocks contacted by the injection water were not reheated quickly enough by more distant rocks.

25,000 barrels per day is towards the high end of oil well flow rates globally, though typical or low for geothermal well flow rates. Reservoir stimulation is very likely to be required to achieve these flow rates in many settings across the globe. In our simulations, we assumed two parallel 15,000 feet vertical depth wells with 10,000 feet laterals with 30 feet cluster spacing, 300 clusters, with matrix permeability of one to two millidarcy and frac permeability of 1,000 millidarcy, 10 inch hole. A 1,200 pounds per square inch drawdown achieved 25,000 barrels per day production, with pumping.

The nine percent real-life conversion efficiency compares to the maximum theoretical (i.e. Carnot) efficiency of 27 percent (assuming T<sub>cold</sub> is 71°C (160°F) for water reinjection). *There is clearly scope for improvement in reservoir heat to electricity conversion efficiency for moderate temperature reservoirs*. As discussed in further detail in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#), some oil and gas entities are positioning themselves to be leaders in this space through "system" based approaches to geothermal projects.

### C. Assumptions For the Global Geothermal Direct Use Heat Calculation

There are potential geothermal Direct Use heat applications across a very wide range of temperatures. Table 7.10 presents the temperatures required for industrial applications (less than 100°C (212°F) to greater than 299°C (570°F)). Supply to residential and commercial heating and cooling as well as District Geothermal Heating Systems can be as low as 35°C (95°F) but more normally between 49°C and 93°C (120°F and 200°F) (Arctic Green, 2022).

Continental crust has a median gradient of around 34°C (18.7°F per 1000 feet) (Jennings 2022, higher than DiPietro, 2013). An onshore oil and gas well drilled to say 13,000 feet total vertical depth ("TVD") is usually simple to drill with low risks of major cost escalation. If we assume this geothermal gradient and a 13,000 foot well, the bottom hole temperature would be about 153°C (308°F). This geothermal gradient assumption is simply for illustrative purposes since we are not estimating the cost of the well. Lower gradients would require a deeper well and vice versa, and frictional energy losses are, amongst others, a function of measured depth. But the range of natural and frac'd rock permeabilities is a much



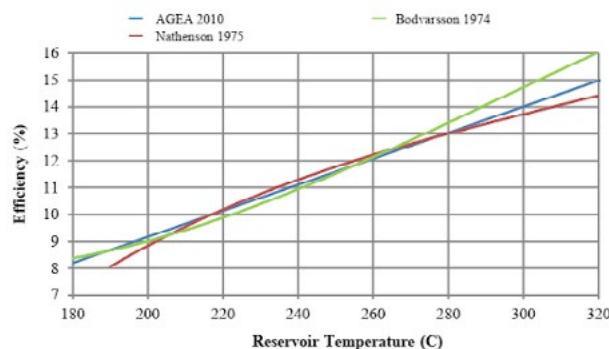


Figure 7.14. Conversion efficiency from heat to electricity. Source: Moon & Zarrouk, 2012.

greater contributor to pumping costs. Water-dominated systems with temperatures between 110°C and 160°C (230°F and 320°F) are believed to be the most abundant geothermal energy resources globally (Ridwan Febrianto, 2019; Franco & Villani, 2009).

We have used the NREL Geophires simulator to estimate the Direct Use heat for a bottom hole temperature of 154°C (310°F), a reinjection temperature of 40°C (104°F) and 25,000 barrels per day (100 pounds per second) as above. The calculation yielded a Direct Use heat output of 19 megawatts thermal. The selection of a cold return 40°C (104°F) is important. If this were instead 50°C (122°F) the power output would be 17.3 megawatts thermal; or 30°C (86°F), 20.7 megawatts thermal.

#### D. The Potential Geothermal Contribution to Global Electrical Power and Direct Use Heat in 2050

We assume then for this scoping calculation:

- The global oil and gas industry were to drill 50,000 geothermal wells per year, which is the same as forecast for oil and gas;
- Wells split 70 percent for electrical power and 30 percent for Direct Use heat;
- Electrical power wells each produce three megawatts electric;
- Direct Use heat wells will be drilled into cooler reservoirs and each produce 19 megawatts thermal.

Tables 7.21 and 7.22 show that under these assumptions, geothermal could contribute more than one terawatt electrical of electricity generation capacity and 2.85

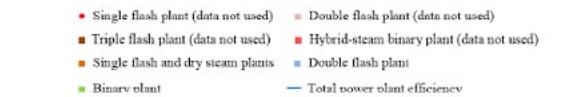


Figure 7.15. Geothermal power plant conversion efficiency. Source: Moon & Zarrouk, 2012.

terawatts thermal of Direct Use heating capacity. Geothermal electricity is reliable enough to achieve a capacity factor greater than 90 percent, but Appendix A, Table 7.30 (IEA 2022, Annex A) quantifies capacity factors for geothermal for IEA's three scenarios at 77 to 79 percent in 2050. 77 percent is used in this scoping analysis, with a sensitivity of 51 percent, which is ERCOT's all-fuel capacity factor (refer Table 7.26 below). Appendix A, Table 7.31 shows the IEA 2022 range of total installed power generation capacity for 2050 is 20 terawatts electric to 34 terawatts electric so our estimate of 1.05 terawatts electric geothermal represents between three percent and five percent of installed capacity. However, geothermal's 77 percent capacity factor is much higher than IEA's all-fuel 25 percent to 29 percent capacity factor (Appendix A, Table 7.30) and this means that higher proportions of global electrical energy are delivered than the proportion of geothermal installed capacity. For comparison, DNV forecast in 2021 that the global wind fleet may reach 5.9 terawatts electric by 2050, and its intermittency will contribute to the lower all-fuel capacity factor.

Notably, Appendix A, Table 7.30 shows IEA's own forecast of geothermal's contribution to power generation capacity to be only 0.3 percent to 0.4 percent and its contribution to electrical energy supply, only 0.9 percent to 1.2 percent, which is approximately one tenth of what our analysis above suggests may be possible.

(Lund, 2021) quantified the capacity factors for actual global geothermal Direct Use heat applications, and we used his measured 44 percent for these calculations.



Table 7.21. Estimation of potential global geothermal supply of electrical power and Direct Use heat by 2050. Measurements in megawatts electric ("MWe") or megawatts thermal ("MWth") as well as tera electric ("TWe") or terawatts thermal ("TWth"). Source: *Future of Geothermal Energy in Texas, 2023*.

Geothermal Application	Geothermal Application	No. of geothermal wells drilled per year	No. of Production wells per year	No. of Injection Wells per year	Total Power Capacity added each year	Total Power Capacity 20 years (2031-2050)
	California	No.	0.074	No.	MWe / MWth	TWe / TWth
Electrical Power	Nevada	35,000	0.0675	17,500	52,500	1.05
Direct Use Heat	Nevada	15,000	0.07025	7,500	142,500	2.85

The International Energy Agency ("IEA") 2022 World Energy Outlook forecasts that electricity demand will grow from 28,000 terawatt hours in 2021 to 50,000 to 73,000 terawatt hours in 2050, depending on scenario. From Table 7.22, assuming IEA 2022's 2050 77 percent capacity-factor and if priced competitively to the local market, 1.05 terawatt electric of geothermal could deliver 7,060 terawatt electric hours, **10 to 14 percent of global electrical energy demand**. Even if ERCOT's 51 percent average capacity factor for its all-fuel electricity generation capacity were to apply globally, geothermal would still supply 4,700 terawatt hours electric, six to nine percent of IEA's total 2050 demand. Appendix A, Table 7.32 shows for all three policy scenarios the detailed calculations for 90, 77, 51 and 26 percent capacity factors discussed above.

Note that in 2021, electricity represented 20 percent of final energy consumption, and in 2050 between 35 and 52 percent of final energy consumption (IEA, 2022).

Table 7.23 uses the IEA forecast scenarios of final energy consumption in 2050, converted from exajoules to terawatt hours. Subtracting electricity and liquid and gas-fuelled transport from these figures yields the

(non-electric) final energy consumption for industry and buildings (and other): 33,000 to 72,000 terawatt thermal hours. From Table 7.22 (and Table 7.21), 2.85 terawatt thermal of geothermal could deliver 11,000 terawatt thermal hours. Hence geothermal if priced competitively to the local market could **deliver 15 to 33 percent of global Direct Use heat demand, which could be deployed in applications such as industry, commerce, defense, hospitals, and isolated settlements, among other examples**.

This calculation is too superficial to establish whether geothermal energy *could be price-competitive* in all global markets. An important factor is whether or not, or how quickly, each individual government decides to transition from coal, fuel oil, and gas to carbon-lite alternatives. The longer the current global fossil fuel supply interruptions continue, the stronger the motivation for governments to seek alternative reliable energy supplies, irrespective of their stance on who should pay the price for decarbonization.

By contrast, there is excellent current energy price transparency in Texas, and Section VI above has attempted to forecast Texas carbon-adjusted fossil

Table 7.22. Estimation of total global geothermal energy that could potentially be delivered in 2050 if priced competitively to the local market. Measurements in terawatt hours ("TW.hr"), terawatts electric (TWe"), terawatts thermal ("TWth"). Source: *Future of Geothermal Energy in Texas, 2023*.

Geothermal Application	Total Power Capacity 20 years (2031-2050)	Capacity Factor (IEA / Lund)	Total Energy delivered in 2050	Contribution to 2050 Electrical & Thermal Energy Supply
	TWe / TWth		TW-hours	percent
Electrical Power	1.05	77%	7062	10%-14%
Direct Heat Power	2.85	44%	11041	15%-33%



fuel energy prices that Texan politicians might adopt to catalyze the transition from fossil fuels to carbon-lite fuels. In Subsection E below, we use current energy demand data by customer segment, and our Section VI fossil fuel energy price forecasts, to estimate what the fleet of start-up geothermal technology companies need to achieve for geothermal to be price-competitive. The metric we have chosen is the maximum capital cost of a geothermal project that still achieves an equity rate of return of 12 percent. This signals to the technology companies what capital costs they need to achieve for geothermal to be competitive.

#### E. The Potential Geothermal Contribution to Texas Electrical Power and Direct Use heat

For the potential of geothermal to serve Texas' electrical and Direct Use heat demand, the same technical assumptions are used as in Subsection D above:

- For Electricity:** 25,000 barrels per day production well; 25,000 barrels per day injection well; 15,000 feet vertical depth; 10,000 laterals, frac'ed. Reservoir temperature: 200°C (395°F). Refer to Section VII-B for more details.
- For Direct Heat:** 25,000 barrels per day production well; 25,000 barrels per day injection well; 13,000 feet vertical depth; 10,000 laterals, frac'ed. Reservoir temperature: 153°C (310°F). Refer to Section VII-C for more details.

Tables 7.24 and 7.25 quantify the size of the Texas gas and fuel oil Direct Use heat markets respectively. Table 7.24 (gas) is for Texas but Table 7.25 (fuel oil) is for Gulf Coast (an over-optimistic proxy for Texas consumption). Excluding gas for power generation and vehicles (and in gas operations), 1,250 terawatt thermal hours per year were consumed in 2021. This is two percent of the 64,000 terawatt thermal hours global consumption for buildings and industry in 2021 discussed in the introduction to this Section VII. As a side note, some of the gas and the fuel oil might be used for industrial feedstock (e.g., for fertilizer) so the percentage for energy may be lower.

In December 2022, ERCOT reported that in 2021, 393 terawatt hours electric were consumed, a 2.87 percent increase on 2020. This is two percent of the 22,800 terawatt hours global electric consumption for 2021 discussed in the introduction to this Section VII.

ERCOT forecast that in 2023, 42 percent of generation capacity will be gas and 11 percent by coal. In previous years, the proportion of gas and coal electricity delivered was about four percentage points higher than the percentage of generation capacity, for example, fossil fuel plants operate at a higher capacity factor than the average. Consistent with Mulloy's analysis (Curry, 2020a), geothermal energy could outcompete wind+solar+battery and nuclear if ERCOT transitions from fossil fuels, releasing gas for export.

Table 7.23. Target for geothermal supply of Direct Use heat by 2050. Measurements in terawatt hours thermal ("TWth.hr") or terawatts thermal ("TWth"). Source: IEA, 2022.

IEA Scenario	Final Energy Consumption	Electricity	Transport: Liquid & Gas fuels	Final Energy Consumption: Industry, Buildings excluding electricity	Geothermal Target Industry & Buildings excluding electricity	Geothermal Target: Industry & Buildings excluding electricity
	TWh	TWh	TWh	TWh	TWth.hr	% of total
IEA Low Case (Zero emissions by 2050)	93,611	48,889	11,111	33,611	11,041	33%
IEA Mid Case (Announced Pledges)	120,278	46,944	23,333	50,000	11,041	22%
IEA High Case (Stated Policies)	151,111	41,944	37,222	71,944	11,041	15%



If we assume demand growth from 393 to 400 terawatt hours electric, then (42 percent + 11 percent + 4 percent) = 57 percent will be supplied by fossil fuels: **228 terawatt hours electric**. As a sense check, 242 and 240 terawatt hours electric were delivered by fossil fuels in 2020 and 2021 (ERCOT 2022; 2021). Note the ten percent of electricity consumed in Texas not supplied by ERCOT is not included in the calculation.

In sharp contrast to this two percent contribution of **Texas energy demand to global energy demand**, Subsection VII-A and Figure 7.13 show that Texas accounts for roughly 30 percent of the global total onshore wells drilled/sidetracked/other activity each year. Table 7.26 presents the Estimation of Potential Geothermal Supply of Electrical Power and Direct Use heat each year, making the same assumption to that in Subsection VII-D, i.e., that the number of global geothermal wells pa from 2030 equals the number of oil and gas wells drilled (i.e., 15,000 Texas wells per year, half producers, half injectors, split 70 percent per 30 percent for electricity generation and Direct Use heat supply).

Using these assumptions and if priced competitively for the local market, Table 7.27 shows that the equivalent of the total fossil fuel energy consumption for Texas could be supplied by geothermal energy by drilling 15,000

geothermal wells per year for four years that produce three megawatts electric or 19 megawatts thermal. The electricity calculation is a slight underestimate for Texas, since it does not include the ten percent non-ERCOT supply, and the Direct Use heat calculation is a possible overestimate because some of the gas and fuel oil may be industrial feedstock.

Tables 7.28 and 7.29 demonstrate that the Texas oil and gas industry could develop large-scale geothermal energy in the State in just a few years. Whether this occurs depends primarily on Texas' political will, geothermal advances to achieve equity rates of return that exceed investors' hurdle rates, and a highly profitable export market for gas.

We used NREL Geophires 2.0 software package to calculate the maximum allowable capital cost of the 25,000 barrels per 154°C (310°F) Direct Use heat geothermal project that would still achieve an equity rate of return of 12 percent. Table 7.27 references the range of carbon-adjusted gas prices in Tables 7.11 and 7.12 for the California carbon permit price, and the European carbon permit price, respectively. The carbon-adjusted prices for No 4 Heating Oil are twice as high as gas, so where geothermal is competing with fuel oil, much higher capital expenditure is possible than shown in Table 7.28

Table 7.24. Texas gas consumption target for geothermal Direct Use heat. Measurements in million standard cubic feet (MMSCF), terawatt thermal hours ("TWth.hr") or gigawatts thermal ("GWth"). Source: EIA, 2022.

Gas Consumption (excluding gas operations)	MMSCF per year	TWth.hr per year	Demand Capacity Factor (Lund)	GWth
Residential	211,133	62	40.5%	7.1
Commercial	181,268	53	45%	6.1
Industrial	1,894,831	555	61%	103.9
Subtotal Direct Use heat (plus feedstock)	2,287,232	670		117
Vehicle	938	0.3		
Electrical Power	1,650,638	484		
Total Gas Consumed excluding gas operations	3,938,808	1154		



Table 7.25. Gulf Coast fuel oil consumption target for geothermal Direct Use heat. Measurements in millions of barrels (MMbbls), terawatt thermal hours ("TWth.hrs") or gigawatts thermal ("GWth"). Source: EIA, 2022.

Fuel Oil Consumption Gulf Coast	MMbbls per year	TWth.hr per year	Demand Capacity factor (assumed)	GWth
Distillate Fuel Oil 0-15 parts per million sulfur	289	490	100.0%	55.9
Distillate Fuel Oil 15-500 parts per million sulfur	7	12	100%	1.4
Residual Fuel Oil	45	76	100%	8.7
Total	342	578		66

We also used Geophires 2.0 to calculate the maximum allowable capital cost of the 25,000 barrels per day 200°C (390°F) geothermal electricity generation project that would still achieve an equity rate of return of 12 percent. Table 7.29 assumes the range of carbon-adjusted gas and coal prices in Tables 7.17 and 7.18; i.e for the California carbon permit price, and the European carbon permit price respectively. Comparing Tables 7.28 and 7.29 shows that geothermal is likely to be much more competitive as a source of Direct Use heat than it is of electricity. The reason is that the electricity conversion efficiency of gas is about 50 percent to 60 percent (and coal about 33 percent) whereas it is historically about ten percent for a reservoir at 220°C (395°F), even though the maximum theoretical efficiency is over 27 percent for a return temperature of 71°C (160°F).

Reservoirs at much higher temperatures would be thermodynamically more efficient, and new technologies could potentially significantly improve geothermal competitiveness in electricity generation; this is discussed in more detail in Subsection VII-B above, and also in [Chapter 1, Geothermal and Electricity Production](#) of this Report.

In the economic calculation, we assumed a 70 percent to 30 percent debt equity split with debt at seven percent and equity at 12 percent, long term inflation at two percent and 30 years of production. We assumed a 30 percent investment tax credit per the Inflation Reduction Act; 7.5 percent royalty interest, and 21 percent taxes. For Direct Use heat, we assumed \$0.07 per kilowatt-hour for electricity for pumping.

Table 7.26. Estimation of potential Texas geothermal supply of electrical power and Direct Use heat by 2050. Measurements in terawatts electric ("TWe") or terawatts thermal ("TWth"). Source: *Future of Geothermal Energy in Texas, 2023*.

Geothermal Application	Power Output per Production well	No. of geothermal wells drilled per year	No. of Production wells per year	No. of Injection Wells per year	Total Power Capacity added each year
		Number	Number	Number	TWe / TWth
Electrical Power	3 MWe	10500	5250	5250	0.01575
Direct Use heat	19 MWth	4500	2250	2250	0.04275



Table 7.27. Estimation of total Texas geothermal energy that could potentially be delivered after one year of drilling 15,000 wells if priced competitively to the local market. Measurements in terawatt hours ("TW.hr"), terawatts electric (TWe"), terawatts thermal ("TWth"). Source: *Future of Geothermal Energy in Texas, 2023*.

Geothermal Application	Total Power Capacity added each year	Demand Capacity Factor (ERCOT / Lund)	Total Energy delivered after one year's drilling	Texas Total Fossil Fuel Energy Consumption	No. of Years Drilling for geothermal to produce 100% of fossil fuel consumption
	TWe / TWth	Percent	TWe-hrs & TWth-hrs per year	TWe-hrs & TWth-hrs per year	Years
Electrical Power	0.01575	51%	70	228	3.3
Direct Use Heat	0.04275	44%	166	655	4.0

#### F. The Potential Geothermal Contribution to Global Power and Direct-Use Heat Under a Hugely Ambitious "Apollo Mission" Development Assumption

As calculated above, an aggressive but technically feasible target for geothermal development in Texas would be to supply the equivalent of all fossil-fuel generated electrical energy, and all heat that is currently serviced by gas and fuel oil, for industry and buildings, by drilling 60,000 geothermal wells. This is equivalent to four years of Texas oil and gas well drilling.

This illustrative calculation we provide for Texas is not unique to Texas, albeit Texas has a high concentration of assets and human resources capable of deploying geothermal projects extremely quickly. But could something similar be envisaged for Africa, India, and other developing countries around the world with burgeoning workforces, who could be skilled to drive their own geothermal drilling booms? What would be the impact on these countries' economic and social development of training and mobilizing their young, sometimes under-employed workforces to drill and develop geothermal

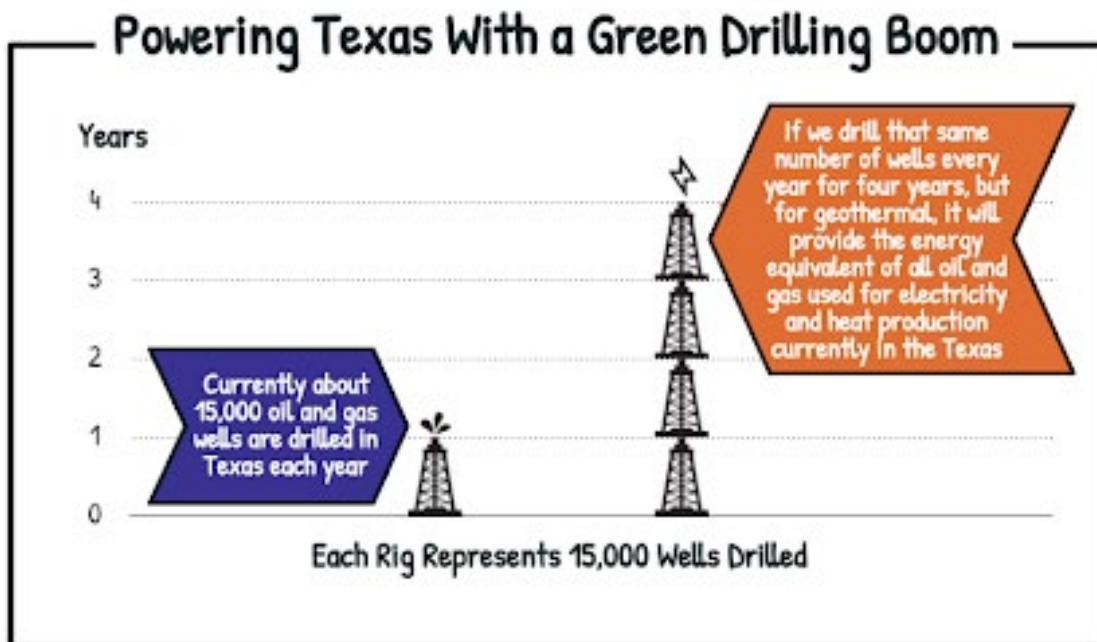


Figure 7.16. A graphic illustration of the potential for a geothermal drilling boom in Texas. It would take approximately four years of drilling at the rate Texas currently drills for oil and gas to produce the equivalent energy of all oil and gas used for electricity and heat production currently in the State from Texas' geothermal resources. Sources: *Future of Geothermal Energy in Texas, 2023*; ERCOT, 2022; NYMEX, 2022.



Table 7.28. Maximum allowable capital cost for Direct Use geothermal project to compete with carbon-price adjusted gas and achieve 12 percent return on equity. Measurements are dollars per million British thermal units ("\$/MMBTU") and U.S. dollars in millions ("\$m"). Source: *Future of Geothermal Energy in Texas, 2023*.

Carbon permit Assumption	Levelized Cost of Heat	Maximum Allowable Capital Cost for Geothermal Project
	\$/MMBTU	\$m
European ETS	\$9.5	\$50
European ETS	\$8.4	\$42
California Permit	\$7.2	\$33.5
California Permit	\$6.0	\$25

projects at the speed and scale we propose for Texas? What would it mean for the world economy if we were to catalyze the growth and prosperity, like that experienced by Texas in the unconventional boom, in every state in the United States, and every country?

The success of such political and educational collaborative initiatives, along with the new technology currently being developed in Texas and elsewhere, would greatly influence the penetration of geothermal in the decarbonized global primary energy supply. As argued above, in a future post-fossil-fuel world, key competitors for primary energy supply are geothermal, nuclear, and solar+wind+battery. **With a few countries leading the way, our current estimate in this Chapter of roughly ten to 14 percent penetration of geothermal electricity and 15 to 33 percent for Direct Use heat estimated above becomes highly credible, and with a few major success stories may prove a gross under-estimate:**

For instance, if the global average electrical power per well were to improve from three megawatts electric through technological advances discussed above and elsewhere in this Report, and/or if more geothermal electric wells were to be drilled, then the potential geothermal contribution for electricity generation would increase in direct proportion.

So for instance, if under the same assumptions, increasing only geothermal well output from three megawatts electric to ten megawatts electric, we get 3.5 terawatts electric of geothermal by 2050 (compared with 5.9 megawatts electric of wind capacity in 2050 forecast by DNV 2021). Or, keeping output the same, but doubling the number of wells drilled per year from 35,000 per year to 70,000 per year, we get 2.1 terawatts electric of geothermal by 2050.

Table 7.29. Maximum allowable capital cost for geothermal electricity generation project to compete with carbon-price adjusted gas and achieve 12 percent return on equity. Measurements are dollars per kilowatt electric hour ("kWe.hr") and U.S. dollars in millions ("\$m"). Source: *Future of Geothermal Energy in Texas, 2023*.

Carbon Permit Assumption	Levelized Cost of Electricity	Maximum Capital Cost
	\$/kWe.hr	\$m
European ETS Coal	\$0.10	\$25
California Coal	\$0.07	\$15
European ETS Gas	\$0.06	\$12
California Gas	\$0.04	\$5



**In a scenario where both occur, for example, increase output ten megawatts electric and drill 70,000 geothermal wells per year, we achieve seven terawatts electric, which assumes the IEA's geothermal capacity factor of 77 percent (47,000 terawatt hours electric per year) would contribute 64 to 94 percent of the IEA's 50,000 to 73,000 terawatt hours electric range of electrical energy demand in 2050.** Even if ERCOT's 51 percent average capacity factor for its all-fuel generation capacity were to apply globally, geothermal would still supply 31,000 terawatt hours electric, 43 percent to 63 percent of total demand). Appendix A, Table 7.31 tabulates these calculations, and Figure 7.18 illustrates geothermal's potential contribution to the 2050 global electrical energy mix assuming the IEA's 77 percent geothermal capacity factor and its "Announced Pledges" scenario.

Assuming the same success scenario of **roughly triple heat output per well and drill double the number of wells per year for the Direct Use heat component of global primary energy supply (in Table 7.20 and 7.21)**, we achieve 19 terawatt thermal, or 73,000 terawatt hours thermal per year at Lund's 44 percent capacity factor, which would exceed **the IEA's forecasted range of thermal energy demand in 2050. This would achieve 33,000 to 72,000 terawatt hours thermal for industry, buildings and "other," excluding electrical energy. Figure 7.19 illustrates the results for the IEA's Announced Pledges Scenario. Appendix A, Tables 7.33 to 7.35 tabulate the calculation results.**

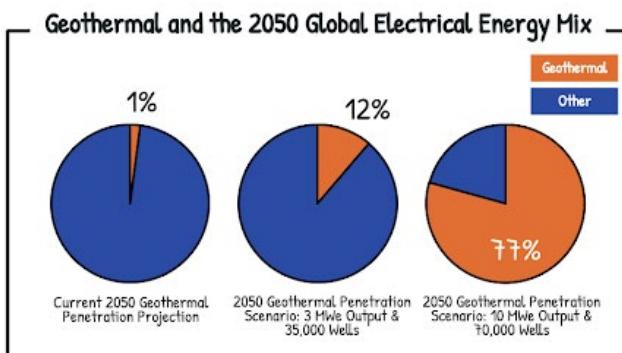


Figure 7.17. 2050 geothermal electrical energy contribution to the global energy mix under three calculated scenarios: 1) current IEA projection (left), 2) scenario of 35,000 geothermal wells drilled per year from 2030-2050, having three megawatts electric per well output (middle), and 3) scenario of 70,000 geothermal wells drilled per year from 2030-2050, having ten megawatts electric per well output (right). Source: Future of Geothermal in Texas, 2023, IEA 2022 Announced Pledges Scenario.

In Table 7.21, we have chosen to highlight aggressive but achievable targets of 1.05 terawatts electric and 2.85 terawatts thermal for electricity and heat respectively by 2050 with currently available oil and gas technologies, and utilizing drilling capacities that are consistent with data from the recent past. But if the above hypothetical scale or efficiency improvement calculations could be achieved by step-changes in system optimization, and/or an approach to speed and scale that would rival the greatest of human achievements—truly an “all hands on deck” approach to geothermal development—then, as we see in the above hypothetical scale estimates, truly massive and globally transformative outcomes are possible in terms of growth of geothermal in the world’s energy mix by 2050, and its contribution to rapid decarbonization.

## VIII. The Scale and Speed of an Oil and Gas Industry Pivot

Though more study needs to be done in this area, much of the oil and gas industry may find sufficient overlap in skills, assets, and institutional knowledge to begin engaging in geothermal in the near term.

Figure 7.19 presents an illustration of Roger's curve of technology adoption, and some insights might be gained from using its concepts (Rogers, et al., 2014). Given current accelerating trends in the industry, perhaps 80 percent of the oil and gas industry could be involved in some capacity with geothermal energy by 2050. Breaking

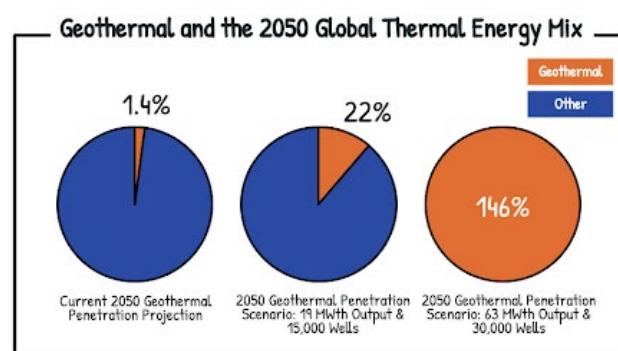


Figure 7.18. 2050 geothermal thermal energy contribution to the global energy mix under three calculated scenarios: 1) current IEA projection (left), 2) scenario of 15,000 geothermal wells drilled per year from 2030-2050, having 19 MWth per well output (middle), and 3) scenario of 30,000 geothermal wells drilled per year from 2030-2050, having 63 MWth per well output (right). Source: Future of Geothermal in Texas, 2023, IEA 2022 Announced Pledges Scenario.



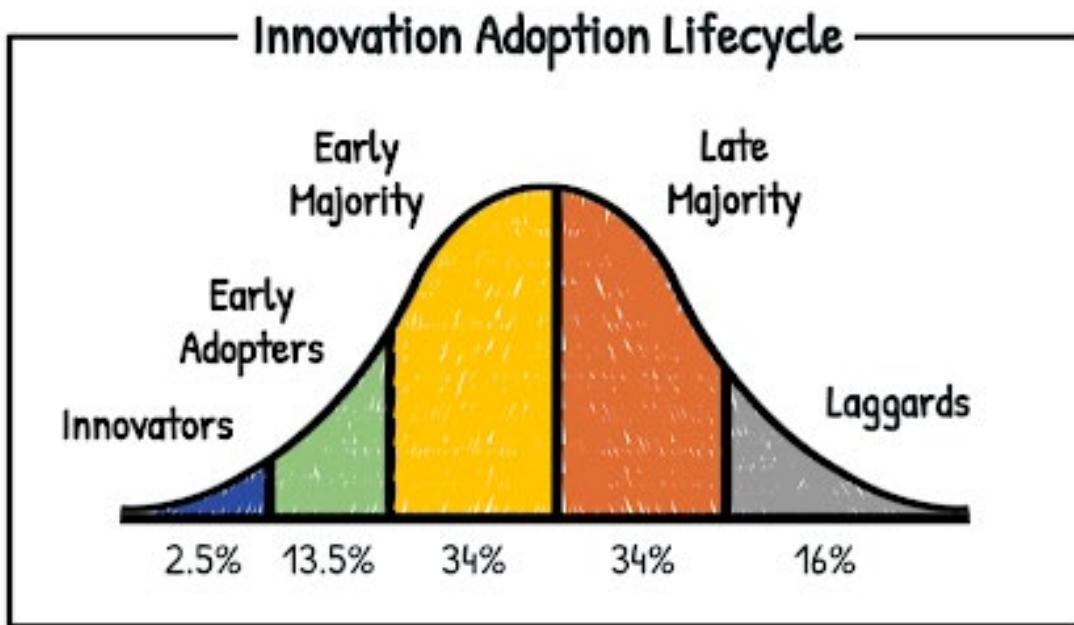


Figure 7.19. Rogers diffusion of innovations. Source: Rogers, et al., 2014.

the many geothermal energy topics in categories, the adoption of geothermal technologies by the oil and gas industry by 2050 might be divided as follows: 15 percent for SuperHot Rock concepts exceeding 400°C or 752°F (innovators and early adopters), 70 percent for emerging Hot Dry Rock concepts like Engineered Geothermal Systems ("EGS"), Hybrid Geothermal Systems, and Advanced Geothermal Systems/Closed Loop Geothermal Systems ("AGS") (early majority and late majority), and 15 percent for Conventional Geothermal and Blind Hydrothermal Systems (laggards).

## IX. Conclusion

Support from the oil and gas industry in Texas could lead to substantial cost reductions for existing and new geothermal technologies, accelerate innovation in new development concepts, boost collaboration between a wider pool of related engineering and innovation sectors, and enhance economies of scale. Texas may be the ideal location globally to apply oil and gas technologies and ways of working to lower geothermal costs and drive innovation in the sector, with its favorable policy environment, strong university system, positive views toward the oil and gas industry, and large-scale renewable development experience. **Texas has the needed mix of upstream oil and gas expertise and resources, a supportive subsurface policy and regulatory regime, and subsurface conditions needed to become a geothermal "Silicon Valley" that can**

**support local industry, and enable export of geothermal technologies around the world.**

While different types of oil and gas entities are approaching geothermal engagement and investment in different ways, it is clear that the potential for scale that the oil and gas industry could deliver for geothermal could have wide ranging global implications in an expedient energy transition, and offer just and equitable outcomes for the oil and gas workforce.

**Our extension of the work done by Mulloy (Curry, 2022a; Curry, 2022b) suggests that even at its current price per kilowatt, geothermal energy is a strong contender for ERCOT's future energy mix. Geothermal is faster to implement than nuclear and currently cheaper per megawatt. If the grid were to be decarbonized and gas instead exported, Mulloy's excellent analysis therefore results in the following conclusion about the most cost-effective replacement for the grid's fossil-fuel mix: geothermal would be cheaper than both new nuclear and new solar+wind+battery storage for base load supply, and could out-compete new solar+wind+battery storage for middle order and peaking supply, and some ancillary services.**

There is substantial scope for improvement in reservoir heat to electricity conversion efficiency for moderate temperature reservoirs, and the oil and gas industry is well placed to achieve it.



Combining robust State leadership and the resources of the oil and gas industry, an aggressive, but technically feasible target for geothermal development in Texas would be to supply the equivalent of all fossil-fuel generated electrical energy, and the equivalent of all heat that is currently serviced by gas and fuel oil to industry and buildings, by drilling 60,000 geothermal wells. This is equivalent to four years of Texas oil and gas well drilling at current levels of activity (or roughly 50 percent of 2014's activity), utilizing currently available technologies from the oil and gas industry.

Texas is endowed with unparalleled oil industry capacity and creativity; high demand for electricity and heat energy across all sectors; and abundant natural resources. It is uniquely qualified to lead the world in geothermal development. By committing to an aggressive programme of geothermal R&D, drilling and development at scale 'at home', its businesses and people will be superbly qualified to deploy geothermal across the world - a massive business opportunity that would result in decarbonizing the planet.

Building a degree of energy independence and resilience through geothermal could be the foundation stone for carbon-lite energy industrial development for many

countries, resulting in higher GDP per capita, cleaner air and water, and fewer CO<sub>2</sub> emissions. It could also usher in a new era of energy independence, and perhaps even less geopolitical conflict given the massive rearrangements in the geopolitical space that a massive, global deployment of localized geothermal energy development may activate.

The reduction in energy price volatility from using geothermal rather than coal and gas for baseload also de-risks investments for industry, commerce, and citizens, reducing their cost of capital. Collaboration with multilaterals having existing relationships with the world's leaders and politicians would provide a platform for dialogue to help governments decide whether geothermal has a role in their energy mix. Close collaboration with the many Middle Eastern and European countries that are members of the International Renewable Energy Agency ("IRENA") that already have advanced geothermal development will also enhance the facilitation of global deployment. And collaboration with the many specialized geoscience institutes around the world will ensure best practices are learned and shared quickly. These topics, among others related, will be the subject of a follow-up study forthcoming in 2023.



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## Conflict of Interest Disclosure

**Tim Lines** serves as CEO of a 2022 start-up Geothermal Wells LLC, to supply direct use geothermal heat, three phase electrical power, and energy storage to energy-intensive industry and commercial customers, and is compensated for this work. Tim Lines also serves as a partner of Oilfield International and provides advisory opinion valuation services to investors and sellers of geothermal and oil & gas assets; and access to capital, which may result in compensation. Outside of these roles, Tim Lines 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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## Chapter 7 Appendix

Table 7.30. 2050 forecast total and geothermal electrical energy supplied, total installed capacity, and average capacity factors. Measurements are in terawatt hours ("TW.hrs") and gigawatts electric ("GWe"). Source: IEA, 2022.

Electricity Energy Supply 2050		Stated Policies	Announced Pledges	Net zero emissions
		TW.hrs	TW.hrs	TW.hrs
Geothermal Energy		458	686	857
Total Generation		49,845	61,268	73,231
Proportion that is Geothermal		0.9%	1.1%	1.2%
<hr/>				
Installed Capacity		Stated Policies	Announced Pledges	Net zero emissions
		GWe	GWe	GWe
Geothermal		66	102	126
Total Generation		19,792	26,541	33,878
Proportion that is Geothermal		0.3%	0.4%	0.4%
<hr/>				
Capacity Factor		Stated Policies	Announced Pledges	Net zero emissions
		%	%	%
Geothermal		79%	77%	78%
Total Generation		29%	26%	25%

Table 7.31. Forecast power generation capacity in 2050 terawatts electric. Source: IEA, 2022 and Future of Geothermal Energy in Texas, 2023.

Well Capacity	No. of Wells	Total Capacity in 2050 (20 yrs)	Stated Policies	Announced Pledges	Net zero emissions	Stated Policies	Announced Pledges	Net zero emissions
MWe	No	TWe	Total TWe	Total TWe	Total TWe	Geothermal Contribution %	Geothermal Contribution %	Geothermal Contribution %
3	35000	1.05	19.8	26.5	33.9	5%	4%	3%
10	35000	3.5	19.8	26.5	33.9	18%	13%	10%
3	70000	2.1	19.8	26.5	33.9	11%	8%	6%
10	70000	7.0	19.8	26.5	33.9	35%	26%	21%



Table 7.32. Forecast electrical energy supplied in 2050 terawatts electric hour for a range of capacity factors from 90 percent to 26 percent. Measurements megawatts thermal ("MWth") and terawatts thermal hour ("TWth.hrs"). Source: IEA, 2022 and Future of Geothermal Energy in Texas, 2023.

Well Capacity	No. of Wells	Total Capacity in 2050 (20 yrs)	Capacity Factor (=Reliability)	Total geothermal electrical energy in 2050	IEA Stated Policies 2050 electrical energy consumed	IEA Announced Pledges 2050 electrical energy consumed	IEA Net Zero Emissions 2050 electrical energy consumed	Stated Policies	Announced Pledges	Net zero emissions
MWe	No	TWe	percent	TWe.hrs	Total TWe.hrs	Total TWe.hrs	Total TWe.hrs	Geothermal Contribution %	Geothermal Contribution %	Geothermal Contribution %
3	35000	1.05	90%	8278	49845	61268	73231	17%	14%	11%
10	35000	3.5	90%	27594	49845	61268	73231	55%	45%	38%
3	70000	2.1	90%	16556	49845	61268	73231	33%	27%	23%
10	70000	7.0	90%	55188	49845	61268	73231	111%	90%	75%
<hr/>										
Well Capacity	No. of Wells	Total Capacity in 2050 (20 yrs)	Capacity Factor Geothermal (IEA)	Total geothermal electrical energy in 2050	IEA Stated Policies 2050 electrical energy consumed	IEA Announced Pledges 2050 electrical energy consumed	IEA Net Zero Emissions 2050 electrical energy consumed	Stated Policies	Announced Pledges	Net zero emissions
MWe	No	TWe	percent	TWe.hrs	Total TWe.hrs	Total TWe.hrs	Total TWe.hrs	Geothermal Contribution %	Geothermal Contribution %	Geothermal Contribution %
3	35000	1.05	77%	7062	49845	61268	73231	14%	12%	10%
10	35000	3.5	77%	23539	49845	61268	73231	47%	38%	32%
3	70000	2.1	77%	14124	49845	61268	73231	28%	23%	19%
10	70000	7.0	77%	47078	49845	61268	73231	94%	77%	64%
<hr/>										
Well Capacity	No. of Wells	Total Capacity in 2050 (20 yrs)	Capacity Factor (All-Fuels ERCOT)	Total geothermal electrical energy in 2050	IEA Stated Policies 2050 electrical energy consumed	IEA Announced Pledges 2050 electrical energy consumed	IEA Net Zero Emissions 2050 electrical energy consumed	Stated Policies	Announced Pledges	Net zero emissions
MWe	No	TWe	percent	TWe.hrs	Total TWe.hrs	Total TWe.hrs	Total TWe.hrs	Geothermal Contribution %	Geothermal Contribution %	Geothermal Contribution %
3	35000	1.05	51%	4691	49845	61268	73231	9%	8%	6%
10	35000	3.5	51%	15637	49845	61268	73231	31%	26%	21%
3	70000	2.1	51%	9382	49845	61268	73231	19%	15%	13%
10	70000	7.0	51%	31273	49845	61268	73231	63%	51%	43%
<hr/>										
Well Capacity	No. of Wells	Total Capacity in 2050 (20 yrs)	Capacity Factor All-Fuels (IEA)	Total geothermal electrical energy in 2050	IEA Stated Policies 2050 electrical energy consumed	IEA Announced Pledges 2050 electrical energy consumed	IEA Net Zero Emissions 2050 electrical energy consumed	Stated Policies	Announced Pledges	Net zero emissions
MWe	No	TWe	percent	TWe.hrs	Total TWe.hrs	Total TWe.hrs	Total TWe.hrs	Geothermal Contribution %	Geothermal Contribution %	Geothermal Contribution %
3	35000	1.05	26%	2424	49845	61268	73231	5%	4%	3%
10	35000	3.5	26%	8079	49845	61268	73231	16%	13%	10%
3	70000	2.1	26%	4848	49845	61268	73231	10%	8%	6%
10	70000	7.0	26%	16159	49845	61268	73231	32%	26%	21%



Table 7.33. Proportion of IEA heat category that is geothermal Direct Use in 2021, and Assumption for 2050. Source: IEA, 2022 and Lund & Toth, 2021.

Category	EJ	TW.hr
Geothermal Direct Use heat	0.421	117
IEA Heat Category	13	3611
Geothermal Proportion of Heat Category in 2021(Calculated)	3%	3%
Geothermal Proportion of Heat Category in 2050 (assumed)	25%	25%

Table 7.34. 2050 forecast total and geothermal heat energy supplied to industry, buildings, and other. Source: IEA, 2022.

Direct Heat Consumption 2050	Stated Policies	Announced Pledges	Net zero emissions	Stated Policies	Announced Pledges	Net zero emissions
	EJ	EJ	EJ	TW.hrs	TW.hrs	TW.hrs
IEA Term: 'Heat', Geothermal Direct Heat contributed 3% of this in 2021)	14	10	5	3889	2778	1389
Proportion of 'Heat' assuming Geothermal heat is 25% of the total in 2050)	3.5	2.5	1.3	972	694	347
Final Energy Consumption: Industry, Buildings, Other, excluding electricity	121	180	259	33611	50000	71944
Proportion of Final Energy Consumption from Geothermal Direct Use Heat, assuming 25% of Heat category	2.9%	1.4%	0.5%	2.9%	1.4%	0.5%

Table 7.35. Forecast Direct Use heat supplied in 2050 terawatts thermal hours. Measurements megawatts thermal ("MWth") and terawatts thermal hours ("TWth.hrs"). Source: IEA, 2022 and Future of Geothermal Energy in Texas, 2023.

Well Capacity	No. of Wells	Total Capacity in 2050 (20 yrs)	Capacity Factor (Lund)	Total geothermal direct use I energy in 2050	IEA Stated Policies 2050 direct use energy consumed	IEA Announced Pledges 2050 direct use energy consumed	IEA Net Zero Emissions 2050 direct use energy consumed	Stated Policies	Announced Pledges	Net zero emissions
MWth	No	TWth	%	TWth.hrs	Total TWth.hrs	Total TWth.hrs	Total TWth.hrs	Geothermal Contribution %	Geothermal Contribution %	Geothermal Contribution %
19	15,000	2.9	44%	11,041	33,611	50,000	71,944	33%	22%	15%
63	15,000	9.5	44%	36,610	33,611	50,000	71,944	109%	73%	51%
19	30,000	5.7	44%	22,082	33,611	50,000	71,944	66%	44%	31%
63	30,000	18.9	44%	73,219	33,611	50,000	71,944	218%	146%	102%





## Chapter 8

# Other Strategic Considerations for Geothermal in Texas Space and Defense

K. Wisian, P. Boul

*The interdisciplinary synergies between space, defense, and subsurface energy production are key to Texas leading the future of geothermal.*

## I. Introduction

Geothermal, with its clean, baseload energy, generated using the abundant heat in Earth's crust, has been an inconsequential part of the energy mix of the United States and the world for more than one hundred years, as has been detailed in other Chapters of this Report. However, as described in this Report, recent developments, many in Texas, have positioned geothermal for quick growth. Advances in exploration, drilling and well construction, and production technologies are poised to revolutionize the accessibility of geothermal energy. These developments will break the geographical constraints that have held geothermal back for a century, enabling the next generation of geothermal development, anywhere demand for energy exists.

Geothermal energy can make a significant impact in both Texas and beyond, as a source of clean energy that will become increasingly cost competitive with wind and solar as we drill deeper and hotter wells. At temperatures exceeding 200°C (392°C), where the potential for cost parity with other renewables is in line of sight, well longevity and integrity, and energy conversion efficiency, will be dependent on the use of the toughest, temperature hardened materials available. The aerospace industry and its developments in extreme temperature materials holds the potential to increase the market size and deployment potential of geothermal, positioning it as a highly scalable, primary, baseload alternative energy source. Technologies developed at the National Space



and Aeronautics Administration ("NASA") and the U.S. Department of Defense ("DOD") may benefit the industry greatly as we look to realize the potential of this large and ubiquitous energy resource beneath our feet.

In this Chapter, we describe how defense and space technologies may both benefit from, and provide benefit to, the growth and scale of geothermal energy. We also highlight how geothermal technologies may lead to new developments and capabilities in aerospace and space exploration, and how materials from aerospace can be adapted to improve well construction and, ultimately, energy production efficiency in geothermal systems.

## II. Defense

DOD and critical infrastructure (such as water supply and hospitals) have a critical need for safe, secure, reliable power. Unfortunately, civilian power grids are notable for their susceptibility to deliberate attacks, the effects of aging infrastructure, and natural disasters (Narayanan, et al., 2020). Advances in technology have increased the susceptibility of power grids world-wide to disruption. Cyberattacks on facilities are an increasing threat as power systems are automated, but it is not just high-tech attacks that present problems. There have been many examples around the world where terrorist groups use physical attacks on power infrastructure to cause blackouts (NRC, 2012, NPR, 2022).

While the incidence of these attacks in the United States has been lower than other less stable regions, in 2013, a sophisticated physical attack on a California transmission substation awakened the power industry to its vulnerability from close-in threats (Smith, 2014). In 2022, an attack on substations in North Carolina shut down power to more than 10,000 people (Morris, 2022), and another such incident followed months later in Washington State on Christmas Day (Domonoske, 2023). For these serious liabilities, the use of commercial power grids for defense and critical infrastructure represents a massive, systemic, and strategic vulnerability in Texas, the United States, and the world.

### A. Geothermal and U.S. National Security

Constructing geothermal power plants "inside the wire" at DOD facilities, using proven and emerging technologies, can provide a real solution to their dependence on civil power grids with a cost-effective, resilient, clean energy

that is less vulnerable to attack and natural disaster. Unlike Conventional Hydrothermal Systems, next generation scalable geothermal concepts like Advanced Geothermal Systems ("AGS"), Engineered Geothermal Systems ("EGS"), and Multi-System Hybrids, are likely to be deployed to meet demand at DOD facilities, due to their ability to be developed anywhere. These next generation geothermal plants possess significant advantages over commercial power from off-site or other on-site solutions, such as:

- **Physical Security:** Location inside the fence-line is relatively secure, and includes the ability to easily ramp-up security as needed under threat warning;
- **Baseload Energy Supply:** Geothermal power is "always on" and can be load following;
- **Self-Contained:** Unlike conventional standby generators, no outside resources for resupply are needed, with decades-long operational lifetimes, and relatively low operations and maintenance costs;
- **Scalable:** If more power is needed, in many cases, more wells can be drilled;
- **Safe:** No combustion or radioactivity is involved in operation;
- **Green, Clean, and Renewable:** AGS and Hybrid Geothermal Systems are expected to emit no pollution/greenhouse gasses, and have the potential to be carbon-negative through sequestration of additional carbon in the heat-exchange path; and
- **Electro-Magnetic Pulse ("EMP") Resiliency:** Extremely short electricity transmission distance to load (co-location) greatly reduces vulnerability to EMP induced power surges.

Note that while this Section is focused on Defense, most of these advantages would apply to critical civilian infrastructure as well. Military base applications will be the use case addressed here for simplicity, and because DOD geothermal development has experienced some notable steps forward in Texas, with at least one project, Ellington Field, funded to the detailed design phase at this time (Richter, 2021), with additional projects in the works.

