Chapter 7

The Geothermal Business Model & the Oil and Gas Industry

Challenges and Opportunities

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> ***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

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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 uninterruptible 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[1], 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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[1] 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,[2] 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

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[2] 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) 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[3]	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	Cyrq 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

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[3] 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[4] 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.

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[4] Calpine (Energy Capital Partners): 725 megawatts; Ormat: 2,000 megawatts; CalEnergy (Berkshire Hathaway): 350 megawatts; Cyrq 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 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

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%
Illustrative Scenario		
Reuse of two suspended frac'ed 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		
Assumptions		
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.		
Cost of Capital assuming 2.5% long term inflation, 30% equity, 70% debt		
Equity: 15%		
Debt: 7%		

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[5]. 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 TNO 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	" "	N/A
	30% of the basis of energy property (ITC)	" "	30% of basis of the battery (ITC)
	Start of construction before Jan 1 2025	" "	" "
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)	" "	" "
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	" "	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	" "	" "
Transferable	Yes, for taxable years 2023 onwards	" "	" "

[5] Calculations using TNO DoubletCalc 2D for produced temperature profiles, fed to NREL Geophires 2.0 bicycle economic model to calculate LCOE and pump power (Reservoir Model 5, Economic Model 3).

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 (10 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)	" "
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	" "
TRANSFERABLE	Yes	" "

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).[6] 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
Carbon Emissions (IEA)						
Pounds CO2/ MMBTU	117	163	165	166	216	26
Ton CO2/ MMBTU	0.058	0.082	0.082	0.083	0.108	0.013
Carbon Permit Price: California / Quebec Western Climate Initiative 7th Auction May 2022						
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
Carbon Permit Price: European Union ETS 15th Dec 2022						
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

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[6] 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/ft3") 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[7]
Gross Heating Value	0.001 MMBTU/ft3	1.04 MMBTU/ft3	1.08 MMBTU/ft3	1.12 MMBTU/ft3	1.01 MMBTU/ ft3	0.74 MMBTU/ ft3
	$/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

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[7] 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, line, 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