DOD is an ideal early adopter of next generation geothermal technologies. While conventional hydrothermal geothermal is a relatively mature technology, the next generation, scalable geothermal paradigm is not. It



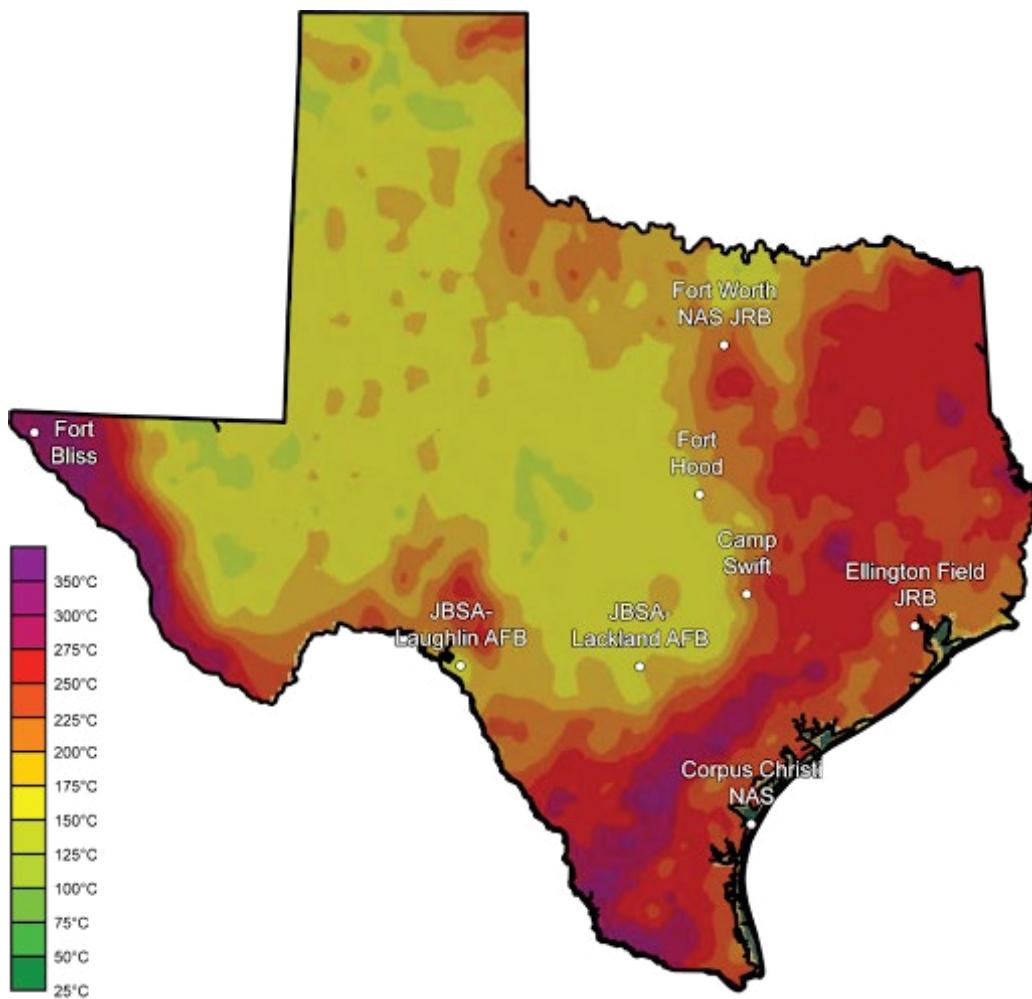


Figure 8.1. Selected military facilities overlaid with temperatures at 5.9 miles (9.5 kilometers). Multiple major DOD installations are in attractive geothermal areas in coastal, East, and West Texas. Source: Adapted from Blackwell, et al., 2006.

is a set of emergent technologies, all of which are in the prototyping and pilot stage. This suggests an opening for DOD to lead the way because: 1) DOD can and does, prioritize operational effectiveness over cost effectiveness when it is mission critical, 2) secure, resilient power supply is mission critical to everything DOD does; and 3) the military is accustomed to working with and furthering cutting-edge technologies.

But by themselves, these two factors will not be sufficient to sustain DOD's attention. What is required is scalability. DOD has been using and managing a Conventional Hydrothermal System in the western United States for decades. This is accomplished through the Navy Geothermal Program Office, which technically has led for all DOD geothermal projects. However, this program, like the current geothermal industry, is focused

on conventional hydrothermal geothermal, and has experienced very little growth over the years.

Currently, DOD is being approached at many levels in a scattered and uncoordinated fashion by companies pitching geothermal projects, including power production projects and Direct Use geothermal for building heating and cooling. Next generation, scalable geothermal concepts have the potential to be applied across almost all of the Earth's surface, breaking free of the current very tight geographical restrictions that are often limiting factors for Conventional Hydrothermal Systems. The potential to power every military installation, not only in the United States, but globally, provides the scalability that will make it worth DOD's while to invest time and money into the next generation geothermal space.





Figure 8.2. The U.S. Air Force has described geothermal as a first priority energy solution for base energy innovation (OEA, 2022), and a critical solution to address energy reliability and resiliency at military installations around the world.

Source: Stock photography.

Given DOD's increasing interest in next generation geothermal concepts, the next question that arises is the preferred location of geothermal deployments on military bases. As DOD is an ideal early adopter of next generation geothermal technologies, Texas is an ideal sandbox in which to develop and pilot them. Texas is the world's energy epicenter, and has led multiple energy revolutions. It has the right combination of industry, research institutions, startups, eager off-takers, a favorable subsurface policy and regulatory environment, and geothermal resources to lead once again in this next generation of geothermal development and deployment. Multiple DOD geothermal projects are brewing, from concept to funded projects, that implicate or will be located in the State of Texas. The project that has advanced furthest is an Air Force Work Project ("AFWERX") funded effort to build a three megawatt geothermal power plant on Ellington Air Force Base ("Ellington") on the Southside of Houston, previously mentioned in this Chapter. This site was selected as a first proof of concept/commercial project for multiple reasons:

- **A High Quality Geothermal Resource:** The project is in a zone of elevated temperatures and pressures, the Gulf Geopressure Zone (see [Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development](#)), where only moderate drilling depths are needed to reach 150 to 200°C (302 to 392°F) temperatures;

- **A Base of Reasonable Size:** Ellington is a relatively small base, with low power needs suitable for a pilot project;
- **Room for the Rig:** There is ample open space for a drilling rig onsite (though little space is actually required);
- **A Need for Resilience:** High-priority, no-fail missions take place on the base;
- **Fast Decision-Making:** As an Air National Guard Base, Ellington has a relatively "flat" chain of command, resulting in quicker decision making; and
- **Houston as an Epicenter:** A successful project in Houston, the epicenter of the petroleum industry, will gain traction amongst ecosystem partners in a way that a project in the western United States would not.

The project is currently nearing completion of Phase 2, the detailed design phase. (Cariaga, 2021).

## B. The Way Forward with Defense

In the winter of 2021, as a result of Winter Storm Uri, the Texas power grid experienced a massive failure. Exposed by this grid collapse were mis-prioritizations of critical infrastructure power needs. A revision of critical infrastructure needs, cross-linked with geothermal potential is a clear first step to building a strategy for maximum and optimized geothermal deployment in Texas for DOD. Parallel, but distinct, would be the same effort for the dozens of large and small military installations across the State of Texas. As described in [Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development](#) of this Report, there is also a need for methodical data collection in promising, but under-explored (i.e., non-oil and gas producing) areas. Finally, favorable policy and incentives at the Federal, State and local level have been critical to the success of previous emergent industries, and will be so for geothermal as well.

It is important to remember that although Texas is widely known as an oil and gas State, it easily jumped into the lead as the number one wind energy producer in the United States via a relatively small shift in State policy (Galbraith and Price, 2013). These policies are considered in further detail in [Chapter 11, Geothermal, The Texas Grid, and Economic Considerations](#) and [Chapter 12, Policy, Advocacy, and Regulatory Considerations in Texas of this Report](#).



Following through on the DOD critical infrastructure potential of geothermal power in Texas would be a win-win for DOD, the State, and its budding geothermal industry. It will position Texas and its industries as the world leader in a major emerging and wide-open energy field, and improve civil and national security. A comprehensive State Department and DOD strategy for deploying geothermal power for military and critical infrastructure is clearly called for, starting with prioritization of the possible projects.

### III. Space

Texas is endowed with the history of a robust and thriving energy industry, but as discussed in [Chapter 9, The Texas Startup and Innovation Ecosystem](#) of this Report, Texas has also been fertile ground for some of the world's great technological innovations and discoveries in nanotechnology, materials science, geoscience, and industrial engineering. Texan inventions like the tricone drill bit, the microchip, 3-D printing, and the lithium-ion battery are all innovations that have had a profound impact on business, society, and the way we live and interact. They are the products of a uniquely Texan spirit for exploration and discovery, which has pushed the limits of human achievement for over a century.

With the Johnson Space Center, SpaceX, Blue Origin, and the Houston Spaceport within its borders, technology transfer from aerospace to the burgeoning Texan geothermal industry is a handshake away. While commercial space efforts are making significant strides in many of the research and development areas discussed below, we will focus for the purpose of this Chapter on technology flow to and from NASA, and the impact that technology transfer in this area may have on the trajectory of geothermal in Texas.

#### A. The Transfer of Materials From Aerospace to Geothermal

Carbon composites are widely used in high performance systems. Just about all modern aircraft contain some amount of composite material currently. The light weight, formability, and high strength of composites make them excellent materials for aerospace applications (Zhang & Zhao, 2016). These materials also have potential in geothermal well construction, particularly in highly corrosive environments. However, temperature tolerances limit use in geothermal applications.

Composites are currently being deployed in the oil and gas industry in a number of different tool applications. They are especially useful for corrosion protection when dealing with a combination of high-temperature and corrosive well fluids. The composites used in oil and gas, however, currently have temperature limitations that restrict their use in the industry (Badeghaish, et al., 2019). Thus, technology transfer from NASA's thermal protection systems could spur a new generation of composites that would enhance how and where we can develop geothermal systems.



Figure 8.3. Artist rendering of an atmosphere reentry vehicle on descent. Skin temperatures on reentry vehicles as well as hypersonic aircraft can reach well over a thousand degrees.

Source: NASA, 2022.

Developments in high-temperature materials at NASA have been a cornerstone for space exploration since before the Apollo moon landings. This robust materials development history has led to a spectrum of exotic materials for the thermal protection of spacecraft. In Apollo, the Thermal Protection System ("TPS") was an ablative resinous material in a fiberglass honeycomb matrix (Natali, et al., 2017). It was designed to protect the Saturn V command module as the spacecraft re-entered the atmosphere, reaching speeds up to 25,000 miles per hour (40,000 kilometers per hour). Development in TPS changed course slightly with the space shuttle program, where ceramic tiles were an essential component to the TPS.

More recently, the Parker Solar Probe, launched in 2018, boasts a non-ablative foamed carbon heat shield designed to withstand extraordinary extremes in temperature and heat (Congdon, 2021). The Parker spacecraft is actively studying the sun and solar flares, and is designed for temperatures higher than 1,200°C (2,192°F). NASA's tradition of excellence, and breadth in high-temperature materials continues into future missions, as non-ablative



thermal protection systems and high-temperature power systems are being designed for NASA's next missions to the extremely inhospitable environment of Venus.

Tough conditions are run of the mill in geothermal, where drilling temperatures can exceed 300°C (572°F), and pressures can easily exceed 5,000 pounds per square inch. Additionally, the extreme vibration loads of launch and reentry are roughly comparable to the downhole environment, both during drilling and production. Thus, aerospace materials meeting these performance metrics could be game-changers in geothermal systems where very high-temperatures, in combination with corrosive fluids, challenge the best materials available.

Beyond the composite materials that are already in use in aircraft and spacecraft are 3-D printed composites. There are enormous performance benefits that are being realized through multi-material 3-D printing. The research arm of NASA has been developing methods in 3-D printed geomaterials in a process called In-Situ Resource Utilization ("ISRU"). These technologies, along with those developed in the oil and gas industry in 3-D printing cements and cement composites, can be used to develop a new generation of Thermal Protection Systems, both for the aerospace and geothermal industries.



Figure 8.4. NASA's VERITAS and DAVINCI's missions will develop the vehicles, materials and instrumentation for missions to Venus in the 2028–2030 timeframe with a total budget of \$1 billion. The average surface temperature of Venus is 465°C (869°F). Source: NASA, 2008.

### B. Heat Management in Space

Spacecraft can be exposed to massive swings in temperature, and extremes in radiation energy and flux. Thermal management is critical to the engineering of space faring vehicles. In space vehicles,

temperature regulation depends on phase-transfer fluids, thermoelectrics, and the intentional inclusion of reflective, absorptive, and emissive materials. The development of these thermal management materials has evolved over decades at NASA, and the opportunity is ripe for technology transfer to the geothermal industry.

NASA's VERITAS and DAVINCI+ missions will launch between 2028 and 2030 to study the surface and atmosphere of Venus. The surface temperature of Venus averages about 465°C (869°F), with an atmospheric pressure roughly 92 times that on Earth. High temperature electronics developed at NASA have been designed for 600°C (1,112°F), with silicon-carbide based transistors at NASA's Glenn Research Center (Francis, et al., 2018). Technologies in high-temperature materials and electronics will be developed further for the Venus landers and probes, to tackle the extreme environmental conditions in the atmosphere of Venus.

Thermoelectrics are materials that are improving rapidly and could significantly benefit geothermal energy systems, in tuning the systems for maximum efficiency (Glavin, 2020). These materials take a temperature differential and turn it into electrical energy. By scavenging waste heat in geothermal power generators, thermoelectrics offer the possibility of greater overall efficiency in geothermal electricity generation.

### C. Nanotechnology and Higher Performance

Nanotechnology has its roots deep in the heart of Texas, from the Nobel prize winning discovery of carbon-60, the soccer ball shaped carbon allotrope, at Rice University in 1985 (Smalley, 1997). Currently all the major universities in Texas have significant nanotechnology programs. Now a multi-billion-dollar industry, nanotechnology offers the possibility of improving the efficiency of geothermal energy generation.

There are many examples of the applicability of nanotechnology in geothermal systems. For instance, research in the use of nanofluids in geothermal heat exchangers, fluids endowed with highly conductive particles each sized 10 million times smaller than a penny, offer the promise of boosting system efficiencies (Boul & Ajayan, 2020; Ponmani, et al., 2013). Additionally, the composite technologies described earlier can benefit from the inclusion of nanomaterials. Nanomaterials can be used to make composites stronger, stiffer, smarter, and even self-healing. Major research and development



programs have been striving for decades to bring nanoelectronics and the use of nanomaterials in energy and power to consumer markets, and military and space applications alike.

Nobel prize winning research at the University of Texas at Austin in lithium-ion batteries has led to many great innovations from which we now benefit, from our cell phones, tablets, and laptops, to appliances and vehicles (Ponmani, et al., 2013). The engineering of these devices at the nanoscale offer higher temperature tolerances and greater storage capacities, which will extend the temperature limits of sensors in the geothermal environment. Geothermal monitoring while drilling, and structural health monitoring of geothermal wells, is important for the longevity of the geothermal well, and for the reduction of potential environmental impacts associated with well construction and energy production.

High temperature tolerant electronics may make it possible for us someday to have a real time heat and structural health map for geothermal wells made available on a smartphone. Further, the U.S. Army Futures Command has launched a major, \$210 million facility at the Texas A&M University Rellis campus, which includes in its mission high-temperature and high g-load electronics development (TAMU, 2019). The potential technology transfer from the military to geothermal, and vice versa from this effort is high.

The Materials Science and NanoEngineering Department at Rice University is now under a five year \$30 million contract with the Army to develop a new class of high-temperature military-grade electronics based on synthetic diamond (Semiconductor Today, 2019). Developments in Radio Frequency communications are beneficial in geothermal for data communications within the wells. Developments in these and other materials offer the possibility of structural health monitoring in geothermal wells having temperatures greater than 200°C (392°F). Currently, temperature limitations in electronics limit the applicability of structural health monitoring in both the geothermal and oil and gas industries.

#### D. Remote Sensing

Sensors embedded into geothermal wells, drill strings, and logging tools are obvious applications for new sensor technologies. Perhaps a less obvious application is remote sensing from the air. Many unconventional

plays in the United States experience gas leaks during production, which reduce and in some cases negate any climate benefit of gas for energy generation, compared to coal and oil. In the case of accidents and blowouts, methane emissions are a serious cause for concern.

Data is being collected from the air and from satellites, by monitoring instruments like the Tropospheric Monitoring Instrument ("TROPOMI") onboard the Sentinel-5 Precursor satellite. The data that TROPOMI is collecting ultimately offers time resolved region-specific methane emissions around the world (Pandey, et al., 2019). Measurements from TROPOMI and other Earth-orbiting satellites offer the extended monitoring capabilities that are likely to influence regulations and policies throughout the world.

The University of Texas at Austin's Bureau of Economic Geology owns and operates airborne instrument survey systems, which offer this kind of imaging, known as multi-spectral imaging. They also collect time-resolved, region-specific methane emissions. This imaging can be used to map surface alteration mineralogy of geothermal sites, in the case of long-term subsidence and uplift of geothermal areas related to exploitation of reservoirs. In addition, multispectral imaging has also been used in the survey of geothermal wells to assess the environmental impact. Studies of the spectral response of vegetation and lichens in proximity to conventional geothermal wells and power stations can be used to assess impacts by hydrogen sulfide, mercury, and other potential contaminants from the wells.

#### E. The Transfer of Oil, Gas, and Geothermal Technologies to NASA Missions

As humans continue to explore space, and missions to other planets and moons increase in their duration and complexity, power systems ranging from solar power to nuclear, wind, and geothermal will be evaluated for their reliability and suitability in supporting NASA's operations. Drilling for geothermal energy in space has been the topic of serious study by experts in space exploration, particularly for colonization and human habitats on moons and other planets (Wisian, 2022; Badescu & Zacny, 2015; Badescu, 2009). In order to make geothermal power a possibility in this context, high fidelity automated well construction must be enabled. It is widely regarded in the ISRU community that the future of mining on other planets, moons, and asteroids will most likely



resemble future mines on earth. Large mining companies are currently developing automation technologies for automated drilling and mining (Badescu, 2009). Automation and digitalization in construction even now extends to housing, where the Austin-based company, ICON, is building neighborhoods of 3-D printed homes (ICON, 2022). And as we saw in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#) of this Report, there is broad consensus in the oil and gas industry that rig automation and digitalization is the future of geothermal drilling.

At Rice University, developments in 3-D printing for well construction applications have had a focus on tough, temperature tolerant, corrosion resistant materials (Boul & Thaemlitz, 2021). 3-D printing is not just a natural method for ISRU of building structures, but also a method to build stronger, more resilient materials for harsh environments. 3-D printing offers a method combining digitalization and automation to build wells and other building structures remotely, ultimately with full automation. With the oil and gas, geothermal, and aerospace industries all requiring high performance in harsh environments, opportunities for transfer of technologies and expertise from oil and gas or geothermal are plenty.

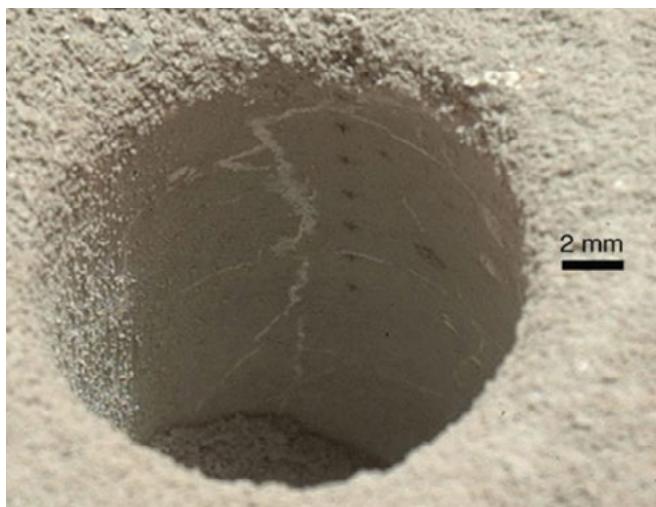


Figure 8.5. A hole drilled by the Mars Science Laboratory ("MSL") on the Curiosity rover. A vertical array of pits can be seen on the side of the hole in the rock, referred to as "John Klein." These pits resulted from the ChemCam tool ("LIBS") to give a composition of the drilled rock (Badescu & Zacny, 2015). Source: NASA, 2022.

In planetary exploration, drilling is necessary to acquire subsurface samples for in-situ analysis or return to Earth. With knowledge of the composition of the surface and subsurface, it may be possible to utilize these resources for energy and for building structures. The drill on the Curiosity rover is the first autonomous extraterrestrial drill to be deployed on another planet since the 1980's, when the Venera missions were deployed to study the surface of Venus. It is also the first autonomous drill deployed on another planet to drill through solid rock. An image of one of the holes drilled on Mars by the MSL is provided in Figure 8.5. Compositional analysis by the Mars Science Laboratory ("MSL") determined the presence and depth dependence of the concentrations of calcium oxide, calcium sulfate, and silica – all useful building materials.

The exploration of Venus in the manner that Mars is being studied for resources will require enhanced drilling capabilities, which match those needed on some of the hottest geothermal wells on Earth, those greater than 300°C (572°F) (Badescu & Zacny, 2015). Table 8.1 shows that the survival times of the Venus landers was greatly limited by the inhospitable environment of the planet. There were, however, four landers which were able to acquire surface samples. For example, Venera 14 was successfully drilled to a 1.2 inch (three centimeter) depth, and gathered a sample for an X-ray fluorescence spectrum in a chamber kept at 30°C (86°F). The sample was determined to be of similar composition to the basaltic rocks on Earth in mid-ocean ridges. This was all done with technology from the 1980's. Developments in high-temperature drilling and automation in recent years can help to determine the composition of such extreme environments as those on Venus. Further developments in high-temperature materials will likely greatly increase the surface time of robotic vehicles on the surfaces of such planets.

Research and development activity in 3-D printing for well construction in oil and gas has been driven by the recognition that on average, approximately 20 percent of all constructed wells in the industry require costly remediation within a 30-year period (Daccord, et al., 2006). In normal operations, failures of these kinds can result in the loss of a well and considerable hazard to field personnel (Plank, 2011). Longevity is particularly important in geothermal wells, where operators look for well lifetimes much longer than the 30-year lifetime for a typical oil or gas well.



Table 8.1. Venus landers, their surface time on Venus, and sample acquisition success. Source: Badescu & Zacny, 2015.

Surface landed mission	Lanuch Year	Surface time*(min)	Surface sample acquision capabilites
Venera 7	1970	23	No
Venera 8	1972	50	No
Venera 9	1975	53	No
Venera 10	1975	65	No
Venra 11	1978	95	Yes. Failed to deposit sample
Venra 12	1978	110	Yes. Failed to deposit sample
Pioneer Venus 2	1978	60	No
Venera 13	1981	127	Yes
Venera 14	1981	57	Yes
Vegra 1 Lander	1984	56	Yes. Activated during decent by error
Vega 2 Lander	1984	57	Yes

The mining of minerals and harvesting of energy are mission critical for NASA in establishing lunar bases or colonies on other celestial bodies. They are necessarily integrated with life-support systems in human space travel. Failure rates of 20 percent are not tolerable in human spaceflight. The precision that is possible with 3-D printing, in addition to the superior toughness in the structures built through 3-D printing, can lead to higher fidelity in well construction. Furthermore, the development of automation in these systems can also transfer directly into mining of materials and automation thereof.

A new class of hypervelocity impact-resistant structures is being developed to broaden the toolset for building wells through 3-D printing (Sajadi, et al., 2019b). The structures combine fracture toughness into load-bearing lightweight structures made from simple thermoplastics. It is the printed architecture of these materials that give them their remarkable toughness. The application of the 3-D printed structures is envisioned not just for oil and gas applications, but also for aerospace applications and development of lightweight armor. The technology is readily tailored to increasing the strength to weight ratio of aerospace composites, and potentially to improvements in a material's thermal tolerance.

Building from research and development activities in 3-D printing of oil and gas wells, smart 3-D printing technologies can be extended to NASA's efforts in ISRU. It is widely recognized that the exploration and colonization of planets and moons beyond our own is an endeavor that will require the use of resources local to the regions of the bases or colonies (Badescu & Zacny, 2015; Badescu, 2009). The manufacture of materials and energy powering longer term missions through ISRU will be essential for the sustainability of long-term missions. 3-D printing of oil well cements (Sajadi, et al., 2019a) and multimaterial cement composites (Sajadi, et al., 2021) has taught us many lessons which can be applied to the building of a Martian base from Martian regolith, for example (Yashar, et al., 2019). 3-D printing is enabling a digitization and automation of construction (Craveiroa, et al., 2019). The construction is not limited to habitats, but extends to wells and mineral mining structures and systems (Zacny, 2012; Zacny & Bar-Cohen, 2009).

There are many other aspects related to additive manufacturing that would be impactful transfers into NASA's missions. The 3-D printing of metals, for example, has undergone major developments in the oil and gas industry. High performance alloys, such as Inconel, can now be printed into parts for gas turbines, compressors,



downhole tools, and sensors (Burns & Wangenheim, 2019). Further development of these technologies can make it possible to mine resources and utilize them for energy production remotely and through automation. They are also useful in hybrid smart systems with sensors and communication systems that are directly integrated with building structures.

### F. Geothermal Power in Space

Texas is and has been a leader in government driven, and also now private space exploration and related technology development. Texas is also driving hard into the new geothermal paradigm. Combining these two areas yields geothermal in space. Remember that the essential ingredient for a geothermal system is a temperature differential, generally in the 100 to 250°C range. Multiple solar system bodies have geologic settings where these differentials might be observed.

The moon is our closest celestial body. The surface “soil” of the moon has a thermal conductivity orders of magnitude lower than typical rocks here on Earth (Yu & Fa, 2016; Grott, et al., 2010). This low conductivity can drive very high thermal gradients of short distances, and not just vertically. The heat flow in the crust of the moon is generally low. Additionally fluids, particularly water, are likely to be quite precious, to the point that an Engineered Geothermal System might not be practical. However thermoelectric (or Seebeck) generators, as discussed further in other Chapters, might be able to generate usable amounts of power without any fluids, or even moving parts, required. Lastly, the need for deep drilling could be avoided by taking advantage of the greater than 200°C (392°F) temperature difference at the rim of lunar polar craters. These craters have near zero temperature inside the permanently shadowed interior, while half the time enjoying temperatures more than 200°C (392°F) warmer on the sunward lip of craters (Figure 8.6). This is a usable temperature difference for geothermal applications (Wisian, 2022).

Mars has no active tectonics, and while geothermal potential cannot be ruled out, it will likely be very restricted geographically, and relatively low-temperature. As you move further out in the solar system to Jupiter, Saturn, and beyond, the solar flux falls off dramatically, making solar power less attractive. Radioactive power

sources of one sort or another have potential, but also significant drawbacks. Thus, geothermal power becomes particularly attractive in the outer solar system. While the gas giants are not settlement targets, their moons are. Lo (a moon of Jupiter) is the most volcanically active body in the solar system, but its sheer level of activity will likely prohibit long-term occupation, and thus will not be considered here.

The remaining (spherical) moons around the gas and ice giants, as well as minor planets such as Pluto and Eros are mostly ice, and this presents an opportunity. Many of the icy bodies in the solar system appear to have subsurface oceans of water (with an indeterminate amount of other constituents in solution). These oceans appear in at least some instances to be “planet”-wide. The net result of these configurations is an ocean top at or near 0°C (32°F) and an average surface temperature around -200°C (-328°F), with kilometers of ice in between (Figure 8.6). Setting aside the considerable engineering challenges, this is a constant 200°C (392°F) differential – a resource that would make a terrestrial geothermal engineer quite happy.

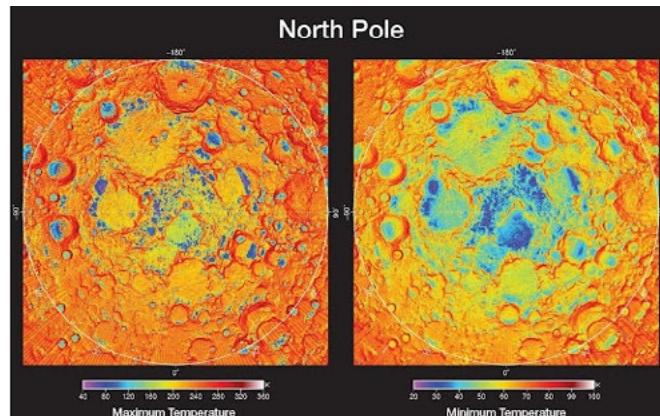


Figure 8.6. Maximum and minimum temperatures at the Moon’s North Pole as measured by the Lunar Reconnaissance Orbiter. Source: NASA, 2014.

### G. A Way Forward with Space

The aerospace, oil and gas, and geothermal industries have developed remarkable technologies, which have been advancing the possibilities within their individual domains. It is the space between the industries where perhaps some of the most exciting developments and applications can be realized. Each industry has developed



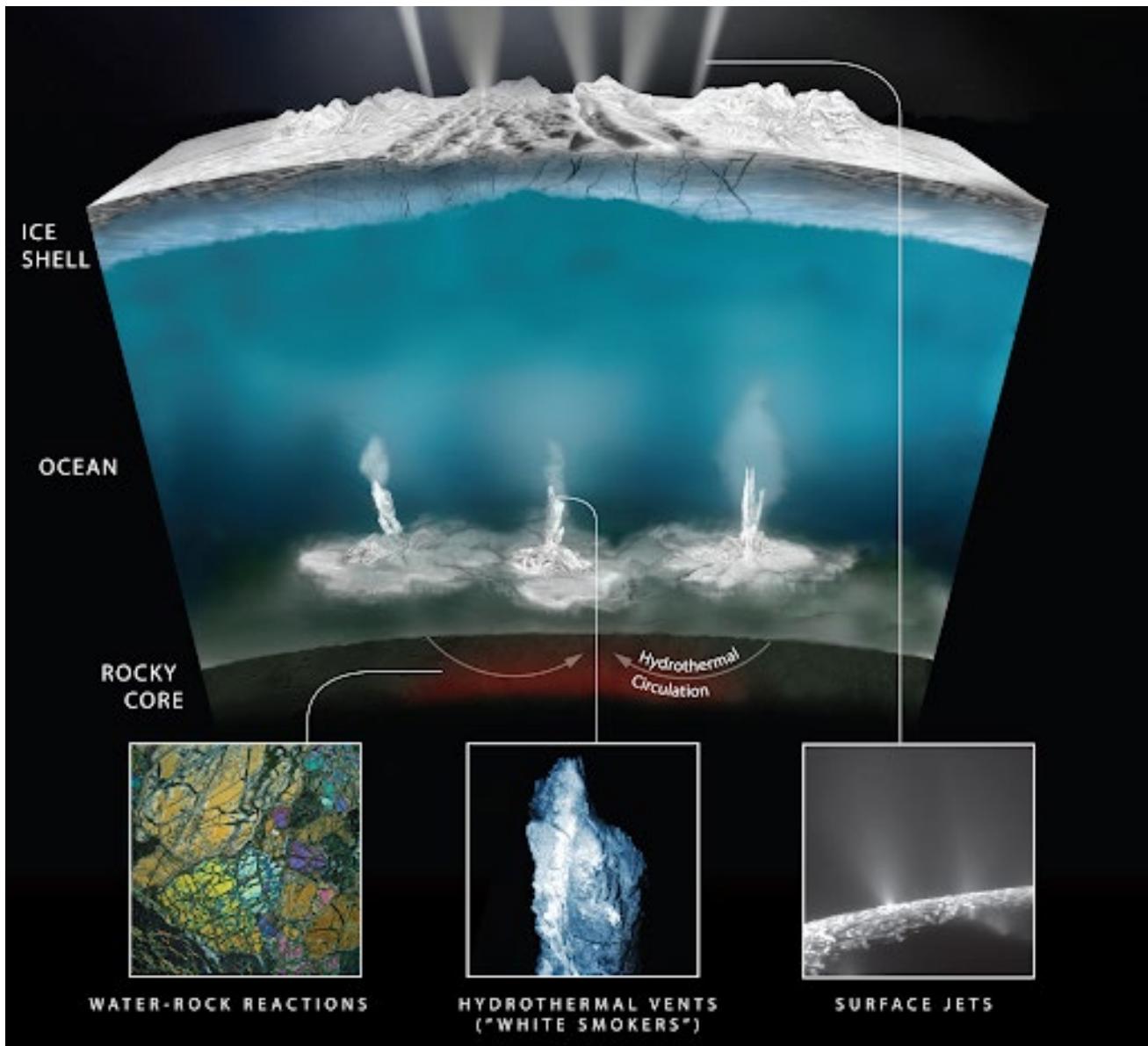


Figure 8.7. Generalized structure of outer solar system icy bodies. Source: NASA, 2017.

#### IV. Conclusion

technologies which are of potential mutual benefit to the other. And beyond established technologies that may readily transfer are research and development activities, which translate well into aerospace and space exploration technology development activities. There may be no better time than now to unlock the potential that we have in establishing Texas as the leader in geothermal power through inter-industry and interdisciplinary collaboration and technology transfer.

Texas has a long history of world-leading science and technology innovation across three major industries, subsurface energy production, defense, and space. The interplay and reinforcing synergy of leading-edge developments in space (both government and commercial), and defense, along with emergent geothermal start-ups, existing energy companies, and academic researchers, is exciting and loaded with near-term potential. This unique convergence of strengths will enable Texas to lead the world in the geothermal revolution.



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## Conflict of Interest Disclosure

**Ken Wisian** serves as an Associate Director of The Bureau of Economic Geology, Jackson School of Geoscience at the University of Texas at Austin, and is compensated for this work. His main area of research for 30 plus years is in geothermal systems. Outside of this role, Ken Wisian 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.

**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 is 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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Texas-based startup Sage Geosystems' South Texas geothermal demonstration. Photo credit: Sage Geosystems.

## Chapter 9

# The Texas Startup and Innovation Ecosystem

J. Beard

**Over the past few years, the Texas geothermal startup ecosystem has grown from nonexistence to the largest and fastest growing geothermal ecosystem in the world. The steps that Texas takes next could grow this burgeoning ecosystem into a major player in the State's future economy, and the world's energy mix.**

## I. Introduction

The Lone Star State, home to nearly 30 million people, is a melting pot of startup companies and legacy industry entities, new ideas and long held traditions, wildcatter culture and "Silicon Hills" buzz, grit and glamor, and a Texas mile of creative energy. Texas and its eccentric and diverse innovation ecosystem has become a magnet for businesses seeking to tap into the talent and energy of the State, with entities like Tesla, Oracle, Caterpillar, and Hewlett Packard joining the dozens of fortune 500 companies who headquartered in the State last year.

Looking to the future of geothermal, Texas' oil and gas industry is perhaps its most valuable asset in achieving fast growth and scale, but rounding the turn in a tight race is the State's burgeoning geothermal startup ecosystem. In this Chapter, we will briefly explore the history of

entrepreneurship in the Lone Star State, the Texas innovation ecosystem at large, and the launch and rapid growth of the State's geothermal startup ecosystem. We will end the Chapter with an analysis of data reported by Texas geothermal startups about their greatest barriers to growth, and recommendations on how to keep the geothermal startup ecosystem growing and supported in the Lone Star State.

## II. Wildcatting - A Uniquely Texan Brand of Innovation and Entrepreneurship

Texas is well known for its high tech innovations, inventions so ubiquitous that chances are, if you are reading this Report digitally, you are interacting with at least one of them right now. The integrated circuit, which



led to the invention of the microchip, was invented in 1958 by Nobel Prize recipient Jack Kilby at Texas Instruments. In 1967, another team at Texas Instruments introduced the handheld calculator, which became a staple in the backpacks of generations of high school and college students. 3-D printing emerged from the University of Texas at Austin, invented by graduate student Carl Deckard. Entrepreneur Mary Kay launched her cosmetics business in Dallas and with it a fleet of pink Cadillacs onto suburban streets. The list goes on. Entrepreneurship is just as much a part of the heritage of Texas as the idyllic scenes of the Texas prairie, and ranch life. Brands and products that call Texas home include everything from the trendy, such as Whole Foods Market, and the lithium-ion batteries that are supercharging electric vehicle markets, to staples of office life, like Dell Computers and Liquid Paper's White Out, to libations such as Dr. Pepper, Tito's Homemade Vodka, and Shiner Bock.

The State's energy industry provides perhaps the most powerful example of the innovative and entrepreneurial spirit of Texas. The first oilfield in the State was developed in 1866, and the first refinery in 1898 (Olien, 2022). These developments, along with the oil 'gusher' at Spindletop in 1901, kicked off the Texas oil boom, and a new economy that would enable the world to industrialize. It also led to the launch of legacy oil and gas industry entities, such as the Texas Company (Texaco), Humble Oil and Refining Company (ExxonMobil), Pennzoil, and the M. Guffey Petroleum Company (Gulf Oil Corporation), among others.

The success of the oil and gas industry in Texas, and its skill at growing, innovating, and meeting the energy needs of the world, are due at least in part to the wildcatter culture that emerged from oil and gas explorers as the industry got traction. Wildcatting has been described as a "mythic identity" synonymous with "intrepid, hardworking, hard-playing" laborers who emerged from limited means and "risked everything to accumulate fortunes" (Simek, 2020). It was a wildcatter who discovered the Yates Oil Field, which led to the exploration of the Permian Basin, a massive resource that sustains the prosperity of the Texas oil and gas industry to this day (Simek, 2020).

With a culture of wildcatting in the State, it's no wonder that Texas has produced so many visionary entrepreneurs who have impacted the world - including industry pioneers such as George Mitchell, who pioneered hydraulic fracturing in the Barnett Shale formation of North Texas. Mitchell's initiative and entrepreneurship

kicked off the shale boom, rearranged global geopolitics, and has provided a model and playbook for the coming exponential growth of the geothermal industry. His legacy continues to exemplify the outsized impact that Texas has had on the rest of the world. The tenacity of Texans like Mitchell continues in the State's pioneers of today, like Whitney Wolfe Herd (founder and CEO of Bumble), Jeff Bezos (Executive Chairman of Amazon), Vanessa Castagna (former JCPenney chairman and CEO), Michael Dell (Chairman and CEO of Dell Computers), and the late Herb Kelleher (co-founder and CEO of Southwest Airlines).

### III. The Texas Innovation Ecosystem of Today

There is currently a robust and thriving ecosystem in Texas built to support startups and entrepreneurs in the State. Based on annual polling from nearly 700 chief executive officers and business owners from around the United States, Texas was identified in 2022 as the number one State for entrepreneurship and startups, and has held this honor for 18 consecutive years (Buss, 2022). Innovation and entrepreneurship ecosystem members in the State are too numerous for individual mention, but include entities such as Capital Factory, DivInc., Sputnik ATX, Texas Venture Labs, MassChallenge Texas, ION, the Austin Technology Incubator, Halliburton Labs, Quake Capital Partners Accelerator, Tech Wildcatters, WIRE accelerator, and many others.

Across the State, there are dozens of startup related programs connected to Texas research institutions, such as the Rice Alliance Clean Energy Accelerator, the Blackstone LaunchPad at the University of Texas at Austin, and the University of Texas at Dallas' Institute for Innovation and Entrepreneurship. Rice's Graduate School of Business took the number one spot in the United States in 2022 in Princeton Review's Best Graduate Programs for Entrepreneurs, while the University of Houston took the number one spot for the Best Undergraduate Programs for Entrepreneurs (PR, 2022). The Rice Business Plan Competition is the world's largest and most well-endowed, with teams competing each year for millions of dollars in cash and prizes.

The more than 200 accelerators, incubators, and entrepreneurship focused entities in Texas, many climate and energy focused, are spread across what the Founder Institute dubs the five Lone Star(tup) Nodes of



# Number of Startup Resources by Location in Texas

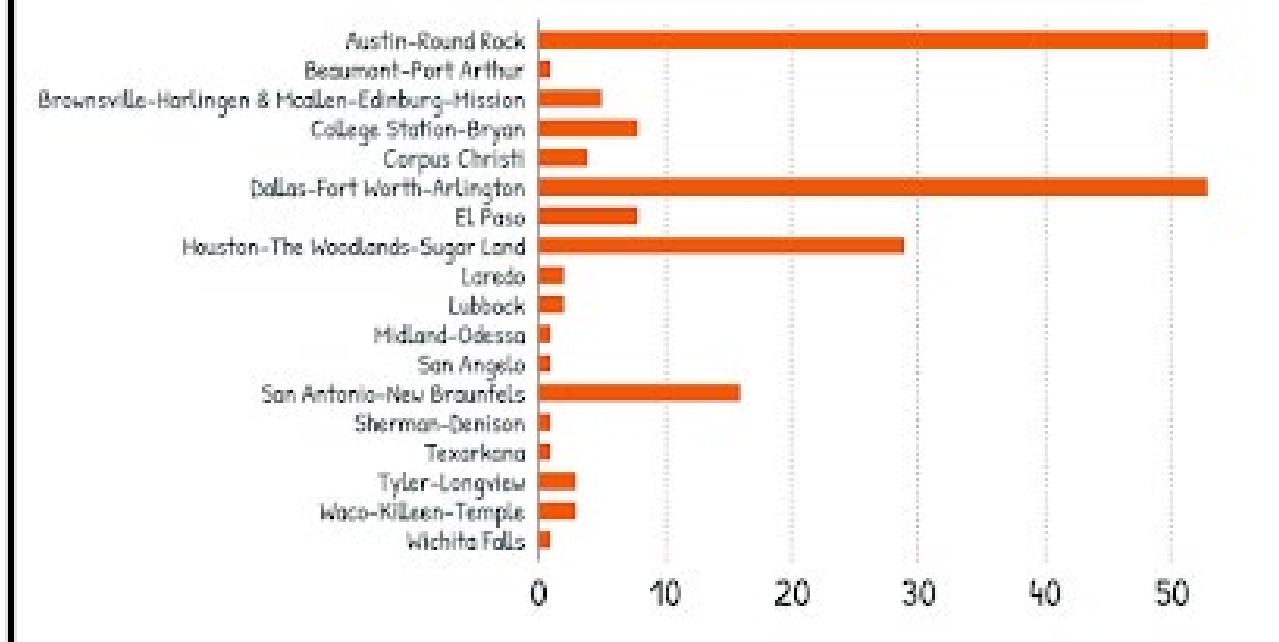


Figure 9.1. Number of entrepreneurial resources by location in Texas.  
Source: Adapted from Texas Office of the Governor.

Innovation, including Dallas-Fort Worth, San Antonio, Austin, Houston, and College Station (FI, 2019; Texas EDT, 2017).

Conveniently for entrepreneurs who catch the geothermal bug, these Nodes of Innovation in Texas sit on top of the State's primary geothermal resource corridor (FI, 2022). The alignment of the State's population centers with geothermal resources in Texas is considered in further detail in [Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development](#).

Simply put, there is a lot going on in the Texas entrepreneurship and innovation ecosystem, and this serves as the background music, so to speak, for the emergent Texas geothermal startup ecosystem.

## IV. The Texas Geothermal Entrepreneurship Organization ("GEO")

In 2018, Chapter author Jamie Beard took a position directing an entrepreneurship program at the University of Texas at Austin ("UT Austin"), with the goal of building enough momentum for geothermal within the institution

to apply for a grant, and fund a geothermal focused innovation ecosystem there. She spent her first months at UT Austin mapping the ecosystem, recruiting faculty into the discipline, building momentum for an organized geothermal effort at the University, and searching for a technical leadership team for the future geothermal effort. At this time there was little, if any, funded geothermal research and development ongoing at UT Austin, and no startup activity associated with geothermal. Few faculty members interviewed had given the discipline much thought or attention, and a fair dose of skepticism about the prospects of geothermal overshadowed the occasional glimmer of interest from a faculty member.

During these early days of effort to build the beginnings of the ecosystem, on average, the ratio of faculty disinterest and intrigue in geothermal was about ten to one, with ten expressing little interest or skepticism, and one expressing enthusiasm. But that occasional enthusiastic collaborator over time turned into small groups of actively engaged faculty, as they began to roundtable and discuss the topics with one another. Over the span of a year, majority disinterest gave way to increasing engagement amongst faculty, researchers, students, even alumni, and we worked to map the skillsets and technologies



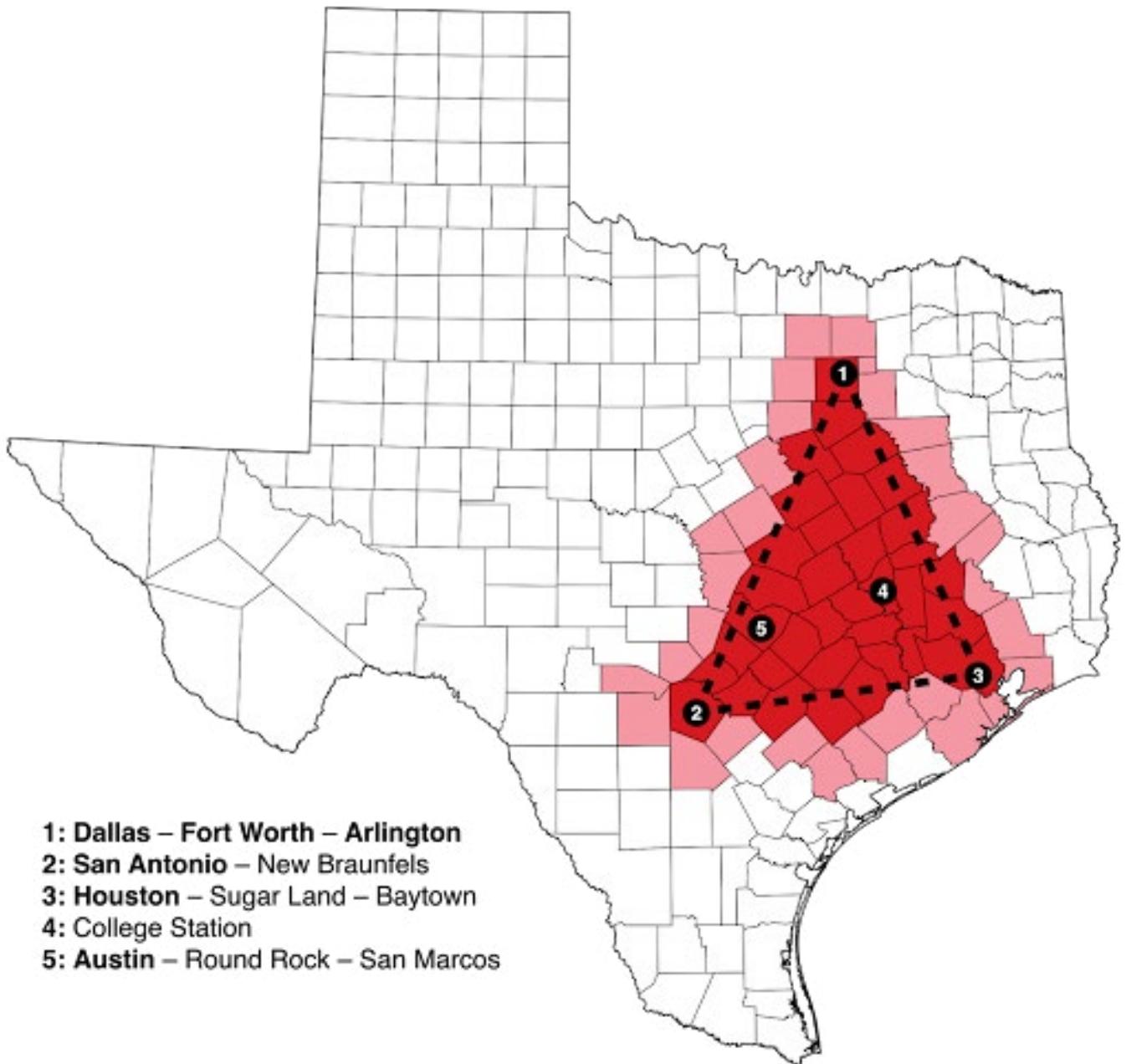


Figure 9.2. Map of the Lone Star(tup) Nodes of Innovation in Texas. Source: FI, 2022.



of faculty across schools in search of technologies and entrepreneurs who would be good candidates to launch geothermal focused research and/or startups. The most enthusiastically engaged faculty became de facto recruiters for geothermal themselves within UT Austin, and the most prolific among them became leaders of UT Austin's first organized geothermal effort, the Geothermal Entrepreneurship Organization ("GEO").

The GEO leadership team included purposefully diverse skill sets, all experts in entrepreneurship, geophysics, and petroleum engineering, and with the exception of one team member, all new to geothermal. The team members were full of fresh ideas, energy, and enthusiasm for solving geothermal challenges, and were spread out purposefully across multiple schools at UT Austin, to amplify our interdisciplinary approach to the geothermal ecosystem we set out to build. GEO leaders included Chapter author, legendary entrepreneur and inventor of the ethernet Dr. Bob Metcalfe, former Air Force Major General and geophysicist Dr. Ken Wisian, and veteran oil and gas industry drilling expert and Professor of Petroleum Engineering Dr. Eric van Oort. After some months of planning and waiting, a funding opportunity announcement from the U.S. Department of Energy ("DOE") was published that fit closely enough with our goals, and we went for it.

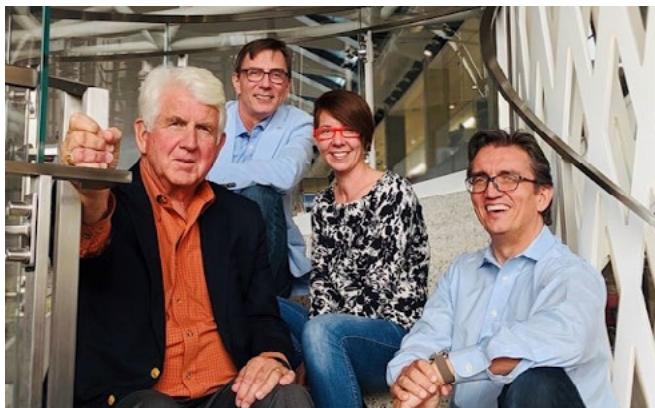


Figure 9.3. The GEO leadership team, including from the left, Dr. Robert (Bob) Metcalfe, Professor of Entrepreneurship and Innovation (now emeritus), Dr. Ken Wisian, Associate Director of the Bureau of Economic Geology, Jamie Beard (Chapter author), Executive Director of GEO, and Dr. Eric van Oort, Professor of Petroleum Engineering in the Hildebrand School of Petroleum and Geosystems Engineering.

Source: Texas GEO, 2022.

In 2019, the DOE granted the UT Austin Cockrell School of Engineering a \$1 million grant to launch GEO, a unique, first of its kind program aimed at building a research, development, and innovation ecosystem within a leading petroleum engineering and geoscience research institution, with legacy oil and gas expertise. Further goals of GEO were outreach and engagement with the oil and gas industry about geothermal related challenges, and recruitment of faculty, students, oil and gas industry veterans, and even oil and gas entities themselves to engage in geothermal ventures, inquiries, and development (Texas GEO, 2022).

The program was funded under the DOE Geothermal Technologies Office Efficient Drilling for Geothermal Energy ("EDGE") funding opportunity announcement. GEO was funded under topic area three of EDGE, which focused on "exploring innovative approaches and models to accelerate the transfer of geothermal drilling and related technologies from the laboratory into the real world" (DOE, 2018).

GEO's primary mission was creation of a self-sustaining innovation ecosystem for geothermal, focused on the number one petroleum and geosystems engineering department in the world, the Hildebrand Department of Petroleum and Geosystems Engineering. The approach was based on the hunch that faculty and researchers within petroleum and geosystems engineering departments would have ample excitement, enthusiasm, and spot-on skill sets and technologies in development to dive head first into geothermal challenges, with fast, breakthrough impact (UT News, 2019).