	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

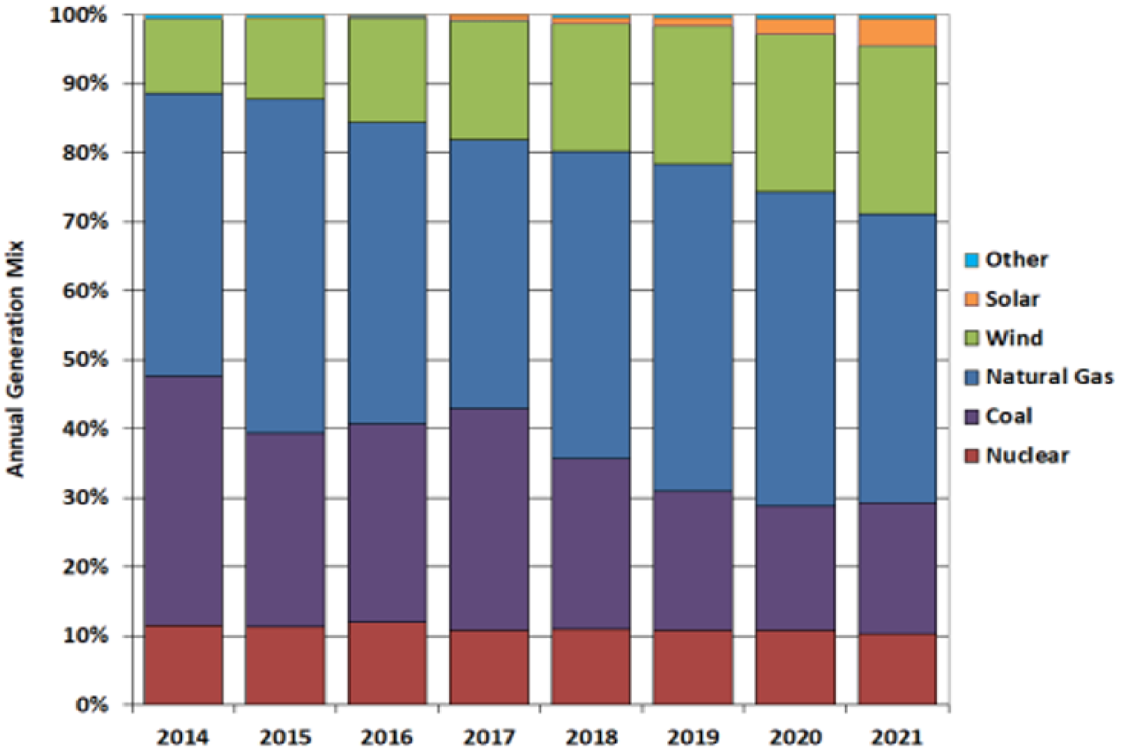


Figure 7.1. 2021 ERCOT generation mix maximum day demand in 2021 was 72.3 gigawatts and 80.0 gigawatts in 2022. Installed capacity in 2021 was 86 gigawatts and in 2022 92 gigawatts. *Source: ERCOT, 2021, 2022.*

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).

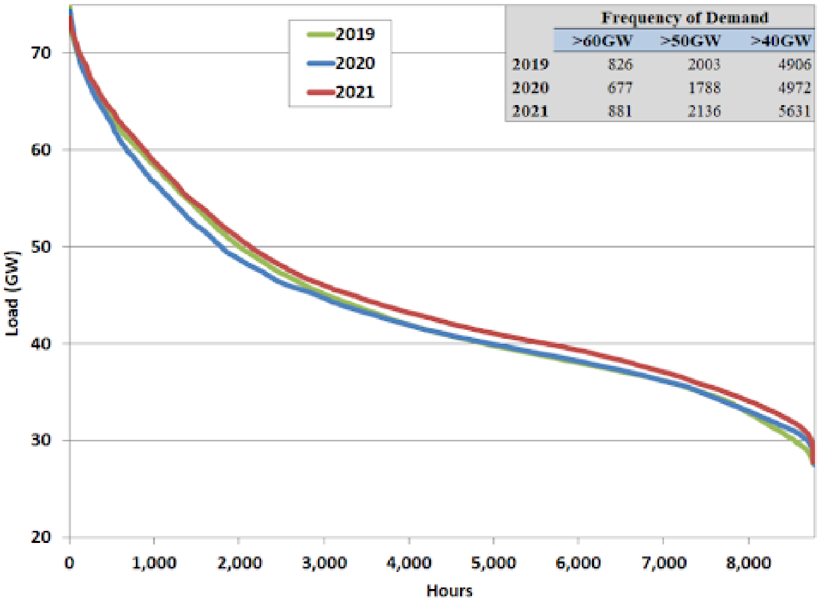
Table 7.15 presents the settlement prices by fuel type in the ERCOT jurisdiction, again the 2021 prices are strongly influenced by Winter Storm Uri so they are also presented excluding this effect, so the 2020 and 2021 prices do provide a comparison.

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)
	Gigawatts	**Terawatts**	**Percent**
	electric	**electric per hour**	
2020	82	382	52
2021	86	393	51
2022	92	TBA	TBA

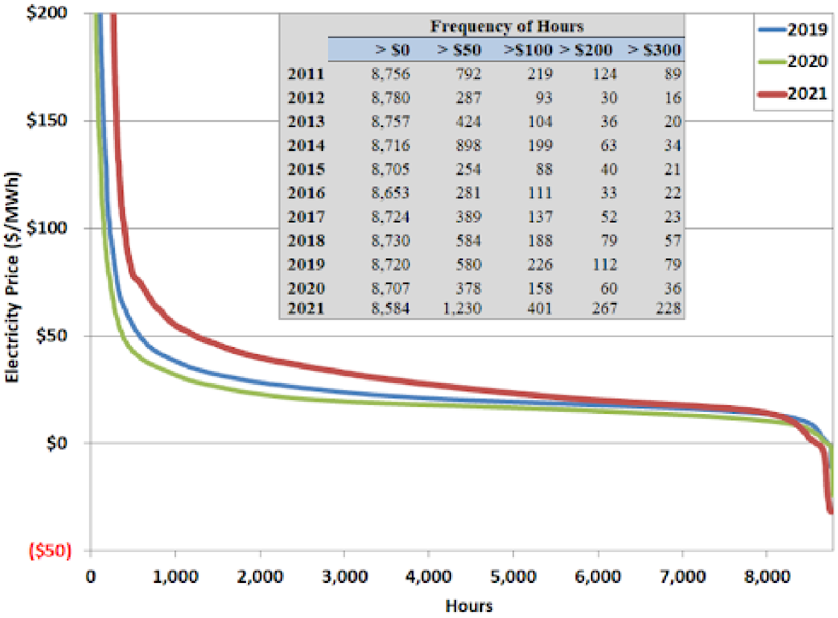
kilowatt electric hour respectively, so prices in 2020 were lower than cost (NEI, 2022). According to the NEI, these generating costs include capital for upgrades related to license extensions of plants, uprates, and completed safety-related investments post-September 11th and post-Fukushima. So notably, 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 levelized 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.