As we got GEO off the ground and built momentum, though we experienced increasing energy and excitement coming from faculty, students, alumni, and even increasingly oil and gas entities, there was no public facing representation of the innovation, ideas, and traction that we were seeing day to day in talking with ecosystem stakeholders. The team decided to launch a blog, called [HeatBeat](#), as an avenue to publish stories, interviews, opinions, and debates to spread the word about what we were finding with a larger community. We hoped the blog would challenge the often sleepy and underwhelming geothermal narrative with new voices, new ideas, and new entrants to the geothermal scene, who were willing to question the status quo. The message was that something new, cutting-edge, and potentially very big for geothermal was happening down



in Texas. HeatBeat became the place we would point media, industry, donors, venture capitalists, students, and others who were excited about this new Texas-based geothermal traction and wanted to dig in further.

Next we discovered that although there were plenty of faculty, researchers, and by this time participants within oil and gas entities interested in contributing to the geothermal conversation, individuals were having difficulty gaining acceptance into journals and conference proceedings, both within the geothermal and oil and gas conference and journal scene. It turned out that geothermal conversations led by oil and gas didn't have a clear home at that time, with new oil and gas entrants viewed as outsiders in geothermal circles, and also as outsiders within oil and gas due to the subject matter. We needed a high visibility public platform for engaged voices to discuss, debate, and get their ideas out into the world, so in 2020, we launched the [PIVOT - From Hydrocarbons to Heat conference](#) ("PIVOT"), and the inaugural PIVOT2020 lit a fire under an already excited and growing ecosystem. At this time, the world was in the midst of the global COVID-19 pandemic, so PIVOT was born as an all virtual conference, and it quickly grew. In its second year, PIVOT had become the largest geothermal gathering in the world, with thousands attending from more than 100 countries globally. More than 60 percent of attendees hail from the oil and gas industry (PIVOT, 2022).

A central component in growing PIVOT was assuring the conference was free to attend. Removing this barrier allowed new entrants, students, researchers, and even the general public a low risk and near effortless avenue to engage with geothermal. The first year, PIVOT2020, required a massive effort from a small and dedicated group of "do-it-yourself" volunteers. By the second year, we had fundraised sufficiently to transition the conference into professional production.

By the end of the two year DOE grant period in 2021, UT Austin had become the epicenter of geothermal research and development in Texas, with faculty members engaging in geothermal research, and geothermal focused research consortia launched across two schools (BEG, 2022). At least two faculty members launched geothermal startups, with others engaging as advisors to geothermal startups and industry entities interested in engaging in the space (Bedrock, 2022; HeatBeat, 2020). UT Austin now has established geothermal curricula, and is a recognized entity and source of experts in the next

generation geothermal space. Further, GEO's work at UT Austin resonated throughout surrounding research institutions in Texas, and amongst alumni, several of which became inspired to begin geothermal research and development at their institutions, or launch geothermal startups of their own. Sage Geosystems, a leading startup in next generation geothermal, is an example of one such entity, founded by UT Austin alumni and former Shell Chief Scientist, Lance Cook.

In sum, a relatively small grant and a two year sprint catalyzed far reaching impact, a new and self-sustaining geothermal innovation ecosystem in the heart of oil and gas country, and a small army, ever increasing in size, of geothermal startups launching into the field, with headquarters and/or operations in Texas. If we wish to keep the fire under geothermal burning bright, we need constant infusion of innovation, ideas, and new entrepreneurs. As such, the GEO model can, and should be, replicated across research institutions globally with legacy expertise in petroleum engineering and geoscience, creating new self-sustaining innovation ecosystems for geothermal, everywhere. In sum, geothermal would benefit immensely from a fleet of geothermal innovation ecosystem builders at institutions and entities globally.

The GEO model is as follows: 1) conduct a full survey of faculty, capabilities, technology readiness levels of commercializable and high-impact geothermal applicable technologies, and create a list of interested and entrepreneurial faculty and postdocs; 2) give seed grants and support to the top motivated faculty who have an "on the bench" technology that can be adapted for geothermal applications quickly with minimal investment, or to new research ideas that could quickly develop into high impact commercializable technologies applicable to geothermal; 3) nurture those faculty members and postdocs through the process of starting a venture, and assist them in obtaining funding to spin out entities from their research and development activities.

This was not always a smooth process as we got GEO off the ground, and we often built the airplane as we were flying it. Below are a few notes on lessons learned in building GEO, and best practices for those interested in building their own geothermal innovation ecosystems in entities and institutions that may not have significant existing geothermal expertise or engagement.



- **Cast a wide net with your technology and capability survey, but not too wide:** We focused on all faculty, in every relevant department and school, which was a significant time commitment. Ultimately, if you plan a handful of presentations at department meetings and faculty lunches as a starting point, the most enthusiastic faculty will come to you.
  - **Resist allowing your initiative to become centered around a single school, program, or faculty member:** Institutional settings are fraught with silos, turf competitions, and academics battling each other for spotlight and recognition. Avoid these dynamics by involving as diverse a group as possible, being inclusive of multiple disciplines, departments, and schools. Letting “1,000 flowers bloom” in your ecosystem is a way to keep the playing field open to new entrants and innovators who may be intimidated if one program or outspoken academic is the only face of your program.
  - **Bust the Silos:** Geothermal needs all types of expertise, including business, finance, marketing, communications, policy, legal, geoscience, and all types of engineering, including mechanical, civil, electrical, chemical, computer, and petroleum/geosystems. If you are able to house your program in a portion of your institution that sits across the various silos, like the Office of the President, Provost, or Vice-President of Research, it will allow you more movement across and through the silos that are so prevalent in large academic institutions.
  - **Disperse Seed Grants Freely and Fast:** Seed grants are an excellent vehicle to use to amplify the excitement of faculty members who have interest and ideas about how they can adapt existing research and/or technologies to apply in the geothermal context. Small grants of \$25,000 or \$50,000 are typically enough to support the work of a student to push inquiries forward. Raise seed grants from corporate or philanthropic sponsors, and grant them early and often to supercharge your ecosystem.
  - **Hire an Entrepreneur in Residence (“EIR”):** In hindsight, this would have been an excellent way to provide faculty and students with the extra attention they needed prior to being ready to plug into an accelerator or incubator program in GEO, and it is the way we have chosen to move forward as we expand GEO into other research institutions in the coming year. An EIR can assist with basic skills, such as building an initial pitch deck, business plan, and answer questions about entity formation, freeing program leaders to focus on stakeholder outreach, discussions with department chairs, fundraising, deploying seed grants, etc.
  - **Don’t Reinvent the Wheel:** Leverage the parts of your innovation ecosystem that are already in place by plugging your teams and entrepreneurs into existing incubators and accelerators after you’ve been successful at recruiting them into geothermal and helping them refine their idea. Every piece of the ecosystem that you do not have to build from scratch will allow you to focus on the primary objective, which is to nurture and seed interest in geothermal across as many disciplines and minds as possible within your institution.
- As an illustration of how your growing geothermal ecosystem can be quickly plugged into existing programs, in the Texas ecosystem, Rice University now has multiple geothermal startups in their accelerator program (Franklin, 2022), and multiple others sit at incubators, co-working spaces, and accelerators in Austin and Houston. Further, Houston’s Greentown Labs has begun hosting geothermal focused networking events. This is an efficient and desired outcome that allows ecosystem builders the bandwidth to focus on recruiting and priming the innovation pipeline, while handing the task of growing and mentoring entities off to programs already in place that are designed to do that work.
- While walking the full course with emerging teams, from idea, to pitching, to funding, to piloting, was helpful for the Chapter’s author in developing an understanding of the novel challenges that the geothermal ecosystem would face, it is an unnecessary component of building a robust and flourishing geothermal innovation ecosystem. Presently, what geothermal needs most urgently is fresh ideas, bold and energetic entrepreneurs, and oil and gas thought leaders to try their hand in geothermal. Geothermal ecosystem builders at research institutions globally can fulfill that critical need.
- The ultimate goal of a geothermal innovation ecosystem is organic, self-sustaining growth. This occurred at UT Austin to such an extent that this Chapter’s author was able to step out and launch new initiatives, while



the ecosystem continues to grow and flourish. At the beginning of the process of building UT Austin's ecosystem, teams had to be actively recruited, and forward momentum required an active, and at times, heavy push. Initial recruitment efforts of targeted subject matter experts were often unsuccessful at first, and even in the second or third attempts. However now, more often than not, new startups and teams emerging from the Texas ecosystem approach the author of this Chapter to introduce themselves, saying that they had been inspired by PIVOT, or another startup making headlines, or were recruited by colleagues, researchers, or friends who had launched a startup, etc. The ecosystem is now catalyzed, self-sustaining, and flourishing. It is a geothermal innovation engine. Let's keep that going. Pick a place to build your own ecosystem, and dive in.

## V. The Geothermal Renaissance - Geothermal Startups and the Innovation Ecosystem

Leading GEO, then becoming the host of PIVOT and leader of Project InnerSpace has introduced the author of this Chapter to emerging geothermal startups from all over the world. Many are based in Texas, but not all. Some have emerged from oil and gas from epicenters of industry globally, such as Calgary, Oklahoma City, Aberdeen, and others.

A few have launched elsewhere in the world, and are considering moves to Texas due to the growing ecosystem and investor pool in the State. A list of geothermal focused or adjacent startups in this quickly growing innovation ecosystem is captured in [Appendix B of this Chapter](#). This ecosystem has raised just over a billion dollars to date, with roughly three-quarters of these funds raised in the past three years.

Below is an illustration of the years the startups in [Appendix B](#) were founded. As one can see, the ecosystem has experienced substantial growth over the past several years, which appears to be accelerating. Keep in mind that this represents startups that have made it onto this Chapter author's radar globally, including entities who are headquartered and have operations in Texas, but also entities who do not. As you'll see in the next illustration, the Texas startup ecosystem accounts for most of the growth of this ecosystem over the past three years.

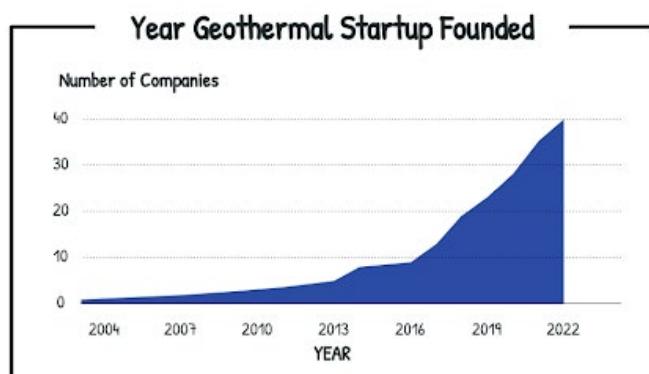


Figure 9.4. Trend of geothermal companies founded globally between 2002 and 2022. Source: *Future of Geothermal Energy in Texas, 2023*.

Over the past three years, nine of the 11 geothermal startups with headquarters in Texas launched. This positions the Texas ecosystem as the driver behind the sharp global growth of the ecosystem. The Texas geothermal startup ecosystem is also quickly gaining on all other states in the number of geothermal startups headquartered in the State, with 11 entities in Texas alone, and 16 entities in all other states combined.

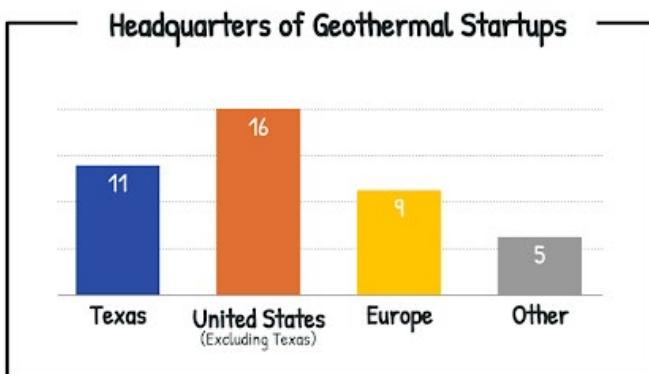


Figure 9.5. Location of geothermal startup headquarters between 2016 and 2022. Source: *Future of Geothermal Energy in Texas, 2023*.

For this Chapter, a subset of geothermal startups in the global ecosystem were interviewed to gain an understanding of what technology areas the ecosystem was focusing on, and what technology challenges the ecosystem views as the most significant facing both geothermal as a whole, and their entities in particular. In the first inquiry, we asked the startups what technology area they were pursuing in geothermal, giving them the choice of Engineered (Enhanced) Geothermal Systems, Advanced Geothermal Systems (which we defined as Closed Loop Geothermal Systems), both of these system



types, which was defined to include Hybrid Geothermal System concepts, or other, which was defined to include endeavors such as tool development or services that could apply broadly across all geothermal technologies.

While slightly more startups reported engagement in Advanced Geothermal System development over those who reported engagement in Engineered Geothermal Systems (39 percent and 23 percent, respectively), 15 percent reported that they were pursuing both or hybrid concepts, or had not yet definitely ruled out one or the other in their development strategies. Interestingly, this data is not entirely consistent with the data emerging out of the oil and gas industry, as presented in [Chapter 6, Oil and Gas Industry Engagement in Geothermal: The Data](#) of this Report, where oil and gas entities reported 87 percent engagement in Next Generation Engineered Geothermal Systems, and 93 percent engagement in Advanced Geothermal Systems. This may be explained by an “all of the above” strategy on behalf of oil and gas entities to engage in all technology types, and wait to see how field trials progress before down-selecting into a specialty, an approach that would be difficult for startups, who are limited by both funding and bandwidth, to execute.

An unrelated, but potentially important observation that may help in interpreting the data emerging from the geothermal startup ecosystem: if you look at the startup table in [Appendix B](#), a large majority of startups (29 of 43 entities) identify currently as “developers/operators,” as opposed to tool, equipment or service providers. This designation has puzzled a number of venture capitalists in private conversations with the Chapter author, as a good number of the companies who identify as developers/operators would be better suited in terms of business model as technology and/or service providers. The question often comes up, “why are these companies trying to go out and develop projects on their own,” and the simple answer to that question is because there is no entity currently out there willing to fill that role. Ideally, and perhaps in the near term, oil and gas entities themselves will be willing to step into that role as geothermal developer/operator, allowing the geothermal startup ecosystem to focus on their specialities and technology development.

Indeed, during pitches early in the fundraising journeys of geothermal startups who began as technology developers and service providers, venture capitalists would often raise the question of the size of the addressable market

for their technology and/or service, and teams were not able to address those questions sufficiently with the funding entities. We are building the tools, services, and market for next generation geothermal in parallel with one another, and often makes for difficult conversations with funding entities. Due to these dynamics, many startups have managed this issue by switching their business model to become operators/developers over the past few years in order to command more control over the project development pipeline for the purpose of fundraising.

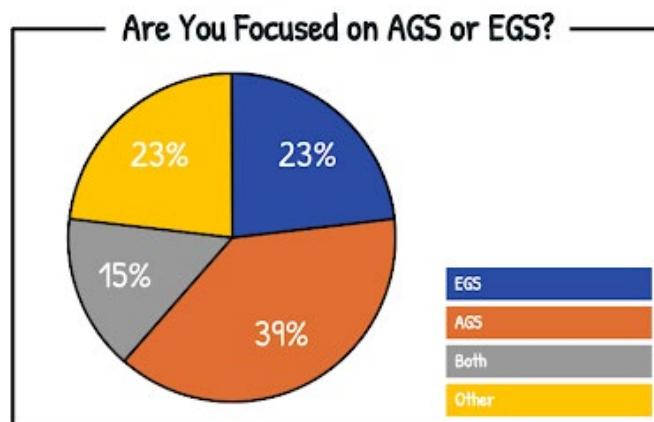


Figure 9.6. Technology focus area of geothermal startups around the globe between 2002 and 2022.  
Source: *Future of Geothermal Energy in Texas, 2023*.

This is an example of a funding pain point that exists within the geothermal startup ecosystem currently, and is one of many. It is also an example of how ill-suited venture capital (“VC”) is for geothermal currently, with VC entities struggling to understand the funding needs of the community, the likely trajectory of the next generation geothermal market, the risks associated with novel “first of a kind” projects, the culture and approaches of the teams emerging from Texas, the incremental nature of forward movement in the drilling industry vs. the “moonshot” approach of Silicon Valley, and the types of teams and expertise who are most likely to be successful in the geothermal space. These themes will be explored further below.

In the next inquiry, we asked the startups if they were focused on Direct Use heat concepts, or power production concepts, giving them the choice of heat, power, both, or not applicable, which was defined as concepts or business models that applied broadly enough across all geothermal concepts as to make this distinction meaningless.



Responses were split fairly evenly between these four responses, with power inching out heat and both by 31 percent, 23 percent, and 23 percent, respectively. Entities who responded not applicable tended to be technology and/or service providers.

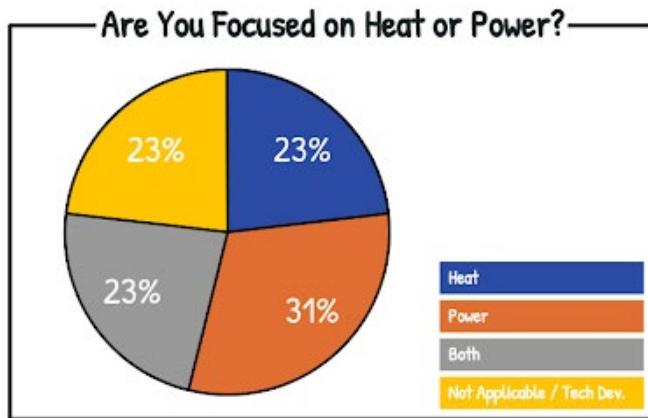


Figure 9.7. Technology focus area of geothermal startups around the globe between 2002 and 2022.  
Source: Future of Geothermal Energy in Texas, 2023.

Half of entities who indicated that they are pursuing power production concepts noted that they would pursue markets for waste heat emerging from their geothermal power operations should those markets become apparent, or if there were off-takers nearby. At least two entities who reported that they are pursuing both have built production of both heat and power into their business model as a central component, and reported that co-locating power production pilots with off-takers for heat was a priority.

## VI. Nurturing the Geothermal Startup Ecosystem in Texas and Globally

As mentioned above, several ecosystem pain points have emerged over the past few years, as an accelerating number of entities, often led by veteran oil and gas industry teams with decades of collective operational and project development experience in industry, progress from concept to pilot in a matter of months. Field iteration and “learning while doing” was an essential component of the success and speed of the national gas shale boom in the early 2000s, and it is sure to have a similar impact on geothermal – but teams have to be adequately funded to pursue field deployments. These teams on several occasions have sought to raise \$30 to 50 million USD for

semi-commercial first of a kind geothermal pilots as their seed round, an approach that VCs have largely failed to support.

Many of the challenges associated with first of a kind geothermal project finance are associated with risk management/mitigation – and first of a kind projects have two types of risk, subsurface and technological, making them unique from a risk perspective. An excellent report was published recently, which explores the first of a kind problem in the broader context of climate finance, and was inspired in part by the challenges encountered by several geothermal teams attempting to raise funding for their projects. (Khatcherian, 2022)

Private equity has also been slow to engage due to these risks, telling teams seeking to deploy first of a kind projects to “come back after your first project is in the ground.” As of the publication date of this Report, we are on the cusp of the public announcement of at least two private equity engagements in next generation geothermal concepts, but these deals have been slow moving, difficult to close, and are not near the prolific level of engagement and funding that is needed to support geothermal into exponential growth.

Insurance has been raised as a likely missing link in the project finance/funding equation for first of a kind projects, but geothermal is not currently a large enough market to engage existing climate risk/insurance entities at any serious level, and there are unique risk profiles requiring subject matter expertise that current entities lack, which dissuades engagement. While there are a small handful of entities globally who have begun to engage in this space, it is an area in need of fast attention and brain power. This Chapter author’s entity, Project InnerSpace, recently funded an initiative to build a bespoke insurance product for novel next generation geothermal projects as a stop gap measure to assist in getting teams into the field and engaged in pilots while new finance and funding mechanisms are built to serve geothermal over the coming years.

If we wish to support the emerging geothermal startup ecosystem into a global powerhouse capable of driving prosperity and growth, we need to listen to and quickly address the needs and pain points of the ecosystem before those pain points cause a loss of momentum. As is explored in other Chapters of this Report, there are roles for all types of stakeholders to play in supporting



this ecosystem, including policy-makers, the oil and gas industry, advocacy groups, funding entities, governments, and others. All stakeholders should quickly dig in and play a role in removing the barriers to growth that stand in the way of the growth of the ecosystem currently.

As part of our interview process of startups for this Chapter, we polled entities about technology gaps, pain points, how they would deploy funding if they had it to achieve maximum impact, and what they most need from the oil and gas industry. Startup responses were aggregated so the results remain anonymous to encourage direct discussions and open discourse. We summarize the data received below.

#### A. What Technology Gaps Could Hold You Back?

The startups interviewed for this Chapter were asked what technology gaps in geothermal are likely to hold them back if not addressed. The question was asked in the context of problems that the startups themselves were not seeking to address, but that had the ability to hold them back if some other entity was unable to address them. Responses varied widely across entities, with little consensus.

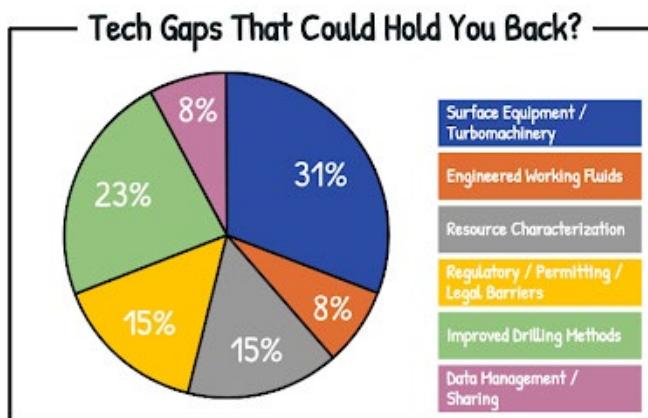


Figure 9.8. Responses from interview participants identifying technology gaps that, if not addressed, could hold their entities back. Source: *Future of Geothermal Energy in Texas, 2023*.

The largest majority of entities at 31 percent reported that surface equipment/turbomachinery is a technology gap that could have impactful and potentially negative outcomes on their own efforts if not addressed by others. This data is consistent with the perspectives emerging from oil and gas entities polled in Chapter 6, who also reported that lack of innovation in surface equipment

is a technical challenge that stands as an impediment to the growth and advancement of geothermal. Faster drilling methods, regulatory barriers, and resource characterization rounded out the next three most popular responses, at 23 percent, 15 percent, and 15 percent, respectively. Advancement of Engineered Working Fluids and the need for data sharing and management across industry each garnered 8 percent.

#### B. What Challenges Keep You Up At Night?

Teams were asked what their biggest pain points were in terms of traction, funding, or other perceived risks. Entities' responses were telling, and echo some of the themes explored in earlier parts of this Chapter, particularly with regard to funding. Many of these pain points involve issues that the teams themselves cannot solve or personally influence, but that will have an outsized impact on their ability to succeed. Responses included:

- **"Green" investors tend to avoid oil and gas technologies and teams.** One team noted that they lost a potential investment due to the fact that their technology could theoretically be applied in the oil and gas context, despite the fact that the team had no intention of pursuing that application or market.
- **Venture capital is largely unfamiliar with geothermal.** Teams reported spending most of their pitch time with VCs explaining basic attributes of geothermal, or dispelling disinformation or misunderstandings within venture capital teams about geothermal before getting to their specific technology or pitch. "We are spending our valuable time educating venture capitalists about the opportunity generally, and then they don't invest" noted one entity. Another team remarked, "we stopped talking to VCs a long time ago."
- **There is bias in the funding ecosystem, and the teams feel it.** One entity recalled a venture capital team cutting a meeting with their team short after addressing their concept, which involved a partnership with an oil and gas entity, in a condescending manner. The founder remarked that "anti-oil and gas bias is rampant, and it's demoralizing."
- **Funding for pilot projects is needed now.** One team noted that investors want data to gauge the potential success of the pilot, but that pilots are the avenue to collect such data, stating "we can't learn until we get



into the field." Another noted "We just need to deploy. It will cause an avalanche of funding if we get the first project in the ground. That's the unconventionals playbook."

- New financing mechanisms are needed for first of a kind deployments.** All teams interviewed expressed this as a concern on some level. Some described the need for oil and gas project finance to engage, since they more fully understand the risks associated with subsurface projects. Another team noted, "we aren't sexy enough for VCs - they want moonshots - we want to build power plants."
- The "F" word is off limits.** At least two teams pursuing Engineered Geothermal or Hybrid Geothermal Systems remarked that discussions about frac'ing with venture capital teams can be tensioned, or fraught with misunderstanding. One team noted, "You can't talk about frac'ing with climate impact funds, no matter how big or positive the impact, or how different the technology is in the geothermal context. They don't want to have anything to do with it."<sup>1</sup>

### C. What Do You Need From Oil and Gas?

When teams were asked what they most need from the oil and gas industry to help them succeed, responses fell into three broad categories. The first is support for pilot projects and first of a kind deployments, noting that many oil and gas entities expect to see the outcome of pilot projects before they will invest. But as we saw reflected in the comments above, funding for first of a kind pilot projects is a significant barrier for startups. To borrow venture capital vernacular, we have here a valley of death. "There is a chicken and egg problem with oil and gas," one team noted. "They want to see field data, but don't want to fund us to deploy so we can get them the field data."

The second category of need lies in the scale, global footprint, and experience in large-scale project execution and management of oil and gas. At least two entities described oil and gas as the key to their concepts achieving fast global scale after a pilot proves successful, with one entity remarking "we are running the sprint now, but once our concept is proven in the field, it would make sense for us to get acquired [by an oil and gas entity] at that juncture."

<sup>1</sup>An excellent piece of scholarship recently published that considers perception spillovers and their impact on next generation energy technology acceptance. This is likely a dynamic at play in the challenges startups are facing with funding entities in the cleantech and climate space (Westlake, et al., 2023).

The third category of need is access to the vast amounts of subsurface data within oil and gas entities for the purpose of pre-project risk assessment and subsurface characterization. Several entities expressed the view that if the oil and gas industry utilized their data for the purpose of geothermal exploration, the outcome would be a product far superior to anything in existence today. "They have a lot of very high quality data that could be really helpful to us if we had it," noted one entity. Another entity noted that they developed a partnership with an oil and gas entity specifically for this purpose.

### D. How Would You Utilize \$100 Million in Funding?

When the startups were asked how they would utilize \$100 million in funding if they had it, the results were largely consistent with the data emerging from prior interview questions, with 69 percent of entities describing some variation of field deployment.

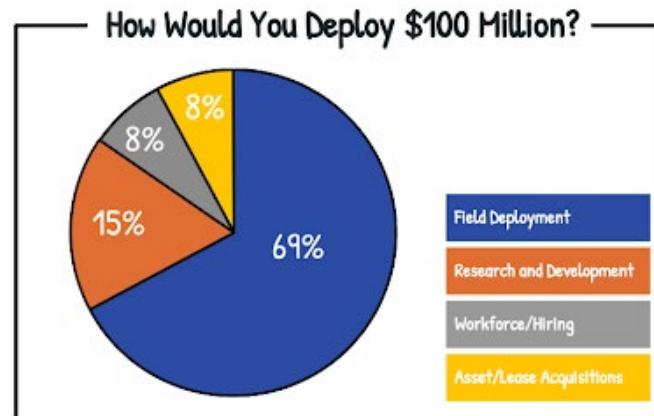


Figure 9.9. Responses from interview participants identifying how they would deploy \$100 million dollars in funding. Source: *Future of Geothermal Energy in Texas, 2023*.

At least two entities expressed the desire to deploy pilots with significant investment in instrumentation on the pilot well, to learn from and analyze the resulting data, and to re-deploy further iterations based on that data. "We need to data mine our test wells, but the cost of that level of data acquisition is likely beyond what most startups can raise for their pilots," noted one entity. "The data, if we could afford to pull out all the stops to capture it, would be invaluable," noted another.



Another entity remarked that \$100 million would afford them the opportunity to deploy multiple iterations of the same design, which would result in an optimized system after multiple wells. This comment is consistent with the responses amongst oil and gas entities who were asked this same question in [Chapter 6, Oil and Gas Industry Engagement in Geothermal: The Data](#) of this Report. Another entity interested in deployment stated that they would try their hand at a coal plant to geothermal conversion with the funds, also consistent with oil and gas entity data from Chapter 6.

Entities who expressed interest in investing in research and development noted that \$100 million may be enough to solve entire and difficult problem sets in geothermal, which may require materials science advances. Two examples given by entities for research and development investments were next generation drilling technologies, and high temperature electronics. High temperature electronics, noted one entity, could enable an entirely new set of capabilities and technology transfer from oil and gas into geothermal, including rotary steerable, and powerful telemetry equipment.

The entities who expressed interest in workforce development and hiring worried that skilled workforce availability was likely to become an impediment to their growth and expansion in the coming years. They remarked that workforce training and certification programs would be very helpful in priming the pipeline of workers ready to pursue careers in geothermal. Finally, the entities expressing an interest in asset acquisition focused on lease acquisition, noting that a significant portion of the projected future value of their entity would likely be related to their portfolio of leaseholds, and where those leases stand in the very long and burdensome federal geothermal permitting timeline. "When oil and gas finally is ready to pull the trigger on projects, we will have a portfolio of leases nearing the end of their permitting process and ready to be launched," one entity noted.

## VII. Conclusion

This Chapter is a long and varied journey through Texas' history of wildcatting, energy innovation, and modern day entrepreneurship, which are all characteristics that have provided fertile ground for the emergent and thriving geothermal startup ecosystem. The next challenge for

Texas, now that an organically growing and self-sustaining geothermal startup system—the fastest growing in the world—now calls the State home, is to find pathways to support the ecosystem by removing barriers to growth.

A few themes emerge from this Chapter. The first is the failure of traditional funding mechanisms such as venture capital and private equity to support and sustain the funding needs of the geothermal startup community. As we explored, a unique mixture of subsurface and technology risk, as well as unfamiliarity with the resource generally has largely constrained the needed flow of capital into the ecosystem. In addition to these factors, bias and a difference in cultures between silicon valley based funding entities and largely oil and gas industry veteran teams from Texas may play a more significant role in forming these impediments than we as an ecosystem are willing to admit. Silicon Valley seeks to fund the 'moonshots' of 'visionaries,' and oil and gas teams who show up to pitches in buttoned up suits to talk low and slow about conservative approaches, incremental steps, and IRR doesn't translate. I've been present in several of these pitches, and the dynamics are to be frank, cringe.

The reality is, we don't need shiny big talkers and slick pitch decks to build geothermal plants. We need teams who have the professional and operational experience to go out and successfully drill and develop projects. In geothermal, we need to build a new definition of what a successful entrepreneur, and what a backable team looks like, because it is highly likely given the skill sets needed that it will not follow the Silicon Valley playbook. There are a few geothermal startups out there who have been successful at merging these two cultures within their executive teams - marrying veteran oil and gas expertise with edgy pitch decks and VC savvy executives. Those teams may have a strategic advantage moving forward, particularly in fundraising efforts. Ideally, oil and gas private equity, or high net worth individuals who amassed their fortunes in oil and gas will be willing to step in over the coming years to support these oil and gas teams who are struggling to make it through a difficult to address funding valley of death.

Incremental steps may sound underwhelming in pitch decks, but that is what we need to prove scalable geothermal concepts in the field. We don't need to fund the sexiest sounding concepts. We need to fund concepts that seem the most obvious, and even boring,



and iterate on incremental successes. It's a different approach than venture capital is accustomed to, but it is one entirely familiar to the oil and gas industry. Our ability as a community to raise the profile of geothermal over the coming years within the oil and gas industry sufficiently to result in significant investment commitments may be determinative of whether geothermal becomes a substantial player in our global energy future, or fails to launch due to insufficient flow of capital.

Over the past few years, the Texas geothermal startup ecosystem has grown from nonexistence to the largest and fastest growing geothermal ecosystem in the world. The steps that Texas takes in the coming years, including its resident oil and gas industry, could grow and support this burgeoning ecosystem into a major player in the State's future economy, and the world's energy mix. Let's not miss this opportunity for the State of Texas, and the world.



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## Conflict of Interest Disclosure

**Jamie Beard** serves as Executive Director of Project InnerSpace, a 501(c)(3) organization that works on issues within the subject matter of this manuscript, and is compensated for this work. She further serves in a non-compensated role as a founding member of the board of the Texas Geothermal Industry Alliance. Outside of these roles, Jamie Beard certifies that she has no affiliations, including but not limited to 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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## Chapter 9 Appendix A

The authors of the Future of Geothermal Energy in Texas report are grateful for the participation and insight provided by the following individuals. Thank you for taking the time to share your knowledge and experiences about the geothermal startup ecosystem in Texas and from around the globe. Data collected from all participants has been aggregated and anonymized to capture and disseminate trends, views, and perspectives.

### **INTERVIEW PARTICIPANTS (listed in alphabetical order)**

- Carlos Araque, Chief Executive Officer, Quaise Energy
- Spencer Bohlander, Chief Executive Officer, Icarus Energy
- John Clegg and Team, Chief Technology Officer, Hephae Energy Technologies
- Karl Farrow and Team, Chief Executive Officer, CeraPhi Energy
- Cameron Grant and Team, Chief Commercial Officer, STRYDE
- Kathy Hannun, President, Dandelion Energy
- Sarah Jewett, Director of Strategy, Fervo Energy
- Kirsten Marcia, Chief Executive Officer, DEEP Earth Energy
- Niall McCorack and Team, Chief Executive Officer, CausewayGT
- Johanna Ostrum, Chief Operating Officer, Transitional Energy
- Danny Rehg and Team, Chief Executive Officer, Criterion Energy Partners
- Joseph Scherer and Team, Chief Executive Officer, Greenfire Energy
- Cindy Taff and Team, Chief Executive Officer, Sage Geosystems



## Chapter 9 Appendix B – Geothermal Startups

Table 9.1. The past few years have seen a dramatic increase in the number of geothermal startups launched. Members of the geothermal startup ecosystem are in various stages of fundraising, research, demonstration, and deployment. Source: *Future of Geothermal Energy in Texas, 2023*.

Company Name	Category	Country	HQ State/Province	Project Location(s)	Year Founded	Type of Geothermal/Technology/Service	Development Stage	Funds Raised (USD)	Funding Type	Funding Stage	Website
Altarock	Developer/Operator	United States	Washington	Oregon	2007	Superhot Rock	Demonstration/Pilot	\$36,500,000	Traditional VC	Series C	<a href="http://altarockenergy.com">altarockenergy.com</a>
Baseload Capital	Developer/Operator	Sweden	Stockholm	Utah, Colorado, Nevada & California	2019	Hydrothermal	Early Deployment	N/A	PE/Corporate	Series B	<a href="http://baseloadcap.com">baseloadcap.com</a>
Bedrock Energy	Tools/Equipment Provider	United States	California	Texas, Alberta	2022	Direct Use	Demonstration/Pilot	\$6,000,000	Climate Impact VC/Traditional VC	Seed	<a href="http://bedrockenergy.com">bedrockenergy.com</a>
Canopus Drilling Solutions	Tools/Equipment Provider	Netherlands	Holland	Europe	2018	Drilling	Research	\$3,100,000	Climate Impact VC	Seed	<a href="http://canopustraillingsolutions.com">canopustraillingsolutions.com</a>
CausewayGT	Developer/Operator	Ireland	Ireland	Texas, Ireland, Northern Ireland	2020	Direct Use	Early Deployment	Fundraising	Climate Impact VC/Corporate	Seed	<a href="http://causewaygt.com">causewaygt.com</a>
Celsius Energy	Developer/Operator	France	Hauts-de-Seine	France, Massachusetts	2018	Direct Use	Demonstration/Pilot	N/A	Corporate	Series A	<a href="http://celsiusenergy.com">celsiusenergy.com</a>
CeraPhi Energy	Developer/Operator	United Kingdom	England	United Kingdom	2020	Well Reuse	Demonstration/Pilot	\$3,000,000	Privately Funded	Seed	<a href="http://ceraphi.com">ceraphi.com</a>
Controlled Thermal Resources	Developer/Operator	Australia	Queensland	California	2013	Hydrothermal/Lithium	Demonstration/Pilot	\$37,000,000	PE/Corporate	Series B	<a href="http://cthermal.com">cthermal.com</a>
Criterion Energy Partners	Developer/Operator	United States	Texas	Texas, Utah, Nevada	2021	Blind/Sedimentary Geothermal	Demonstration/Pilot	Fundraising	Government/Corporate	Series A	<a href="http://criterionep.com">criterionep.com</a>
Crust Harvest	Developer/Operator	Norway	Stavanger	Norway	2022	Hydrothermal	Research	N/A	Privately Funded	Seed	<a href="http://crusharvest.com">crusharvest.com</a>
Dandelion Energy	Service Provider	United States	New York	Northeast United States	2017	Direct Use	Deployment	\$134,500,000	Traditional VC	Series B	<a href="http://dandelionenergy.com">dandelionenergy.com</a>
DEEP Corp	Developer/Operator	Canada	Saskatchewan	Saskatchewan	2010	Blind/Sedimentary Geothermal	Demonstration/Pilot	\$53,500,000	PE/Government	Series B	<a href="http://deepcorp.ca">deepcorp.ca</a>
DeepPower	Tools/Equipment Provider	United States	Utah	Utah	2022	Drilling	Research	N/A	Traditional VC	Series A	<a href="http://deeppower.com">deeppower.com</a>
Earthbridge Energy	Developer/Operator	United States	Texas	N/A	2021	Storage/Sedimentary Geothermal	Research	Fundraising	Climate Impact VC/Corporate	Seed	<a href="http://earthbridgeenergy.com">earthbridgeenergy.com</a>
Eavor	Developer/Operator	Canada	Alberta	Global	2017	Closed Loop	Early Deployment	\$100,000,000	Climate Impact VC/Corporate	Series B	<a href="http://eavor.com">eavor.com</a>
Eden GeoPower	Service Provider	United States	Massachusetts	N/A	2020	EGS	Research	\$3,796,672	Government	Series C	<a href="http://edengeopower.com">edengeopower.com</a>
Eden Geothermal Ltd	Developer/Operator	United Kingdom	England	United Kingdom	2019	Direct Use	Demonstration/Pilot	\$22,200,000	PE/Government	Series A	<a href="http://edengeothermal.com">edengeothermal.com</a>
EnhancedGEO	Developer/Operator	United States	Florida	N/A	2022	EGS	Fundraising	N/A	Privately Funded	Seed	<a href="http://enhancedgeo.com">enhancedgeo.com</a>
Fervo Energy	Developer/Operator	United States	Texas	Nevada, Utah	2017	EGS	Deployment	\$184,915,000	Climate Impact VC	Series C	<a href="http://fervoenergy.com">fervoenergy.com</a>
GA Drilling	Tools/Equipment Provider	Slovakia	Slovakia	Global	2013	Drilling	Demonstration/Pilot	\$36,900,000	Traditional VC	Series A	<a href="http://gadrilling.com">gadrilling.com</a>
Geothermal Engineering (GEL)	Developer/Operator	United Kingdom	England	United Kingdom	2008	EGS	Early Deployment	\$19,000,000	PE/Government	Series A	<a href="http://geothermalengineering.co.uk">geothermalengineering.co.uk</a>
GeoGen Technologies	Developer/Operator	Canada	Alberta	N/A	2021	Well Reuse	Research	N/A	Privately Funded	Seed	<a href="http://geogen.com">geogen.com</a>
Geothermal Technologies	Developer/Operator	United States	Maryland	Colorado	2018	EGS	Demonstration/Pilot	\$25,000,000	Traditional VC	Series A	<a href="http://geothermal.tech">geothermal.tech</a>
Geothermal Wells(GTW)	Developer/Operator	United States	Texas	N/A	2022	Well Reuse	Research	Fundraising	Privately Funded	Seed	<a href="http://geothermalwellsllc.com">geothermalwellsllc.com</a>
Geothermic Solutions	Tools/Equipment Provider	United States	California	USA	2014	Superhot Rock/Closed Loop	Demonstration/Pilot	\$22,500,000	Traditional VC	Series A	<a href="http://geothermicsolution.com">geothermicsolution.com</a>
GeoX Energy	Developer/Operator	United States	California	Global	2019	Superhot Rock	Demonstration/Pilot	\$11,000,000	Corporate	Seed	<a href="http://geoxenergy.com">geoxenergy.com</a>
Greenfire Energy	Developer/Operator	United States	California	California	2014	Closed Loop	Demonstration/Pilot	\$22,700,000	Government/Corporate	Series A	<a href="http://greenfireenergy.com">greenfireenergy.com</a>



Table 9.1. (Continued)

Company Name	Category	Country	HQ State/ Province	Project Location(s)	Year Founded	Type of Geothermal/ Technology/ Service	Development Stage	Funds Raised (USD)	Funding Type	Funding Stage	Website
Hephae Energy Technology	Tools/Equipment Provider	United States	Texas	N/A	2021	Drilling	Research	\$3,100,000	Climate Impact VC/Corporate	Seed	<a href="http://hephaet.com">hephaet.com</a>
HyperSciences	Tools/Equipment Provider	United States	Washington	N/A	2014	Drilling	Early Deployment	\$15,000,000	Corporate/ Crowdfunded	Series B	<a href="http://hypersciences.com">hypersciences.com</a>
Icarus Energy	Developer/ Operator	United States	Texas	Texas, California, Australia	2021	Closed Loop	Demonstration/ Pilot	Fundraising	Privately Funded	Seed	<a href="http://icarus.how">icarus.how</a>
ICE Thermal Harvesting	Developer/ Operator	United States	Texas	California	2021	Well Reuse	Demonstration/ Pilot	\$1,700,000	Government	Govt Funded	<a href="http://ice-th.com">ice-th.com</a>
Lilac Solutions	Developer/ Operator	United States	California	California	2018	Hydrothermal	Early Deployment	\$150,000,000	Climate Impact VC/Corporate	Series B	<a href="http://lilacsolutions.com">lilacsolutions.com</a>
OGL Geothermal	Developer/ Operator	United Kingdom	England	N/A	2021	Blind/ Sedimentary Geothermal	Demonstration/ Pilot	Fundraising	Climate Impact VC	Seed	<a href="http://ogl-geothermal.com">ogl-geothermal.com</a>
Particle Drilling	Tools/Equipment Provider	United States	Texas	N/A	2003	Drilling	Early Deployment	\$80,000,000	PE/Corporate	Series B	<a href="http://particledrilling.com">particledrilling.com</a>
Qheat	Developer/ Operator	Finland	Finland	Finland	2018	Direct Use	Early Deployment	\$5,800,000	Traditional VC/ Government	Series A	<a href="http://qheat.fi">qheat.fi</a>
Quaise	Developer/ Operator	United States	Massachusetts	N/A	2018	Drilling	Demonstration/ Pilot	\$75,000,000	Climate Impact VC/Corporate	Series A	<a href="http://www.quaise.energy">www.quaise.energy</a>
Sage Geosystems	Developer/ Operator	United States	Texas	Texas	2020	Blind/ Sedimentary Geothermal/ Storage	Early Deployment	\$25,000,000	Climate Impact VC/Corporate	Series A	<a href="http://sagegeosystems.com">sagegeosystems.com</a>
Strada Global	Tools/Equipment Provider	United Kingdom	England	N/A	2019	Drilling	Research	\$2,500,000	Traditional VC	Seed	<a href="http://stradaglobal.com">stradaglobal.com</a>
STRYDE	Tools/Equipment Provider	United States	Texas	Global	2019	Geothermal Services	Deployment	N/A	Corporate	Series A	<a href="http://strydefurther.com">strydefurther.com</a>
TERRACOH	Developer/ operator	United States	Minnesota	N/A	2016	Hydrothermal/ CCUS	Demonstration/ Pilot	\$2,500,000	PE/Government	Series B	<a href="http://terracob-age.com">terracob-age.com</a>
Transitional Energy	Developer/ Operator	United States	Colorado	Nevada	2020	Well Reuse	Early Deployment	\$4,329,000	Government	Series A	<a href="http://transitionalenergy.us">transitionalenergy.us</a>
Upflow	Service Provider	New Zealand	New Zealand	New Zealand	2017	Geothermal Services	Deployment	N/A	Government/ Corporate	Series A	<a href="http://upflow.nz">upflow.nz</a>
Viridly	Developer/ Operator	United States	Texas	N/A	2022	Direct Use	Research	Fundraising	Privately Funded	Seed	<a href="http://www.viridly.com">www.viridly.com</a>
Zanskar Geothermal and Minerals	Service Provider	United States	Utah	N/A	2018	Geothermal Services	Research	\$15,000,000	Climate Impact VC	Series A	<a href="http://zanskar.com">zanskar.com</a>
<b>Total</b>		<b>\$1,101,540,672</b>									



## PART III

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# **Environmental, Policy, Economic, & Legal Considerations for Geothermal in Texas**



## Chapter 10

# Environmental Considerations and Impact

M. H. Young, K. Wisian

**When compared with other sources of energy, including other renewables, nuclear, and fossil fuels, geothermal energy has the lowest carbon emissions rate, smallest surface footprint, and low potential for water contamination.**

## I. Introduction

All energy technologies, from traditional fossil based sources to renewables like solar and wind, have some environmental impact. When we seek to understand and quantify those impacts across the various sources, ultimately we should consider more than the energy production operation itself. Impact should be measured beginning at the supply chains used to manufacture and support the technologies, and also include end of life outcomes related to each, like recyclability, disposal, and waste. It is important as we navigate our energy

transition over the coming decades that we proceed with thoughtful, fact based analysis of the impacts and externalities of each energy technology we seek to adopt, deploy, and scale. Without considering the full life-cycle environmental impact of emerging energy technologies, including renewables, the risk of unintended environmental consequences will grow substantially, potentially offsetting the gains we seek as we build our future.



## II. Past Research on the Environmental Impact of Geothermal

In 2006, an influential report was commissioned by a panel of experts, and published by the Massachusetts Technology Institute ("MIT") to assess the future of geothermal energy, focusing on Engineered (or Enhanced) Geothermal Systems ("EGS") in the U.S (Tester, et al., 2006). The report, entitled *The Future of Geothermal Energy*, was a ground-breaking, seminal, and visionary work that remains today the most encompassing and high impact report conducted about geothermal in the world.

*The Future of Geothermal Energy* included a chapter on the environmental impacts of geothermal. The authors discussed several environmental aspects (both positive and negative), including water, air, and thermal pollution, water use, and induced seismicity. They referenced a number of works that significantly influenced the conceptual thinking of geothermal. In their analysis, a consensus of scientists found that geothermal has a lower environmental impact than all other fossil energy sources, and possibly lower than other renewables (Tester, et al., 2006). Since then, several papers have considered the broader environmental impacts of conventional geothermal technologies, focusing in particular on Conventional Hydrothermal Systems and thermal networks (Sayed, et al., 2021; Bošnjaković, et al., 2019; Bayer, et al., 2013). Bayer, et al. (2013) found that comprehensive datasets on the environmental impacts of these conventional geothermal technologies are lacking, and that full life-cycle assessments are generally restricted to the western United States (e.g., the Geysers site). Bošnjaković, et al. (2019) considered a broad range of possible environmental impacts, given the potential for geothermal to be developed and deployed in Croatia. They compared geothermal with traditional fossil fuel powered generation (coal, oil, and gas), and showed that carbon dioxide ("CO<sub>2</sub>") and nitrogen oxide ("NO<sub>x</sub>") emissions, as well as surface footprint, were considerably lower for geothermal, though the release of waste heat was much higher in the case of conventional geothermal plants.

In a recent study, Sayed, et al. (2021) compared a number of renewable technologies with geothermal, and reported that the most significant environmental impacts implicated by geothermal included the potential for land subsidence, induced seismicity, higher water use, and surface footprint, a few of which are prevalent in other energy systems.

Although all energy sources are accompanied by some environmental impacts, the consensus produced by *The Future of Geothermal Energy* report provides an important foundation to this analysis. Geothermal development and deployment results in lower environmental impact than other energy sources, especially fossil and nuclear energy, partly because the fuel cycle (i.e., subsurface heat) lies immediately below the generating plant, therefore physical mining is not required, and the fuel requires no processing, as is the case for gas and nuclear fuel sources. Importantly also, *The Future of Geothermal Energy* predicated the significant technology developments that are now enabling the next generation of geothermal technologies, like Advanced Geothermal Systems/Closed Loop Geothermal Systems ("AGS"), which hold promise for even less environmental impact.

## III. Subsurface Exploration and Resource Development

The exploration and drilling phases of geothermal development carry environmental concerns distinct from the operational phases. Potential exploration and development impacts for geothermal projects may implicate water (e.g., quantity, groundwater contamination, disposal, and remediation), induced seismicity, and land subsidence caused mainly by fluid withdrawal. We will examine these in turn.

### A. Water and Fluid Management

Techniques and approaches used for drilling wells for geothermal are nearly identical to those of any mud-rotary drilled oil and gas well, with some variations depending on the particular geothermal concept. Well drilling requires water and (commonly) some type of bentonite-rich additive that increases viscosity enough to return drill cuttings to the surface.

As is also the case in the oil and gas context, drilling processes require a number of necessary environmental considerations that range from identifying a water source with sufficient volumes, managing fluids with potentially dissolved contaminants or cuttings, and ensuring that local groundwater resources are not impacted by the drilling and completion processes.



Before diving into water implications of drilling processes, it may be useful to put the broader operational context of water use for geothermal into perspective. Figures 10.1 and 10.2 below place the scale of water consumption impacts associated with geothermal operations, as compared with other energy sources, into perspective.

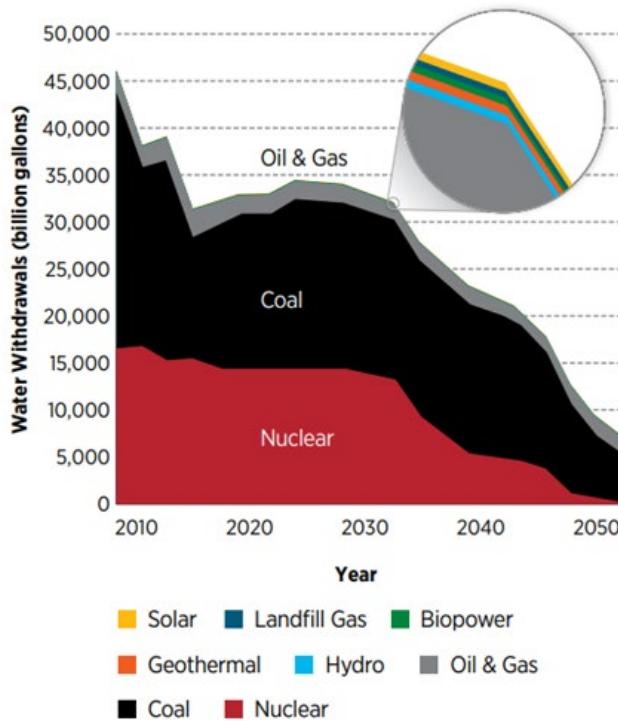


Figure 10.1. Power-sector water-withdrawal impacts in billions of gallons (1 gallon=3.8 liters).

Source: Adapted from Millstein, et al. (2019).

## B. Water for Well Drilling and Hydraulic Stimulation

According to the U.S. Energy Information Agency, nearly 1,000,000 oil and gas production wells are in operation today, and many more have been drilled over the last 100 years, each of these wells required water for drilling (EIA, 2021). Depending on the region of the country (more humid East Coast versus drier Southwest), water may be more or less plentiful and/or readily available. A more recent history of horizontal drilling indicates that the volume of water used for drilling and cementing oil and gas wells is about 380,000 gallons per well (Scanlon, et al., 2014). If the well were to require hydraulic stimulation, then the volume needed could increase tenfold. These numbers have increased with time because subsurface engineering in the form of horizontal laterals have

increased in length, and now approach 10,000 feet (1.9 miles or three kilometers) or longer.

Wells drilled for geothermal energy production would need to identify and source similar volumes of water, especially for EGS, which also can use a form of hydraulic fracturing (DOE, 2012). For new types of geothermal technologies, such as AGS, the volume of water required for the drilling and cementing of wells should be similar to that of recent experiences with horizontally drilled wells without stimulation. In nearly all cases, wells drilled to substantial depths require fluids augmented with bentonite or other additives that increase viscosity to entrain cuttings, cool the drilling bit and pipe, and maintain borehole stability.

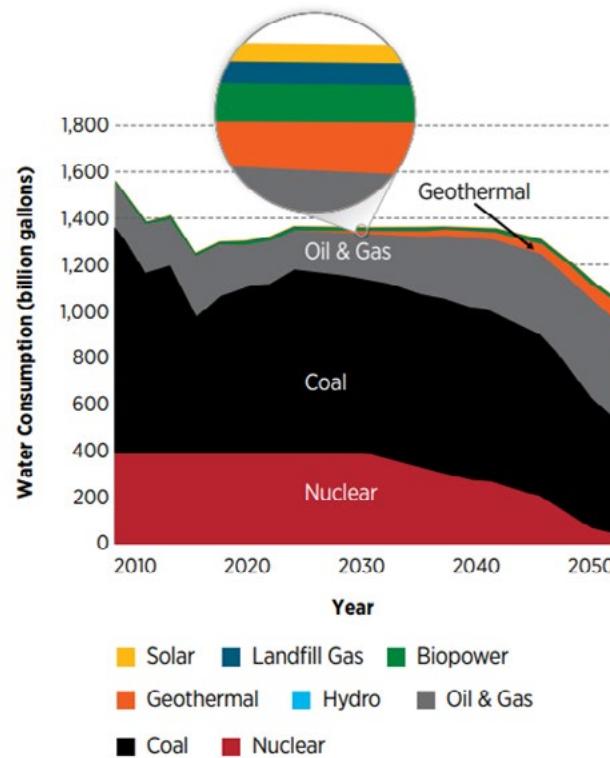


Figure 10.2. Water-consumption impacts from the geothermal power section in billions of gallons (1 gallon=3.8 liters) under the Technology Improvement scenario. Source: Adapted from Millstein, et al. (2019).

Depending on bottom-hole temperature, fluids and cuttings that return to the surface from a hot reservoir need to be cooled before being recirculated downhole. In some cases, long-term exposure to elevated temperatures greater than 150°C (302°F) could increase



the viscosity of bentonite, potentially clogging pipes, and leading to degraded circulation. Use of high temperature resistant polymers could reduce this potential. An excellent source of information on the drilling of hot geothermal wells is found in Pálsson, et al. (2014) and Friðleifsson, et al. (2014), along with other articles in that special issue of Geothermics. Figures 10.1. and 10.2 detail water withdrawal and water consumption impacts, separated by power sector. Regardless of the technology, the potential for local impacts requires careful analyses using location specific data and information.

Since around 2005, a combination of directional drilling and hydraulic fracturing (also known as frac'ing) has become a game changer in oil and gas exploration and development. Not surprisingly, the practice has undergone significant innovation and improvement in the nearly 20 years since widespread use began, including a new understanding of the chemical additives used in the process. In general, frac fluids are dominated by water and proppants (particles used to wedge open fractures), often sand, but sometimes mixed with chemicals to inhibit corrosion and scaling, reduce friction along the inside of the drilling pipe, and reduce biological buildup. The FracFocus (2021) Chemical Disclosure Registry, which is managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission, has become a necessary tool for governments, industry, and the general public in obtaining information on fracturing fluid chemistry. Although not all chemical concentrations are disclosed due to intellectual property concerns, the Registry is a significant step forward in transparency.

### C. Potential Pathways of Water Contamination

Similar to any well drilling, especially for oil and gas exploration, some wastewater and waste material are generated, ranging from drilling cuttings, to drilling mud, to associated wastewater, when geothermal projects are developed. Moreover, the methods of management and safe disposal are also similar. Many lessons have been learned and best practices established that minimize the potential for inadvertent release, and that improve our understanding of the pathways leading to contamination of land, surface water, or groundwater.

As indicated earlier, typical drilling waste can contain, aside from rock cuttings, bentonite, polymers (e.g., polyacrylamide), and salts. Depending on the

concentration of these chemicals and constituents leached from the host rock, post-processing of the water could remove dissolved constituents for alternative industrial uses. If not, and specific regulations in the state, province, or country allow, land application of these waste products may be allowable with appropriate permits.

Recently, the Environmental Protection Agency ("EPA") released a comprehensive report that described water cycle impacts from hydraulic fracturing operations in the United States (EPA, 2016) in the oil and gas context. The EPA concluded that hydraulic fracturing operations can impact water resources (both groundwater and surface water) under some circumstances, with severity depending on a number of considerations. Primary pathways include surface spills of fluids, poor well casing or cement integrity, and improper design leading to injection of fluids into groundwater resources. In general, a lack of relevant pre and post frac'ing groundwater monitoring has hindered our ability to quantify the extent and severity of groundwater contamination resulting from unconventional oil and gas operations.

Findings from the fossil fuel industry are relevant to geothermal development because the technologies for well drilling and frac'ing are similar to those of oil and gas operations. However, utility scale geothermal operations (as opposed to smaller scale and localized technologies, like heat pumps) have a relatively shorter history with fewer examples, and for some technologies, no existing case studies. For example, the proppant material used during stimulation activities requires substantial excavation and, in some cases, water resources to mine and process the sand. One recent analysis found that a total of 10,000 to 40,000 acre feet per year of water was being consumed for proppant mining in west Texas, or between 60 and 250 gallons of water per ton of sand (Mace & Jones, 2021). Depending on the climate of the region and the number of wells to be stimulated, the volume of water could be significant.

Authors note that the hydraulic fracturing envisioned in many Next Generation EGS concepts are of a different nature and magnitude than oil and gas, but as these methods are generally in the prototype stage, there is little data to allow a thorough analysis. As data emerges from pilot projects, further study will be needed.



## D. Risk, Monitoring, and Mitigation of Induced Seismicity

Induced seismicity from fluid injection into the subsurface has become a topic of significant public concern and research since around 2010, after a significant uptick in seismicity in the southern midcontinent of the United States. Research has shown that oilfield operations for enhancing oil and gas production from shales and other tight rocks are responsible for a significant portion of the seismic activity. Media attention, public meetings with hundreds of attendees, and findings from initial research papers that yielded more questions than answers have led to responses by individual states, ranging from new regulations to deployments of state run seismic monitoring programs that could deliver near-real-time data on earthquake occurrences. For example, in Texas, the State seismicity-monitoring program ("TexNet") is run by the Bureau of Economic Geology at The University of Texas at Austin, in which a catalog of seismic activity (TexNet, 2021) is publicly available and used by industry, regulators, researchers, and others.

Several other states run seismic networks, as well as the U.S. Geological Survey. As described by Ellsworth (2013) and Rubenstein and Mahani (2015), earthquakes can be induced when fluids are injected into the subsurface, including water for hydraulic fracturing or wastewater disposal, or gasses (often CO<sub>2</sub>) for enhanced oil recovery (Gan & Frohlich, 2013). State agencies that regulate oil and gas exploration and production (e.g., the Texas Railroad Commission) typically lead regulatory responses that can include well shut-ins, reduction of injection volumes or rates, modifications of depth of injections, requirements for enhanced reporting of injection practices (rates, volumes, downhole pressures), and/or requirements for enhanced monitoring of seismicity through deployment of seismometer stations proximal to the injection well. In Texas, the main driver of induced seismicity has been found to be deep well injection of wastewater or hydraulic stimulation, depending on the basin in question (Savvaidis, et al., 2020; Hennings, et al., 2019; Scanlon, et al., 2019; Walter, et al., 2018). The potential for induced seismicity by basin in Texas is considered in further detail in *Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development* of this Report.

Although originally not thought to induce seismic events, hydraulic fracturing has more recently been identified as a causal factor, especially when hydrocarbons are

being sought in shales or other tight rocks. In hydraulic fracturing in the geothermal EGS context as it exists today, fluid is injected into rocks to open pre-existing fractures, thus enhancing rock permeability (DOE, 2012).

Recently, research was conducted on EGS and seismicity to explain where and when injection activities could lead to earthquakes. For example, Cladouhos et al. (2015) reported on a field demonstration project in which certain materials, thermally degradable zonal isolation materials ("TZIM"), could be used to isolate permeable zones so that hydraulic fracturing of low permeability zones would be more effective. In their field demonstration conducted in Oregon, workers recorded nearly 400 events, ranging in magnitude from M0 to M2.26, all below levels of seismicity perceived by humans. Research has also been conducted in Switzerland (Deichmann & Giardini, 2009), in which 11,500 cubic meters of fluid was injected into a 3.1 mile(five kilometer) deep borehole, resulting in 10,000+ recorded events in a period of about one week, the maximum event being recorded at M3.4. Although the well was opened to relieve pressure, events were recorded intermittently for two years.

Majer, et al. (2007) reported on knowledge and gaps(at that time) in geothermal induced seismicity, reviewing several case studies from sites in the United States and elsewhere (e.g., the Geysers site near San Francisco; Cooper Basin, Australia; Berlin, El Salvador; France). In general, and consistent with other studies, (Xie, et al., 2015; Grunthal, 2013), findings show that creating permeability in EGS reservoirs through hydraulic fracturing does lead to the onset of induced seismicity, although careful planning and knowledge of subsurface fault stress, proximity to basement rock, and pressure control during injection can control the magnitude of events to levels below what can be felt by humans.

To be sure, the general public has a heightened awareness of the potential for inducing earthquakes from energy development, particularly oil and gas, and has called upon regulators to adopt measures that will mitigate future events and reduce earthquake hazard and risk from injection. For example, the Alberta Energy Regulator (AER, 2015) adopted a regulatory approach, known as a traffic light protocol or some variation, which mandates a potential range of actions on the basis of recorded magnitudes of events that are proximal in time and space to injection activities. Other energy producing states have adopted similar actions. A similar approach



was proposed at the recent PIVOT2022 geothermal conference for application in geothermal contexts, followed by a panel of experts who discussed the topic in detail (PIVOT 2022; 2022). Robust data sharing and standardization of processes were discussed by the panel as an essential foundation of knowledge for managing seismicity risk in geothermal development. Other actions to mitigate events can range from enhanced seismic monitoring to ceasing operations, based on the magnitude of earthquakes detected. Kim, et al., (2018) adopted protocols suggested by the DOE for earthquakes induced by injection, while correcting for quarry blasts and noise from transportation.

When these protocols, or other controls, were instituted by regulatory agencies responsible for oil and gas permitting, earthquake occurrences decreased. In Oklahoma, for example, which experienced perhaps the largest ramp up of seismic activity from fluid injection, the Oklahoma Corporation Commission issued regional directives to reduce injection of fluids into formations (e.g., the Arbuckle Formation) near the crystalline basement, mandated plugback of hundreds of disposal wells, increased reporting of fluid disposal by operators, and created digital tools that provided significantly more and timely information on earthquakes and injection volumes and pressures (OCC, 2021a). As a result, earthquake rates and magnitudes have decreased significantly over the last five years (OCC, 2021b), partly from reduced injection (as a result of lower oil and gas prices) and partly from these controls, illustrating the value in proactive management of injection activities that can be applied to geothermal systems.

It is important to note that although Conventional Hydrothermal Systems do re-inject used water, these systems have injector and producing wells, and are ideally operated in equilibrium between the two. This is in contrast to wastewater injection in oil and gas, the origin of much of the induced seismicity experienced by industry, which does not involve producing any fluids in conjunction with injection. Further, induced seismicity concerns are associated primarily with Open to Reservoir geothermal concepts, such as Conventional Hydrothermal Systems ("CHS"), and EGS. Next generation geothermal concepts, particularly non-hydraulic fracture based systems such as AGS and some Hybrid Geothermal Systems, in which fluids are not injected into, or pumped from, subsurface reservoirs, should carry low induced

seismicity risk. This is particularly true as compared with oil and gas operations that require extensive hydraulic stimulation or significant disposal of oilfield wastewater through injection. This is an area that will require more study as next generation geothermal concepts, several in pilot phase currently, produce field data.

## E. Potential for Land Subsidence

In general, if fluid removal rates and volumes exceed reinjection rates and volumes, subsurface reservoirs could consolidate, leading to land subsidence observed at the surface. Land subsidence can be a significant concern. First, surface and/or near-surface infrastructure (e.g., buildings, foundations, pipelines, roads) could be damaged, depending on subsidence severity, including the geothermal infrastructure itself. Second, consolidation of reservoirs reduces available pore space, fracture apertures, and fracture pathways for fluid storage and movement, which could decrease the efficiency or operability of the geothermal system.

The potential for subsidence depends on the type of geothermal technology, whether a Conventional or Next Generation system. Large geothermal fields using traditional fluid management (i.e., injector-to-producer movement of fluids) need to manage pressures carefully to avoid positive void ratios that might lead to local (or larger) subsidence. For example, Allis (2000) reported on Wairakei field in New Zealand, where a maximum subsidence of 46 feet (14 meters) was measured. New Closed to Reservoir geothermal concepts, particularly AGS and some Hybrid Geothermal Concepts, in which water is not withdrawn from the reservoir itself, should not alter subsurface pressure regimes, thus avoiding subsidence.

## IV. Power Plant Operations

Potential environmental impacts related to geothermal plant operations and maintenance ("O&M") include water, air, solids (heavy metals and/or other contaminants), land use, traffic, and noise. We will consider each in turn.

### A. Water and Fluid Management

Produced fluid management during geothermal plant operations depends primarily on the type of plant under consideration. We will consider Conventional



Hydrothermal Systems ("CHS") and Engineered Geothermal Systems ("EGS"), which are both Open to Reservoir systems, and Advanced Geothermal Systems/Closed Loop Geothermal Systems ("AGS"), which are Closed to Reservoir systems.

### **1. Open to Reservoir Systems**

Open to Reservoir Systems, for the purposes of this Report, are those in which the working fluid comes in direct contact with subsurface reservoir, flowing from an injection well through the rock to a production well (Figure 10.3).

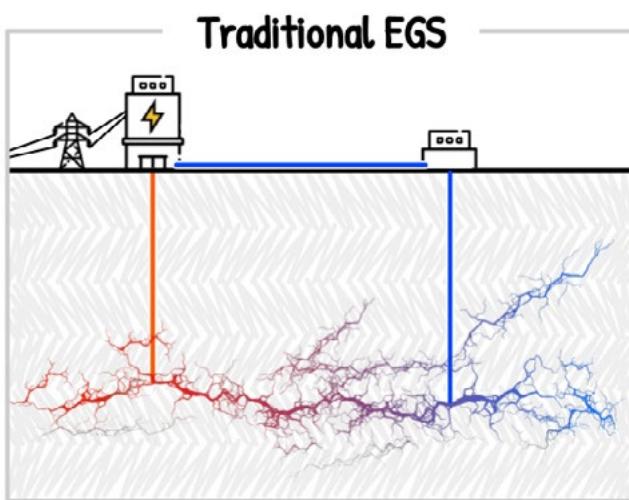


Figure 10.3. An open to reservoir geothermal system. Shown is a traditional EGS concept.

Source: *The Future of Geothermal in Texas*, 2023.

The fluid might be sent through heat exchangers of different types to convert the energy contained in the heated fluid into steam, which turns the turbine to generate electricity. After generating power, the fluid is then run through a cooling tower or facility, and then pumped back down into the subsurface to gather more heat.

As discussed in detail in [Chapter 1, Geothermal and Electricity Production](#) of this Report, Open to Reservoir Systems, like EGS and CHS, operate using a network of natural or engineered fractures, created via hydraulic fracturing, through which the working fluids flow. Because fluid flowing through these systems comes into direct contact with the rock in the subsurface, fluids can leach constituents from the rock and carry them in the fluid to the surface, after which they must be removed

for disposal (DiPippo, 2016), or potentially scavenged for critical materials (DOE, 2019). Potential loss of fluid continuity between injection and production wells can also occur, meaning that some fluid may be lost to the surrounding rock.

Although reports of soil and surface water contamination are uncommon near geothermal facilities, some studies have shown that poor water and materials management can lead to both (Balaban, et al., 2017). Others have described pathways to groundwater contamination from operating systems. In one case, Aksoy, et al., (2009) reported that hot geothermal fluids traveled through geologic faults and annular spaces in poorly constructed boreholes and contaminated potable surficial aquifers with heat, arsenic, antimony, and boron, rendering the water unusable for drinking or irrigation. Jiang, et al., (2018) also identified arsenic and other constituents in geothermal fluids in Tengchong, China, concluding that they most likely were the source of contamination of surface water and shallow groundwater. These cases highlight the importance of proper well construction and active management of geochemical reactions between fluids and well construction materials. Construction of monitoring wells to detect potential groundwater contamination near Open to Reservoir Systems is also prudent.

Engineered Geothermal and Next Generation Geothermal Systems interact with the subsurface far below the water tables and aquifers used for drinking water and in visible, natural hot springs. Subsurface engineering, in the form of horizontal laterals, has increased in length and now approaches 10,000 feet (1.9 miles or three kilometers) or longer in the oil and gas context. Conventional Hydrothermal Systems have rigorous water resource management protocols so the risk of water contamination and spring water depletion are unfounded or nonexistent.

### **2. Closed to Reservoir Systems**

AGS/Closed Loop Geothermal Systems ("AGS"), as discussed in depth in [Chapter 1, Geothermal and Electricity Production](#) of this Report, maintain separation (in some designs, to a greater or lesser degree) between the Working Fluid and the reservoir, and are therefore referred to as Closed to Reservoir. Fluids are introduced into the subsurface through vertical injection boreholes, flow through well pipes of assorted designs, and exit through production wells. AGS are most commonly used in



shallow Direct Use Geothermal Systems. System designs are codified by state environmental regulatory agencies. Working Fluids are nontoxic, or they contain low-toxicity additives to enhance volumetric heat capacity of the fluid (hence, efficiency of the system). Working Fluids, available in many locations and commonly glycol based, must be carefully chosen to avoid corrosion, scaling, and/or biological buildup in pipes and other system components, all of which reduce efficiency and operational life.

AGS are increasingly proposed as utility scale systems with capacities in the tens of megawatts per borehole. These systems are being proposed and/or demonstrated using several designs, from “pipe-in-pipe” configurations within a single borehole, to U-shaped loops that are connected by vertical boreholes several kilometers apart from one another. Designs such as proposed by geothermal startup Eavor (Eavor, 2021), uses a combination of horizontally drilled laterals connected to one to two (or more) sealed vertical wells to create a subsurface radiator pattern, in which colder (denser) fluids are introduced into the injection well that displace hotter (less dense) fluids from the production well, after which heat is harvested from the fluid and reinjected (Fallah, et al., 2021; Yuan, et al., 2021). This thermosiphon approach theoretically avoids the parasitic loads that occur in Conventional Geothermal Systems and some EGS concepts. Figure 10.4 shows the subsurface configuration of an AGS.

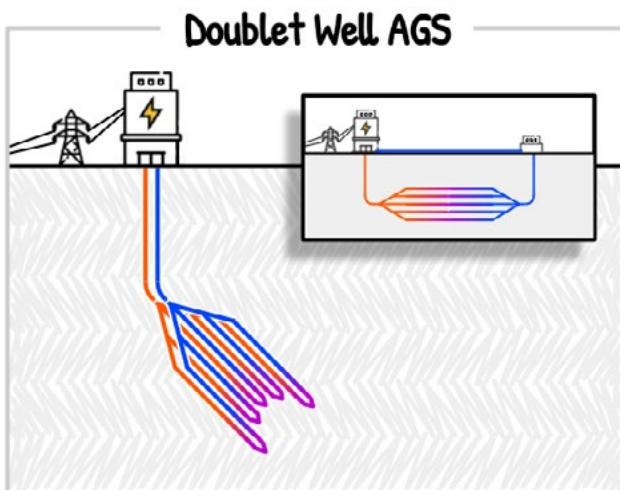


Figure 10.4. Example of a “Closed to Reservoir” AGS design. Source: Adapted from Eavor, 2021.

Whereas concepts like proposed in Figure 10.4 have a number of advantages, the system nevertheless relies on effective connection of drill pipes while in the borehole, requiring long term operations without deterioration of connecting points that might be sources of leakage of Working Fluid into the reservoir. Advances in completion and casing technologies and methodologies may be required to assure that systems such as these operate in a truly closed loop manner, without leakage into the surrounding reservoir. Monitoring studies would provide confidence in the operational integrity of this emerging technology. As discussed in [Chapter 1, Geothermal and Electricity Production](#) of this Report, engineered Working Fluids for use in AGS are being studied extensively, mostly through numerical models or plot scale demonstration projects (Fallah, et al., 2021; Amaya, et al., 2020; Hu, et al., 2020; Oldenburg, et al., 2016).

Some of the emerging “Geothermal Anywhere” concepts described in this Report, such as some Hybrid Geothermal Systems, combine open and closed to reservoir concepts, but a majority of these designs report to maintain separation between the Working Fluid and reservoir. Recently, for example, Fallah, et al. (2021) described a U-shaped design with an open-hole, horizontal borehole connecting two vertically cased boreholes. Their modeled design maintained positive pressure through the horizontal section, thus avoiding potential mixing of formation water with the Working Fluid. However, this team did not address the potential loss of Working Fluids into the formation, an aspect of the design that deserves more attention.

### **3. Potential for Using Produced Water**

Water that is co-produced with oil and gas is a potential source of Working Fluids for geothermal, depending on fluid chemistry, need, and access to alternative sources. Two ongoing challenges when using produced water for geothermal (or any other beneficial use) are (1) the spatiotemporal variability of produced water quality, especially for constituents at concentrations that could lead to corrosion, scaling, bioclogging, etc., and (2) the availability of sufficient quantities of water where and when it is needed.



Scanlon, et al., (2020a, 2020b) assessed and compared the quantity and quality of produced water across ten U.S. oil and gas, and five coalbed methane ("CBM") plays, considering different beneficial uses and requirements for quality (e.g., when irrigating crops for human consumption). They found median concentrations varying from 9,000 to 200,000 milligrams per liter total dissolved solids ("TDS") in the oil and gas plays, and from 1,000 to 10,000 milligrams per liter in the CBM plays. Depending on fluid chemistry needed for the geothermal technology in question, water with this level of TDS may or may not be suitable without primary or secondary treatment to remove salts, stabilize pH, etc. If treatment is needed, as Scanlon, et al., (2020a) pointed out, the volume of produced water available could drop by 50 percent, and the concentrate would still require handling and disposal. The decision about using produced water for a geothermal system thus needs to be based on availability of other suitable sources of water, and the economics of treating the water onsite, versus purchasing higher quality water elsewhere, as well as other operational factors.

## B. Other Considerations

### 1. Solid-Waste Generation and Fluid Management

Two methods of fluid management can be used to address dissolved constituents in return Working Fluid in geothermal systems. One is a flash crystallizer that permanently removes dissolved constituents for subsequent disposal, and the other is pH modification that keeps constituents in dissolved phases for reinjection (DiPippo, 2016). Depending on the concentration, mineral recovery in the returned geofluids could be economically favorable.

For example, the country's recent pivot toward renewable electricity generation using wind and solar, as well as the need for substantial electricity storage in batteries, has added urgency to finding sustainable sources of rare earth elements ("REE") and critical materials for manufacturing and technology development. Research that matches the presence of REEs and favorable sites for geothermal has been reported for some time (Fowler, et al., 2019; Williams-Jones, et al., 2012; Lottermoser, 1992), and we can expect those activities to continue, especially in geothermal technologies in which fluids contact host rock directly.

Although reinjection of used Working Fluids is the conventional geothermal industry standard (for environmental and reservoir management reasons), if for some reason Working Fluids were disposed of at the surface, the unused heat in the return flow would be a source of waste, and a potential source of thermal contamination. Surface disposal of geothermal wastewater containing heat and dissolved constituents could also lead to downward movement of contaminants (Kjaran, et al., 1989), which would require site-specific analyses to assess possible impacts.

## 2. Surface Emissions and Monitoring

With regard to any Open to Reservoir geothermal design, Bayer, et al., (2013) noted potential atmospheric emissions, especially from flash or dry steam plants, including waste heat through steam, and non-condensable gasses ("NCG") such as H<sub>2</sub>S, CO<sub>2</sub> and methane. The waste heat, for example, could be an issue for surrounding biota or residents, and release of NCGs could, of course, offset the value of replacing fossil fuel generating plants with geothermal.

Bayer, et al., (2013) cited Bloomfield, et al., (2003), who in turn cited Goddard and Goddard, (1990). The data provenance in these references, published by the Geothermal Research Council, are unknown, but they provide an early discussion on the potential release of NCGs and their risk to the emission benefits of geothermal power. For example, Dumanoglu, (2020) examined this topic using both passive and continuous monitoring, primarily for H<sub>2</sub>S, at a 50 megawatt power plant near Aydin and Manisa, Turkey. They found 14 day average concentrations between 51.4 and 52.5 micrograms per cubic meter to be below World Health Organization ("WHO") criteria of 100 micrograms per cubic meter, although over the short term, concentrations peaked above regulatory limits several times, with concentrations exceeding the odor threshold many times.

Peralta, et al., (2013) also monitored meteorological conditions around a (then) 720 megawatt power plant in Cerro Prieto, Mexico, one of the largest in the world, generating nearly five terawatt hours in 2003. Their systems, deployed across five monitoring locations in the field, collected significant micrometeorological and air quality data, with constituents that included gasses such as H<sub>2</sub>S, CO<sub>2</sub>, SO<sub>X</sub>, and NO<sub>X</sub>, (hydrogen sulfide, carbon



dioxide, sulfur, and nitrogen oxides). They found average measured H<sub>2</sub>S concentrations of between 1.5 and 45 micrograms per cubic meter, depending on location and time of day of sampling from variability of the boundary layer around the plant influencing downwind concentrations.

Parisi, et al., (2019) conducted a life-cycle assessment (a comprehensive environmental impact study) on 34 operational power plants in the area of Tuscany, Italy. Air quality data in their study were collected by the regional environmental regulatory agency. NCGs collected from the condenser unit were analyzed for NCGs (CO<sub>2</sub>, CH<sub>4</sub> (methane), NH<sub>3</sub> (ammonia), H<sub>2</sub>S), as well as gaseous mercury, and numerous other trace metals were also monitored. These data were then expressed in units of grams per megawatt hour of electricity generation for each constituent.

Considering concentrations alone (outside of typical life cycle assessment) and assuming a plant capacity of 50 megawatts (arbitrary) operating 24/7 for one year (438 gigawatt hours per year), H<sub>2</sub>S release could range from 404.7 to 709.6 megagrams per year, where one megagram is equal to 1,000 kilogram. Abatement infrastructure could substantially reduce these emissions, feed them back into the injection stream, and further mitigate the potential for release into the environment or into nearby communities.

To restate a key point, in Texas, particularly with the development of Closed to Reservoir geothermal systems as opposed to Conventional Hydrothermal Systems, which are the subject of the case studies above, the concerns outlined above may be substantially mitigated, or even eliminated with some next generation geothermal concepts. Closed to Reservoir systems, such as AGS and some Hybrid Geothermal Systems, separate formation fluids and Working Fluids. These systems are designed to just produce heat, without producing unwanted contaminants and gasses from the subsurface. Emissions during operations should therefore be kept to a minimum, or eliminated altogether.

## V. Comparing Surface Impacts with Renewable and Fossil Energy

In this final Section, we will consider surface impacts of geothermal development, and compare it with other energy sources, including both renewable and fossil based sources. Topics that will be considered include surface footprint, traffic, and noise levels associated with the development and operation of plants.

### A. Surface Footprint

All energy systems, whether they generate molecules or electrons, require construction of infrastructure, such as wells, turbines, pipelines, power plants, transmission lines, etc. Surface space to host production facilities is required across the board, whatever the energy source may be. Fortunately, given the design, deployment, and use of many different utility scale energy systems for over a century, we have a thorough understanding of the surface footprints that (at least historically) have been required for these systems.

Crucially also, innovation has reduced surface footprints as systems have evolved with time, experience, and an acknowledgment of the importance of land conservation as an ancillary goal. In Figure 10.5, the surface footprint of all major sources of energy is compared (Lovering, et al., 2022). Of these energy sources, including renewables like wind and solar, geothermal takes up the least amount of space on the surface, per unit of electricity production.

#### 1. Oil and Gas

In research relevant to geothermal development, Pierre, et al., (2017; 2020) reported on a time series of land surface alteration from drilling pads (and, by extrapolation, from pipeline construction) for the Eagle Ford and Permian Basin areas of Texas, respectively. They showed a spectrum of current land alteration scenarios that depended on degree of drilling and number of multi-well drilling pads, though restoration following on-site activities have mitigated some of these impacts. Because geothermal development in Texas is likely to follow the paradigm of drilling used in oil and gas, also known as "pad drilling," this research gives perspective of what large-scale geothermal deployment might look like in Texas.



Beginning in the early 2000's, unconventional (shale and tight rock) plays became the dominant source of fossil energy exploration, leading to a larger per well support area needed for each well, particularly in the size of the drill pad; 1.5 hectares and up, much larger than typical well pads (Johnson, 2010). Because of the need for tight lateral spacing and much smaller drainage volume per well, the spacing of well pads have become closer, creating denser landscape alteration patterns (McClung & Moran, 2018).

Note that, although the number of geothermal plants in the U.S. is relatively small, and in Texas there are currently zero, experience that could be transferred from the oil and gas industry is significant, especially with respect to land use needs. Both industries require drilling pads for hosting boreholes, both benefit from horizontal drilling and stimulation (in the case of EGS), and both connect wellheads to infrastructure that captures an energy product.

## 2. Wind and Solar

Renewable energy generating facilities, specifically in the form of wind and solar installations, also impact landscapes in diverse ways. Land alteration from wind energy in particular differs from other energy sources, not only because the tower, turbine, and blades are above ground, but also because the blades have a wingspan that far exceeds its surface footprint. Different researchers approach the total (direct and indirect) impact of onshore wind energy differently. One well cited study (Denholm, et al., 2009) evaluated 172 existing or proposed (at the time) projects, focusing more on land area occupied and less on intensity of the impact. These researchers illustrated nuances of the direct impact of turbine pads, roadways, support areas, etc., and a more vague, more subjective use of indirect land use that is included in total area, including spaces between turbines or the blades themselves (depending on blade length).

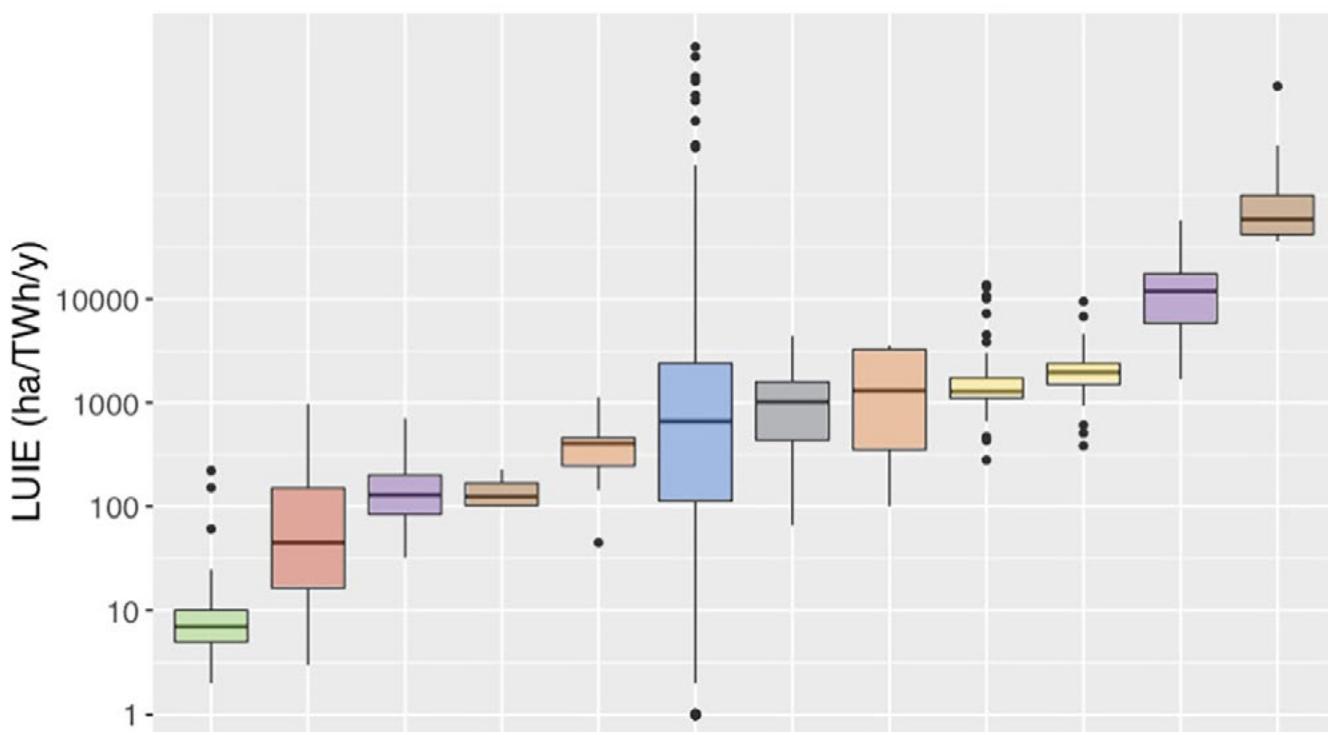


Figure 10.5. Comparison of land use intensities between different energy systems. Notes: Wind- refers to wind towers only and Wind+ includes the land in between the towers. NG- refers to gas fired generation at the plant only and NG+ includes the generation plant and the drilling and transportation infrastructure. Geo refers to geothermal energy generation including the generation facility and onsite production wells.

Source: Adapted from Lovering, et al. (2022) for explanations and assumptions.



Land alteration for wind in particular is sometimes vaguely defined, because the land between turbines, still within the facility boundary, often remains in use (e.g., for agriculture), hence the use of two different land use intensity values for wind; one for just the land use for the tower (Wind-), and the other that includes the space between the towers (Wind+). Impacts to habitats, avian species, and other site operations (e.g., other infrastructure) are often site specific and would require specific analyses, sometimes down to a species level, or ecosystem service approaches (e.g., Stanford University's Natural Capital Project). The potential impacts on viewsheds, soundsheds, and local communities in the form of externalities like shadow flicker could also come into play, again, depending on site-specific factors.

Land alteration from solar energy infrastructure is easier to quantify than from wind energy because photovoltaic panels and related hardware are closer to the ground, often one to two meters above the surface. Moreover, the infrastructure is often more densely packed, removing some of the ambiguities of indirect impacts, as is the case for turbines. As reported by Lovering, et al., (2022), the land use intensity for ground mounted solar photovoltaic panels is over 40 times higher than for geothermal.

### **3. Geothermal**

In general across all technologies, a single representative value of land use for all of geothermal facilities and designs is difficult to determine. Estimates of geothermal direct land use range from approximately 350 megawatts per square kilometer (or 0.70 acres per megawatt) (Kagel, et al., 2007) to approximately 830 megawatts per square kilometer (or 0.30 acres per megawatt) (DiPippo, 2016), with a midrange estimate ranging from 500 megawatts per square kilometer (or 0.49 acres per megawatt) (DOE & EPRI, 1997) to approximately 1,000 megawatts per square kilometer (0.97 acres per megawatt) (Lovering, et al., 2022). DiPippo (2016) also noted that a geothermal-flash or binary plant requires two percent of the land area required for a solar photovoltaic plant located in the best insolation area in the United States, when compared side-by-side in capacity.

Factors relevant to geothermal land needs are, to name a few, the quality and lateral extent of the reservoir, the efficiency factor of the plant, and the number and interspatial distances between drilling pads and pipelines needed for moving fluids.

Bayer, et al., (2013) reported the land footprint to require around 0.85 square kilometers per 50 megawatt plant, an area that includes well pads, cooling towers, roadways, transmission lines, etc.

A key factor in total land use is the potential need to store wastewater brines, particularly in the case of conventional geothermal systems. Though this is less likely to be relevant in Texas as next generation concepts are deployed, if necessary, these vessels could increase land use by 75 percent.

Once drilling is complete, next generation geothermal systems (AGS, EGS, etc.) offer the potential for smaller footprints relative to hydrothermal systems in two ways. First, these systems are anticipated to be in the low tens of megawatts per installation, with density of installations kept low for geophysical reasons. Generation will therefore most likely be located immediately adjacent to the drilling pad, minimizing the footprint created when above or below ground pipelines are needed to move fuel. Second, the emerging supercritical CO<sub>2</sub> based turbines have demonstrated an order of magnitude or greater reduction in size when compared to current state-of-the-art Organic Rankine Cycle turbines, thus allowing for a small post drilling footprint. These new technologies may allow next generation geothermal plant turbomachinery components for a several megawatt pilot plant to fit within the size of a tractor trailer container (Sage Geosystems, 2022).

That said, currently, even next generation plant concepts will require fluid cooling/condensing, which is a contributor to the surface footprint of geothermal developments. Further, the Texas climate in summer months poses a challenge for traditional air cooling technologies, and may increase the square footage requirement of cooling systems to maintain performance efficiency. This is an area where both innovation and piloting is needed to further understand the impact that geothermal plant cooling/condensing requirements will have on the footprint of new future developments in Texas.



#### **4. Other Land Use Considerations**

The impact of transmission lines constitutes the largest source of the range in land use estimates reported at around 0.215 to 1.485 square kilometers per 30 to 50 megawatt plant. This is equivalent to about nine acres per megawatt, assuming a 40 megawatt capacity, which is a footprint similar to that of utility-scale solar.

Land alteration should be considered through direct and indirect lenses, since ecosystem impacts extend away from direct alteration. Many authors have used a buffer of approximately 90 to 100 meters around directly altered areas (Pierre, et al., 2020; Drohan, et al., 2012; Johnson, 2010; Jordaan, et al., 2009) as a measure. Therefore, for those geothermal well fields that require a large number of wells, especially if the wells are spaced more than 328 feet (100 meters) apart, the sum of direct and indirect alteration could become sizable, even if the power plant itself is relatively compact.

To further reduce an effective land footprint and potential land fragmentation issues, site remediation and conservation practices should be considered at the initial stages of facility design and then implemented as soon as practicable, so that long term impacts are minimized. Measurable reductions in regional land alteration were noted in the Eagle Ford Shale play (Pierre, et al., 2015), one of the largest in Texas, after consistent land reclamation practices were implemented.

Disturbances from removal of vegetation can increase dust emission potential, which can be a respiratory hazard in humans, especially for utility scale solar energy, with blading and grading for the panels, frames, and roads. Dust erosion, although potentially significant in long-term solar panel efficiency, is probably not an issue in the geothermal context.



Figure 10.6. The cooling towers of the Ormat Tungsten Mountain hydrothermal plant, located in Nevada.  
Photo Credit: Ormat Technologies.



## B. Road Traffic

Few, if any, studies have been published in open literature on traffic issues related to geothermal development, though, exploration, well drilling, and infrastructure development activities would be similar to oil and gas development. The Academy of Medicine, Engineering and Science of Texas ("TAMEST") recently summarized changes in truck traffic and truckloads associated with unconventional oil and gas exploration. In chapter seven (Transportation) of the TAMEST report (2017), the authors noted that increased truck traffic resulting from initial exploration, pad drilling and development, site maintenance, and other site activities can significantly increase traffic through communities, representing a significant negative externality to community members during the development phase of a project.

Moreover, Quiroga, et al., (2012) reported on study results showing the increased number of truckloads traveling in rural areas of Texas, both empty and full load vehicles, can impact roadways. These impacts are particularly noteworthy on rural roads, which often are not designed to carry heavy loads. Quiroga, et al., (2012) showed, for example, that a 25 percent increase in vehicle weight from 80,000 to 100,000 pounds would result in an increased pavement impact of 140 percent. An obvious trade off seems to exist between reducing the number of trucks on the road, which benefits local residents in a number of ways, against the heavier load of each truck imparting a larger impact on road quality. Quiroga, et al., (2016) also estimated a total number of truckloads, normalized to a single-axle vehicle of equivalent weight (e.g., 18,000 pounds) and reported a range of per well truck trips from 5,513 in the Barnett Shale to 11,211 in the Permian Basin.

Although operations for geothermal projects will differ in some ways from those of an unconventional hydrocarbon well field, impacts related to fluid management and disposal, truck traffic and road impact/damage need to be accounted for in initial planning and impact mitigation activities for projects under consideration in areas where populations may be impacted.

## C. Noise levels

Geothermal plants in general terms are likely to be no different than any other power or industrial facility of equivalent size and scale. Noise levels are elevated during road construction, excavation and drilling at well sites, and well testing. This quality of life concern, which has been noted in oil and gas exploration and development (Anderson & Theodori, 2009), is typical of other well drilling activity, which is of high intensity, and short duration. Noise from drill sites can be mitigated through the use of sound walls or barriers, a relatively standardized practice.

After the wells have been constructed and plants begin normal operations, components of the plant contribute to elevated ambient noise, including compressors, generators, motors, pumps, and fans. Noise also occurs during abnormal operations, such as when the plant is forced offline, or when/if emergencies occur that require adoption of measures that are not a typical part of standard operating procedures.

Gupta and Roy (2007) listed a number of environmental concerns related to geothermal development, including noise pollution from fluid handling, especially for venting or fluid release to manage pressure. At high noise levels due to waste fluid release, they recommended subwater release (e.g., into a storage pond). For low noise management, they recommended the use of silencers, which are vertically oriented pipes that increase in diameter with height. Other options that co-manage water and associated noise are also described.

As noted above, it is important to note that these observations have been made in the context of conventional hydrothermal geothermal development, which will likely be a small part of Texas' geothermal development. With the development of next generation geothermal concepts in Texas, many of the environmental externalities that have been observed to be associated with conventional hydrothermal geothermal operations are not expected to be of concern. This is an area where further inquiry is needed, as the first plants piloting next generation concepts come online in the coming years.



## VI. Conclusion

While this Chapter took a hard look at potential negative environmental externalities associated with geothermal developments, when compared with other sources of energy, including other renewables, geothermal shines in the realm of environmental impact, having the lowest lifecycle carbon emissions, small surface footprint, and low potential for water contamination. From a broad global environmental standpoint, a low or no carbon, baseload, small footprint energy source, without significant waste streams, has substantial upsides and value as the world seeks to decarbonize its electricity generating systems. Even so, all energy sources have some environmental impact, and geothermal is not an exception.

Many environmental considerations discussed herein and related to geothermal, like high water use, the potential for emissions to ground surface, and the potential for induced seismicity, are most relevant to Conventional Hydrothermal Systems ("CHS"), and potentially also

to Traditional EGS. These potential impacts may be significantly mitigated, or simply not present, in next generation geothermal concepts such as AGS, and some Hybrid Geothermal Concepts. For example, next generation AGS/Closed Loop concepts may not involve induced seismicity risk, which is a concern in CHS and Traditional EGS geothermal contexts. Further, the use of engineered Working Fluids, like supercritical CO<sub>2</sub> instead of water may mitigate high water use, which is also implicated by CHS and Traditional EGS.

Nonetheless, a majority of these next generation geothermal concepts have not been sufficiently field deployed to allow for data collection and analysis of the environmental impact in real world deployments. While this Chapter represents a step forward in this area of analysis, these areas of fast moving innovation will require further analysis and study as new data from field trials of next generation concepts becomes available over the coming years.



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## Conflict of Interest Disclosure

**Michael H. Young** serves as a Senior Research Scientist at the Bureau of Economic Geology, Jackson School of Geosciences, the University of Texas at Austin, and is compensated for this work. His main areas of research for over 35 years have been in the broad area of environmental geosciences, water resources, and landscape scale processes, particularly applied to understanding impacts from energy development. Outside of these roles, Michel Young 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.

**Ken Wisian** serves as an Associate Director of The Bureau of Economic Geology, Jackson School of Geoscience at the University of Texas at Austin, and is compensated for this work. His main area of research for 30 plus years in geothermal systems. Outside of this role, Ken Wisian 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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## Chapter 11

# Geothermal, the Texas Grid, and Economic Considerations

M. Webber, D. Cohan, B. Jones

**Geothermal energy offers environmental and performance benefits to the power sector in Texas, and will gain market share if technology transfer and cross over learnings from the oil and gas industry can be leveraged, along with new innovations, to drive down installation and operating costs.**

## I. Introduction

This Chapter focuses on the Texas grid and the future role geothermal might play in Texas, with consideration of the potential economic impacts, cost reductions, and knowledge transfer from oil and gas, and how those reductions could accelerate geothermal market share in a decarbonizing Texas grid. The Chapter will begin with a discussion of the structure of the Texas grid, a configuration unique to Texas, and explore the political realities of energy in Texas. Next, we will dig into the impact of gas on the global economy, and the geopolitical considerations of geothermal development in the Lone Star State. Later in the Chapter, we consider the impact of technology and knowledge transfer from the oil and gas industry into the geothermal industry, including a

discussion about the learning spillover effect analyzed in [Chapter 5, The Oil and Gas Industry Role](#). We will conclude with a discussion about the impact the growth of geothermal in Texas could have on the Texas workforce.

## II. The Structure of ERCOT

Three electricity jurisdictions called Interconnections service the continental United States. These Interconnections monitor and balance the flow of electricity from generation sites (i.e., power plants) to load centers (i.e., where electricity is consumed such as cities, towns, industrial plants, data centers, farms/ranches, manufacturing facilities, etc.).



### The Three U.S. Interconnections Include:

- The Eastern Interconnection, which operates primarily in states east of the Rocky Mountains;
- The Western Interconnection, which operates mostly in states west of the Rocky Mountains;
- The Texas Interconnected system, which is wholly contained within Texas' borders.

Texas is the only jurisdiction in the contiguous United States that manages and operates its own bulk grid, presenting a unique case study for the deployment of geothermal.

There are "ties" between Interconnection systems, which allow electricity to flow within and between these three

Interconnection systems. These ties are high-voltage direct current power transmission lines that allow limited amounts of electricity to flow between Interconnections. These pathways, or redundancy, are built into the system to balance and minimize loss of service due to localized failures from weather events, maintenance, or other external factors.

There are four weak ties to the Texas Interconnection; two to the Eastern Interconnection (near Oklaunion and Monticello), and two to Mexico. The ties into the Texas Interconnection carry between 200 and 600 megawatts when at full capacity (Hartmann, et al., 2020). There are no ties between the Texas and Western Interconnections. There are six ties between the Eastern and Western Interconnections.

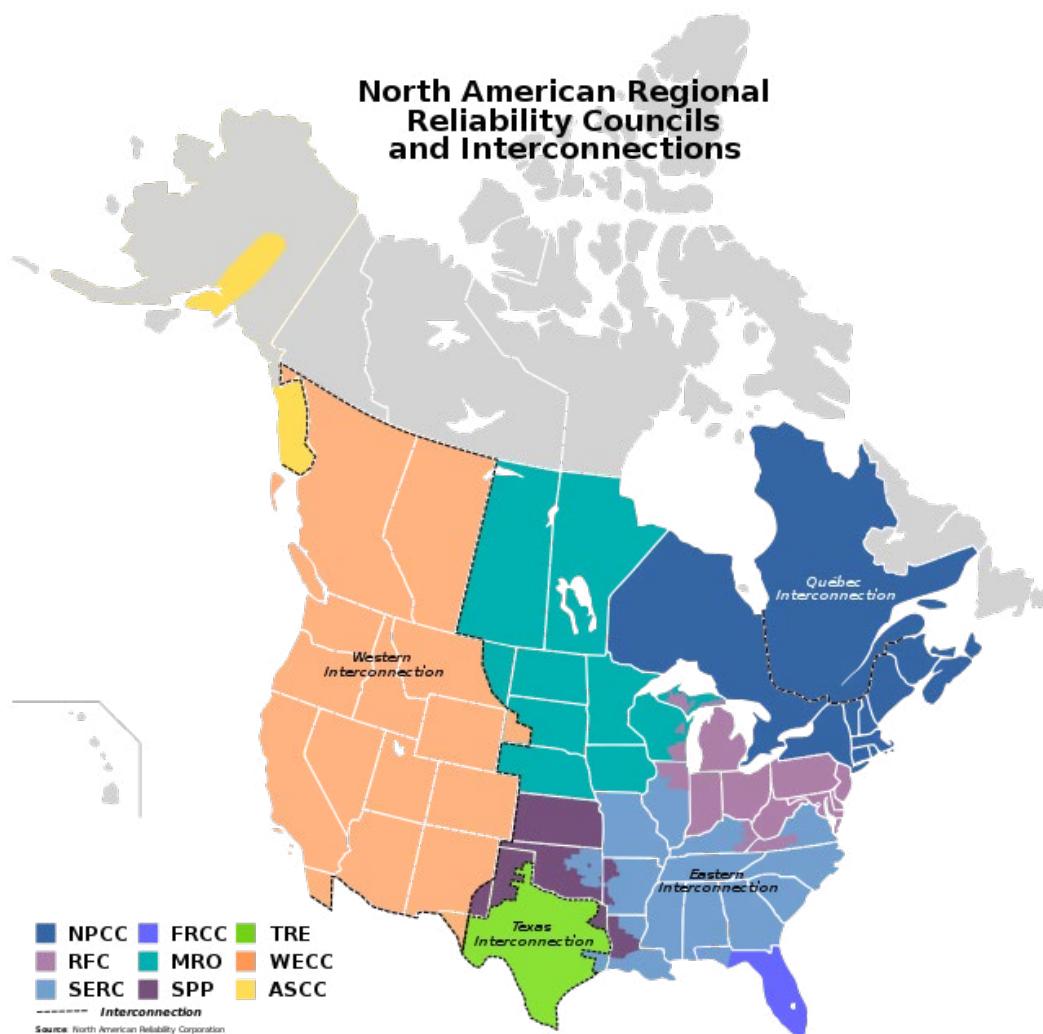


Figure 11.1. Depicts the four Interconnections and nine regions of the electrical grid in North America.  
Source: Bouchecl, 2009.



Additionally, there are several regions and subregions within the three major Interconnections. The Electric Reliability Council of Texas (“ERCOT”) can be viewed as its own interconnected system, region, and subregion within the North American electrical grid, making it a configuration that is unique to Texas (Figure 11.1).

ERCOT manages 90 percent of the electricity load in Texas, and supplies power to 26 million Texans (ERCOT, 2022b). ERCOT is a 501(c)(4) nonprofit corporation with a board of directors that provides operational structure. The Public Utilities Commission (“PUC”) of Texas, along with the Texas legislature, have oversight responsibilities of ERCOT. ERCOT is composed of members that include investor owned electric utilities, independent generators, municipally owned electric utilities, electric cooperatives, independent power marketers, retail electric providers, transmission and distribution providers, and consumers (ERCOT, 2022a).

The ERCOT grid has been evolving in response to changing customer preferences, and fuel and technology costs. Figure 11.2 shows the evolution of ERCOT fuel mixes from 2006 to 2020. Currently, 36 percent of the ERCOT grid’s electricity is derived from zero-carbon sources (wind, solar, nuclear), with the majority of the remainder generated by gas and coal. The U.S. Energy Information Administration projects that nearly 50 percent of ERCOT’s generation will come from zero-carbon sources by the end of 2023. While the portion of

generation from gas has stayed relatively constant over time, electricity production using coal has decreased by approximately 52 percent from 2006 to 2020. Even as total Statewide electricity generation has increased, the evolving generation mix has facilitated an overall drop in emissions from the electric power sector (Campbell & Hattar, 1991).

As a result of variability in power plant availability and dynamic load, there is a need for flexible demand, greater grid connectivity between regions, energy storage, and/or firm (e.g., “dispatchable”) sources of low-carbon generation for grids to remain stable. Firm energy is defined as the ability to turn on and off at will, or controllable (Sepulveda, et al., 2018). Geothermal is particularly appealing, as it is a firm and flexible source of electricity with no direct emissions that can balance the growth of solar and wind generation in the Texas electricity sector. But while each of the energy sources in Figure 11.2, as well as geothermal, which is not represented in the Figure, could play a part in the Texas grid of the future, how the grid ultimately evolves will depend significantly (though not exclusively) on costs.

There are currently no geothermal power plants located in Texas. A small scale (about one megawatt) Hybrid Geothermal System on the Texas Gulf coast provided power to a local utility for one year in the early 1990s, as part of a demonstration project that ended and shut down the plant (EIA, 2022).

ERCOT Generation by Fuel, 2006–2020

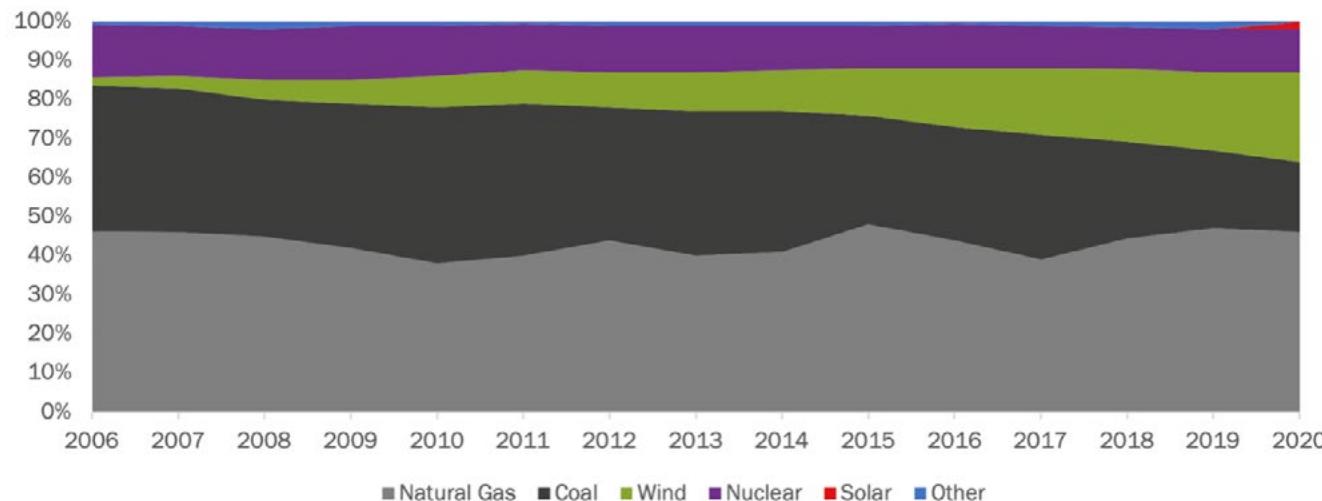


Figure 11.2. Percentage of electricity generation by fuel type in ERCOT from 2006 to 2020. Source: Rhodes, 2021.



### III. Energy Independence and the Lone Star State

Texas has a deep and rich culture as an energy producer. The State literally and figuratively fuels the economies of not only the United States, but also the world. In 2021, according to the EIA, Texas produced 43 percent of the oil and gas in the United States (EIA, 2022). Texas is the fourth largest oil producing entity in the world, behind Saudi Arabia, Russia, and the rest of the United States, and the third largest producer of gas, behind Russia and the rest of the United States (Figure 11.3). In Texas alone, the Texas Oil and Gas Association estimates that the oil and gas industry, during fiscal year 2021, supported more than 422,000 direct jobs, and paid \$15.8 billion in State and local taxes and State royalties, funding Texas' schools, roads, and first responders (TXOGA, 2022). Additionally, energy produced in Texas helps support energy independence and national security for the United States, and more recently, for allies who are attempting to reduce their dependence on Russian gas imports (Collins, et al., 2022).

Social license to operate in the State is an important enabler for Texas' robust energy industry. The oil and gas industry enjoys broad acceptance amongst the Texas

population, with many residents working directly or indirectly for the industry. This social license to operate and a supportive culture for industries engaged in drilling or other subsurface activities sets Texas apart, and provides an advantage when considering the growth and development of geothermal in the State.

#### A. The Politics of Power in Texas

In ERCOT, and many other electric grids, the addition of new power generation capacity is currently dominated by three mature technologies: onshore wind turbines, utility scale solar photovoltaic panels, and gas power plants (ERCOT, 2022c). These deployments, especially wind and solar, are largely driven by low installation costs, short permitting times, and customer demand for clean energy sources.

After the deadly Winter Storm Uri hit Texas in February 2021, political and consumer preference emphasized reliability with greater attention. Uri dramatically surpassed the parameters of ERCOT's seasonal planning, bringing prolonged freezing temperatures, ice, and snow, which caused upstream and downstream energy assets in Texas to go offline (Potomac Economics, 2022). All major types of power generation were forced at least partially offline during the five day storm, including gas,

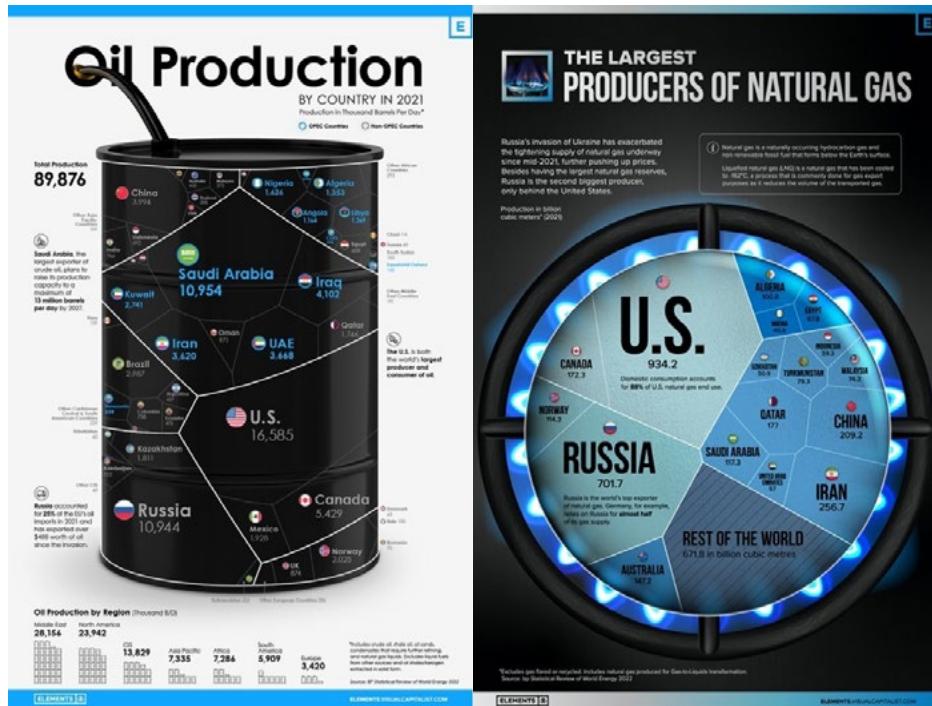


Figure 11.3. Global oil and gas production in 2021 according to BP Statistical Review of World Energy 2022. Sources: Amoros, et al., 2022; Venditti & Lam, 2022.



coal, nuclear, wind, and solar. Uri was one of only four comparably deep freezes to hit Texas since 1950 (Doss-Gollin, et al., 2021).

Despite the fact that Uri took all types of power generation in the State offline, the storm changed the political narrative about wind and solar in the State. After Uri, key Texas legislators and other officeholders signaled their desire for more gas power plants to be built in Texas, and more reliability to be built into the Texas grid.

The shift in tone post Uri marked a departure from traditional bipartisan support for wind and solar in Texas. For example, during the Administration of Republican Governor Rick Perry in 2005, the Texas Legislature ordered the PUC to work with ERCOT to identify and build out competitive renewable energy zones ("CREZ") to deliver renewable energy, generated primarily from wind, but also solar. The goal of CREZ was to enhance rural economic development, and increase the amount of electricity delivered to customers by using renewable generation resources in Texas. CREZ also aimed to alleviate a disconnect between development timelines for wind projects in West Texas, and transmission capacity (Dorsey-Palmateer, 2020; Gould, 2018). By 2013, CREZ had nearly tripled the capacity of the Texas grid to accommodate wind power in the CREZ regions (Dorsey-Palmateer, 2020).

CREZ is generally regarded as a success from a policy, economic, and technical perspective. However, from a political perspective, the marked shift in political climate in the Texas Legislature in the aftermath of Uri may hinder the progress of additional large scale transmission projects, at least in the near term. If congested transmission lines constrain opportunities to add wind and solar farms in West Texas, the buildup of new generation sources close to demand centers in the eastern half of the State could be relatively favored, and this presents an opportunity for geothermal and the Texas grid. As is considered in detail in [Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development](#) of this Report, regions ripe for geothermal development in Texas are located near, or directly under, a majority of the State's major population centers.

Opportunities for hydropower in Texas are scarce due to the arid climate and minimal surface water. No coal plants, and only two nuclear reactors are under construction nationwide, and neither is likely to be deployed in Texas

in the next decade due to high costs, and environmental concerns. Most battery storage facilities are being built with one and two hour dispatch times, which can help smooth short term imbalances, but will not address multi-day events like Uri. This leaves gas and geothermal as the two most likely candidates for adding dispatchable resources in Texas in the coming decades.

## IV. Gas and Geothermal in Texas

As of the publication date of this Report, Russia has entered the twelfth month of its invasion of Ukraine. With no end to the conflict in sight, and energy markets across Europe in turmoil, Europe is struggling to quickly find a path to wean itself from Russian fossil fuels. In March, 2022, U.S. President Joe Biden met with the President of the European Commission, Ursula von der Leyen, to announce a plan for the U.S. to support an end to Europe's reliance on Russian gas. The two described a plan to increase liquid natural gas ("LNG") exports from the United States to European markets by the end of 2022, with volumes increasing further beginning in 2023. "We will sharpen our sanctions and we will break free from Russian fossil fuels," noted von der Leyen at a recent summit focused on Russia's war in Ukraine (EUCO, 2022).

The potential for U.S. LNG to reduce European imports of Russian gas is not trivial (Collins, et al., 2022; Ravikumar, et al., 2022), but the European desire for American LNG marks a shift from the previous decade, when Texan LNG received a chilly reception in Europe. Some European governments had rejected the import of Texas gas due to the use of hydraulic fracturing in its production, and a perception that Texas lagged behind in regulating releases of greenhouse gasses associated with gas production (Field, et al., 2014). But as prices soared after Russia's invasion of Ukraine, and concerns about energy security and price stability grew, European ports and entities became eager to accept Texas LNG (IEA, 2022; Smith, 2022). As recently reported in Texas Monthly, "Europe was plunging into the worst energy crisis in a generation, and Texas gas was sailing to the rescue" (Gold, 2022).

In April 2022, the U.S. Department of Energy authorized additional exports of LNG from ports in Texas and Louisiana, but it will take several years to build additional capacity to meet growing export demand. Two of the five LNG terminals that make up 90 percent of U.S. LNG exports are located in Texas – one in Freeport, and the



other in Corpus Christi. One additional terminal is under construction in Sabine Pass. There are also new LNG regasification terminals under construction throughout Europe (Global Data, 2022; Agarwal, et al., 2020) developing in parallel with the new LNG export terminals under construction here in Texas (S&P Global, 2022).

The United States temporarily became the world's largest exporter of LNG in 2022, a trend accelerated by the war in Ukraine and the resulting European energy crisis. Once the energy crisis subsides and the urgency, price spikes, and scarcity recede, so too may European demand for Texan LNG. Once this crisis fades and alternatives become available, Europe could return to being choosier about the fuel it imports. Europe could turn toward nuclear, or choose between Texan LNG and other producers, for example Algeria, or re-engaging with Russian gas for long term supply. These dynamics present an opportunity for Texas, however, to lead and forge new and lasting export partnerships.

So why the discussion of Texas' future as an LNG exporter in a Report about the future of geothermal energy in the State? Many concerns associated with a growing percentage of domestic energy supply being slated for export are related to the impact of exports on U.S. energy prices and markets. As an illustration of the angst the topic of increasing exports has created amongst U.S. lawmakers, in February, a group of ten Democratic U.S. Senators wrote to the Secretary of Energy urging consideration of the impact of increasing LNG exports on domestic energy prices (U.S. Senate, 2022).

Substantially increasing the availability of a firm clean energy source like geothermal in Texas could free up gas for export, which would have been utilized for domestic energy production. Increased geothermal development would increase the size of total available energy resources in the State, reducing the criticality of Texan gas for in-State consumption, thereby enabling more gas exports to other parts of the world who need it to stabilize their markets. Texas' status as a grid island, which limits its ability to export substantial amounts of electricity to other parts of the U.S., further supports this premise. If Texas developed its domestic geothermal resources for use in the State, it may allow for the resulting excess gas resources, which are readily exportable into lucrative markets, to meet export demand.

## V. The Oil and Gas Technology and Workforce Transfer, and Impact on Cost

As discussed in detail in [Chapter 1, Geothermal and Electricity Production](#) and [Chapter 5, The Oil and Gas Industry Role](#) of this Report, geothermal technology deployment would utilize a vast array of technologies and workforce capabilities developed in the oil and gas sector. But technology transfer from the hydrocarbon industry into the geothermal industry is still in its infancy. In response to increasing traction for geothermal within the oil and gas industry over the past few years, the U.S. Department of Energy ("DOE") issued a \$165 million dollar Funding Opportunity Announcement ("FOA") in July 2022 to facilitate technology and workforce transfer from oil and gas into geothermal. The FOA, titled the Geothermal Energy from Oil (and gas) Demonstrated Engineering ("GEODE"), seeks to facilitate "collaborative research, development, and demonstration focused on realizing technology improvements and transfer from oil and gas, deploying geothermal energy nationwide, evaluating and recommending ways to address regulatory and permitting barriers, and developing opportunities in the geothermal sector for the skilled oil and gas workforce."

GEODE is part of another recently announced DOE initiative related to geothermal, called the "Enhanced Geothermal Shot," ("Earthshot") announced in September 2022. The goal of Earthshot is to reduce the cost of Enhanced Geothermal Systems, also referred to as Engineered Geothermal Systems ("EGS"), by 90 percent, to \$45 per megawatt hour by 2035 (DOE, 2022). In an ongoing study funded by Project InnerSpace, and led by Chapter author Daniel Cohan at Rice University, a team is modeling potential geothermal deployment scenarios in the electric grid from current to 2050 using a capacity expansion model called the Regional Energy Deployment System model ("ReEDS"). ReEDS, developed by the National Renewable Energy Laboratory ("NREL"), is widely used to project the evolution and operation of the electric grid in the contiguous United States (Ho, et al., 2021). The Rice University team will model a series of geothermal cost projections, with a close look at EGS cost reduction scenarios consistent with DOE's Earthshot targets. The study is expected to be published in late 2023 or early 2024.

Deployment of scalable concepts like AGS and EGS is one pathway toward "Geothermal Anywhere" that would



enable oil and gas companies to utilize technologies and techniques from industry to develop geothermal energy in Texas. The potential for breakthrough impact the application of oil and gas technologies and know-how may have on geothermal development has been demonstrated in the DOE's Frontier Observatory for

Research in Geothermal Energy ("FORGE") project, an EGS demonstration project located in Milford, Utah. Below is a case study that highlights the significant impact of oil and gas engagement on FORGE outcomes, and the potential for innovations such as these to push the cost of geothermal development down over the coming decade.

## Case Study: Increasing Performance and Driving Down Cost *Oil and Gas Technology Transfer and Learning Spillover Into Geothermal*

Polycrystalline Diamond Compact ("PDC") drill bits are used in over 90 percent of oil and gas wells that are drilled today. (Xie, et al., 2020). Though PDCs are regarded as industry standard in oil and gas due to their reliable performance and durability, particularly in hard sedimentary rocks, they have not been widely adopted in the geothermal drilling context, especially in crystalline rocks like granite.

In 2021, an oilfield consortium consisting of Texas A&M petroleum engineering faculty members Sam Noynaert and Fred Dupriest, who also served as former chief drilling engineer at ExxonMobil, oilfield service company NOV, and technology provider Sanvean International was selected by the U.S Department of Energy ("DOE") to demonstrate that application of oilfield workflows and modern technologies from oil and gas, including PDC bits, could produce breakthrough outcomes in the harder and hotter subsurface environments encountered in geothermal drilling.

When the Texas team deployed their technology and techniques in the field trial, performed at the DOE's Frontier Observatory for Research in Geothermal Energy (FORGE) site, their performance significantly exceeded expectations, resulting in the geothermal wells being drilled in half the allotted time. As a result of this oil and gas technology and knowledge transfer into the geothermal industry, previous hard rock drilling records were exceeded by approximately 10X(Pink, et al., 2023; Sugiura, et al., 2021). Because drilling is the largest expenditure associated with the development of geothermal projects, large reductions in drilling time will translate into significant cost savings for projects.

Building on this outcome, in 2021, NOV and Houston based startup Particle Drilling, teamed up to design and build a hybrid Particle/PDC bit that would combine the reliable performance of PDCs, with an innovative new technology that continuously shoots millions of steel pellets into the rock while drilling. After the rock is impacted by the pellets in the drilling process, the PDC portion of the bit



Figure 11.4. The Particle/PDC drill bit, combining leading edge PDC technology with an innovative steel shot drilling method. Source: Image from NOV.



then drills the rock that remains, cutting drilling time. This design was aimed at drilling very hard and hot rocks, which are typically associated with the most economically interesting global geothermal opportunities. The newly designed bit was prototyped within months of the conclusion of the DOE test, and ready for a field trial.

In August 2021, NOV and Particle Drilling deployed a drilling rig to a granite quarry in Coldspring, Texas, where the team tested two new particle drilling bits, shown on the right. The newly designed bits drilled the rock twice as fast as the best PDC used in the FORGE demonstration, which was used as a control sample. This new bit, when deployed in a geothermal project, is expected to deliver another step change forward in drilling performance in hard rock, within an ultra-fast design cycle, concept to field deployment, of about a year.

Innovative new technologies, and the fast innovation cycles of the oil and gas industry, like the Particle/PDC drill bit example, are key to driving down the cost of geothermal projects, and to unlocking broader access to deeper and hotter geothermal resources. 🔥

The spillover learning showcased in the Case Study with PDC and industry workflow deployment at FORGE, as well as subsequent advances resulting from quick-turn, iterative innovation that led to the NOV/Particle Drilling field trial, is just one example of the types of outcomes, time savings, cost reductions, efficiency increases, and capability gains that oil and gas engagement in geothermal would enable.

The authors of [Chapter 5, The Oil and Gas Industry Role](#) modeled the extent of potential cost reductions in geothermal from immediate learnings and technology transfer across all geothermal technology types from the oil and gas industry, and found cost reduction potential to be between 20 to 43 percent, without the need for new inventions or technology leaps. To explore details, see [Chapter 5, The Oil and Gas Industry Role](#).

The cost reductions that can be realized through learning and technology spillover from oil and gas, as illustrated in the above Case Study, are likely to improve the case for more deployment of geothermal assets on the Texas grid. But as is explored in detail in [Chapter 7, The Geothermal Business Model & the Oil and Gas Industry: Challenges and Opportunities](#) of this Report, even its current price per kilowatt hour, geothermal is well positioned as a competitive contender in ERCOT's future energy mix.

## VI. Co-location of Geothermal Resources with Existing Infrastructure

Every energy source has siting limitations. Access to fueling infrastructure, local emissions constraints, security requirements, and cooling water availability can limit the placement of thermal power plants, such as gas, coal, and nuclear. Wind and solar are often limited to areas that have available land, favorable wind speeds, and sufficient solar insolation.

Because the temperature of the Earth's subsurface is not homogeneous, there are locations that are better suited for geothermal development than others. Figure 11.5 shows the various classes of available underground heat across the State. In the case of EGS as an example, which the Figure focuses on, about 11 percent of the State (about 28,225 square miles, 73,100 square kilometers) consists of Class 2 EGS development regions, the second highest class in quality of resources (Turchi, et al., 2020). [Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development](#) provides in-depth consideration of the different classes and qualities of geothermal resources in Texas.

The majority of the Class 2 EGS regions in Texas are located in northeast Texas, with other regions along the Eagle Ford Shale formation in southern Central Texas down to the Mexican border in South Texas. There are also some smaller pockets of Class 2 EGS regions in far West Texas. These areas either contain or are located nearby a majority of the Texas population, with the greater metro



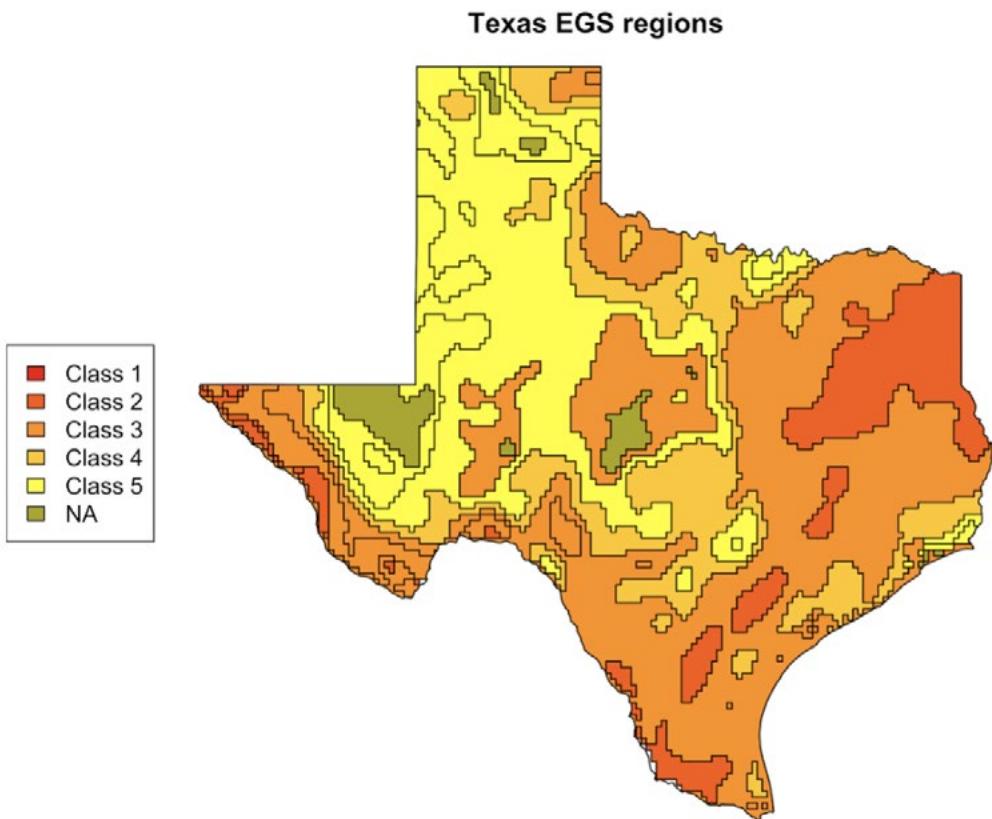


Figure 11.5. Classes of engineered or enhanced geothermal system ("EGS") resources across Texas.  
Source: NREL, 2022a.

areas of Houston, San Antonio, Dallas Fort Worth, and Corpus Christi, among others, within or nearby these EGS regions.

It is reasonable to assume that the development of geothermal resources in Texas would start in regions that would result in the lowest overall costs. These regions would include those with the best available underground temperatures, as well as those that already have existing infrastructure that could be utilized to reduce the capital costs of the geothermal power plant.

For example, if a coal power plant retired in a location that had viable geothermal resources, the site's existing cooling water and electric substation/switchyard could be repurposed for geothermal power production. In the case of SuperHot Rock coal plant conversions, some existing coal plant turbomachinery may be able to be repurposed for geothermal power production. This is a quickly developing area of inquiry and innovation in Texas that will require further study. We consider the opportunity in further detail below.

#### A. Coal Power Plant Conversions in Texas

There is growing interest in the U.S., including in Texas, to investigate the feasibility of utilizing both old coal mines (Kowalski, 2021; Andrews, et al., 2020; Madera-Martorell, 2020) and coal plants slated for decommissioning (Petty, 2016) for geothermal generation.

A case study of retrofitting coal-fired power plants in Poland to geothermal found that EGS systems could theoretically operate at up to 90 percent of a smaller coal plant's annual output using the same land footprint, and that retrofitting can decrease costs compared to building new plants; though this does not necessarily guarantee their competitiveness in the market (Qvist, et al., 2020). There are constraints to retrofitting, however. The same study of Poland found that some of the existing coal plants in the region analyzed were co-located with geothermal resources with subsurface temperatures below 300°C, which was too cold to use in existing steam cycles that operate between 510-600°C without modifications to the equipment.





Figure 11.6. An operating coal power plant. Texas based CPS Energy has publicly expressed interest in exploring geothermal as part of a conversion project for its J.K. Spruce Power Plant, located southeast of San Antonio, Texas. Source: Stock photography.

There are about 38 existing power plants that overlay the Class 2 EGS regions of Texas. Table 12.2 shows the number, capacity, and average capacity factor of power plants, by fuel type, located within Texas' Class 2 EGS regions. These power plants produced about 20 percent of the total electricity consumed in Texas in 2019 (EIA, 2022).

The Class 2 EGS regions also intersect with over 530 major electric substations and about 6,500 miles of high-voltage (greater than or equal to 69 kilovolt-ampere) electric transmission lines. Thus, there appears to be a significant amount of infrastructure already in place in the regions of Texas with the best geothermal potential. There are over 750 coal power plants in the United States, of which only 200 remain in operation (Richter, 2022). The rest are shuttered due to economics, as coal is not an economically viable baseload electricity generation source, often being outcompeted by gas (Morris, et al., 2019).

A potential conversion candidate from a coal power plant to a geothermal power plant is the J.K. Spruce Power Plant, operated by CPS Energy and located southeast

of San Antonio, Texas (Mendoza-Moyers, 2022). CPS Energy indicated in 2022 that the company is considering converting unit 1 into a source of zero carbon emissions, which may include an AGS geothermal component, and unit 2 into a gas power plant (a source of less carbon emissions compared to coal).

Currently, the J.K. Spruce Power Plant is the largest generator of carbon emissions in Bexar County, Texas, producing about 60 percent of greenhouse gas emissions in the county, or 5,800,000 metric tons of carbon emissions into the atmosphere (Mendoza-Moyers, 2022; Sabawi, 2022). Additionally, the coal power plant is no longer economically viable using coal as a fuel source primarily because of competition from gas (Morris, et al., 2019). The San Antonio and Bexar County region sources a quarter of its electricity from the J.K. Spruce Power Plant, resulting in a significant amount of demand to convert from coal to other reliable sources. The subject of coal plant to geothermal conversion was explored by a panel of experts at the PIVOT2022 conference, where entities, including CPS, expressed their views of the future of this application (PIVOT, 2022a; 2022b).



Table 11.1: The number, capacity, and capacity factor of thermal power plants, by fuel type, located within Texas' Class 2 EGS regions. Source: *Future of Geothermal Energy in Texas*, 2023.

Power plant type	Number of power plants	Capacity of power plants (megawatts)	Average capacity factor
Gas	16	7,136	38%
Coal (subbituminous)	5	5,744	49%
Coal (lignite)	5	7,095	74%

### B. Abandoned and Orphaned Oil and Gas Wells

According to the Texas Railroad Commission ("RRC"), there are over 140,000 abandoned or orphaned oil and gas wells ("AOGW") in Texas (RCC, 2022). These AOGW could be used for geothermal electricity generation if they provide sufficient temperatures, but are more likely to be used as a heat source for nearby buildings, agriculture, manufacturing, or industry. This is a unique opportunity in Texas due to the number of and density of wells.

Recently, the Department of the Interior under the Biden Administration approved \$4.7 billion to address the growing challenge of AOGW management, including efforts to plug the wells to avoid errant emissions (BLM, 2022; Menon, 2022; Kang, et al., 2021; S&P Global, 2021). However, thousands of these wells may have the potential to be repurposed for heat or electricity production. We raise this point briefly in this Chapter because this is an interesting opportunity for geothermal co-location with existing Texan infrastructure. For additional details on the technical aspects of Oil and Gas Well Reuse, refer to [Chapter 3, Other Geothermal Concepts with Unique Applications in Texas](#).

## VII. Expanding Geothermal Power Generation Creates Jobs

A report on the future of Texas climate jobs published by the Workers Institute at Cornell University notes that a policy decision to encourage the installation of 5,000 megawatts of geothermal electricity capacity in Texas will create 162,500 new jobs, far more per megawatt than solar and wind. The addition of 5,000 megawatts of geothermal

capacity in Texas creates 62,500 direct jobs, 53,750 indirect jobs, and 46,250 induced jobs over ten years (Skinner, et al., 2021; Pollin, et al., 2014). This is significant because geothermal jobs offer six figure salaries, are eligible for participation in a number of labor unions, and value subsurface skills and knowledge. Furthermore, NREL's Jobs and Economic Development Impacts ("JEDI") model estimates that geothermal power has a (direct and indirect) jobs impact of about 1.36 twenty-year full-time equivalent ("FTE") jobs per megawatt of capacity (NREL, 2022b). The JEDI model also estimates that wind produces about 0.38 twenty-year FTE jobs per megawatt, while solar produces roughly 0.26 twenty-year FTE jobs per megawatt. Because geothermal power plants also have higher capacity factors, that means each megawatt of capacity from geothermal resources can be expected to create more jobs and generate more electricity over its operational lifespan (NREL, 2022b).

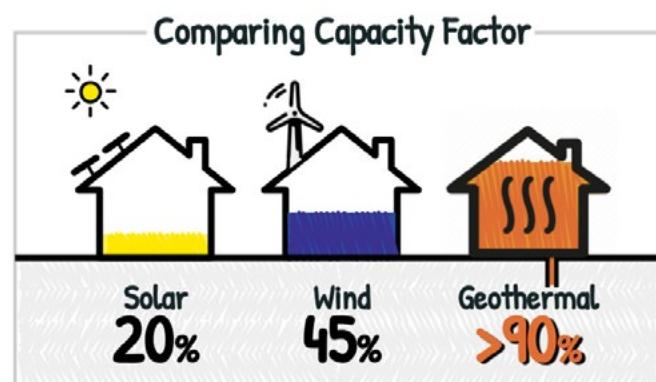


Figure 11.7. Generator capacity factor data for renewable energy technologies. Capacity factor is the percentage of time that a plant is generating electricity. Source: EIA, 2014.



## VIII. Conclusion

Although the business models for the oil and gas industry and the geothermal industry differ, the technical skills and competencies of their workforces have many similarities. For instance, the technical disciplines listed by the Society of Petroleum Engineers, the largest professional organization for the professionals from the oil and gas industry in the world, are: reservoir engineering; including geomechanics and reservoir characterization; drilling; completions; production engineering and facilities; data science and engineering analytics; and health, safety, environment, and sustainability ("HSE&S"). All of these disciplines apply directly to geothermal resource exploration and development, thus, oil and gas industry workforce retraining and redeployment for geothermal may be easily achievable. However, government support may be needed initially to expand the geothermal industry, including building robust workforce retraining and transition programs for oil and gas workers entering the geothermal industry. This, and other policy based solutions to growing geothermal in Texas are considered in further detail in [Chapter 12, Policy, Advocacy, and Regulatory Considerations in Texas](#) of this Report.

Currently, a primary hurdle facing geothermal power for gaining market share is its high up-front costs. However, as other parts of the energy sector such as wind, solar, and batteries have shown, costs can drop significantly in the span of a decade or so with technology development, scale, and proper support and incentives. Presuming that technology and learnings transfer from the oil and gas industry enables new capabilities and cost reductions, as we saw in the Case Study in this Chapter, geothermal as a clean, firm source of energy may be well positioned to play a significant role in the future Texas grid. Further, significant geothermal deployment in Texas may position the State to increase its gas exports as heat and electricity demands of the State are increasingly met with geothermal at home, providing an opportunity for Texas to strengthen export relationships, and assist allies in stabilizing their energy markets.



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## Conflict of Interest Disclosure

**Michael Webber** serves as a Professor of Mechanical Engineering at the University of Texas at Austin, and is compensated for this work. He also serves as chief technology officer of the venture capital firm Energy Impact Partners. Outside of these roles, Michael Webber 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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**Bryant Jones** serves as the Head of Education and Policy at Project InnerSpace, a 501(c)(3) organization that works on issues within the subject matter of this manuscript, and is compensated for this work. He is also a full-time Ph.D. candidate at Boise State University where he researches at the nexus of policy studies, science and technology studies, and energy transition studies. Outside of this role, Bryant Jones 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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## Chapter 12

# Policy, Advocacy, & Regulatory Considerations

B. Jones, M. Hand, J. Beard

***The private sector is poised to launch the geothermal industry in Texas, but it needs policy support from the Texas legislature to ignite the geothermal decade.***

## I. Introduction

Texas has a long history of successfully supporting the development of energy industries, from early and present day support of the oil and gas industry, to more recent efforts to support the wind and solar industries. This Chapter describes the history and influence of Texas policy-making on the energy industry, and policy and societal hurdles facing the geothermal industry. It further offers recommendations to address hurdles that will empower large-scale development and commercialization of geothermal technologies in Texas, leveraging private markets, competition, and the core competencies of the Lone Star State.

Below, we explore five hurdles to the growth and scale of geothermal in Texas, and offer recommendations to address them. The five hurdles are:

1. Lack of familiarity with geothermal technologies and applications among both lawmakers and the general public;
2. A lack of policies that would incentivize geothermal energy;
3. An insufficient workforce transition and training structure;
4. The need for improvement in State government coordination; and
5. Regulatory obstacles that hinder the commercialization and scaling of geothermal energy in the State.

Throughout our exploration of these five hurdles, we identify how civic leaders, and the Texas legislature can support the geothermal industry by: 1) becoming



geothermal education and policy champions, 2) proposing geothermal specific legislation relevant to their districts and regions, 3) facilitating access of geothermal technologies to capital, 4) increasing opportunities for geothermal companies to access public and private finance, and 5) fine-tuning regulation that would support the quick scaling of geothermal in the State.

## II. Texas Policy-makers' Role in Building the Texas Energy Economy

### A. Building Texas' Oil and Gas Industry - Then and Now

For over 100 years, policy-makers in Texas have supported the growth and development of the State's energy industries. This support began when the State legislature gave the Texas Railroad Commission ("RRC") jurisdiction to regulate the production of oil and gas in 1919. When the global price of crude oil dropped dramatically in the 1930s, the RRC intervened with producer quotas to maintain price levels, and to quell violence that had broken out in the East Texas oil fields. Under the leadership of Ernest O. Thompson, who served as a RRC commissioner from 1932 to 1966, the RRC championed and oversaw rules and regulations that further empowered the oil and gas industry and the Texas economy. The RRC played an instrumental role in navigating the oil and gas industry in Texas through tumultuous energy shocks of the 1970s, increased competition from other hydrocarbon entities, such as the Organization of Petroleum Exporting Countries and Russia, the 2008 to 2009 financial crises, and most recently the economic and supply chain challenges caused by the COVID-19 pandemic. The RCC, with the support of the Texas legislature, has profoundly shaped, empowered, and supported the oil and gas industry over the past century. As Texas historian David Prindle writes, "The domestic petroleum industry was enmeshed in a web of State regulations specifically designed to shield it from the ravages of the market." With support of the RRC, oil and gas became the largest industry in Texas, and one of the most powerful hydrocarbon production industries in the world.

In the early 2000s, hydraulic fracturing (more commonly known as frac'ing), and innovations in horizontal drilling led to a new era of oil and gas development in the United States, with Texas once again leading the way. It also ushered in a new era of State level support for the oil and gas industry, including a tax credit program for high cost

gas wells designed to support the commercialization and scaling of the Texas gas industry. Originally passed in 1989 under the Administration of Republican Governor Bill Clements, and made permanent in 2003 by Republican Governor Rick Perry, this credit program was used to support 61 percent of gas wells in the State by 2009. The tax credit cost the State of Texas \$1.5 billion a year before factoring in Federal research and demonstration appropriations from the U.S. Department of Energy during the Administration of Republican U.S. President George W. Bush, a former Texas governor. The support from the Federal government helped to underpin the development of hydraulic fracturing innovation in Texas, further driving progress. Benefits were compounded by Texas' comparatively low levels of regulation on oil and gas development, and severance tax incentives (Ong & Munson, 2018).

More recently, during the 2021 State legislative session, several bills were proposed and designed to protect the oil and gas industry in the face of headwinds from the international financial system, as well as Federal and international efforts to address the climate crisis. In sum, both historically and on an ongoing basis, local and public support from policy-makers and political champions, targeted policies, and industry-specific efforts has empowered the oil and gas industry throughout its globally and economically impactful 100-year history in Texas.

### B. Building the Texas Intermittent Renewable Energy Industry

The intermittent renewable energy industry in Texas found its footing in 1999 through the deregulation of the State's power market, and the passage of a renewable portfolio standard to establish 2,000 megawatts of electricity capacity from renewable energy by 2009. These policies were enacted by the Texas legislature, signed into law by Republican Governor George W. Bush, and amplified in 2009 to 10,000 megawatts of capacity during the Administration of Republican Governor Rick Perry. In addition, the Perry Administration launched the Competitive Renewable Energy Zone ("CREZ") program, a \$7 billion project connecting the wind farms of West Texas with the population centers in the eastern half of the State (Gould, 2018; Lasher, 2008). In that effort, the Public Utility Commission ("PUC") authorized companies to negotiate with private landowners and use eminent



domain to acquire land on which private companies constructed transmission lines across the State, facilitated through the CREZ program. The actions of these two Administrations ushered in the dramatic growth of the renewable energy industry in Texas. CREZ is discussed in more detail in [Chapter 11, Geothermal, the Texas Grid, and Economic Considerations](#).

For much of the past 25 years, State support for the oil and gas industry has run in parallel with intended and unintended support for renewable energy. In more recent years, however, conflict between these two energy industry giants has begun to arise and become politicized. During the 2021 Texas legislative session, conducted in the wake of Winter Storm Uri, much of the legislation proposed pitted the intermittent renewable (wind, solar) and nonrenewable (oil, gas, nuclear) energy industries against one another. This conflict is likely to continue in the 2023 legislative session.

Geothermal offers a potential “third way” policy solution for Texas policy-makers. It will require support and empowerment from the Texas legislature, the Governor of Texas, and the RRC to chart a path forward that emboldens a largely proven, accelerating, but underutilized energy technology. Geothermal is poised to amplify and support the oil and gas industry, while also providing firm, reliable, and clean power to the grid that complements the intermittency of renewables like solar and wind.

The next Section explores tools available to policy-makers that will help commercialize and scale the geothermal industry in Texas.

### III. Supporting Growth of the Texas Geothermal Industry: A Policy-Makers Handbook

In this Section, we identify hurdles to the growth of Texas’ geothermal industry, and identify areas where policy-makers can support the industry. As discussed above, the growth of geothermal in Texas faces five major hurdles:

1. Lack of familiarity with geothermal technologies and applications among both lawmakers and the general public;
2. A lack of policies that would incentivize geothermal energy;

3. An insufficient workforce transition and training structure;
4. The need for improvement in State government coordination; and
5. Regulatory obstacles that hinder the commercialization and scaling of geothermal energy in the State.

We consider each hurdle in turn, with an eye to the five primary avenues that elected leaders and the Texas legislature can utilize to support the industry: 1) becoming geothermal education and policy champions, 2) proposing geothermal specific legislation relevant to their districts and regions, 3) facilitating access of geothermal technologies to capital, 4) increasing opportunities for geothermal companies to access public and private finance, and 5) fine-tuning regulation that would support fast scale for geothermal in the State.

#### A. Lack of Familiarity With Geothermal Technologies and Applications

In the case of solar and wind, both intermittent renewables experiencing accelerating growth, decades of generous support, and a strong advocacy apparatus at Federal and State levels have driven down cost. This strong advocacy apparatus helped brand these renewable sources in public perception as the future of energy, and have catalyzed a flood of private investment into global commercial-scale development (Ahmed, et al., 2021; Culhane, et al., 2021; Kim, et al., 2021; Liu, et al., 2019; Polzin, et al., 2018; Pacheco, et al., 2014; Lyon & Yin, 2010; Chandler, 2009). Indeed, all energy generation technologies, including hydro, solar, hydrocarbons, nuclear, biofuels, and wind, receive tens of billions of dollars each year from states and the Federal government to develop a path to widespread use (EIA, 2018). This support has encouraged fast growth and scale of wind and solar in Texas, which private markets have amplified, and we can see the results of that fast growth along the Interstate 35 corridor in West Texas. For example, before CREZ was enacted in 2005, Texas had the capacity to produce less than 1,400 megawatts of electricity from wind power. In 2022, the State has an installed wind energy capacity of 37,422 megawatts, with 4,418 megawatts of wind projects under construction (DOE, 2022c).





Figure 12.1. Wind farms in West Texas experienced rapid private market investments after the creation of the Competitive Renewable Energy Zone and the Texas Renewable Portfolio Standard. Source: Daxis/Flickr (CC BY-ND 2.0).

Developing and often nascent technologies that are perceived as “new” or “innovative,” such as direct air carbon capture, the hydrogen “rainbow,” major advances in intermittent renewables, small modular nuclear, and long duration storage, are at the forefront of public debate and policy discussions. They frequently appear on the world stage at annual events like the Conference of Parties (“COP”) and World Economic Forum. Fusion, for example, a technology that has attracted billions of dollars of investment despite a long and still uncertain development roadmap, is the subject of breathless strategic consideration, investment, and celebration (Barbarino, 2020; Merriman, 2015).

On the other hand, traditional geothermal technologies have a long and proven track record of generating electricity and providing heating and cooling, which is an obstacle to the perception of geothermal as a new technology worthy of active consideration and discussion. Policy-makers rarely hear about the geothermal opportunity, not only in Texas, but in the world due to a lack of a cohesive and coordinated geothermal advocacy apparatus. The promising and potentially impactful future of next-generation geothermal technologies is simply not on the minds of policy-makers, investors, media, the public, and other stakeholders.

Currently lagging behind intermittent renewable incumbents like solar and wind, geothermal needs abundant, focused, and determined policy attention to drive technology development, support new deployments, and empower investors and markets to engage. In other

words, geothermal will need to play catch-up if it is to have a significant role in the energy transition. But Texas is in a uniquely powerful position with regard to geothermal to lead the world, as it did to support the nascent oil and gas industry a century ago, into an energy future that leverages the core competencies and industries in the State, while driving a decarbonized, reliable, and secure energy future.

#### **Recommendation #1: Convene Geothermal-Specific Committee and Subcommittee Hearings**

Geothermal ecosystem members need time in front of policy-makers to showcase applications, benefits, risks, and potential impact. Texas’ geothermal resources are distinct from the mostly hydrothermal (i.e., highly visible and easy to identify) geothermal resources available in other states such as Nevada, Idaho, and California. Research is underway in Texas, to develop geothermal heat and power from hot sedimentary basins, and novel technologies like supercritical CO<sub>2</sub> power plants. But these next generation geothermal technologies are largely nascent, and further investment in research, development, and field deployment (“RD&D”) of pilot projects is needed.

During the 2021 Texas legislative session, Democrat Representatives Bobby Guerra, Oscar Longoria, and Sergio Jr. Muñoz proposed House Bill (“HB”) 3576 to expand access to finance for geothermal projects through the development of an equity-based strategic geothermal investment fund managed by the RRC. One obstacle for geothermal developers in gaining access to finance is meeting the cash requirements of many lending institutions, which according to one expert interviewed, typically require developers to raise \$3 of equity for every \$1 they plan to borrow, a particular problem for geothermal which has very high capital expenditure costs. The House Committee Report for HB 3576 from the 2021 legislative session would have funded research on how Texas might support the geothermal industry, and sought to be a strong first step toward placing geothermal onto the policy agenda in Texas. More hearings building from this foundation initiated by Representative Guerra are critical to familiarizing Texas policy-makers with geothermal technologies and applications (Guerra, 2022).

To further educate and inform the public, policy-makers, and the media, former Texas RRC Commissioner and past chairman of the Public Utility Commission of Texas, Barry Smitherman, founded the Texas Geothermal Energy





Figure 12.2. Sage Geosystems CEO Cindy Taff speaking at the April 12, 2021 public hearing of the House Committee on Energy Resources relating to the authority of the RCC to study geothermal energy and associated resources as proposed in HB 3576. Source: Sage Geosystems, 2022.

Alliance ("TxGEA") in 2022 to promote the geothermal industry in Texas. TxGEA is a Texas-based, Texas-led advocacy organization that aims to support the transfer of technology, knowledge, and workforce from the oil and gas industry to the geothermal industry in Texas.

#### **Recommendation #2: Learn About the Benefits of Geothermal and Visit the Entities Leading the Way in Texas**

Geothermal has wide ranging applications that could meet key Texan agricultural, industrial, commercial, and residential needs, including oil and gas refining and chemical processing, aquaculture farming, dairy production, processing pulp and paper, mineral recovery, desalination, heating and cooling for residential and commercial structures, and zero-carbon electricity generation, to name a few. Geothermal technologies include Geothermal Heat Pumps for heating and cooling, as well as power production technologies like Engineered (Enhanced) Geothermal Systems, Advanced Geothermal Systems, and other system types.

A recent study showed that only a quarter of Americans in western states, where utility-scale geothermal energy is already deployed, were "familiar" or "very familiar" with geothermal, and a third of respondents said they were

"not familiar" with geothermal (Karmazina & Steel, 2019). However, Texas voters who are knowledgeable about geothermal express high levels of favorability toward the energy source. Polling data from Conservative Texans for Energy Innovation showed that Republicans, Democrats, and Independents all support a greater emphasis placed on geothermal energy technologies, and view geothermal as a part of the future energy mix in Texas (CTEI, 2021).

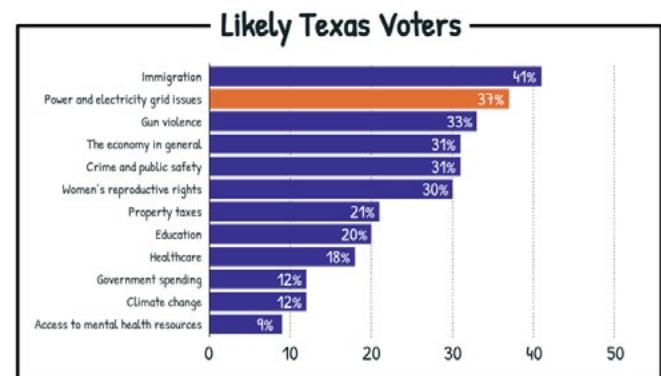


Figure 12.3. Top policy concerns for Texas voters during the 2022 midterm elections. Concerns about the electrical grid in Texas are second only to immigration as top of mind for Texas voters. Source: Adapted from DFP, 2022.



Further, Federal mid-term 2022 polling data from Data for Progress found that Texans place power and electricity grid issues as the second most important policy issue for State lawmakers to address (DFP, 2022).

Recently, the Western Governors Association ("WGA") expressed interest in geothermal energy. WGA comprises the governors of all 19 states west of the Mississippi River, including Texas. The 2022 chair was Republican Governor Brad Little of Idaho, and the 2023 chair is Democratic Governor Jared Polis of Colorado. Both Governors Little and Polis have made investigating geothermal a priority for the WGA. States like Idaho, Colorado, Alaska, California, and Nevada are researching and inquiring if their states can take the geothermal baton and become the vanguard of the geothermal industry in the United States. The WGA is preparing a report on the potential of geothermal in the western United States, to be released in the summer of 2023.

## B. Policies that Support Clean Baseload Energy Sources

As discussed in Chapter 11, Geothermal, the Texas Grid, and Economic Considerations of this Report, geothermal development creates high quality local job opportunities that align with the skill sets of the Texas workforce. However, there are some hurdles to growth in Texas for geothermal, including the lack of rewards or incentives for producing clean (i.e., low or zero-carbon) or baseload energy. The Electric Reliability Council of Texas ("ERCOT") is mandated to purchase the cheapest source of power, and Texas long ago exceeded the minimum amount of renewable energy on the grid required by Texas' Renewable Energy Portfolio Standard, last increased during the Administration of Republican Governor Rick Perry.

### Recommendation #3: Tax Incentives for Clean Baseload Energy Sources

Texas could adopt a tax credit that targets only clean and baseload energy sources, using a market maturity approach. The Federal Investment Tax Credit and Production Tax Credits sunset too often and offer support with time periods that are ill-suited for geothermal development, which make them difficult for geothermal power developers to utilize (Sherlock, 2020; Speer & Young, 2016; Lund, et al., 2012). Texas could adopt a tax credit that targets only clean and baseload energy sources, using a market maturity approach, or an approach more attuned

to the development and investment cycles of geothermal. Instead of the tax credit sunsetting after two, five, or ten years, a Texas focused and market-driven approach could be for the tax credit to sunset in phases once a technology reaches a certain level of market maturity. One suggestion might be for adoption of an investment credit of 3.5 percent, or a production credit of 2.6 cents per kilowatt that sunsets when the clean and baseload energy technology reaches 12 or 15 percent of market share in Texas, or begins to ramp down in phases after the technology reaches 8 or 10 percent of market share on the ERCOT grid. Renewable energy tax incentives provided in the Inflation Reduction Act of 2022 were drafted with intermittent energy and battery storage in mind. However, the exact levels of support (tax credit) to be provided and market penetration for the beginning of the sunset period need further study and should be prioritized in supporting geothermal research.

### Recommendation #4: Value-based Compensation for Grid Resources

The Texas legislature, in collaboration with RRC and ERCOT, could consider other metrics instead of relying solely on a leveled cost of electricity ("LCOE") valuation. One such metric to consider is the leveled avoided cost of electricity ("LACE") valuation. The LACE represents a power plant's value to the grid, whereas LCOE considers only the capital and operational costs of a power plant (EIA, 2018). The goal of using a more integrated set of metrics would be to incentivize and compensate resources based on their value to the grid. Depending upon timing and location, geothermal's high capacity factor greater than 90 percent and low land use footprint would add to the economic attractiveness and value delivered to the grid by geothermal. LACE creates a comparable apples-to-apples valuation among different energy generation technologies.

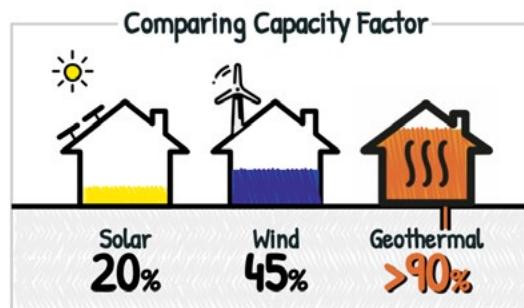


Figure 12.4. Capacity factor comparison for renewable energy technologies. Capacity factor is the percentage of time that a plant is generating electricity. Source: Adapted from EIA, 2014.



### **Recommendation #5: Create a Geothermal Energy Portfolio Standard**

The energy portfolio standard created during the Administration of Republican Governor George W. Bush, and updated during the term of Republican Governor Rick Perry can be revised to incorporate a goal, for example, of 5,000 megawatts of electricity capacity by 2030 that specifically applies to clean and baseload renewable energy technologies, which would apply to geothermal, and also other baseload sources, such as nuclear.

A report on the future of Texas climate jobs published by the Workers Institute at Cornell University notes that a policy decision to encourage the installation of 5,000 megawatts of geothermal electricity capacity in Texas will create 62,500 direct jobs and 53,750 indirect jobs over ten years (Skinner, et al., 2021; Pollin, et al., 2014). This is significant because geothermal jobs offer six figure salaries, are eligible for participation in a number of labor unions, and value subsurface skills and knowledge. Additionally, the Texas climate jobs report notes the importance of making existing buildings more efficient, and the role geothermal can play in reducing costs and decarbonizing buildings. The report notes however that in Texas, the "lack of policy drivers hinders the State's energy efficiency initiatives and blocks substantial energy savings" (Skinner, et al., 2021, p. 30).

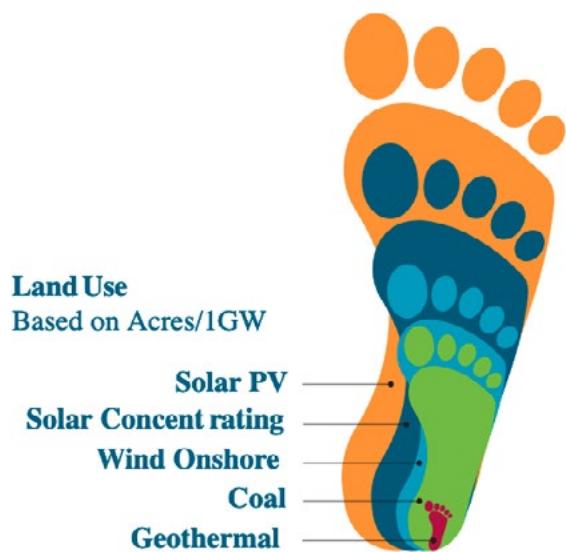


Figure 12.5. The project footprint, acre for acre for one gigawatt of generating capacity, is smallest with geothermal. Source: Geothermal Engineering, 2022 and adapted from NREL, 2022c.

The Texas legislature is in a position to support policies that will encourage the production of clean, always-on, and weather resilient electricity generation as well as heating and cooling, particularly in the wake of Winter Storm Uri. These are key technological advantages of geothermal, along with its small surface footprint compared with all other energy sources, black start ability, dispatchability, and local sourcing, positioning it well to potentially provide secure supply chains and Texas based jobs (NREL, 2022; Skinner, et al., 2021).

With its own electricity grid, Texas is in a unique position to support geothermal, simply by rewarding energy sources serving the grid for offering what the Texas grid needs. This could take several forms, including feed-in tariffs, pricing dispatchability and reliability of resources offered on the grid, clean and baseload renewable energy credits, and tax rebates for the off-grid use of geothermal energy. Another existing mechanism by which Texas could incentivize geothermal energy growth is to extend rebates for high cost gas wells to include geothermal wells. Presently, gas wells receive tax rebates to offset their risk. This incentive, if it is allowed to continue, could also cover high risk geothermal wells.

### **C. Insufficient Workforce Transition and Training Structure**

As geothermal scales, policy-makers and other State stakeholders may have a role to play in defraying geothermal labor costs by supporting the pivot of oil and gas workers into geothermal. The Texas oil and gas workforce is already primed for geothermal development. Expertise in drilling, reservoir management, geoscience, and power plant management are all critical for the growth of geothermal. Texas can support that transition through skills-building programs, retraining subsidies, and labor-focused advisory programs. It can draw on the strength of and work with its oil and gas trade, industry, and professional associations to build these programs.

### **Recommendation #6: Build Community College Geothermal Course/Training Offerings**

With appropriations from the Texas legislature, community colleges can build upon and expand existing programs, such as drill rig crew member training programs like that at Houston Community College, and cooling/heating apprenticeship programs such as those at Tarrant County College and Tyler Junior College, all community colleges in Texas.



Community colleges and Texas research institutions need to build geothermal capabilities into curricula, and deepen the knowledge of professionals who install, sell, market, and manufacture geothermal products and technologies.

#### **Recommendation #7: Provide Support to Build the Future of Geothermal Higher Education, Research, and Development**

The Texas legislature should consider potential options and develop support mechanisms to fund geothermal curriculum development at Texas universities, as well as research and development of geothermal technologies and applications incubated and launched from within Texas' premier engineering and subsurface academic programs.

Declining enrollment in petroleum engineering programs across Texas could be addressed with the establishment of geothermal engineering schools of the future, with robust, interdisciplinary research programs funded through these support mechanisms, such as the Permanent University Fund ("PUF"). The PUF is managed by The University of Texas Investment Management Company, a 501(c)(3) corporation charged with overseeing PUF investments to support the The University of Texas System and The Texas A&M University System. See [Chapter 13, State Stakeholders](#) for greater detail about opportunities to use the PUF to develop and deploy geothermal in Texas. Texas has a unique opportunity to turn the clean energy transition into an energy expansion that benefits all Texas' core competencies and areas of legacy expertise, and that values the State's existing skill sets and workforce in the hydrocarbon industry.

#### **Recommendation #8: Explore the Opportunity of Geothermal Development on State and University Owned Lands**

As explored in [Chapter 13, State Stakeholders](#) of this Report, State owned lands, like University Lands, are a great place to demonstrate and take advantage of geothermal applications, such as Direct Use and power production technologies. Lands owned by University Lands can be used for applications like Oil and Gas Well Reuse to produce geothermal energy, to provide Direct Use heat to nearby agriculture and ranching operations, to heat and cool buildings, and many other uses. Further, given the growing trend among colleges and universities, as discussed in further detail in [Chapter 2, Direct Use Applications](#) of this Report, to install district Direct Use heating and

cooling systems to heat and cool campuses, Texas should incentivize adoptions of these geothermal systems across institutions in the State. Finally, lands owned by University Lands could be future sites of geothermal electricity production, helping generate revenue for the PUF.

Examples of universities in other states utilizing geothermal energy include Boise State University in Boise, Idaho; Colorado Mesa University in Grand Junction, Colorado; Cornell University in Ithaca, New York; and North Dakota University in Grand Forks, North Dakota, to name a few. Universities that switched to geothermal energy, such as Ball State University in Muncie, Ohio are saving millions of dollars in operational costs and reduce thousands of tons of carbon from annual operations (Lowe, et al., 2010).

#### **D. Resolve Regulatory Hurdles and Improve Coordination Among State Agencies**

There is little coordination among government entities in Texas with regard to geothermal energy, which is regulated, according to the Department of Energy's OpenEI project, by the General Land Office, RCC, the Public Utility Commission of Texas ("PUC"), and the Texas Commission on Environmental Quality ("TCEQ"). This lack of coordination creates regulatory, mineral and water rights, and permitting uncertainty among government agencies in Texas.

#### **Recommendation #9: A Single Geothermal State Agency**

Consolidate authority to release and monitor rules and regulations for geothermal exploration, development, and deployment under a single government agency, whether an existing agency such as the RCC, the PUC, the TCEQ, or a new agency.

Generally, Texas is a regulatorily friendly State in the realm of subsurface energy production. In pursuit of clearing the regulatory path, Texas should consider establishing a State-level goal for the development of geothermal, designating a State agency supported by adequate staff, tasked with organizing resources across agencies to prioritize that goal. Part of this team's responsibilities might be to examine the State's regulatory stance toward geothermal energy. The permitting process for geothermal developers is spread across multiple state agencies, with no single agency responsible for overseeing the development of geothermal projects.



One regulatory step that Texas can take is to create a clear set of definitions and clarify associated ownership rights of geothermal energy, which will be explored in more detail in [Chapter 14, Who Owns Heat? Legal Considerations for Texas Geothermal Developers](#). Until this issue is settled legislatively or by the courts, it will hinder geothermal development in Texas, as it creates uncertainty for developers and financiers alike.

#### **Recommendation #10: Resolve Who Owns Subsurface Heat**

The Texas legislature should clarify if ownership rights to geothermal heat and energy should belong to the surface estate, or if they belong to the mineral estate.

Because next generation geothermal technologies create new capabilities, like the ability to recover only heat from the subsurface, without the production of water, they also present novel legal issues that few, if any, states have tackled to date. This is an area of fast moving innovation where Texas can lead by coordinating policy development with technology development, much of which is occurring in the State.

Other states have taken steps to make clear how geothermal resources are classified. Nevada, for example, classifies geothermal resources as minerals, though it is managed as a water resource. Many other western states, such as Idaho, have a temperature gradient to distinguish between resource type, typically between 97-121°C (207-250°F), above which water is regulated as a mineral and below which as water.

#### **Recommendation #11: Clarify Water Rights by Geothermal Technology System**

Enact legislation clarifying rights to energy produced from water-source geothermal, as well as by waterless closed loop systems. This would materially reduce risk and cost for geothermal developers.

There are over 7,000 abandoned oil and gas wells ("AOGW") in Texas that no longer have a responsible entity to oversee or operate them, referred to as orphaned wells (RCC, 2022; Malewitz, 2015). Current law allows for AOGW with no responsible operator to be adopted, but only for continued oil and gas purposes. This is a missed opportunity for the private sector that the geothermal industry could leverage.<sup>1</sup>

<sup>1</sup>The RCC recently published a tool that allows the public to search and locate well plugging activities funded by a grant from the U.S. Department of Interior in 2022. Consideration should be made to assure that geothermal candidate wells are not prioritized to be plugged under this initiative (RCC, 2023).

#### **Recommendation #12: Allow Geothermal Companies to Adopt Orphaned Wells**

Revise and/or clarify current Texas law regarding the adoption of orphaned oil and gas wells to present an opportunity for the geothermal industry to build a new market, reduce liability for the State, and reduce the number of wells without a responsible owner.

Land use is another major cost to geothermal energy producers. Relative to other states, a small percentage of Texas is Federally-owned land (roughly five percent) putting Texas in the bottom five states in the country (CRS, 2020). This means that in addition to building transmission infrastructure, geothermal developers on private land must pay for leases and royalties. An analysis to identify how and whether land use policies might defray these costs should be performed.

Though this is less relevant in the geothermal context than in the intermittent renewables space, since the State's geothermal resources are largely co-located with the State's major population areas as discussed in detail in [Chapter 4, The Texas Geothermal Resource](#), there may be infrastructure projects that could lower the cost of transmission to high load areas, in the spirit of CREZ. Further, tax credits for grid interconnects for geothermal projects might be considered. The State may also be able to play a role in subsidizing geothermal energy development through incentives for conservation and restoration of land around geothermal plants, which could overlap with oil and gas producing areas, agriculture, manufacturing, as well as intermittent renewable energy farms.

### **E. Government Programs to Empower Private Markets**

Texas has a rich history of long-term investments in game-changing technologies with support for research, development, and the demonstration ("RD&D") of new technologies. Geothermal offers multiple areas for potential RD&D support, through research grants or tax credits. Drilling, subsurface characterization, reservoir creation and operation, and Direct Use for heating and cooling are all areas where technology is being developed and could be supported.



### **Recommendation #13: Heating and Cooling Agriculture and Manufacturing Grants**

The Texas legislature can support geothermal development by creating a grant program for agricultural and industrial manufacturing processors to install and deploy geothermal Direct Use, both for industrial heat, and heating and cooling systems for buildings. This could also be set up as a tax credit that could include housing and commercial developers to incorporate geothermal Direct Use heating and cooling systems.



Figure 12.6. Houses in the Whisper Valley subdivision are heated and cooled with Geothermal Heat Pumps. Photo taken during Winter Storm Uri.  
Photo credit: O.Nealio.

Private companies and developers need incentives to transition from legacy and incumbent operations. This is particularly true given that geothermal projects require a supply chain that is quite different from the upstream oil and gas industry. Instead of pipelines, refineries, and ships shuttling a liquid commodity around the globe, geothermal projects require utility grid connections, electricity off-takers, and power purchase agreements. Further, operating a geothermal project requires operating entities to become or behave more like electricity generators.

### **Recommendation #14: Geothermal Utilities Grants for Electricity**

A Texas inspired geothermal utilities grant program could assist geothermal power developers in partnering with municipalities, electric or energy cooperatives, and public utilities to produce electricity for ERCOT.

Geothermal energy, generally located closer to population centers than Texas' primary wind resources, will not require hundreds or thousands of miles of transmission

lines in order to grow and scale. But the PUC could support private projects, and especially the ability for geothermal developers to recoup costs over time through taxes similar to benefits received by gas, petroleum, wind, and solar developers. Policy-makers can look to the success of the Cancer Prevention & Research Institute of Texas ("CPRIT") as an example of how the State can support the growth of a new industry of strategic importance to the State through public-private development of infrastructure and RD&D. CPRIT is now a \$6 billion, 20-year initiative, and the second largest cancer research and prevention program in the world. A geothermal fund would seek similar objectives to CPRIT, such as investments in the State's research university systems with world leading expertise in subsurface engineering, as well as the State's community colleges, expansion of geothermal energy in the State, and empowerment of innovation and technological breakthroughs leveraging the State's legacy industries, such as those discussed in [Chapter 8, Other Strategic Consideration for Geothermal in Texas](#) of this Report.

Geothermal requires large, long-term capital expenditures, the type of capital that State governments are well situated to support. Loan guarantees, insurance entities to mitigate risk, risk mitigation funds, and strategic investment funds are all potential methods to stimulate capital flows into the geothermal industry, particularly for demonstration projects and pilots, which is a top priority. As discussed in detail in [Chapter 6, Oil and Gas Industry Engagement in Geothermal](#) of this Report, piloting was the preference of 87 percent of industry participants interviewed. An early draft of Texas House Bill 3576, introduced in 2021 by Democrat State Representatives Bobby Guerra, Oscar Longoria, and Sergio Jr. Muñoz lays out another approach to expanding access to finance, through the development of an equity-based strategic geothermal investment fund managed by the RCC.

### **Recommendation #15: Risk Mitigation Funds**

The Texas legislature can create a risk mitigation fund to provide loans to cover a portion (e.g., 60 percent) of the drilling cost for geothermal pilots and projects, that can be converted into grants if development of the geothermal field is unsuccessful. To minimize losses, a premium can be charged to ensure a positive return based on risk, and limits set on total wells covered and monetary claims to limit losses.



Risk mitigation funds were used successfully in the United States in the 1980s through the Public Utility Regulatory Policies Act of 1978, of which the program has since sunsetted, and more recently through financing models that have supported dramatic growth of geothermal power in Germany, Denmark, Kenya, Turkey, Costa Rica, Switzerland, France, Iceland, Indonesia, and the Netherlands (Gehringer, 2017; Ngugi, 2014; Lund, et al., 2012; Robertson-Tait, et al., 2008; PURPA, 1978).

Continuing with the topic of the capital-intensive aspect of geothermal development, Chapter 313 of the Texas Economic Development Act helped Texas school districts attract high-capital intensive industry to local communities, many of them rural (Texas Comptroller, 2022). This tax program works by discounting local school district property taxes for corporations, but was not renewed during the 2020 legislative session.

#### ***Recommendation #16: Consider Reviving Texas Chapter 313***

*Inclusion of clean and baseload energy in a revived Chapter 313 tax program could enable the geothermal industry to commercialize and scale, while supporting Texas industry, and local schools. Careful study of the pros and cons of reviving Texas Chapter 313 for the benefit of the geothermal industry and local schools and communities should be a priority area for supporting research in geothermal.*

## **IV. Geothermal and Opportunity to Build Bipartisan Coalitions**

Geothermal sits in a rare political and social space in an increasingly polarized political and policy climate. It is on the precipice of gaining significant political support from policy-makers across the ideological spectrum, who see specific aspects of interest for their constituents, in which their values can be realized through the development and deployment of geothermal technologies. The predicament for the geothermal industry is how to balance its desired attributes, while avoiding polarization and partisanship.

Organizations such as the Environmental Defense Fund, the National Audubon Society, Clean Air Task Force, the Natural Resources Defense Council, as well as labor unions increasingly recognize the climate, environment, economic, and societal benefits of geothermal technologies and applications (Audubon, 2022; CATF, 2022; NRDC, 2022; EDF, 2021). This new recognition

provides the geothermal industry with the opportunity to weave through the polarization of energy policy, as it offers a path forward for both sides of the aisle.

The oil and gas industry supports geothermal because it leverages the skillsets, technologies, intellectual property, and assets of the industry, and provides a just transition for workers within their existing core competencies in drilling and subsurface science. In Texas, terms such as resilience, energy independence, national security, drilling, black start, and baseload are used to describe the attributes of geothermal. Oil and gas is increasingly viewing geothermal as a global market in which they can play an outsized role, and with increasing development and scale comes increasing visibility. (Beard, 2020) This creates the need for outreach and collaboration with environmental organizations if we are to avoid the friction and conflict that resulted from the shale boom.

Environmental organizations, on the other hand, are attracted to geothermal because it is a clean, ubiquitous, small footprint, and limitless source of renewable energy that could be deployed to help achieve climate and environmental goals. Environmentalists point out that geothermal doesn't require mineral extraction, or need vast amounts of critical minerals for manufacturing. Further, it advances decarbonization goals, reduces the need to construct additional long-distance transmission infrastructure, and creates opportunities to advance environmental justice and equality goals in disadvantaged communities.

In climate impact circles, phrases such as climate mitigation, decarbonization, renewable energy, green baseload, and diversity, equity and inclusion are often associated with geothermal. Climate activists seek to address the existential and global threat caused by the climate crisis, which requires a coordinated international response using technologies that are quickly deployable at impactful scale.

These narratives describe the same unique energy source, but with different political and cultural constituencies using different languages, narratives, and terminologies to describe why they support it. This presents a rare and unique political and policy opportunity for geothermal, where even the most polarized political adversaries may find themselves both in support of the same geothermal effort.



There is an active negotiation occurring in geothermal currently, on all levels, between the oil and gas industry to startups, red states and blue states, Democrats and Republicans, challengers and incumbents, and everywhere in between - all seeking to capture the geothermal narrative (Jones, 2022). But all stakeholders have the same end goals: to see geothermal grow. The challenge over the coming years, which will impact the trajectory of geothermal development, will be for all entities to find the political courage to stand together inside the same tent.

The next three Sections of this Chapter widen the perspective of geothermal industry growth and RD&D outside of Texas and into a global market.

## **V. An Opportunity for the U.S. to Lead the Geothermal World, From Texas, Through a Dedicated Federal Geothermal National Laboratory**

Due to the nascent stage of the geothermal industry, and the period of growth and innovation that it is experiencing, much of it emerging from Texas, there is currently no world leader in the geothermal field. Some countries and regions are better known for their deployment of geothermal technologies than others, but a clear vanguard has yet to be identified. With purposeful leadership, Texas is poised to take on this role as the global epicenter of the oil and gas industry, and its transferable skills, workforce and assets. Establishing a dedicated national lab with a singular focus on geothermal and related technologies and applications will require a consortium of geothermal champions, including the Texas legislature, Texas Federal and State congressional delegations, and the Texas governor, in cooperation with the Federal government, private sector, and other organizations.

The study of geothermal energy technologies and applications is currently fragmented in the United States. Geothermal research is conducted individually across U.S. government agencies and DOE national labs such as Idaho National Lab, Sandia National Labs, National Energy Technology Lab, Lawrence Berkeley Lab, U.S. Geological Survey, Geothermal Technologies Office, National Renewable Energy Laboratory, Brookhaven National Lab, Bureau of Land Management, U.S. Forest Service, Argonne National Lab, and Oak Ridge National Lab, among others.

Additionally, there are research universities across the country individually studying geothermal, and pursuing research consortia on the subject.

Texas can initiate a Federal and State partnership to locate a geothermal specific lab in West Texas, which could be modeled after CPRIT. A geothermal lab could consolidate and coordinate the many parallel and disorganized research efforts from across the nation to refocus, streamline, and empower a vision for the future of geothermal RD&D in the United States. The research authorities of this lab could include geothermal, but perhaps also carbon capture, usage, and storage ("CCUS"), as well as the recovery of critical minerals from geothermal brines such as lithium, manganese, zinc, potassium and boron (Jones & McKibben, 2022; McKibben, et al., 2021). Both CCUS and mineral recovery from brines, lithium in particular, are related to both geothermal and the subsurface. These technologies could thus provide force multipliers for the work of the proposed lab. The advancement and study of the composition of geothermal brines, engineered Working Fluids for geothermal projects, and advanced surface equipment for geothermal plants might also be within this lab's purview.

Currently, the United States must import processed lithium to meet demand related to energy storage, and most lithium is mined from geopolitical rivals or countries with authoritarian governments such as Russia, China, and the Congo. Further, many of the lithium mines in Australia and Chile are owned and managed by the Chinese government. A geothermal national lab in West Texas might explore, research, demonstrate, and develop technology and tools to address challenges such as how to increase U.S. lithium production through the deployment of geothermal.

## **VI. Building Public-Private Partnerships Between Industry and State Government**

There are some circumstances where the most effective and efficient way to advance a complex and multi-disciplinary goal is within the cooperative structure of a public-private partnership ("P3") between the government and private industry. Perhaps the most notable recent example of the upside of such endeavors is the partnership between NASA and Space-X to shuttle people and cargo to the International Space Station, and more recently,



collaborations supporting deep space exploration.

Through these partnerships, the government benefits from the speed, nimbleness, and specialized expertise of industry partners, while saving money, and the industry partner is able to pursue internal programs of strategic interest with a wide berth to incorporate innovation, commercializing and scaling new markets, and “out of the box” approaches. Geothermal development offers exactly that type of mutually beneficial P3 arrangement, with the promise of speeding development, deployment, and commercialization, and getting first of their kind projects into the field and prepared for scalability by private industry. Governments at the Federal or State level will need to create finance tools and appropriate funds that facilitate, encourage, and increase private investment into geothermal technologies.

### **1. What Would the Geothermal P3 Look Like?**

There remains a large government role in P3s to create the foundation for a new industry such as geothermal, and facilitate an expansive and expensive deployment of energy infrastructure. There are two main components to a P3: 1) government financing and 2) government funding to leverage private sector know-how, cost mind-set, and optimization.

Reducing financial hesitancy from the private sector can be achieved through risk mitigation tools, the first component of a P3. Sound policies and innovative risk mitigation mechanisms are helpful. Risk mitigation tools can target early phases of geothermal projects, which is crucial to unlock investment in industry. A risk mitigation fund, for example, with the authority to issue loans of up to \$4 billion, if enacted by the Federal government, or \$750 million in mitigation authority, as a Texas initiative, specific for district cooling/heating and electricity drilling and exploration projects. A risk mitigation fund will need to have proper operational, due diligence, execution, and evaluation support. In Texas, such a program could be administered through the RCC or another State agency.

Governments can look to geothermal industry associations, national labs, research universities, and geothermal companies to determine what aspects and quantities the geothermal risk mitigation fund would cover for drilling and exploration costs (Gehringer, 2017; Ngugi, 2014; Lund, et al., 2012; Robertson-Tait, et al., 2008). For unsuccessful geothermal wells, the loans

would convert into grants, thus be forgiven. Successful well explorations repay loans through a success fee or premium. An example could be 130 percent repayment of the cost of a geothermal exploration project or well. Parameters will need to be established for levels of loan repayment and forgiveness for successful, unsuccessful, and partially successful exploration projects or wells. Definitions and parameters will need to be agreed upon upfront with developers and government agencies.

Risk mitigation tools, in various forms, have a proven track record, and have proven to be a catalyst for geothermal development in countries such as Germany, Denmark, Kenya, Turkey, Costa Rica, Switzerland, France, Iceland, Indonesia, and the Netherlands (Gehringer, 2017; Ngugi, 2014; Lund, et al., 2012). The GEORISK Project in Europe, the GREM Project in Indonesia, the GRMF for eastern Africa, and the GDP in Turkey are all various risk mitigation programs designed for geothermal development in those locations. Financing support to mitigate early-stage exploration risk is a critical hurdle to address if geothermal is to scale, and this is where a P3 offers unique leverage.

The second component of a P3 is securing appropriations from the Texas State legislature to help build a marketplace and initial demand for geothermal technologies. Funds will need to be appropriated to government agencies to provide loans and grants to agriculture, manufacturing, commercial, electric utilities, and industry to transition from hydrocarbons to geothermal. One example is grant programs administered by state departments of agriculture to dairy farmers, greenhouses, or food dehydration companies to pivot to geothermal heating and cooling systems (i.e., thermal systems). Another example is state departments of commerce grants for rural and urban communities to install district thermal systems or for rural municipalities to partner with geothermal electricity developers to build power plants and enter into purchase power agreements with utilities. Geothermal specific grant programs established through existing government agencies and programs will build a marketplace around geothermal that the private sector can then amplify.

Both components can be tied to market maturity; as market maturity shifts from emerging markets to mature markets, the risk mitigation program scales down and eventually sunsets. This could happen when the geothermal market share reaches, for example, 10 percent



in the electricity market and 40 percent in the heating and cooling market for the agriculture, commercial, and industrial economic sectors. Other market maturity levels could be established by megawatts of electricity on the grid, or megawatts of thermal energy produced rather than market penetration.

## VII. An Opportunity to Lead the World in Subsurface Environmental Policy

As discussed in detail in [Chapter 10, Environmental Considerations and Impact](#) of this Report, among available energy technologies, geothermal has the smallest lifecycle carbon impact, smallest land footprint per megawatt of energy generated, and lowest use of minerals required to build and operate power generation facilities and Direct Use applications.

As a leader in subsurface energy extraction, and leveraging the environmental health and safety, process and protocol development, standardization, and seismicity monitoring knowledge base of the oil and gas industry, Texas has the opportunity to take the lead on environmental policy related to the growth and development of geothermal energy technologies.

Every energy technology creates a carbon footprint and causes harm to the climate and environment; solar, wind, and geothermal included. However, some energy technologies have greater environmental consequences and greenhouse gas emissions than others. Decisions about what energy technology to deploy may be best decided at regional or local levels taking into account geography, weather, climate, population, load centers, and other important factors.

The proposed West Texas geothermal focused national lab, in partnership with Texas research institutions and universities, might explore the climate and environmental offsets caused by geothermal, such as seismicity, drilling noise, and the use of frac'ing for Engineered (or Enhanced) Geothermal Systems. Better understanding of climate and environmental impacts of energy technologies could become part of the mission of a West Texas geothermal lab.

Additionally, a national lab focused on geothermal can research other environmental concerns, as well as social license and community engagement issues before they become impediments to geothermal development. A

recent lawsuit by the Burning Man Project to prevent Ormat Technologies from exploring northwestern Nevada for geothermal resources is an example of the need to address community engagement and other social license and environmental concerns before they delay or stop developments (Mindock, 2023). A national lab could help with this and research other environmental, social license, and community concerns such as in the case of the endangered green horned frog (Malo, 2021), debunking misinformation about geothermal technologies, and respecting and observing the spiritual and religious uses of geothermal resources by indigenous populations in the United States (Grandoni, 2022).

## VIII. Guide to Becoming a Geothermal Policy Champion

As has been mentioned throughout this Chapter, there are few geothermal policy champions in Texas, or indeed in the United States currently. Because of this, geothermal fails to be placed on policy agendas. There is a disparity between the way geothermal is viewed and treated in the policy process, versus the maturity of geothermal technologies in the field, and the accelerating innovation that is occurring in the geothermal startup ecosystem and oil and gas industry.

The policy process as shown in Figure 12.7 views geothermal as if it was in a stage one level of development. This first policy development stage is for technologies or concepts that are unproven or have never been studied, lack a skilled workforce with technical expertise, and/or are nascent concepts with no previously installed infrastructure. Examples might include the hyperloop to transport people in individual pods below ground to relieve traffic aboveground, or lifting giant blocks of cement with a crane as a form of mechanical energy storage to be used later to create electricity.

However, the reality of geothermal is more complex, and in many ways much more mature. Geothermal systems such as Direct Use, Conventional Hydrothermal Systems ("CHS"), and even some Engineered Geothermal Systems ("EGS") concepts, are far beyond the first stage of the policy development process. Policy-makers need to catch up and move to stage two and three. This third stage of the policy process is to scale and commercialize already proven geothermal technologies using the power and capabilities of the private sector. Stage two is to



# Policy Development Framework

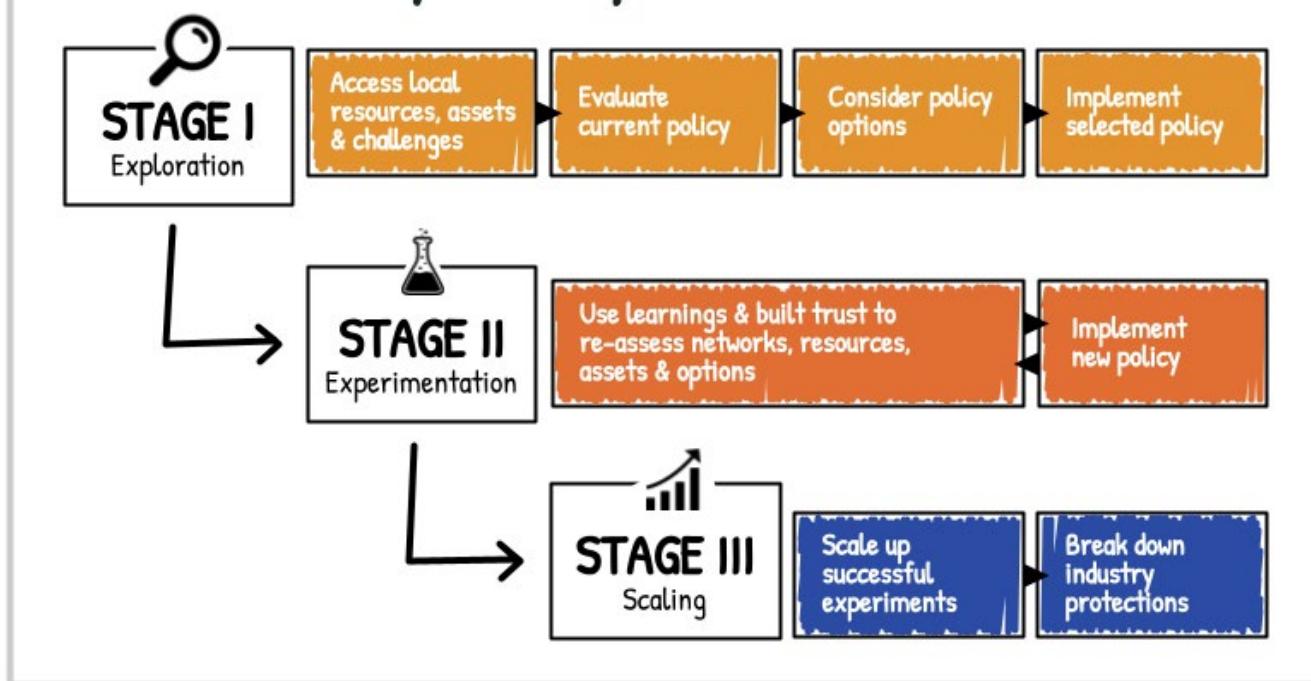


Figure 12.7. The policy stage where the geothermal industry currently sits does not align with the proven, demonstrated, and deployed technology stage of the geothermal industry. Source: *Future of Geothermal Energy in Texas, 2023*.

## IX. Conclusion

support demonstration and pilot projects of innovative geothermal concepts, such as SuperHot Rock and AGS/Closed Loop Geothermal Systems in Texas.

To remedy this hurdle, policy-makers in Texas have the opportunity to leverage a skilled existing oil and gas workforce, supportive subsurface policies and regulations, existing and proven hydrocarbon technologies, and deep cultural ties to subsurface energy production to promote and launch a geothermal industry in Texas. By shifting attention to the second and third policy stages, Texas policy-makers can knock down policy and regulatory hurdles, scale up successful demonstration and pilot projects, and launch the next generation geothermal industry in the heart of Texas.

This Chapter explored the vast potential for geothermal technologies in Texas and the role of the State government. A world leader of the growth and scale of next generation geothermal development has yet to appear on the world stage. Texas, through its State and Federal policy-makers, is poised to grab the reins and become that champion, if it adopts a position of bold action and leadership. Texas legislators, officials from State government, the media, and Texan citizens are therefore encouraged to increase their engagement and become familiar with geothermal technologies and applications. State policy-makers are encouraged to debate, hold hearings, make site visits to pilot geothermal projects, and to learn more about how geothermal can serve constituencies throughout the State. By championing geothermal technologies and building the required policies and supportive regulatory environment, Texas can accelerate the launch of geothermal globally, as it did for the oil and gas industry 100 years ago.



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## Conflict of Interest Disclosure

**Bryant Jones** serves as the Head of Education and Policy at Project InnerSpace, a 501(c)(3) organization that works on issues within the subject matter of this manuscript, and is compensated for this work. He is also a full-time Ph.D. candidate at Boise State University where he researches at the nexus of policy studies, science and technology studies, and energy transition studies. Outside of this role, Bryant Jones 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.

**Mark Hand** serves as a visiting lecturer in the Political Science Department at Southern Methodist University, and is compensated for this work. Outside of this role, Mark Hand 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.

**Jamie Beard** serves as Executive Director of Project InnerSpace, a 501(c)(3) organization that works on issues within the subject matter of this manuscript, and is compensated for this work. She further serves in a non-compensated role as a founding member of the board of the Texas Geothermal Industry Alliance. Outside of these roles, Jamie Beard certifies that she has no affiliations, including but not limited to 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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## Chapter 13

# State Stakeholders: Implications & Opportunities

## Texas General Land Office and University Lands

J. Moss, J. Tackett

***Texas public education, from Kindergarten to University, benefits from oil and gas activities on public lands. Geothermal can play a meaningful role in expanding and diversifying the use of State-owned lands, ensuring the continued prosperity of public education in the State.***

### I. Introduction

Texas public lands, and income derived from these lands, are dedicated to free public education for present and future generations. Such is the mandate of the Texas Permanent University Fund ("PUF") and the Texas Permanent School Fund ("PSF"). The PUF benefits higher education, and is managed by University Lands. The PSF helps support K-12 public schools, and is managed by the Texas General Land Office ("GLO").

The Texas General Land Office ("GLO") is the trustee of the PSF portfolio of land and mineral rights. University Lands, an office within the University of Texas System, manages PUF Lands. As administrators, the GLO and University

Lands are responsible for generating income to the trusts, as well as preserving and protecting the land assets (Reid, 1998). Energy development leases, land leases, land sales, and investment gains generate revenue for both funds.

With the mission of protecting the economic future of Texas by leasing the State's vast land and mineral holdings, trustees value "innovative responsible stewardship" and diverse leasing activities (Bush, 2020). Geothermal energy provides an opportunity for the State to gain experience with clean, baseload electricity generation through stewardship of its lands (Fiscal Notes, 2022).



This Chapter explores considerations for leasing State-owned lands for geothermal energy projects. Drawing from insights described throughout this Report, geothermal may be well positioned to provide opportunities for diversification on State-owned lands, through applications such as electricity generation, desalination, and powering oil and gas operations.

## II. Public Education Endowments

Both of the public education endowments in Texas rely on revenues from leasing public lands. The PUF advances higher education by supporting The University of Texas and Texas A&M University Systems. The Texas PSF is dedicated to public K-12 education. As of 2021, the total value of the PUF was over \$30 billion (UTIMCO, 2021), and the value of the PSF was \$56 billion (Timmins, 2021).

To promote the economic well being of future generations, public education endowments create a stock of wealth from fees or other revenue streams from present day natural resource extraction (i.e., gas, oil, and other minerals). The assets are carefully managed similar to any financial investment portfolio. In Texas, annual distributions are carefully allocated based on strict guidelines first outlined in the State Constitution (Texas PSF, 2021).

### A. Land Holdings

As of 2021 reporting, the PSF portfolio of land and mineral rights totaled approximately 13 million acres (Table 13.1), roughly 65 percent of the State land and mineral rights that the GLO manages. Of this acreage, just over 658,000 acres of PSF land is surface real estate, much of it in West Texas. Of the surface assets, some parcels are not accessible, because they are landlocked by private acreage. Roughly four million acres of the PSF portfolio are Gulf Coast beaches and bays, and all submerged lands to 10.35 miles out into the Gulf of Mexico (Texas PSF, 2021). University Lands manages another 2.1 million acres of State-owned land that benefits the PUF. Most of these parcels are in West Texas.

Of note, the U.S. government claims less than 2 percent of Texas land. Of the 3.2 million Federally-owned acres in Texas, the National Park Service has oversight of 37.3 percent, the Fish and Wildlife Service has 23.4 percent, the Department of Defense has 21.1 percent, and the Bureau of Land Management has just 0.4 percent (Stacker, 2022).

### B. History of Texas Public Lands

To understand the opportunities for geothermal projects on Texas public lands, it is useful to describe the history of the lands. Texas public lands can be traced to the State's history as an independent nation. When Texas joined

Table 13.1. Overview of Texas Public Education Endowment. Source: *Future of Geothermal Energy in Texas, 2023*.

Fund	Permanent School Fund (PSF)	Permanent University Fund (PUF)
Trustee	General Land Office	University Lands
Beneficiaries	K-12 state public education	UT and TAMU systems
Value in 2021	\$56 billion	\$32 billion
Acreage	13 million	2.1 million acres
Location (primary)	West Texas and coastal	West Texas

<sup>1</sup>The U.S. does not have a national Sovereign Wealth Fund. Rather, there are a number of State funds. In addition to Texas, other states with extraction-based state level endowments include Alaska, New Mexico, Wyoming, Montana, North Dakota, Idaho, and Utah (McIntosh, et al., 2022; SWFI, 2021).



the United States in 1845 as the 28th State, it retained ownership of its public land<sup>2</sup>. The Texas Constitution of 1876 bestowed millions of acres and formalized the PSF.

The Texas Constitution of 1876 also marked the beginning of the PUF, calling for the creation of the University of Texas (“UT”) with an initial land grant of one million acres. These one million acres became forever known as “the constitutional million.” State leaders added an additional million acres to the University Lands in 1883, the same year that UT Austin officially opened with a single building.

UT grew slowly over its first 40 years, but growth accelerated roughly 100 years ago. Oil was first discovered on PUF Lands in 1923 at the Santa Rita No. 1 well in Reagan County. As oil flowed, revenue fed into the PUF and sparked new development for the University in the 1920s and 1930s. The core of the Austin campus was built, including the iconic UT Tower. In 1931, the Texas

legislature added Texas A&M University (“TAMU”) as a PUF beneficiary, and authorized a split in net income from PUF investments that still exists today, with UT receiving two-thirds of the funds, and TAMU receiving one-third (University Lands, 2022b).

### III. University Lands

University Lands is the fiduciary steward of 2.1 million acres of land across 19 counties in West Texas, including large parts of the Permian Basin, managing both the surface and mineral interests for the benefit of the PUF. Today, the PUF is the largest public university endowment in the United States, valued at over \$30 billion. Unlike other endowments that support just one university, the PUF provides funds to 27 UT and TAMU institutions and agencies that collectively enroll more than 500,000 students (University Lands, 2021).

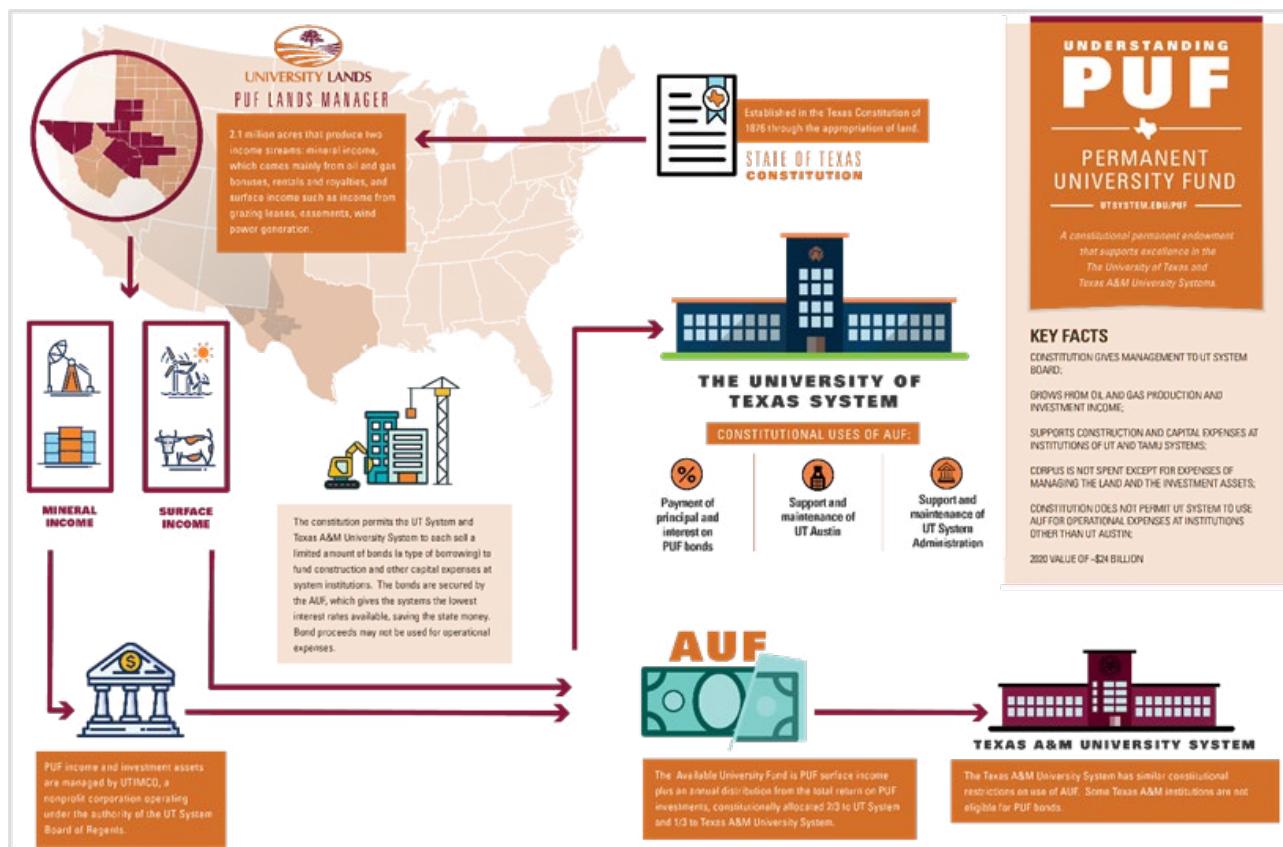


Figure 13.1. Permanent University Fund (“PUF”) revenue comes from leasing surface and mineral rights for energy development, schools, hospitals, churches, and ranching. Source: University Lands, 2021.

<sup>2</sup>The story of Texas retaining its lands when it joined the U.S. also explains why there are so few lands in the State of Texas owned by the U.S. and managed by the Bureau of Land Management (Hewett, 2020).



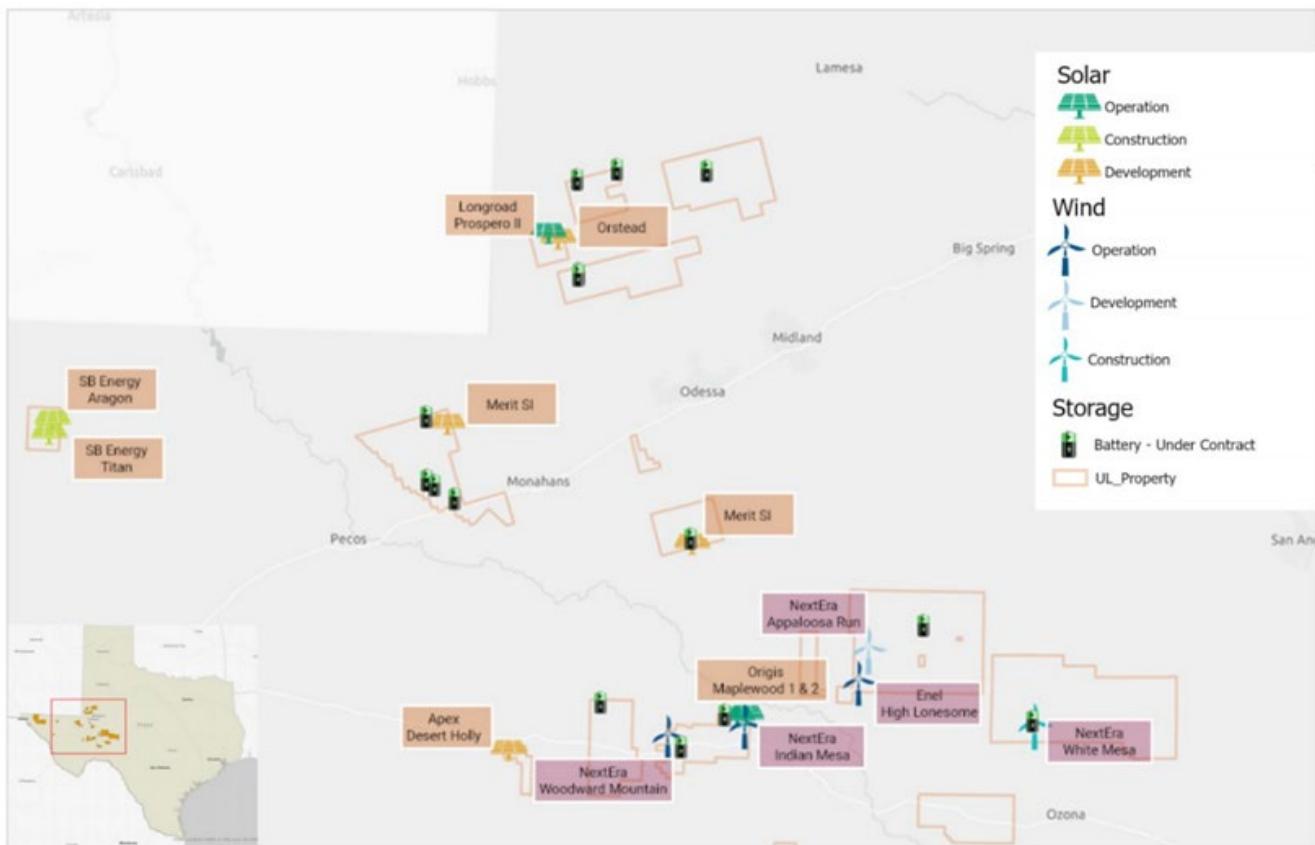


Figure 13.2. A map of West Texas PUF lands with renewable energy projects. Source: University Lands, 2021.

Leasing the surface and mineral rights of PUF lands produces two income streams. Mineral income is primarily derived from oil and gas production in the form of rentals and royalties. Surface income results from a diversity of land uses, including hospitals, churches, livestock grazing, pipeline and power line easements, wind and solar power generation, and agriculture (Figure 13.1). University Lands can also supply water to several West Texas municipalities from major and minor aquifers on the lands.

There is support and interest in diversifying the use of PUF Lands beyond oil and gas production, as is demonstrated by the growth of renewable energy projects on PUF Lands since 2020. Renewable energy is a growing source of land endowment income, with several solar and wind energy developments located on PUF lands (Figure 13.2).

#### A. Oversight of PUF Lands

The leasing of oil and gas on PUF Lands is under the purview of the Board for Lease (“BFL”) of University Lands

(Figure 13.3). Serving on this board are the Commissioner of the GLO, two members of the Board of Regents of the UT System, and one member of the Board of Regents of the TAMU System. For all minerals other than oil and gas, the UT System Board of Regents has management authority.

The Texas Constitution requires that income from mineral rights be invested. PSF funds are managed and invested by the Texas Education Agency (Mills, 2018). PUF investments are managed by The University of Texas/Texas A&M Investment Management Company (“UTIMCO”), with oversight of the UT System Board of Regents. Returns from PUF investments, as well as surface lease income, are deposited in the Available University Fund (“AUF”) and distributed for the exclusive benefit of the UT and TAMU Systems.

The endowment’s annual distributions are governed by the Texas Constitution, and managed by The University of Texas System Board of Regents (Texas PSF, 2021).



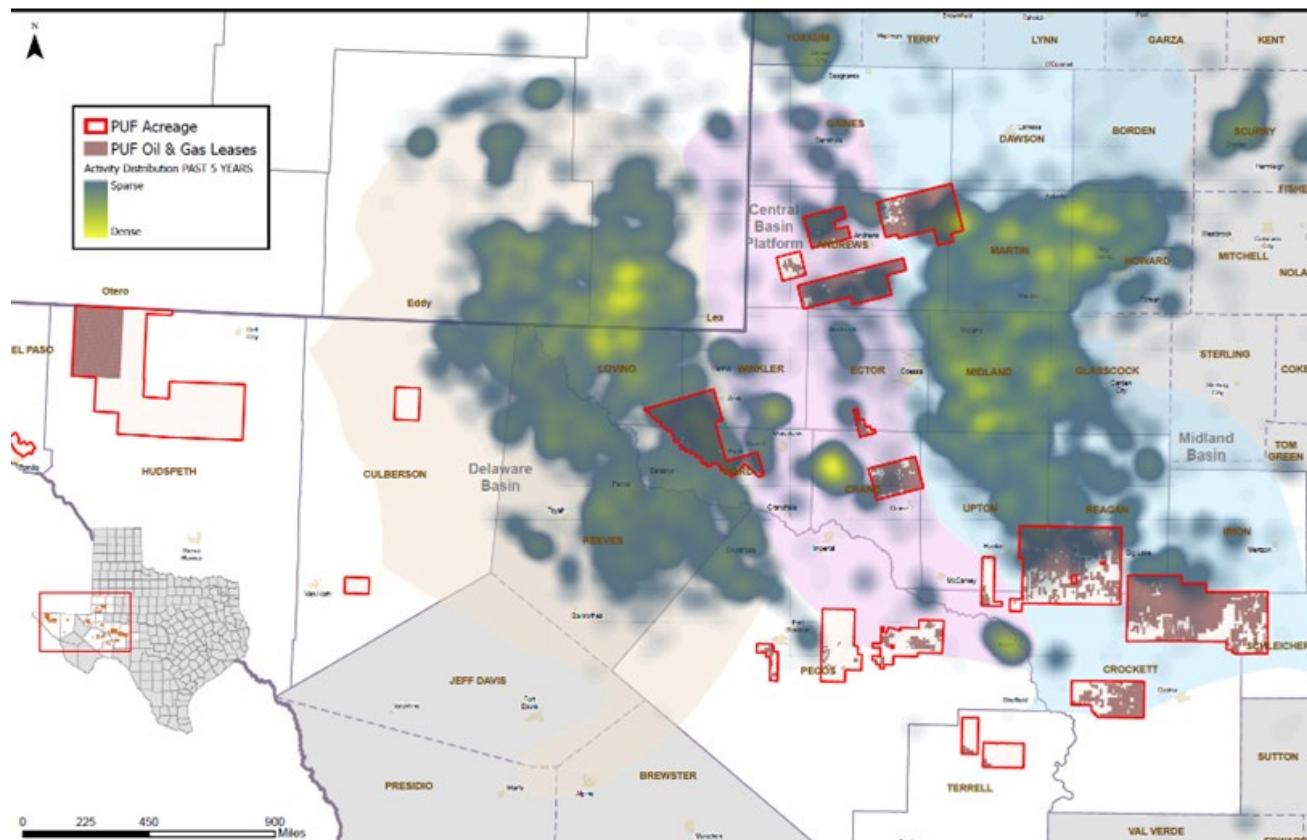


Figure 13.3. PUF acreage in West Texas Permian Basin outlined by red polygon. Previous five years of Oil & Gas activity (as of November 2022) described by dark blue for sparse activity and yellow for dense activity.  
Source: University Lands, 2021.

### B. Sustainability of PUF Lands

University Lands strives to be the best land management organization in the country, providing prudent stewardship aimed at protecting the environment while earning the best possible return on investment. According to University Lands, achieving this mission ensures the lands continue to thrive for generations to come, supporting not only Texas public higher education, but also life changing and life saving research and innovations that improve the lives of Texans and people around the world (University Lands, 2021).

To this end, the organization employs experienced professionals in environmental, conservation, land, geoscience, engineering, and information technology disciplines who work to protect the interests of the UT and TAMU systems, promote awareness and sensitivity for the environment, and maximize the value of PUF Lands (University Lands, 2021).

University Lands prioritizes sustainability on PUF Lands, with attention to reducing truck traffic, monitoring construction, promoting shared infrastructure, and restoring surface leases that have expired or terminated. University Lands monitors water resources to ensure prudent water related commercial activities on PUF Lands. All mineral developers are required to meter and report water sources. In 2019, the organization implemented a groundwater import fee to encourage recycling of produced water and decrease use of freshwater.

The Lease Evaluation Team evaluates leasehold performance and compliance. This team identifies oil and gas leases that are non-producing or low producing. If a lease is terminated, the operator is required to properly plug the wells and remove all equipment and restore the acreage back to pastureland.



## IV. Texas General Land Office

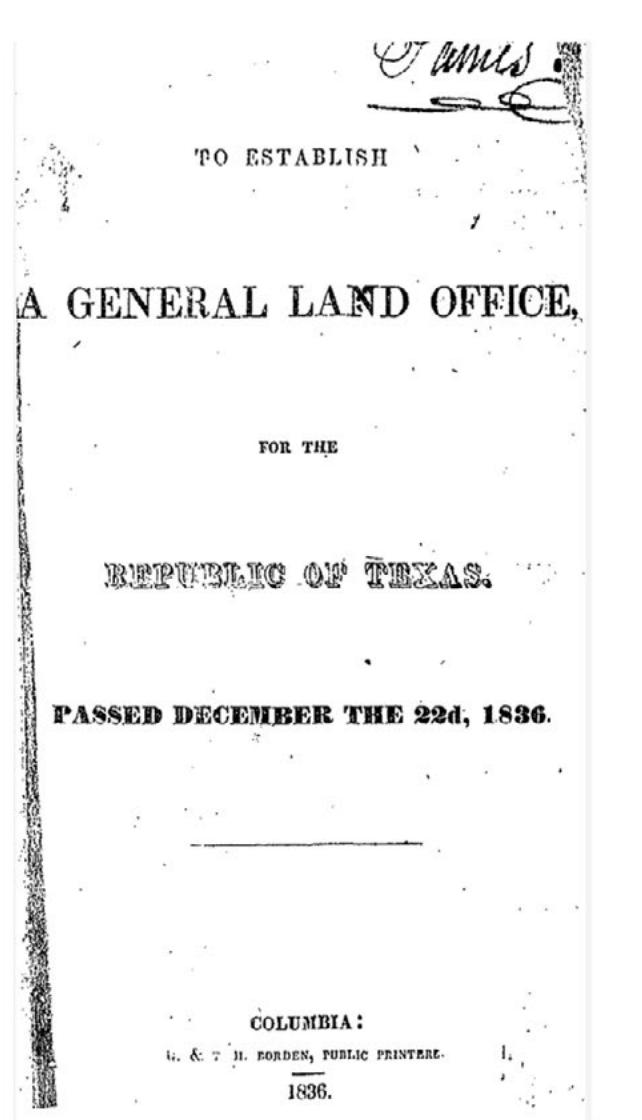
In 1836, the Republic of Texas Congress (Texas was a sovereign republic from 1836 to 1846) formed the GLO to collect and keep records, provide maps and surveys, and issue titles (Figure 13.4). To this day, the GLO manages State lands and mineral rights, including submerged lands out to three marine leagues (about 10.3 miles) into the Gulf of Mexico. The agency's mission is to serve Texas schoolchildren, veterans, and the environment (Texas, 2022b).

In addition to leasing Texas lands, the GLO surveys for exact location of State owned land and minerals, oversees coastal protection, administers Disaster Recovery from Community Development Block Grants ("CDBG-DR") as

well as Mitigation funds ("CBBG-MIT"), preserves historic archives, and watches over the Alamo. Two veteran programs are also under the purview of the GLO, the Texas Veterans Land Board (Veterans Homes) and Texas State Veterans Cemeteries.

Through its State Energy Marketing Program, the GLO sells gas and electricity competitively to public entities through its State Energy Marketing Program. The State's electricity market to public retail customers is being phased out as of 2019, but the gas market continues (Texas, 2022a; Texas PSF, 2021).

The GLO Commissioner is elected by Statewide ballot and serves a four year term. While the titles "Commissioner of the Texas General Land Office" and "Texas Land Commissioner" are used interchangeably, there is no



## AN ACT TO ESTABLISH A GENERAL LAND OFFICE FOR THE REPUBLIC OF TEXAS.

*SEC. 1. Be it enacted by the senate and house of representatives, of the republic of Texas, in congress assembled, That there shall be and is hereby established a general land office, the chief officer of which shall be styled the commissioner of the general land office, who shall hold his office at the seat of government, whose duty it shall be to superintend, execute and perform all such acts and things touching or respecting the public lands of the republic of Texas.*

*SEC. 2. And be it further enacted, That there shall be in the said office, an inferior officer, to be appointed by the said principal officer, to be employed therein as he shall deem proper, and be called the chief clerk of the general land office; who, in all cases, when the said principal office shall become vacant, during such vacancy shall have the charge and custody of the seal and all records, books and papers belonging to the said office.*

*SEC. 3. And be it further enacted, That the said principal officer and every other person to be appointed and employed in the said office, shall, before he enters on the duties of his office, take and subscribe the following oath of office: "I, A B, do solemnly swear or affirm, that I will honestly and faithfully discharge the duties of my office as without favor or partiality, so help me God."*

*SEC. 4. And be it further enacted, That the said commissioner of the general land office shall cause a seal to be made, and*

Figure 13.4. The Republic of Texas formed the General Land Office in 1836.  
Source: Texas General Land Office.



Land Commission (Texas, 2022a). The sale and mineral leasing of PSF lands are managed by the School Land Board ("SLB"). The SLB is composed of three members. The Commissioner of the Texas General Land Office serves as Chairman of the SLB, and is joined by two citizen members. The fund's financial assets are managed by the State Board of Education, overseen by an office within the Texas Education Agency (Texas PSF, 2021).

### A. State Land Classifications

As shown in Figure 13.5, public land parcels are distinguished by State interests in the minerals. A brief history lesson is necessary to explain the patchwork of

classifications on any map of State owned lands. This Section describes Relinquishment Act lands, free royalty lands, and minerals fully retained.

Before 1895, when Texas sold its public lands, the minerals were released to landowners. After 1895, Texas retained the rights to minerals during land sales (McFarland, 2009). But in response to the surge of oil discoveries in Texas in the early 1900s, lawmakers passed the retroactively enforced Relinquishment Act of 1919 (updated by the Relinquishment Act of 1931). Designed to prevent "armed rebellion" by surface owners eager to profit on the discovery of oil, this law appointed the surface owners as the mineral leasing agents of the State.



Figure 13.5. Map of Texas State lands produced from an online, customizable map.  
Source: Bush, 2020.



The legacy of this law is that when an entity wants to develop a "Relinquishment Act" parcel, the surface owner is the only party who can lease the lands for oil and gas development. While surface owners negotiate the mineral rights, the GLO provides final approval of leasing terms, and the State retains half of the bonus, rentals, and royalties. Furthermore, the State has the authority to enforce and cancel the lease. These rules are specific to oil and gas. Other minerals are subject to different provisions (Covert & Sweeney, 2019; Fambrough, 2013).

Sold after 1931, "free royalty" lands transferred nearly all mineral rights to the surface owner. Leases are resolved by private negotiations, and the GLO does not approve the terms of the lease; however, the State receives an additional royalty payment, in the range of 1/8th to 1/16th share of output, on top of the bonus and royalty payments paid to the surface owner (Whitworth & Miller, 1986). The oil crisis of the 1970s prompted yet another change. As of 1973, the State retained full mineral rights on all PSF lands (i.e., minerals fully retained).

### B. Leasing of PSF Lands

The primary source of income for the PSF and PUF are proceeds from leasing mineral interests for oil and gas activities. In the 2021 Financial Statement of the PSF, mineral interests accounted for 81 percent of the fund's Real Assets value (Texas PSF, 2021). The GLO typically earns a 20 to 25 percent royalty from oil and gas produced from leases. Royalty payments are accepted as cash or in-kind, meaning sold competitively to public entities as gas or electricity through its energy market. Leases are also available for a variety of other purposes, including agricultural related activities, commercial development, and solar, wind, and geothermal power (Texas, 2022a).

The State awards leases on PSF parcels through a sealed bid lease sale offered by the SLB (Covert & Sweeney, 2019). Interested parties can also request to the GLO that a tract be made available for a lease sale according to the Texas Natural Resources Code, Chapter 9, Section 9.22, Leasing Procedures.

Between 2007 and 2009, the GLO issued a total of nine offshore geothermal energy production leases in State owned coastal waters. Each lease had a primary ten year term to begin generating electricity. Had they met this goal, the lessors had the option for a 30-year lease

extension. The focus on these earlier leases was to produce enough electricity to participate in the ERCOT market. At that time, geothermal sourced electricity was not sufficiently competitive. All leases expired by 2012 without any geothermal power being developed (Batir & Richards, 2022).

Until recently, no other geothermal leases had been granted on State lands. In September 2022, the GLO opened bidding on six geothermal leases near El Paso. Only one of the tracts received a bid, which won at \$8.46 per acre for 640 acres (EnergyNet, 2022). The lease was listed with the following stipulations:

*The royalty on all surveyed school land is 10% of the gross revenue of geothermal energy. The primary term of the lease shall be ten (10) years. The annual delay rental thereon is fixed at \$3.00 per acre beginning with the first year of the lease (EnergyNet, 2022).*

The sample lease goes on to say:

*If the drilling or reworking operations result in the completion of a well incapable of producing sufficient Geothermal Energy for the Commercial Production of Electricity (hereinafter an "Inoperable Well"), the Lease shall terminate, unless the Lessee commences additional drilling or reworking operations within sixty (60) days after the completion of the Inoperable Well. This Lease shall remain in full force and effect for so long as such operations continue in good faith and in a workmanlike manner without interruptions totaling more than sixty (60) days (Texas GLO, 2022).*

## V. Geothermal Energy on Texas Public Lands

In the spirit of an all-of-the-above energy transition, there is support and interest in diversifying the use of Texas public lands beyond oil and gas production (Bush, 2020). Leasing for geothermal energy production can build on the existing leasing processes for oil and gas or renewable energy projects. The question of "who owns heat?" is important to resolve, and is considered in detail in [Chapter 14, Who Owns Heat? Legal Considerations for Texas Geothermal Developers](#) of this Report. As explained earlier in this Chapter, the State retains mineral interests in much of the land for which it sold the surface rights.



Typically, royalty fees are based on the value of the resource produced. With geothermal, the resource is heat, steam, or fluids, and valuation is likely based on revenue from electricity (or Direct Use heat) production. As a potential model, the U.S. Bureau of Land Management favors a valuation model that escalates – starting lower for the first ten years to offset the high capital expenditure. “Royalty rates for geothermal resources produced for the commercial generation of electricity but not sold in an arm’s length transaction are: 1.75 percent for the first 10 years of production and 3.5 percent after the first 10 years” (BLM, 2007).

While the actual leasing process is likely to be familiar, administrative and operational oversight for geothermal projects may require additional training. Mineral audit and field inspection teams will need a better understanding

of pricing, production, and transportation of geothermal heat and electricity to ensure that proper royalty payments are being made. Furthermore, lease valuation would need to consider the added value of geothermal resources when pricing leases.

#### A. State Owned Lands & Geothermal Energy Considerations

When analyzing a State owned tract for geothermal electricity production, developers should consider proximity to transmission infrastructure, distance from population centers, as well as the depth required to access high temperatures compared to other parts of Texas. Texas Geothermal Resources are considered in depth in [Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development](#).

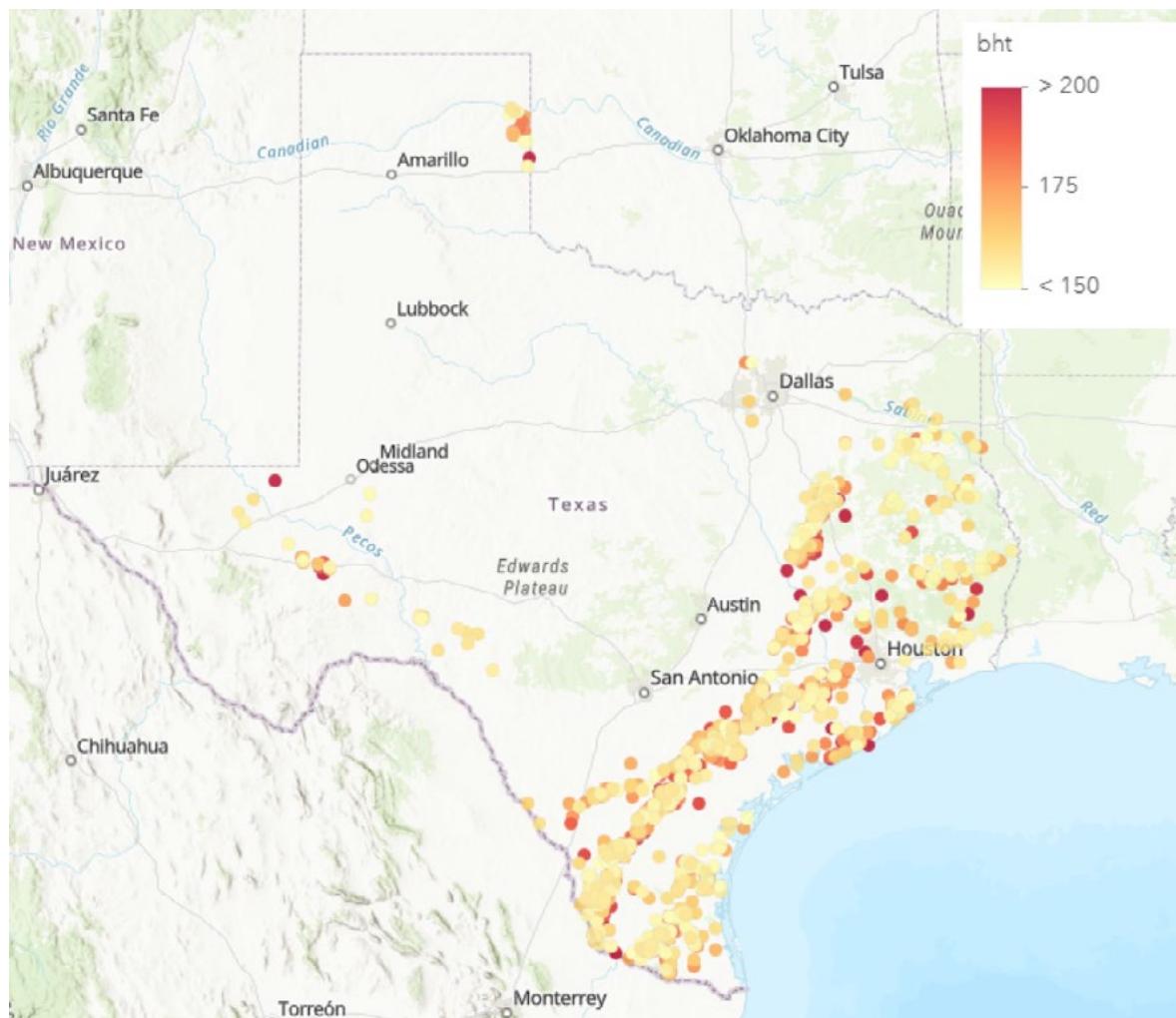


Figure 13.6. Mapping GLO tracts by bottom hole temperatures (BHT). Source: Adeoshun et al., 2021.



Table 13.2. Top three leasing opportunities identified by Texas A&M MBA team. Source: Adeoshun, et al., 2021.

Location	City Intended to Provide Power	GLO PSF Availability	Temperature	Average Depth	Future Population Projects in Area	Distance from Populated Area	Distance from Transmission Line	Score
Camp Creek Lake	College Station/Waco	3	5	5	5	5	3	4.3
Jennings/ Armstrong Oil Fields	Laredo	5	5	5	1	3	3	4.0
Fort Stockton	Fort Stockton	5	3	1	5	5	3	3.6
Weight		25%	20%	20%	15%	10%	10%	

Acting as consultants to the GLO, an MBA capstone team from TAMU produced a report that rated State land holdings for geothermal energy production potential (Adeoshun et al., 2021). With their permission, we synthesize here their analysis and findings.

The MBA team identified three regions that were promising, specifically at Camp Creek Lake, Jennings West Oil and Gas Field, Armstrong Oil Fields, and Fort Stockton. The team's recommendations were informed by mapping bottom hole temperature ("BHT") data from the SMU Geothermal Lab for wells near GLO tracts (Figure 13.6). Areas were then ranked for geothermal suitability using temperature, distance from population centers (including projected growth), proximity to transmission lines, and GLO land availability (Table 13.2).

The team found that the Camp Creek Lake location had high temperature ranges with BHTs in excess of 200°C (392°F), some of which were within 3.1 miles (five

kilometers) of transmission lines or less. These GLO tracts are within 30 miles (48.2 kilometers) of College Station. The Jennings and Armstrong oil fields are located within 50 miles (80.5 kilometers) of Laredo. With active oil and gas production here, there is an opportunity for geothermal co-generation. With an average viable temperature depth of 4.3 miles (seven kilometers), Fort Stockton represented a PUF lands prospect.

Another PUF prospect was discussed in [Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development](#). In the eastern and central portions of Crockett County (east of Fort Stockton), recent heat flow mapping from BHT data indicated temperatures reaching 150°C (302°F) on PUF Lands at 3.4 miles (5.5 kilometers) depth, and areas at 125°C to 150°C (257°F to 302°F) at 11,480 feet (3.5 kilometers) depth. At 10 km depth, resource temperatures range from 200°C (392°F) to over 300°C (572°F) on PUF Lands (Batir & Richards, 2020; 2021).

Table 13.3. Two land acquisition opportunities identified by Texas A&M MBA team. Source: Adeoshun, et al., 2021.

Location	City Intended to Provide Power	GLO PSF Availability	Temperature	Average Depth	Future Population Projects in Area	Distance from Populated Area	Distance from Transmission Line	Score
Brushy Creek & Helen Oil Fields	Victoria	1	5	5	3	5	3	3.5
Brenham	College Station/Waco	1	3	5	5	3	5	3.4
Weight		25%	20%	20%	15%	10%	10%	



The TAMU team also recommended three locations for GLO land acquisition based on the same criteria. Those prospects were Brushy Creek, Helen Oil Fields, and a plot in Brenham (Table 13.3).

Brushy Creek and Helen Oil Fields were selected because of high temperatures near active oil and gas production, suggesting the possibility of geothermal co-generation. Brenham was promising because of its proximity to two growing population centers – Houston and College Station.

## B. Geothermal Co-Production with Oil and Gas Operations

There are almost 1.2 million wells in Texas. Of the nearly 300,000 wells that are actively producing oil and gas in Texas, the State owns an interest in over a third of them (Bush, 2020). That leaves millions of abandoned wells (Malewitz, 2016). Further, when transmission lines are not nearby, oil and gas producers typically run diesel or gas generators for their large power needs (for pumps, compressors, drilling rig motors, and other field equipment).

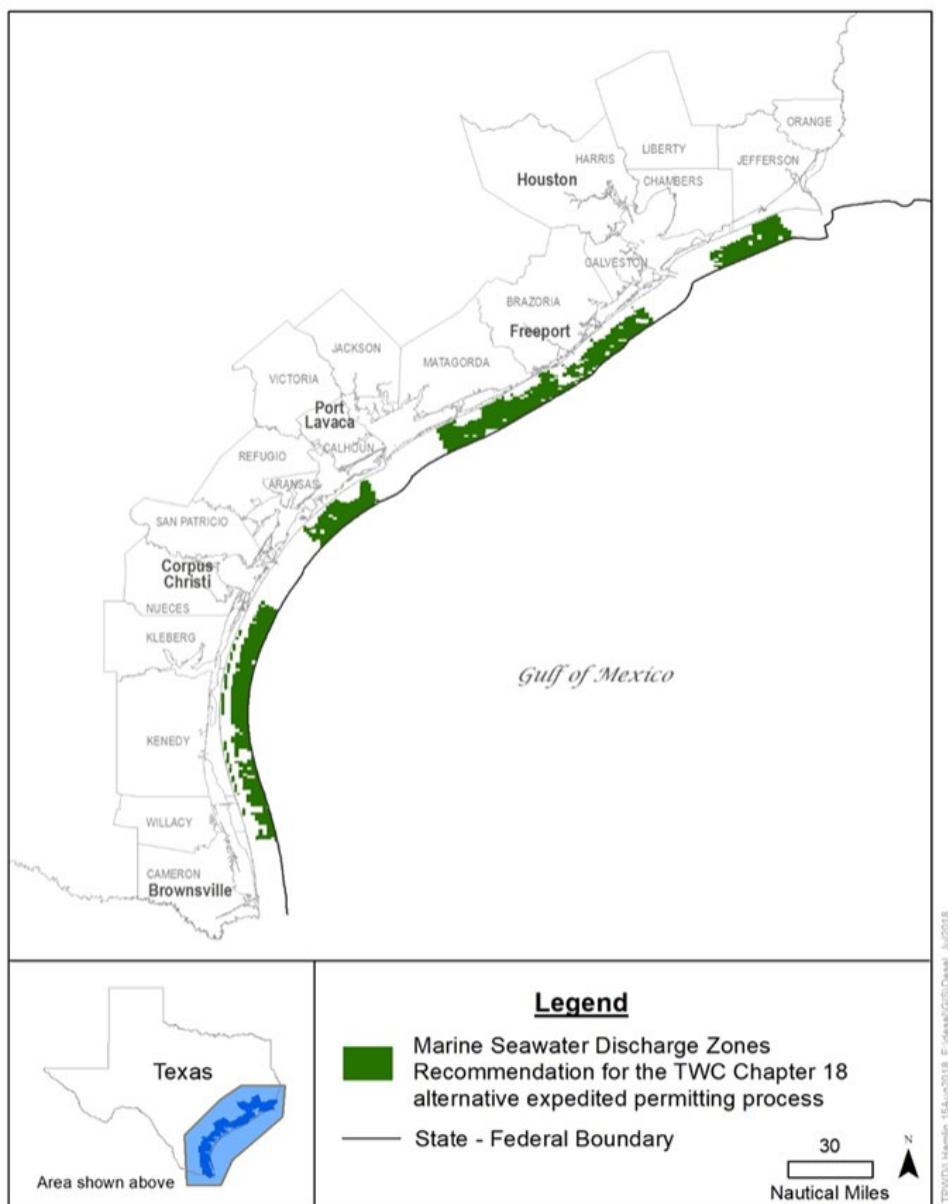


Figure 13.7. In a 2018 report prepared for the 84th Texas Legislature in response to HB 2031, Texas Parks and Wildlife Department ("TPWD") and the GLO mapped zones deemed appropriate for the discharge of desalination waste into the Gulf of Mexico. Source: TPWD & GLO, 2018.



As discussed in [Chapter 3, Other Geothermal Concepts with Unique Applications in Texas](#), there are concepts in development that utilize abandoned and existing wells for geothermal energy production. Modular, Organic Rankine Cycle geothermal power plants can generate electricity with a small surface footprint to power oil and gas operations in the field, and can easily be removed once they are no longer needed.

### C. Geothermal for Desalination

Tapping into seawater accessed along the 367-mile (590-kilometer) Texas coastline may be necessary to meet increasing demand for water (e.g., municipal, industrial, and agricultural) in a changing climate (TWDB, 2019). As discussed further in [Chapter 2, Direct Use Applications](#), desalination is the energy intensive process of purifying salt water for drinking or agricultural use. Geothermal energy can be utilized to reduce the environmental footprint of desalination (Aminfard, et al., 2019).

At the direction of the 84th Texas Legislature, the GLO worked with the Texas Parks and Wildlife Department to identify zones that are appropriate for the discharge of desalination brine, and diversion to protect marine organisms (Figure 13.7). The goal of their study was to expedite the permitting process for desalination projects (TPWD & GLO, 2018).

### D. Support from University Lands and Public Universities

University Lands can support geothermal in Texas by contributing to subsurface studies and exploration, as well as piloting field trials for geothermal projects. Further, the UT and TAMU Systems could support their campuses in the installation of Direct Use geothermal projects, like district heating and cooling system installations, as is discussed in further detail in [Chapter 2, Direct Use Applications](#) of this Report.

Furthermore, the UT and TAMU Systems can provide valuable assistance to geothermal energy development by offering tailored courses, certificates, majors, and

minors in critical areas geothermal drilling engineering, plant design, geophysics, and other unique aspects of geothermal energy production, and even geothermal focused research and development, which the two Systems could support through funding to the schools. In Fall 2022, for instance, Dr. Ken Wisian, an author on this Report, taught a course at The University of Texas at Austin called "Fundamentals of Geothermal Energy Systems," a first for the university. Students explored traditional hydrothermal systems, as well as the potential for Advanced Geothermal Systems in Texas. The class was attended by graduate and undergraduate students with concentrations ranging from Geology, Energy and Earth Resources, and Public Policy. Geothermal curriculum should be offered at all UT and TAMU System universities to support the education of the future geothermal workforce in the State of Texas.

## VI. Conclusion

Ensuring the future of Texas public education means managing Texas public lands responsibly, sustainably, and with vision. Geothermal provides an opportunity for the State to expand its revenue sources, while gaining experience with new technologies, reducing greenhouse gas emissions, supporting local communities, and creating jobs.

In addition to electricity generation, powering oil and gas operations, and desalination, more immediate opportunities for geothermal on public lands include bitcoin mining, storage for excess solar and wind generation, or direct air capture and CO<sub>2</sub> sequestration. These concepts are discussed in further detail in [Chapter 3, Other Concepts with Unique Applications in Texas](#). Furthermore, University Lands and the UT and TAMU systems have extensive resources and capabilities to contribute to geothermal exploration on public lands. Both University Lands and the GLO have demonstrated interest in diversifying the use of State owned lands to ensure the continued prosperity of public education in the State. Geothermal provides a viable and unique pathway to accomplish that goal.



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## Conflict of Interest Disclosure

**John Tackett** serves as Geoscience Manager & Chief Geologist for University Lands in Texas, and is compensated for this work. Outside of this role, John Tackett 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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## Chapter 14

# Who Owns Heat? Ownership of Geothermal Energy and Associated Resources Under Texas Law

B. Sebree

***Heat, energy, steam, hot water, hot brines, and geopressured water are not minerals under Texas law. Therefore, in the event of a severance of the mineral estate from the surface estate in Texas, geothermal energy and associated resources should be held as belonging to the surface estate, absent a specific statement to the contrary in a controlling document.***

## I. Introduction

At the time of this writing, no Texas Court ruling can be found determining the ownership of geothermal energy and associated resources as a constituent of the surface or of the mineral estate, and in 1975 the Texas Legislature expressly declined to express an opinion regarding ownership.<sup>[1]</sup> However, well-established legal precedents, rules of construction under Texas case law, and statutory law inevitably lead to the conclusion that geothermal energy and associated resources belong to the surface owner of real property in Texas, absent a controlling document to the contrary.

### A. Key Concepts

The ownership of any real property interest in Texas is determined by the intent of the parties to the deed, conveyance, reservation, lease, or other legally binding document in question.<sup>[2]</sup>

In the event of a severance between the surface and the mineral estates, we look to the intent of the parties as expressed within the four corners of the controlling document(s) in the property records.<sup>[3]</sup>



With the exception of the minerals and their accompanying rights, Texas law establishes that all interests in the original parcel of land from which an “oil, gas, and other minerals” estate is severed remains the property of the original parcel of land, i.e., the surface estate.<sup>[4]</sup> This includes all property interests without limitation, unless there is a specific controlling document to the contrary.<sup>[5]</sup> This encompasses ownership of all non-mineral molecules of the land, of the mass of earth undergirding the surface, and even of empty space within the earth.<sup>[6]</sup> Therefore, it includes geothermal energy and associated resources.

If the records are silent with no mention of any conveyance, reservation, or lease of any geothermal energy and associated resources, the inquiry should be complete, because Texas law firmly establishes that the surface owner retains possession of everything that was not severed.<sup>[7]</sup> Therefore, the surface owner retains possession of the geothermal energy and associated resources, because there was never a severance of such resources from the original parcel of land.

Nonetheless, because certain advocates may argue that “other minerals” in a mineral estate conveyance, reservation, or lease should be interpreted so as to include “geothermal energy and associated resources,” we follow Texas statutes and established Texas Supreme Court precedents regarding how to analyze the phrase “other minerals.”

## B. Texas Statutes

The Texas Property Code provides that “mineral” means “**oil, gas, uranium, sulphur, lignite, coal, and any other substance that is ordinarily and naturally considered a mineral in this state, regardless of the depth at which the oil, gas, uranium, sulphur, lignite, coal, or other substance is found.**”<sup>[8]</sup> Geothermal energy and associated resources do not fit that definition.

## C. Texas Supreme Court Precedents

### 1. The Surface Estate as a Matter of Law Test

The following resources contained in the definition of “geothermal energy and associated resources”<sup>[9]</sup> all belong to the surface estate as a matter of law because

they are all forms of groundwater: steam, hot water and hot brines, and geopressured water.<sup>[10]</sup>

### 2. The Ordinary and Natural Meaning Test

The Texas Supreme Court established the ordinary and natural meaning test to determine if a substance is or is not a mineral as follows, “**We now hold a severance of minerals in an oil, gas and other minerals clause includes all substances within the ordinary and natural meaning of that word, whether their presence or value is known at the time of severance.**”<sup>[11]</sup>

Other than groundwater, the remaining two resources contained in the definition of “geothermal energy and associated resources” which require analysis are “heat” and “energy.”<sup>[12]</sup> Under Texas law, all minerals are substances.<sup>[13]</sup> “Heat” and “energy” are not substances. “Heat” and “energy” are intangible qualities or properties of the earth itself, and thus, are definitively not minerals.

Certainty in the ownership of this abundant and inexhaustible energy resource is critical if Texas is going to develop this resource. This article discusses and traces the applicable statutes, legal precedents, and rules of construction under Texas law and demonstrates how they lead to the conclusion that geothermal energy and associated resources belong to the surface estate.

## 2. The Geothermal Resources Act of 1975

Texas has recognized “geothermal energy and associated resources” as a valuable energy resource since 1975. This is the phrase that was adopted and defined by the Texas Legislature when it passed the Geothermal Resources Act of 1975 [“the “Act”].<sup>[14]</sup> Section 141.002 of the Act declares it to be “the policy of the State of Texas that … the rapid and orderly development of geothermal energy and associated resources located within the State of Texas is in the interest of the people of the State of Texas.”

The Act achieves a number of things. First, it defines the nature and scope of geothermal resources. Second, it vests in the Railroad Commission of Texas (“RRC”) the jurisdiction to regulate the exploration, development, and production of geothermal energy and associated resources on public and private land for the purpose of



conservation and the protection of correlative rights.<sup>[15]</sup> Finally, it grants the Commissioner of the General Land Office ("GLO") the power to explore and issue permits for the development of geothermal energy and associated resources on land belonging to the Permanent School Fund.<sup>[16]</sup>

#### A. Definition

The Act defines "geothermal energy and associated resources" as follows:

**Sec. 141.003. DEFINITIONS.** In this chapter:

**(4) "Geothermal energy and associated resources"** means:

- (A) products of geothermal processes, embracing indigenous steam, hot water and hot brines, and geopressured water;**
- (B) steam and other gasses, hot water and hot brines resulting from water, gas, or other fluids artificially introduced into geothermal formations;**
- (C) heat or other associated energy found in geothermal formations; and**
- (D) any by-product derived from them.**<sup>[17]</sup>

**(5) "By-product"** means "any other element found in a geothermal formation which is brought to the surface, whether or not it is used in geothermal heat or pressure inducing energy generation."<sup>[18]</sup>

#### B. Geothermal Resources Are to Be Treated and Produced as Mineral Resources but that Does Not Mean that They Are Minerals

The Texas Geothermal Resources Act states the following:

**(4) since geopressured geothermal resources in Texas are an energy resource system, and since an integrated development of components of the resources, including recovery of the energy of the geopressured water without waste, is required for best conservation of these natural resources of the state, all of the resource system components, as defined in this chapter, shall be treated and produced as mineral resources....**<sup>[19]</sup>

It is crucial to note that the act says that geothermal energy and associated resources are to be "treated and

produced as minerals." It does not say that they are minerals. Nor does the act pronounce that geothermal energy and associated resources are considered to be the property of the mineral estate. Moreover, in the very next clause, the act states the following:

**(5) in making the declaration of policy in Subdivision (4) of this section, there is no intent to make any change in the substantive law of this state, and the purpose is to restate the law in clearer terms to make it more accessible and understandable.**<sup>[20]</sup>

The above statement in Subdivision (5) is a clarification by the Texas Legislature that it is neither establishing nor attempting to reestablish any property rights regarding the ownership of geothermal energy and associated resources. Moreover, Subdivision (5) is an acknowledgement by the Legislature that the Legislature does not possess the authority to alter established property rights.<sup>[21]</sup> In other words, if geothermal energy and associated resources are and always have been a property right possessed by surface owners, then the Legislature does not have the authority to take this resource away from surface owners and give it to mineral owners, nor vice versa. Whether a property interest, be it oil, gas, mineral, water, geothermal energy, or any other resource is owned by the mineral estate, the surface estate, or some other estate is determined by the intent of the parties to the property interest in question.

### III. Original Ownership of Real Property in Texas Includes Everything

Texas real property law begins at the starting point where the original owner of a parcel of property owns everything on the surface and beneath the surface. This concept is reflected in the Latin "ad coelum" doctrine attributed to the 13th-century jurist Accursius, "cujus est solum, ejus est usque ad coelum et ad inferos." Typically translated as meaning "whoever's is the soil, it is theirs all the way to Heaven and all the way to Hell." Although the doctrine contains obvious poetic hyperbole, it is well established in Texas that a fee simple owner of land owns *everything* concerning that parcel of real property without limitation unless so stated.<sup>[22]</sup> Fee Simple means "[a]n estate in land that is conveyed or devised is a fee simple unless the estate is limited by express words or unless a lesser estate is conveyed or devised by construction or operation of



law.<sup>[23]</sup> This concept is often referred by analogy as the “bundle of sticks” or “bundle of rights” as in, an owner of property owns all of the bundle of sticks or property rights until and unless one or more of those rights is specifically severed and conveyed to another.<sup>[24]</sup>

The original owners of parcels of land historically were called owners of the soil, and are now commonly referred to as surface owners.<sup>[25]</sup> Landowners may divide their property or convey any portion or right in their property to anyone else as they see fit.<sup>[26]</sup> A common severance of real property interests in Texas – and the one which concerns this article – is the severance between the surface and the mineral estates. For purposes of illustration, it is useful to imagine the original, full bundle of sticks or property rights. If the original owner severs the oil, gas, and other minerals, then the question becomes, who owns the geothermal energy and associated resources? Is it the surface owner, or the owner of the oil, gas, and other minerals? The answer is the surface owner, because the severance did not include any geothermal energy or associated resources. Therefore, they stayed with the rest of the original bundle of sticks. The surface owner retained ownership of all the other sticks in the bundle. The severance only included oil, gas, and other minerals. Because geothermal energy and associated resources are neither oil, nor gas, nor other minerals under Texas law, the geothermal energy and associated resources remained with the surface owner. This will be demonstrated throughout the article below.

Importantly, the “surface estate” does not mean that it only refers to the surface, as is sometimes misunderstood. The surface estate refers to everything – to *all* property rights – except those which have been severed. In the example where “oil, gas, and other minerals” have been severed from the original fee simple estate, the surface estate refers to all the bundle of property rights, *everything*, except the oil, gas, and mineral rights.<sup>[27]</sup> Long ago in a case which has been upheld numerous times, the Texas Supreme court held that the “surface, and **everything** in the land itself, except the minerals covered by the lease, was still in their possession and was their property, subject to a reasonable use, qualified only by the express provisions of the lease....”<sup>[28]</sup> In another case, the Texas Supreme Court clarified, ‘In the law of servitudes, the mineral estate is called ‘dominant’ and the surface estate ‘servient’, not because the mineral estate is in some sense superior, but because it receives the benefit of the

implied right of use of the surface estate.”<sup>[29]</sup>

## IV. How to Interpret an “Oil, Gas, and Other Minerals” Conveyance Concerning the Unspoken Ownership of Geothermal Energy and Associated Resources

Because of abundant oil and gas, Texas has a long history of parties severing real property into surface and mineral estates. By far, the most common phrase used to accomplish this severance is “oil, gas, and other minerals” when the parties convey or reserve those substances. Naturally, if the phrase “geothermal energy and associated resources” or similar terms are specifically expressed in a deed, conveyance, reservation, lease, or other legally binding document, then such a document would be clear and controlling, and the inquiry into ownership would be complete. Such language is likely to become more common in the future, but it is exceptionally uncommon in Texas property records currently. Accordingly, where real property has been severed into a surface and a mineral estate, the question whether geothermal energy and associated resources was included as part of the mineral or of the surface estate will be left to the courts – unless the Legislature decides to act – when attempting to ascertain the intent of the parties, and will most likely depend on the interpretation of the phrase “oil, gas, and other minerals.”

### A. Introduction. The Ownership of Any Real Property Interest in Texas is Determined by the Intent of the Parties to the Deed, Conveyance, Reservation, Lease, or other Legally Binding Document in Question

The ownership of any real property interest in Texas is determined by the intent of the parties to the deed, conveyance, reservation, lease, or other legally binding document.<sup>[30]</sup> In the absence of controlling language in an applicable document in the property records, courts follow established rules of construction to determine ownership of the real property interest in question. Texas has a long history of well-developed case law, as well as statutory law, for analyzing whether a property interest belongs to the surface or to the mineral estate. When the applicable documents are silent in Texas, pertinent



statutes, legal precedents, and rules of construction individually and collectively reach the same answer – geothermal energy and associated resources belong to the surface estate and not the mineral estate. Again, this is because heat, energy, steam, hot water, hot brines, and geopressured water are not minerals under Texas law.

### **B. Brief History of Mineral Ownership in Texas, the Texas Constitution, and Severance**

Before addressing how to interpret an “oil, gas, and other minerals” conveyance, reservation, lease, or other document to determine the intent of the parties regarding geothermal energy and associated resources, it is helpful to review Texas history regarding the ownership and severance of minerals.

As explained by Williams and Haigh [31], “Private title to all land in Texas originates from a grant by the sovereign of the soil.” Successively, the sovereigns were Spain, Mexico, the Republic of Texas, and the State of Texas. “Under the laws of Spain and Mexico, mines and their metals or minerals did not pass by the ordinary grant of the land without express words of designation. In one of the earliest acts of the Congress of the Republic of Texas, this rule was adopted, and it was continued in force after Texas became a state. Accordingly, a grantee of land before 1866 had no interest in the minerals in the land unless that interest was expressly granted.” [32] Because the sovereign of Spain declared all minerals and mines to be sovereign property, the first severance of the surface estates and mineral estates in Texas actually began with an 18th century Spanish royal decree which declared that all minerals and mines in the “new Spain” to be property of the throne. [33] Additionally, because of this, the right to sever the mineral estate in Texas originates in Spanish law, which recognized that “a property may be acquired in mines which will be quite independent of the property in the lands in which they are situated.” [34]

However, the State Constitution of 1866 changed the rule that private title to land does not include mines and their metals or minerals. This change was carried over in substantially the same language into the constitutions of 1869 and 1876. Pursuant to the new provision, the State released to “owners of soil” (commonly known today as “surface owners”) all mines and mineral substances therein. [35] This constitutional provision had retrospective

effect. Therefore, landowners (excluding Relinquishment Act lands) were given complete ownership of the minerals in all lands that passed from the sovereign before the effective date of the Constitution of 1876. [36]

The provision, adopted in 1866, read: “That the State of Texas hereby releases to the owner of the soil all mines and mineral substances, that may be on the same, subject to such uniform rate of taxation, as the Legislature may impose.” The provision was re-adopted in substantially the same words as Section 9, Article IX of the Constitution of 1869 and as Section 7, Article XIV of the present Constitution of 1876.) (That provision and numerous other sections which were considered “deadwood” were repealed by ballot proposition in 1969.).

Importantly, the provision in question did not define either “mines” nor “minerals” and it also did not define mineral estate nor surface estate. Therefore, it has been left to the courts and to the Legislature to interpret these terms and to provide clarity in various factual circumstances.

The phrase, “oil, gas, and other minerals” is the most widespread language found in Texas for severing the mineral and surface estates. This phrase and similar phrases are the subjects of numerous Texas Supreme Court and lower court decisions. Accordingly, we must engage in a review of Texas case law regarding the construction of documents in general and in particular of case law construing the phrase “oil, gas, and other minerals” and similar phrases to ascertain whether geothermal energy and associated resources are likely to be held to be a constituent of the surface or of the mineral estate in the absence of controlling language in a legally binding document.

### **C. In the Event of a Severance Between the Surface and Mineral Estates, the Intent of the Parties as Expressed Within the Four Corners of the Property Records Determines Ownership of Geothermal Energy and Associated Resources**

When property records, such as deeds, conveyances, reservations, or mineral leases, dividing land into separate estates are unclear and disputes arise, courts must interpret the documents and rule on their meanings. Acts of the Legislature, such as the Property Code, the Natural Resources Code, the Water Code, The



Geothermal Resources Act of 1975, etc. may provide guidance to the courts in their quests to ascertain the most reasonable meaning of the parties. However, because the Legislature does not have the power to alter established private property rights, Texas courts pronounce judgments regarding private property rights by interpreting the documents and facts in evidence. Otherwise, private property rights may be established, recognized, or clarified through acts of the Legislature and through amendments to the Texas Constitution, as was established by the amendment in 1866 releasing all "mines and minerals" to the owner of the soil.

### **1. Oil, Gas, and Mineral Severances**

Texas courthouse records are replete with mineral deeds which commonly grant or reserve interests in "oil, gas, and other minerals" (not to mention all of the oil, gas, and mineral leases which convey a fee simple determinable title to the oil, gas, and other minerals in place).<sup>[37]</sup> However, because these terms are rarely defined or described with sufficient particularity, it has been left to Texas courts to interpret their meaning.

Oil, gas, and mineral estates are accomplished by either a grantor reserving minerals or by a conveyance of minerals. In *Benge v. Scharbauer*,<sup>[38]</sup> the Texas Supreme Court stated: "It is well settled that the owners of land may reserve to themselves minerals or mineral rights, including the oil or any right or ownership therein."<sup>[39]</sup>

When the intent of the parties is unclear as to whether or not a particular substance or resource was conveyed by a document, the Texas Supreme Court has stated that the primary analysis for ascertaining the parties' intent is the Four Corners Rule.<sup>[40]</sup>

### **2. The Four Corners Rule**

This is the umbrella rule of law which controls when interpreting a deed, conveyance, reservation, lease, or other legally binding document. Conveyances, exceptions, reservations, and even leases of oil, gas, and minerals are frequently unclear. The instruments are often silent regarding what specific substances, other than oil and gas, are included in the conveyance. To resolve these matters, the intent of the parties is to be determined first by considering the instrument as a whole and is known as

the Four Corners Rule.

**"The primary duty of the courts in interpreting a deed is to ascertain the intent of the parties. But it is the intent of the parties as expressed within the four corners of the instrument which controls."<sup>[41]</sup> "The intention of the parties to a deed is the paramount consideration, and their intention is to be gathered from a consideration of the entire instrument taken by its four corners."<sup>[42]</sup>**

In an earlier case called *Garrett v. Dils Company*, the Texas Supreme Court explained what has become known as the Four Corners Rule as follows:

**[W]e shall be guided by the well-established rule which we recently reaffirmed in *Harris v. Windsor*, Tex., 294 S.W.2d 798, 799, 800, in this language: 'We have long since relaxed the strictness of the ancient rules for the construction of deeds, and have established the rule for the construction of deeds as for the construction of all contracts, - that the intention of the parties, when it can be ascertained from a consideration of all parts of the instrument, will be given effect when possible. That intention, when ascertained, prevails over arbitrary rules. *Benskin v. Barksdale*, Tex.Com.App., 246 S.W. 360.; *Sun Oil Co. v. Burns*, 125 Tex. 549, 84 S.W.2d 442 (Tex. 1935)'<sup>[43]</sup>**

The definitions of reservations and exceptions were stated in *Bagby v. Bredthauer*, 627 S.W.2d 190 (Tex.App.—Austin 1981, no writ) as follows:

**Technically, a reservation is the creation, by and in behalf of the grantor, of a new right issuing out of the thing granted—something which did not exist as an independent right before the grant, a taking back of a part of the thing already granted. See *Coyne v. Butler*, 396 S.W.2d 474 (Tex.Civ.App.—Corpus Christi 1965, no writ). An exception operates to exclude from the grant some part of the thing granted which would otherwise pass to the grantee, with the whole of the thing granted. An exception does not itself pass title but rather prevents the particular excepted interest from passing with the grant. Title to the interest excepted remains in the grantor by virtue of his original title. In *Coyne v. Butler*, supra, the grantor "excepted" the interest in question from his grant. The court held that no new interest was created since no words of reservation were used in the instrument.**



Additionally, in *Patrick v. Barrett*, 734 S.W.2d 646 (Tex. 1987) the Texas Supreme Court stated:

**The keystone of this opinion is a clear understanding of the distinctions between an exception and a reservation. It is manifest that an exception does not pass title itself; instead it operates to prevent the excepted interest from passing at all. *Pich v. Lankford*, 157 Tex. 335, 339–40, 302 S.W.2d 645, 648 (1957). On the other hand, a reservation is made in favor of the grantor, wherein he reserves unto himself royalty interest, mineral rights and other rights. *Benge v. Scharbauer*, 152 Tex. 447, 451–52, 259 S.W.2d 166, 167–68 (1953).**

In many cases, a conveyance or reservation of "oil, gas, and other minerals" occurred many decades ago, either when the mineral estate was first severed from the surface estate, or when an oil and gas lease that is still held by production was granted. As such, the typical severance document most likely is silent regarding the property interest called geothermal energy and associated resources. How then do we ascertain the intention of the parties from the four corners of the instrument?

When applying the Four Corners Rule – as mandated by the Texas Supreme Court – to a typical "oil, gas, and other minerals" conveyance, reservation, or mineral lease, when the document is silent regarding geothermal energy and associated resources, the obvious, reasonable, and logical conclusion to reach under the Four Corners Rule is that the parties evidenced no intent to include geothermal energy and associated resources, just as they did not include any other resource, substance, or property interest other than oil, gas, and other minerals (unless stated). Therefore, the geothermal energy and associated resources remain as property of the owner of the soil (i.e., the surface owner).

In other words, if there was a severance which conveyed the "oil, gas, and other minerals," but was silent regarding geothermal energy and associated resources, then under the Four Corners Rule, the geothermal energy and associated resources were not conveyed along with the "oil, gas, and other minerals." They were retained by the surface owner. Similarly, if the owner of the soil conveyed the surface of a property but reserved the "oil, gas, and other minerals," then the geothermal energy and associated resources were conveyed along with the rest of the surface estate not including the "oil, gas, and other

minerals." Therefore, the Four Corners Rule establishes that the surface owner owns the geothermal energy and associated resources, absent a specifically spoken statement to the contrary in a controlling document. The same conclusion is also reached through application of the Retention Rule, discussed below.

#### **D. Retention Rule – Following a Severance of Oil, Gas, and Other Minerals, the Surface Owner Retains Ownership of all Property Interests Except the Mineral Interests**

In addition to the Four Corners Rule, there is a long line of cases specifically under Texas oil, gas, and mineral case law which establishes a rule of law that in the event of a severance of the surface and mineral estates, the surface owner owns all property interests – everything – left in the land except the severed mineral interests and their accompanying rights. This includes all non-mineral molecules, all geologic structures including empty space and the space in which the minerals are embedded. This also includes all resources other than the severed minerals such as geothermal energy and associated resources and any other resource. This article names this rule of law, the Retention Rule, because the rule establishes that the surface owner retains ownership of everything that was not severed.

As mentioned, the 1939 case called *Gulf Production Co. v. Continental Oil Co.*<sup>[44]</sup> featured a dispute between a surface owner lessor and the lessee of the oil, gas, and other minerals. Ruling in favor of the surface owner, the Texas Supreme Court held that the "surface, and **everything** in the land itself, except the minerals covered by the lease, was still in their possession (referring to the surface owner) and was their property, subject to a reasonable use, qualified only by the express provisions of the lease...."<sup>[45]</sup> Accordingly, the Texas Supreme Court established the rule that when there is a severance of oil, gas, and mineral interests (in this case, an "oil, gas, and other minerals" lease) from a surface owner's fee simple estate, that the surface owner retains ownership of everything except the specifically severed oil, gas, and other minerals and their accompanying interests.

This Retention Rule was carried forward by the United States Court of Claims in the leading case of *Emeny v. United States*.<sup>[46]</sup> In that case, the court was required to



apply Texas law to a property rights dispute between The United States government, as the lessee of certain oil and gas leases, and the surface owners of the tract overlying the leases. The United States contended that it had the right to store helium in a depleted natural gas reservoir, the same reservoir out of which the government had the rights to extract natural gas under the leases. The surface owners asserted that they owned the empty space in the depleted natural gas reservoir. Therefore, they argued, the United States had no right to such space, and any use of such space amounted to an unconstitutional taking without just compensation.

The Court in *Emeny* agreed with the surface owners stating, “[t]he surface of the leased lands and **everything** in such lands, except the oil and gas deposits covered by the leases, were still the property of the respective landowners. *Gulf Production Co. v. Continental Oil Co.*, supra, 132 S.W.2d at page 561. This included the geological structures beneath the surface, together with any such structure that might be suitable for the underground storage of ‘foreign’ or ‘extraneous’ gas produced elsewhere.”<sup>[47]</sup>

Citing with approval the decision in *Emeny*, the Texas Supreme Court reaffirmed this rule of law that the surface owner of a tract with a severed mineral interest owns everything except the mineral interest and accompanying rights. Specifically construing a severance of royalties on oil, gas, and other minerals, the Court stated that the ownership of the surface “includes not only the surface ... but also the matrix of the underlying earth....”<sup>[48]</sup>

More recently, in 2017, in a case called *Lightning v. Anadarko*<sup>[49]</sup>, the Texas Supreme Court cited with approval all of the foregoing decisions and expanded on them. In *Lightning*, the Court stated, “the surface owner, and not the mineral owner, ‘owns all non-mineral ‘molecules’ of the land, i.e., the mass that undergirds the surface’ estate.”<sup>[50]</sup> The Court continued, “there is a distinction between the earth surrounding hydrocarbons and earth embedded with hydrocarbons.”<sup>[51]</sup> Continuing, the Texas Supreme Court quoted with approval a statement from the lower court that “ownership of the hydrocarbons does not give the mineral owner ownership of the earth surrounding those substances.”<sup>[52]</sup> This distinction illustrates that while severed mineral interests may be owned by the mineral party, the surface owner owns **everything else** except that

which has been severed. Finally, the Court emphasized “we agree that the surface owner owns and controls the mass of earth undergirding the surface.”<sup>[53]</sup>

Accordingly, the Texas Supreme Court and the other cases establish a Retention Rule that when there is a severance of the surface and mineral estates in Texas, the surface owner retains ownership of **everything** – all property interests without limitation – except the severed minerals and their accompanying rights. In other words, everything in the original parcel of land from which an “oil, gas, and other minerals” conveyance is severed remains the property of the original parcel of land, i.e., the surface estate. This includes ownership of all non-mineral molecules of the land, ownership of the mass of earth undergirding the surface, and even ownership of empty space within the earth. Therefore, it follows beyond any reasonable dispute, that such ownership includes any heat and energy which are properties of those very same molecules contained within “the mass of earth undergirding the surface.”<sup>[54]</sup>

## **E. Texas Law Regarding How to Interpret the Phrase “Oil, Gas, and Other Minerals” with Respect to “Geothermal Energy and Associated Resources”**

Even though the Four Corners Rule and the Retention Rule appear to resolve the inquiry, certain advocates may argue that the phrase “other minerals” should be interpreted so as to include geothermal energy and associated resources. Therefore, if not satisfied that the Four Corners Rule and the Retention Rule conclusively answer the question, we can follow Texas statutes and established Texas Supreme Court precedents regarding how to interpret the phrase “other minerals.”

The Texas Legislature has adopted a statutory definition of the term “mineral” and a statutory definition of the term “geothermal energy and associated resources.” These two definitions are separate, distinct, and irreconcilable. Pursuant to the express definitions, geothermal energy and associated resources are not minerals. Additionally, the Texas Supreme Court has provided three tests to apply to factual circumstances regarding conveyances or reservations of “oil, gas, and other minerals” which specifically direct us how to analyze the phrase “other minerals.” Application of these tests also leads to the



conclusion that geothermal energy and associated resources are not minerals.

1. Texas Statutory Definitions of "Geothermal Energy and Associated Resources" and "Mineral"

a. Geothermal Energy and Associated Resources  
[55]

To begin our analysis, it is insightful to observe that the Texas statutory definition of "geothermal energy and associated resources" contains the following two subsets:

- (1) tangible substances -- "steam, hot water and hot brines, and geopressured water."<sup>[56]</sup>; and
- (2) intangible qualities or properties of the earth itself -- "**heat or other associated energy.**"<sup>[57]</sup>

All of the tangible substances — **"steam, hot water and hot brines, and geopressured water"** — belong to the surface estate as a matter of law in Texas because they are all forms of groundwater. Groundwater, including saltwater brines, have been ruled by both the Texas Supreme Court as well as the Texas Legislature to be owned by the surface estate as a matter of law in Texas (absent a controlling conveyance or reservation to the contrary).<sup>[58]</sup>

**"Heat" and "other associated energy"** are not substances. As established by science as well as Texas law,<sup>[59]</sup> oil, gas, and other minerals are all substances. By contrast, "heat" is "energy that is transferred from one body to another as the result of a difference in temperature."<sup>[60]</sup> "Energy" means "the capacity for doing work."<sup>[61]</sup> Oil, gas, and other minerals are all tangible substances. Heat and energy are not substances. Heat and energy are intangible qualities or properties of the earth itself and, thus, are definitively not minerals.

b. Mineral

The Texas Statutory Definition of "Mineral" excludes "Geothermal Energy and Associated Resources." The Texas Property Code defines mineral as follows:

**"Mineral"** means oil, gas, uranium, sulphur, lignite, coal, and any other substance that is ordinarily and naturally considered a mineral in this state, regardless of the depth at which the oil, gas, uranium, sulphur, lignite, coal, or other substance is found.<sup>[62]</sup>

As is readily apparent, "geothermal energy and associated resources" do not fit within the definition of "mineral." To reiterate, all of the tangible substances listed in the definition of "geothermal energy and associated resources" are all forms of groundwater, and are not minerals. Additionally, they all belong to the surface estate as a matter of law. Heat and energy are intangible properties of the earth. Heat and energy are not minerals.

Moreover, once substances such as oil, gas, and other minerals are extracted from the subsurface, they are gone (unless replaced). Minerals are exhaustible. Geothermal heat and energy radiate from the earth itself and remain properties of the earth itself even when developed and utilized as a resource.

Thus, even though geothermal heat and energy can be used for the production of electricity and other forms of energy, the heat and energy derived from the earth, for all intents and purposes of humanity, is essentially inexhaustible. Therefore, heat and energy are not minerals. Consequently, unless the heat and the energy or some other portion of the geothermal resources were specifically conveyed in a controlling document, geothermal energy and associated resources remain property interests of the surface estate.

Finally, the Texas Legislature has adopted two distinct definitions because "minerals" and "geothermal energy and associated resources" are two different and distinct types of resources. The two statutory definitions are separate, distinct, and irreconcilable. The definition of "mineral" cannot be read so as to include "geothermal energy and associated resources" and "geothermal energy and associated resources" cannot be read so as to include "minerals."



2. Rules of Construction Prescribed by the Texas Supreme Court for Determining if a Substance Is or Is Not a Mineral

If not convinced by the Four Corners Rule, nor by the Retention Rule, nor by the distinctions between the statutory definition of "mineral" in relation to the statutory definition of "geothermal energy and associated resources," there are three tests prescribed by the Texas Supreme Court specifically to address the phrase "other minerals" and to determine whether a substance is or is not a mineral, as intended by the parties. These tests are summarized as follows:

**The surface-destruction test** (applicable to conveyances prior to June 8, 1983); *Acker v. Guinn*, 464 S.W.2d 348 (Tex. 1971); *Reed v. Wylie II*, 597 S.W.2d 743 (Tex. 1980).

**Substances that belong to the surface estate as a matter of law test;** *Moser v. United States Steel Corp.*, 676 S.W.2d 99 (Tex. 1984). In *Moser*, the Court replaced the surface-destruction test with a list of substances that belong to the surface estate as a matter of law; and

**The ordinary-and-natural-meaning test.** Additionally, in the *Moser* case, the Court adopted the ordinary-and-natural-meaning test when determining whether a substance is or is not a mineral. *Id.*

a. The Surface-Destruction Test

This test was first pronounced by the Texas Supreme Court in *Acker v. Guinn*, 464 S.W.2d 348 (Tex. 1971) and adjusted in a line of cases before being fully expressed in *Reed v. Wylie II*, 597 S.W.2d 743 (Tex. 1980). The Surface-Destruction Test does not determine what substances are and are not minerals. Rather, it was a way for the Texas Supreme Court to protect landowners from the effects of their own documents by creating a theory that if the surface had to be destroyed to mine the minerals, the minerals belonged to the surface owner. Under this test, the Court ruled that substances located within three or four feet belonged to the surface estate owner as a matter of law. Substances within 200 feet of the surface belonged to the surface estate owner if any reasonable method of extracting the substance would destroy the surface.

Under this test, one might conclude that geothermal energy and associated resources do not belong to the surface estate (unless the geothermal resources are located within three or four feet of the surface, or within 200 feet of the surface and destruction of the surface is reasonable to produce them). However, the surface-destruction test does not provide guidance for determining which substances are or are not minerals. It only determines which substances belong to the surface owner as a matter of law. Therefore, as stated by Smith and Weaver in *Texas Law of Oil and Gas*, "Hence, if an instrument was executed prior to June 8, 1983, and there is controversy over ownership of a substance that is too deep to have been extracted by surface-destructive methods and that is not surface-owned as a matter of law, the controversy will be resolved through application of the ordinary-and-natural meaning test." Smith and Weaver, *Texas Law of Oil and Gas* at 3.6(B)(1) (2020). Accordingly, the surface-destruction test is not applicable in determining whether parties to an oil, gas, and minerals conveyance intended to include geothermal energy and associated resources in the conveyance or reservation. The Surface-Destruction Test is potentially applicable only if the geothermal energy and associated resources are located within three to four feet of the surface or within 200 feet of the surface and destruction of the surface is necessary to produce them. However, at this time, even if the geothermal energy and associated resources are located within 200 feet of the surface, it is highly unlikely that destruction of the surface would be necessary to access and to produce them as an energy source.

b. Surface-Owned as a Matter of Law Test

Prior to *Moser v. United States Steel Corp.*, 676 S.W.2d 99 (Tex. 1984), there was a long line of Texas Supreme Court decisions and lower court decisions where the courts held that certain substances belonged to the surface estate. In the *Moser* decision, the Texas Supreme Court reaffirmed many of those previous decisions and announced that they belong to the surface estate as a matter of law. Accordingly, when ascertaining whether a substance was included as part of an oil, gas, and other minerals conveyance, we look to see if the substance is on the list as belonging to the surface owner as a matter of law.



### (i) The List of Substances Belonging to the Surface Estate as a Matter of Law

In *Moser* (and other cases as noted) the Texas Supreme Court established that the following substances belong to the surface estate as a matter of law:

1. Fresh water;
2. Saltwater<sup>[63]</sup>;
3. Building stone;
4. Limestone;
5. Caliche;
6. Surface Shale;
7. Sand;
8. Gravel; and
9. Near-surface lignite, iron, and coal. <sup>[64]</sup>

Reviewing the list, we find that water and saltwater are on the list of substances which belong to the surface estate as a matter of law. <sup>[65]</sup> Therefore, as discussed, because they are all forms of water or saltwater, we can definitively conclude that the following substances listed in the Texas statutory definition of geothermal energy and associated resources belong to the surface estate (absent a controlling document to the contrary) as a matter of law: **steam, hot water and hot brines, and geopressured water.**

Continuing our review of the list, we see that **heat** and **energy** are not included on the list. For the reasons discussed above, heat and energy should not be considered to be minerals. However, this is a discussion of the three rules of construction prescribed by the Texas Supreme Court for how to analyze the term "mineral," so we will move on to the next test. Having determined that the surface-destruction test is not applicable and having determined that neither heat nor energy has been held to be part of the surface estate as a matter of law, we proceed to the ordinary-and-natural-meaning test to address whether parties to an "oil, gas, and other minerals" conveyance intended for heat and energy to be included in the conveyance or reserved as part of the surface estate.

#### c. The Ordinary-and-Natural-Meaning Test

The ordinary-and-natural-meaning test found in *Moser* is applicable for conveyances after June 8, 1983, and for previous conveyances if the intent of the parties is unclear or unspoken, and the "substance" in question is too deep

to be determined by the surface-destruction test. This test is to be applied if the "substance" in question has not previously been held to belong to the surface estate as a matter of law, if the intent of the parties to the "oil, gas, and other minerals" conveyance is unclear, and if it is necessary to determine if the "substance" in question (such as geothermal resources) is or is not a mineral.

This test was announced by the Texas Supreme Court in the leading case of *Moser* following its listing of substances which belong to the surface estate as a matter of law. <sup>[66]</sup> The Court articulated the test as follows:

**"We now hold a severance of minerals in an oil, gas and other minerals clause includes all substances within the ordinary and natural meaning of that word, whether their presence or value is known at the time of severance."** <sup>[67]</sup>

As illustrated previously, the Texas Property Code defines all minerals as substances. <sup>[68]</sup> The ordinary and natural meaning test also classifies minerals as substances. <sup>[69]</sup> As established, "**heat**" and "**associated energy**" are not substances. They are properties or qualities of the earth itself. They are resources but they are not substances. Therefore, "**heat**" and "**associated energy**" are not minerals under the ordinary and natural meaning test because they are not substances.

In conclusion, all of the substances listed in the definition of "geothermal energy and associated resources" belong to the surface estate as a matter of law because they are all forms of groundwater. "**Heat**" and "**associated energy**" belong to the surface estate because they are not minerals and, thus, were not included in a conveyance or reservation of "oil, gas, and other minerals."

## V. Application of Texas Law to the Texas Definition of Geothermal Energy and Associated Resources Subsection by Subsection

To wrap up, it is useful to analyze the Texas definition of geothermal energy and associated resources by breaking it down, subsection by subsection.

For ease of reference, once again the Texas Geothermal Resources Act defines "geothermal energy and associated resources" as:



- (A) products of geothermal processes, embracing indigenous steam, hot water and hot brines, and geopressured water;
- (B) steam and other gasses, hot water and hot brines resulting from water, gas, or other fluids artificially introduced into geothermal formations;
- (C) heat or other associated energy found in geothermal formations; and
- (D) any by-product derived from them. Tex. Nat. Res. Code § 141.003(4).

"By-product" is defined as "any other element found in a geothermal formation which is brought to the surface, whether or not it is used in geothermal heat or pressure inducing energy generation." Tex. Nat. Res. Code § 141.003(5).

**Subsection (A).** As established, the substances listed in subsection (A) are all forms of groundwater. The Texas Supreme Court as well as the Legislature both declare that groundwater, including saltwater brines, belong to the surface estate as a matter of law.<sup>[70]</sup>

Section 36.001(5) of the Texas Water Code, defines groundwater as "water percolating below the surface of the earth." This begs the question whether "indigenous steam, hot water and hot brines, and geopressured water" are "percolating." It would require geologic and hydrologic experts to investigate and to examine whether specific "indigenous steam, hot water and hot brines, and geopressured water" in question are or are not percolating. However, even if such steam, water, brine, or geopressured water is trapped and not percolating, that does not lead to the conclusion that they are minerals or otherwise belong to the mineral estate. To the contrary, as discussed, Texas law establishes that most forms of water, including brines, belong to the surface estate as a matter of law<sup>[71]</sup> (excluding produced water which is geologically entrained in an oil or gas reservoir and defined under Texas law as waste).<sup>[72]</sup>

**Subsection (B).** Everything listed in this subsection refers to substances which result from fluids or gas artificially injected into geothermal formations. Therefore, they would belong to the person performing the injection assuming the injection was conducted lawfully. The phrase "steam and other gasses" is modified by the phrase "resulting from water, gas, or other fluids artificially introduced into geothermal formations." Accordingly, "other gasses" cannot be read as referring to naturally existing mineral gasses, such as hydrocarbons, as sometimes inferred by other readers.

**Subsection (C).** This subsection lists, "heat or other associated energy found in geothermal formations." As established, heat and energy are not substances as are minerals. Heat and energy are properties of the earth. Heat and energy are not minerals.

**Subsection (D).** This final subsection lists "any by-product derived from them." "Them" refers to the first three subsections. This is critical because the first three subsections, as discussed, do not include any minerals. Therefore, any by-product derived from non-minerals would also be a non-mineral. It strains reason that any by-product derived from non-minerals could transmute its fundamental nature and somehow become a mineral. Therefore, subsection (D) should not be read as including any substances that are minerals.

However, it is acknowledged that "By-product" is defined as "**any other element found in a geothermal formation which is brought to the surface, whether or not it is used in geothermal heat or pressure inducing energy generation.**"<sup>[73]</sup> If it were not for the fact that subsection (D) specifically lists "**any by-product derived from them,**"<sup>[74]</sup> this would be problematic because "by-product" by itself was given an all-inclusive definition otherwise applicable to any and every element brought to the surface from a geothermal formation. In such a case, a court would need to analyze each particular element individually to determine whether it is or is not a mineral. For example, any oil or natural gasses brought to the surface from a geothermal formation should be ruled to be minerals.



Nonetheless, “by-product” by itself was not included in the definition of geothermal energy and associated resources. Instead, the Legislature narrowed the scope of the otherwise expansive term, “by-product” when they included it in Subsection (D) and modified it with “derived from them.” “By-product derived from them” is much more circumspect than “by-product.” This is because the full phrase narrows the scope of all potential by-products to only those derived from the items listed in Subsections (A)-(C), all of which are non-minerals. Accordingly, any by-product derived from a non-mineral should also be a non-mineral.

Finally, just as the Legislature does not possess the legal authority to alter established property rights by providing that geothermal energy and associated resources belong to the mineral estate, neither does the Legislature have the authority to provide that any minerals found in a geothermal formation belong to the surface estate.<sup>[75]</sup> Therefore, the most reasonable conclusion is that the Texas Legislature did not intend for the meaning of “by-product derived from them” to include any substances which actually are minerals. This is evident because the Legislature narrowed the scope of all potential by-products to only by-products derived from non-minerals.<sup>[76]</sup> In any event, the inclusion of any minerals in the definition of geothermal energy and associated resources likely would be ruled unconstitutional.<sup>[77]</sup>

## VI. Caveat

It is always imperative to review the specific controlling documents such as deeds, conveyances, reservations, and leases in the property records. This is because, as discussed, it is the intent of the parties to the deed, conveyance, reservation, lease, or other legally binding document in question which controls. It is possible that specific facts and language in applicable documents may evidence an intent to convey some or all of the geothermal energy and associated resources to someone other than the surface owner. However, when the applicable documents are silent, geothermal energy and associated resources should be held as belonging to the surface estate and not the mineral estate in Texas.

## VII. Conclusion

Heat, energy, steam, hot water, hot brines, and geopressured water are not minerals under Texas law. Therefore, in the event of a severance of the mineral estate from the surface estate in Texas, geothermal energy and associated resources should be held as belonging to the surface estate, absent a controlling document to the contrary which specifically conveys the geothermal energy and associated resources or some portion thereof to the mineral estate.

There are five reasons for this outcome:

- The Four Corners Rule establishes that there never was an intent evidenced in the property records to convey the geothermal energy and associated resources from the surface estate to the mineral estate;
- The Retention Rule establishes that all property interests, including geothermal energy and associated resources, are retained by the surface estate except the severed mineral interests and their accompanying rights;
- Texas statutes establish separate, distinct, and irreconcilable definitions of “mineral” and “geothermal energy and associated resources” and the definition of the latter simply does not fit within the definition of the former;
- The tangible resources (steam, hot water and hot brines, and geopressured water,) contained in the definition of geothermal energy and associated resources all belong to the surface estate as a matter of Texas law because they are all forms of groundwater; and
- The remaining intangible resources (heat and energy) contained in the definition of geothermal energy and associated resources belong to the surface estate under Texas law because they are not minerals for the reason that they are qualities or properties of the earth undergirding the surface.



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## Conflict of Interest Disclosure

**Ben Sebree** serves as General Counsel for The Texas Geothermal Energy Alliance, a 501(c)(6) organization that works on issues within the subject matter of this Report, and is compensated for this work. Additionally, he is the founding member of The Sebree Law Firm PLLC which represents clients who are active in the geothermal industry and the oil and gas industry, as well as land and mineral owners, who have interests in the subject matter of this Report. Outside of these roles, Ben Sebree 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.



## Chapter 14 References

[1] Tex. Nat. Res. Code § 141.002(5). See discussion in Section II.B., *infra*.

[2] Altman v. Blake, 712 S.W. 2d 117, 118 (Tex. 1986).

[3] *Id.* City of Stamford v. King, 144 S.W.2d 923 (Tex.Civ.App. Eastland 1940, writ ref'd).

[4] Gulf Production Co. v. Continental Oil Co. 132 S.W.2d 553, 561 (Tex. 1939), Emeny v. United States, 412 F.2d 1319, 1323 (1969), Humble Oil & Refining Co. v. West, 508 S.W.2d 812, 815 (Tex. 1974). Dunn-McCampbell Royalty Interest, Inc. v. Nat'l Park Serv., 630 F.3d 431, 441 (5th Cir. 2011), Springer Ranch, Ltd. v. Jones, 421 S.W.3d 273, 283 (Tex. App. - San Antonio 2013, no pet.), Lightning Oil Co. v. Anadarko E & P Onshore LLC, 480 S.W.3d, 628, 635 (Tex. App. - San Antonio 2015) aff'd, 520 S.W.3d 39 (Tex. 2017), Lightning Oil Co. v. Anadarko E & P Onshore LLC, 520 S.W.3d 39 (Tex. 2017). See discussion at Section V, *infra*.

[5] *Id.*

[6] *Id.*

[7] Gulf Production Co. v. Continental Oil Co. 132 S.W.2d 553, 561 (Tex. 1939), Emeny v. United States, 412 F.2d 1319, 1323 (1969), Humble Oil & Refining Co. v. West, 508 S.W.2d 812, 815 (Tex. 1974). Dunn-McCampbell Royalty Interest, Inc. v. Nat'l Park Serv., 630 F.3d 431, 441 (5th Cir. 2011), Springer Ranch, Ltd. v. Jones, 421 S.W.3d 273, 283 (Tex. App. - San Antonio 2013, no pet.), Lightning Oil Co. v. Anadarko E & P Onshore LLC, 480 S.W.3d, 628, 635 (Tex. App. - San Antonio 2015) aff'd, 520 S.W.3d 39 (Tex. 2017), Lightning Oil Co. v. Anadarko E & P Onshore LLC, 520 S.W.3d 39 (Tex. 2017). See discussion at Section V, *infra*.

[8] Tex. Prop. Code § 75.001.

[9] Tex. Nat. Res. Code § 141.003. See Section II.A., *infra*. for full definition of "geothermal energy and associated resources."

[10] Moser v. United States Steel Corp. 676 S.W.2d 99, 102 (Tex. 1984). See also Edwards Aquifer Auth. v. Day, 369 S.W.3d 814, 832 (Tex. 2012); Tex. Water Code Ann. § 36.002.; Sun Oil Co. v. Whitaker, 483 S.W.2d 808, 811 (Tex. 1972); Fleming Foundation v. Texaco, Inc., 337 S.W.2d 846, 852 (Tex.Civ. App. 1960, writ ref'd, n.r.e.) and Robinson v. Robbins Petroleum Corp., 501 S.W.2d 865 (Tex. 1973).

[11] Moser at 102.

[12] Tex. Nat. Res. Code § 141.003. "Any by-product derived from them" addressed separately in Section VI, *infra*.

[13] Tex. Prop. Code § 75.001; Moser at 102.

[14] Tex. Nat. Res. Code § 141.001 et. seq.

[15] *Id.* at § 141.011.

[16] *Id.* at § 141.071.

[17] *Id.* at § 141.003(4).

[18] *Id.* § 141.003(5).

[19] *Id.* at § 141.002(4)(emphasis added).

[20] *Id.* at § 141.002(5).

[21] U.S. Const. Amend. V applied to the states through U.S. Const. Amend XIV; Tex. Const. Art. I. § 17.

[22] Tex. Property Code § 5.001.

[23] *Id.*

[24] See *Dolan v. City of Tigard* 512 U.S. 374, 384, 393 (1994), *Kaiser Aetna v. United States*, 444 U. S. 164, 176 (1979), *U.S. v. General Motors Corp.*, 323 U.S. 373, 378, (1945) ("property" denotes the group of rights "to possess, use, and dispose of it") *Severance v. Patterson*, 370 S.W.3d 705, (Tex. 2012), *Lightning v. Anadarko*, 520 S.W.3d 39, 49 (Tex. 2017).



[25] See Tex. Constitution of 1869. Art. IX. § 9 and Tex. Constitution of 1876. Art. XIV. § 7.

[26] "As a rule, parties have the right to contract as they see fit as long as their agreement does not violate the law or public policy...." *Coyote Lake Ranch, LLC v. City of Lubbock*, 498 S.W.3d 53, 59 (Tex. 2016) quoting *In re Prudential Ins. Co. of Am.*, 148 S.W.3d 124, 129 (Tex. 2004) citing *Sonny Arnold, Inc. v. Sentry Sav. Ass'n*, 633 S.W.2d 811, 815 (Tex. 1982) (recognizing 'the parties' right to contract with regard to their property as they see fit, so long as the contract does not offend public policy and is not illegal'....").

[27] *Gulf Production Co. v. Continental Oil Co.* 132 S.W.2d 553, 561 (Tex. 1939), *Emeny v. United States*, 412 F.2d 1319, 1323 (1969), *Humble Oil & Refining Co. v. West*, 508 S.W.2d 812, 815 (Tex. 1974). *Dunn-McCampbell Royalty Interest, Inc. v. Nat'l Park Serv.*, 630 F.3d 431, 441 (5th Cir. 2011), *Springer Ranch, Ltd. v. Jones*, 421 S.W.3d 273, 283 (Tex. App. - San Antonio 2013, no pet.), *Lightning Oil Co. v. Anadarko E & P Onshore LLC*, 480 S.W.3d, 628, 635 (Tex. App. - San Antonio 2015) aff'd, 520 S.W.3d 39 (Tex. 2017), *Lightning Oil Co. v. Anadarko E & P Onshore LLC*, 520 S.W.3d 39 (Tex. 2017). See discussion at Section V, infra.

[28] *Gulf Production Co. v. Continental Oil Co.* 132 S.W.2d 553, 561 (Tex. 1939).

[29] *Coyote Lake Ranch, LLC v. City of Lubbock*, 498 S.W.3d 53, 60 (Tex. 2016); see also *Acker v. Quinn*, 464 S.W.2d 348, 352 (Tex. 1971) and Restatement (Third) of Prop.: Servitudes § 1.1(1) (Am. Law Inst. 1998) ("A servitude is a legal device that creates a right or an obligation that runs with land or an interest in land. (a) Running with land means that the right or obligation passes automatically to successive owners or occupiers of the land or the interest in land with which the right or obligation runs. (b) A right that runs with land is called a 'benefit' and the interest in land with which it runs may be called the 'benefited' or 'dominant' estate. (c) An obligation that runs with land is called a 'burden' and the interest in land with which it runs may be called the 'burdened' or 'servient' estate.").

[30] *Altman v. Blake*, 712 S.W.2d 117, 118 (Tex. 1986).

[31] Williams and Haigh, Mineral Rights and Royalties in Texas, Texas State Historical Association, <http://www.tshaonline.org/handbook/entries/mineral-rights-and-royalties> (last accessed November 24, 2022).

[32] *Id.*

[33] See Wallace Hawkins, *EI Sal Del Ray*, 7-15 (Austin, Tex. State Historical Ass'n. 1947) (providing a detailed history of the royal mining ordinances and their impact on the development of Texas mineral law).

[34] *Cowan v. Hardeman*, 26 Tex. 217, 223 (1862) (quoting John A. Rockwell, a Compilation of Spanish and Mexican Law, in Relation to Mines, and Titles to Real Estate, in Force in California, Texas and New Mexico 580 (New York, John S. Voorhies 1851)).

[35] Williams and Haigh, Mineral Rights and Royalties in Texas, Texas State Historical Association, <http://www.tshaonline.org/handbook/entries/mineral-rights-and-royalties> (last accessed November 24, 2022).

[36] *Id.*

[37] *Stephens County v. Mid-Kansas Oil & Gas Co.*, 113 Tex. 160, 254 S.W. 290 (1923).

[38] 259 S.W.2d 166 (Tex. 1953).

[39] *Id.* at 166-167 citing *Humphreys-Mexia Co. v. Gammon*, 113 Tex. 247, 254 S.W. 296; 29 A.L.R. 607; *Hoffman v. Magnolia Petroleum Co.*, Tex.Com. App., 273 S.W. 828(4); *Watkins v. Slaughter*, *supra*; *Curry v. Texas Company*, Tex.Civ.App., 18 S.W.2d 256, writ dismissed; 31-A T.J. 64, Sec. 32, and authorities therein cited.

[40] *Altman v. Blake*, 712 S.W.2d 117, 118 (Tex. 1986).

[41] *Altman v. Blake*, 712 S.W.2d 117, 118 (Tex. 1986). See also, e.g. *Garrett v. Dils Company.*, 299 S.W.2d 904, 906 (Tex. 1957); *Luckel v. White*, 819 S.W.2d 459, 461 (Tex. 1991); *JVA Operating Co. v. Kaiser-Francis Oil Co.*, 11 S.W.3d 504, 506 (Tex. App.-Eastland 2000).

[42] *City of Stamford v. King*, 144 S.W.2d 923 (Tex. Civ. App. Eastland 1940, writ ref'd).

[43] *Garrett v. Dils Company.*, 299 S.W.2d 904, 906 (Tex. 1957).

[44] 132 S.W.2d 553 (Tex. 1939).

[45] *Id.* at 561 (emphasis added).

[46] 412 F.2d 1319 (1969).



[47] *Id.* at 1323 (emphasis added).

[48] *Humble Oil & Refining Co. v. West*, 508 S.W.2d 812, 815 (Tex. 1974).

[49] 520 S.W.3d 39 (Tex. 2017).

[50] *Id.* at 46 and 48 (quoting *Dunn-McCampbell Royalty Interest, Inc. v. Nat'l Park Serv.*, 630 F.3d 431, 441 (5th Cir. 2011)).

[51] *Id.* at 47.

[52] *Id.* at 48 quoting *Lightning Oil Co. v. Anadarko E & P Onshore LLC*, 480 S.W.3d, 628, 635 (Tex. App. – San Antonio 2015) aff'd, 520 S.W.3d 39 (Tex. 2017) (quoting *Springer Ranch, Ltd. v. Jones*, 421 S.W.3d 273, 283 (Tex. App. – San Antonio 2013, no pet.)).

[53] *Lightning*, 520 S.W.3d 39, 47 (Tex. 2017).

[54] *Id.*

[55] Entire definition reprinted at Section II., *supra*. and Section VI., *infra*.

[56] Tex. Nat. Res. Code § 141.003(4)(A).

[57] Tex. Nat. Res. Code § 141.003(4)(C). “Any by-product derived from them” addressed separately in Section VI., *infra*.

[58] The Texas Supreme Court established in multiple holdings that water belongs to the surface estate, absent a controlling document to the contrary. “Water, unsevered expressly by conveyance or reservation, has been held to be a part of the surface estate.” *Sun Oil Co. v. Whitaker*, 483 S.W.2d 808, 811 (Tex. 1972) (citing *Fleming Foundation v. Texaco, Inc.*, 337 S.W.2d 846 (Tex. Civ. App. 1960, writ ref'd, n.r.e.). Additionally, the Texas Supreme Court ruled that fresh water belongs to the surface estate as “a matter of law.” *Moser v. United States Steel Corp.*, 676 S.W.2d 99, 101–102 (Tex. 1984). The Texas Supreme Court also ruled that salt water belongs to the surface estate. *Robinson v. Robbins Petroleum Corp.*, 501 S.W.2d 865, 873 (Tex. 1973). The Texas Legislature adopted a law which expressly recognizes “that a landowner owns the groundwater below the surface of the landowner’s land as real property.” Tex. Water Code § 36.002(a). Finally, the Texas Supreme Court in *Edwards Aquifer Auth. v. Day*, 369 S.W.3d 814 (Tex. 2012) explained that the ownership of groundwater in place is a perfected property right in Texas. Quoting a previous Texas Supreme Court decision which restated the law regarding ownership of oil and gas in place, the Texas Supreme Court in *Day* held, “The [groundwater] beneath the soil [is] considered a part of the realty. Each owner of land owns separately, distinctly and exclusively all [groundwater] under his land and is accorded the usual remedies against trespassers who appropriate the [groundwater] or destroy their market value.” *Id.* at 832 quoting *Elliff v. Texon Drilling Co.*, 210 S.W.2d 558, 561 (Tex. 1949).

[59] Tex. Prop. Code § 75.001.

[60] <https://www.britannica.com/science/heat> (last accessed November 12, 2022).

[61] <https://www.britannica.com/science/energy> (last accessed November 12, 2022).

[62] Tex. Prop. Code § 75.001.

[63] Saltwater (brine) was not included on the list in the *Moser* decision. However, the Texas Supreme Court in other decisions specifically included saltwater (brine) as belonging to the surface estate absent a controlling document to the contrary. *Robinson v. Robbins Petroleum Corp.*, 501 S.W.2d 865, 873 (Tex. 1973). See also *Sun Oil Co. v. Whitaker*, 483 S.W.2d 808, 811 (Tex. 1972) (not limiting “water” to “fresh water.”).

[64] *Moser* at 101–102.

[65] See also *Edwards Aquifer Auth. v. Day*, 369 S.W.3d 814, 832 (Tex. 2012); Tex. Water Code Ann. § 36.002. See also *Moser v. United States Steel Corp.*, 676 S.W.2d 99, 102 (Tex. 1984); *Sun Oil Co. v. Whitaker*, 483 S.W.2d 808, 811 (Tex. 1972); *Fleming Foundation v. Texaco, Inc.*, 337 S.W.2d 846, 852 (Tex. Civ. App. 1960, writ ref'd, n.r.e.) and *Robinson v. Robbins Petroleum Corp.*, 501 S.W.2d 865, 873 (Tex. 1973).

[66] *Moser* at 99.

[67] *Id.* at 102.

[68] Tex. Prop. Code § 75.001.

[69] *Moser* at 102.



[70] Edwards Aquifer Auth. v. Day, 369 S.W.3d 814, 832 (Tex. 2012); Tex. Water Code Ann. § 36.002. See also Moser v. United States Steel Corp. 676 S.W.2d 99, 102 (Tex. 1984); Sun Oil Co. v. Whitaker, 483 S.W.2d 808, 811 (Tex. 1972); Fleming Foundation v. Texaco, Inc., 337 S.W.2d 846, 852 (Tex. Civ. App. 1960, writ ref'd, n.r.e.) and Robinson v. Robbins Petroleum Corp., 501 S.W.2d 865 (Tex. 1973).

[71] *Id.*

[72] Tex. Water Code § 27.002(6); Tex. Nat. Res. Code § 91.1011; and Tex. Nat. Res. Code § 122.001(2). See Sebree and Cusimano, Texas Law of Produced Water Ownership, 38th Annual Advanced Oil, Gas, and Energy Resources Law Course, Chapter 2, Sponsored by the State Bar of Texas, Houston, September 24-25, 2020

[73] Tex. Nat. Res. Code § 141.003(5).

[74] Tex. Nat. Res. Code § 141.003(4)(D)(emphasis added).

[75] U.S. Const. Amend. V applied to the states through U.S. Const. Amend XIV; Tex. Const. Art. I. § 17.

[76] Tex. Nat. Res. Code § 141.003(4)(D).

[77] U.S. Const. Amend. V applied to the states through U.S. Const. Amend XIV; Tex. Const. Art. I. § 17.



## PART IV

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### Moving Forward



Photo Credit: Ormat Technologies

## Chapter 15

# Roadmap for Action

J. Beard

**If we follow the roadmap of the greatest human achievements in our approach to collaboration and cooperation across industries, disciplines, and even party lines, we can achieve or even exceed global decarbonization goals with geothermal by 2050.**

Perhaps we should tackle the challenge of summarizing hundreds of pages of content in a few paragraphs by exploring the themes - and within each theme - the headlines of this Report. The themes allow us to spot trends (i.e. what path we are likely to take over the coming decades), while the headlines might give us line of sight on where we are headed (i.e. what outcome we are likely to achieve by the end of those decades). So let's roll the themes of the Future of Geothermal Energy in Texas:

### **Oil and Gas Industry 'Booms' Have Enabled Modern Life, and Provide a Playbook For Building the Future of Geothermal Energy:**

Talk with anyone who has found their profession in oil and gas, particularly rig crew members who are often the first to feel the ebb and flow of the industry, and observations are fairly consistent. The oil and gas industry and its workers, buoyed by the resilience and grit that a boom-

and-bust industry requires, nearly always turn periods of downturn into periods of determined resurgence, breakthrough technological innovation, and forward movement in the upswings. These shorter-term upswings and downturns, driven largely by geopolitical events, news cycles, even weather, fit into a larger context of the big, world changing shifts and pivots of industry over the past century, the so-called "Booms."

The first Boom to emerge from Texas was the Oil Boom, thrust into existence by the gusher at Spindletop, and pushed the world fully into the Second Industrial Revolution, the age of science and mass production, where the world welcomed inventions such as the Model T and electric lighting. From the first Boom, we got the modern world as we know it today.

The next Boom to emerge from Texas, the Shale Boom, or rise of "unconventionals" in oil and gas vernacular, had every bit of the scale and impact of the Oil Boom,



propelling the United States into its position as a world leader in the production of gas. For those who doubt the dramatic impact of the Shale Boom on the geopolitical arrangement of the world, consider what the world would look like if the United States was not producing the volumes of gas it does currently, with the ongoing crisis in Ukraine, and resulting global energy market disruptions.

It is the Booms that have produced the major leaps forward, the paradigm shifts, and we may be on the brink of another, driven by the quest for fast global decarbonization. But, if you look closely, the Oil and Shale Booms were not singular technological leaps. They were the result of years of small steps, incremental changes in approach, optimization, iteration, stick-to-itiveness, grit, and determination in the industry. Which brings us to our next Report theme:

#### **We Don't Need a Sexy Moonshot. We Need Fast, Incremental Steps:**

In 100 years of small steps, the oil and gas industry has progressed from mining oil from pools on the surface of the Earth, to deep and ultra-deepwater oil and gas exploration. The incrementality, and indeed necessity of the steps in between these two should not be overlooked. To make the jump from land-based drilling to offshore drilling, just as an example, drillers started by building wooden platforms in ten feet (three meters) of water, and caught rides with shrimp boats out to their rigs in the morning. Now, decades later, industry drills the most technically complex wells in the world with price tags in the billions, from offshore rigs the size of small cities, in 5,000 feet (1,500 meters) of water. Which brings us to our next Report theme:

#### **We May Be on the Cusp of a Green Drilling Boom:**

So that brings us to the third Boom set to emerge from Texas, and it is one that is both upon us, and on us to build: the Heat Boom. Geothermal, particularly Next Generation Geothermal as often referenced in this Report, is in its nascent stage. Its development stage is much like oil and gas was back in the days of Spindletop, where we aimed to harvest what we could easily access, and what we could see, close to or on the surface. In the geothermal context, queue the pictures of Iceland, the Blue Lagoon, and geysers – and the geothermal power plants that sit beside them. Right now in geothermal, we are harvesting what we can easily access, and what we can see. But there is a geothermal “deepwater” that we refer to in this Report

as “geothermal anywhere,” and the oil and gas industry is well positioned to go get it. Which brings us to our next Report theme:

#### **Geothermal is No Longer Just About Volcanoes. A New Generation of Technologies and Methods from the Oil and Gas Industry Can Help Us Develop “Geothermal Anywhere.”:**

While we can't see it bubbling up from the surface of the ground in Texas, or in most places in the world for that matter, geothermal is big, underneath us everywhere, and can serve the needs of Texas and the world, in many ways for thousands of years. Texas, and indeed the world, has enormous geothermal resources, sufficient for many thousands of years of heat and electricity production. In Texas, these are not the traditional geothermal resources you find in Iceland, or along the Ring of Fire – Texas geothermal lies in its sedimentary geology. While we do not yet know how much of this enormous heat resource beneath us can be extracted, or how efficiently we can extract it, this is among the technological challenges that lie ahead of us. Which brings us to our next Report theme:

#### **The Oil and Gas Industry is Well Equipped to Solve Geothermal Challenges and Achieve Fast Global Scale:**

The nexus between the oil and gas industry, and the potential for fast, global deployment and scale of geothermal energy, not only in Texas, but everywhere in the world is clear. There are historical aspects of the relationship between the oil and gas industry and environmental and climate groups, local communities, even existing traditional geothermal operators that will require an open minded, inclusive, and reflective approach to the future of geothermal development. This is the concept in the Report we see emerge often of “social license to operate.” I touched on these topics in a piece in 2020 entitled [“If Oil and Gas Becomes Geothermal, What Does Geothermal Become?”](#) If the oil and gas industry is up to the task of geothermal development at fast global scale, it would be helpful if the rest of the world was onboard with the plan. There is work to be done there.

Yet a conclusion underlying all analyses and major outcomes presented in this Report is that Texas and the oil and gas industry are indeed poised to grab the reins of this unique opportunity and run with it. Which brings us to our next Report theme:



### **The Oil and Gas Industry is Stepping Up to the Plate:**

There are many examples in this Report of oil and gas entities taking on the challenge of developing bespoke technologies for geothermal, making investments, and pursuing geothermal pilot projects. It is a pivotal moment in time for the oil and gas industry, where the world is focused on decarbonization, and where the skilled workforce of the industry are struggling to find paths forward in the future energy mix. Amongst this uncertainty, geothermal is a beacon. Numerous innovations and collaborations are emerging from oil and gas entities making significant effort to modify existing equipment, services, and technologies used in oil and gas to support geothermal development.

Oil and gas industry engagement in the realms of technology transfer, project development, and scale has accelerated rapidly over the past three years. Almost 80 percent of oil and gas entities interviewed for this Report noted that they have a geothermal strategy in place or in development, and almost 70 percent reported that there is no geothermal related technical challenge that the oil and gas industry cannot solve. Further, and interestingly, this historically conservative industry is embracing technologically difficult geothermal concepts at increasing rates, with nearly 100 percent of entities reporting engagement or interest in next generation geothermal concepts like Closed Loop Geothermal Systems. There appears to be a trend in the data outlined in this Report of the oil and gas industry “jumping into the deep end” of the most difficult challenges facing geothermal, which is an intriguing and exciting deviation from business as usual.

Another deviation from business as usual in industry is the origin of geothermal initiatives within oil and gas entities. As the data in this Report suggests, several geothermal initiatives within the oil and gas industry have originated from “top-down” management dictates, while more than half of the recent initiatives came from “grassroots” efforts to diversify and strengthen a company’s business portfolio. This is a trend to watch as both internal and external activism becomes a theme in itself in the oil and gas industry. Which brings us to our next Report theme:

### **Disruptors Gonna Disrupt:**

Startups are leading the way with big, bold ideas, and new innovators are entering the space faster than we could incorporate them into this Report. Disruption results in step-changes, which geothermal desperately needs.

So charge forward, lead the way, and forget business as usual, disruptors. Which brings us to our next Report theme:

### **Other Stakeholders Are Also Bucking “Business as Usual.” Stepping Up to Support and Drive Geothermal:**

Geothermal is experiencing a massive infusion of new voices, faces, entities, and ideas, including new initiatives within government from agencies interested in fast deployment of the resource. A 2023 solicitation for scalable microgrid geothermal systems by the United States military, discussed in this Report, is a prime example. New off-takers are fast emerging – municipalities, utilities, even private landowners. New startups are launching at an accelerating pace, mostly headquartered in Texas and led by oil and gas industry veterans, another new trend. New innovations and ideas are emerging from the oil and gas industry, and the number of entities engaged is quickly growing. New investors are entering the space, eager to support teams, technologies, and scale. These trends combined have created a convergence and are acting as force multipliers on one another.

In the realm of environmental impact, and environmental and climate activism, we are seeing the beginning of a shift in perspective there as well. As the world charges forward with decarbonization and energy transition strategies, it is important to keep eyes wide open on the environmental footprint of the technologies that we are choosing to deploy and scale, and what their life cycle environmental impacts are. Currently, the terms “renewable” and “clean” are being used to describe technologies that require high impact, environmentally destructive mining operations, extensive use of critical and Rare Earth minerals extracted by geopolitical rivals or from unstable regions of the world. Many minerals required for these energy technologies are mined in countries where human rights abuses are rampant, and with little regard to environmental or workplace safety. Further, many of these materials cannot be recycled at the end of their productive lives, creating massive waste streams with toxic by-products that end up in landfills.

By comparison, geothermal is a standout, and we are seeing a steady trend in the past few years of environment and climate groups not only engaging in the details of the supply chains and carbon footprints of traditional renewables, but also in the benefits and attributes of geothermal energy. All energy technologies have an environmental impact, and we need to take a levelheaded, fact-based approach to how we deploy technologies over



the coming decades to assure that we do not repeat the environmental impacts of our past energy sources, with the energy sources of our future. Which brings us to our next Report theme:

### **Aggressive Targets, a Bold Vision, and Interdisciplinary Collaboration Directed at Geothermal Will Drive Down Cost, and Drive Up Scale:**

Cost is a central challenge that has constrained geothermal development historically and is a recurring theme across Chapters. But while cost challenges associated with geothermal are today's reality, as technology and methods transfer from oil and gas optimizes systems, and risk is mitigated, successful business models will emerge. As the Report concluded, all geothermal concepts, including Next Generation, scalable geothermal concepts like Engineered Geothermal Systems and Advanced Geothermal Systems will benefit significantly from oil and gas technology and knowledge transfer, providing quick wins and achievable learnings projected to deliver 20 to 43 percent in cost savings, depending on the type of geothermal technology. And these cost reduction estimates do not consider the impact of new innovations and technology breakthroughs.

Cost reduction, increased efficiency, and optimization of scalable geothermal systems stands as a "grand challenge" for Texas to aim for by the end of this decade. There are strong parallels here with the trajectory of the oil and gas industry historically. As the utilization of oil and gas scaled, the business model became successful, and that business model has dominated the world's energy production for a century. There is no reason to reinvent the wheel to build our clean energy future. We have the playbook - we just need to apply it to grow and scale geothermal. But industry cannot do this alone, which brings us to our final Report theme:

### **An 'Apollo' Style Mobilization of Stakeholders Could Drive Sufficient Global Scale for Geothermal to Supply a Majority of Global Demand for Electricity and Heat by 2050:**

The final recurring theme is the need for robust, focused engagement from governments and world leaders to realize the targets identified in this Report. Geothermal will benefit from a laser focus on how policy incentives and market shaping can help build this new global industry with a firm root in the State of Texas. Ultimately, the development of geothermal systems at scale - the coming

Heat Boom - is likely to follow closely in parallel with the Shale Boom. As Texas is a world leader in unconventional oil and gas production, it is positioned to become the world leader in the production of the scalable geothermal systems of the future. It will take time and significant investment, but as this Report concludes, the potential for Texas to become the global geothermal epicenter is exceptional.

Which brings us to the subject of global impact. From this Report emerges disruptive and globally significant headlines, like the possibility that Texas could fully decarbonize its grid, utilizing existing oil and gas technologies and capacity, in only four years of drilling geothermal wells in the State. **In another groundbreaking estimate, a strenuous "all hands on deck" development scenario where 1.4 million geothermal wells are drilled globally between 2030 and 2050, would result in 77 percent of global projected electricity demand being supplied by geothermal by 2050. Drilling another 600,000 geothermal wells globally in that same period for heat production could supply more than 100 percent of global projected heat demand by 2050. This is a pathway to decarbonization that, while aggressive and extraordinary in its scale, is perhaps more realistic than any other path to decarbonization in existence currently.**

In oil and gas, we've followed the trajectory of industry from Spindletop at the turn of the century, to the Deepwater exploration and production of today. Similarly, we will follow the trajectory of geothermal development near volcanos of today, to the sedimentary development in Texas prairies of the near future, to SuperHot development anywhere in the world in the further out future. There will be steps in between, as there always have been, in ways of learning and progress of the industry - but our Heat Boom, Green Drilling Boom - whatever you want to call it, is here and it is up to us to build. We can get there. The oil and gas industry has achieved this speed and scale before, with rapid global impact. **If we follow the roadmap of the greatest human achievements in our approach to collaboration and cooperation across industries, disciplines, and even party lines, we can achieve or even exceed global decarbonization goals with geothermal by 2050.**

So let's go.

Since we began with a geothermal pun in the introduction of this Report, perhaps we should end with one that seems fitting:

Well, well, well Texas, what do we have here... 