Frequency of Demand

	>60GW	>50GW	>40GW
2019	826	2003	4906
2020	677	1788	4972
2021	881	2136	5631

Figure 7.2. Frequency of Demand ERCOT. *Source: ERCOT, 2022.*



Frequency of Hours

	> $0	> $50	>$100	> $200	> $300
2011	8,756	792	219	124	89
2012	8,780	287	93	30	16
2013	8,757	424	104	36	20
2014	8,716	898	199	63	34
2015	8,705	254	88	40	21
2016	8,653	281	111	33	22
2017	8,724	389	137	52	23
2018	8,730	584	188	79	57
2019	8,720	580	226	112	79
2020	8,707	378	158	60	36
2021	8,584	1,230	401	267	228

Figure 7.3. Frequency of Electricity Prices During 2021. *Source: ERCOT, 2022.*

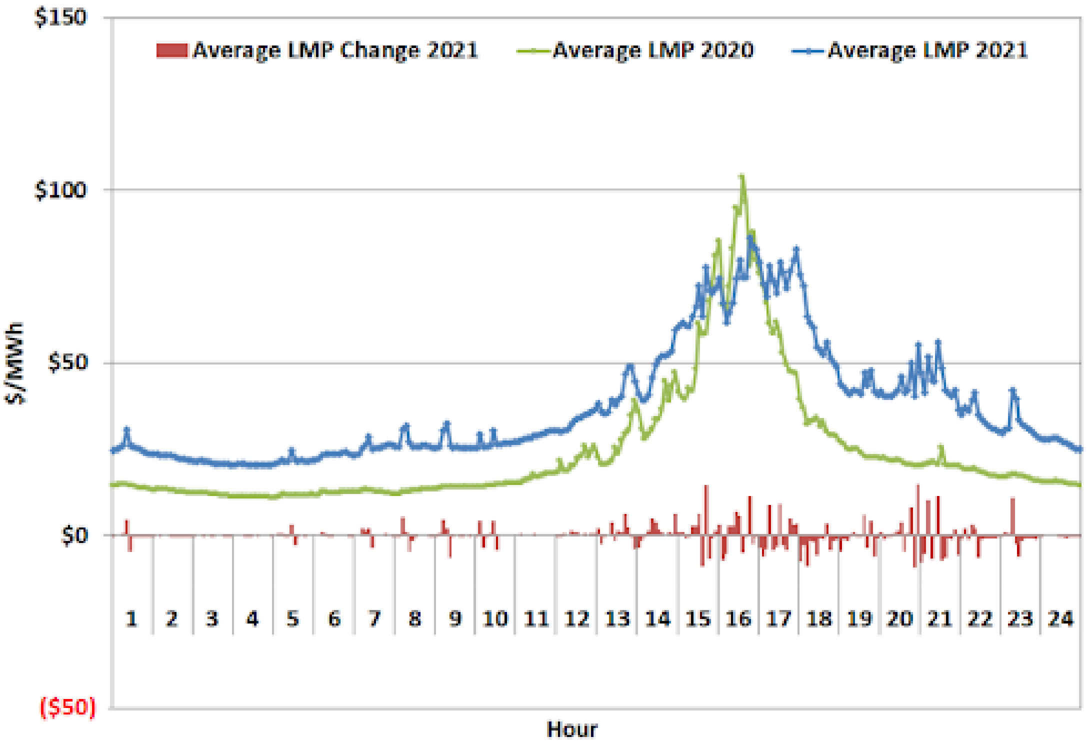


Figure 7.4. Price by Time of Day May to Sept 2021. *Source: ERCOT, 2022.*

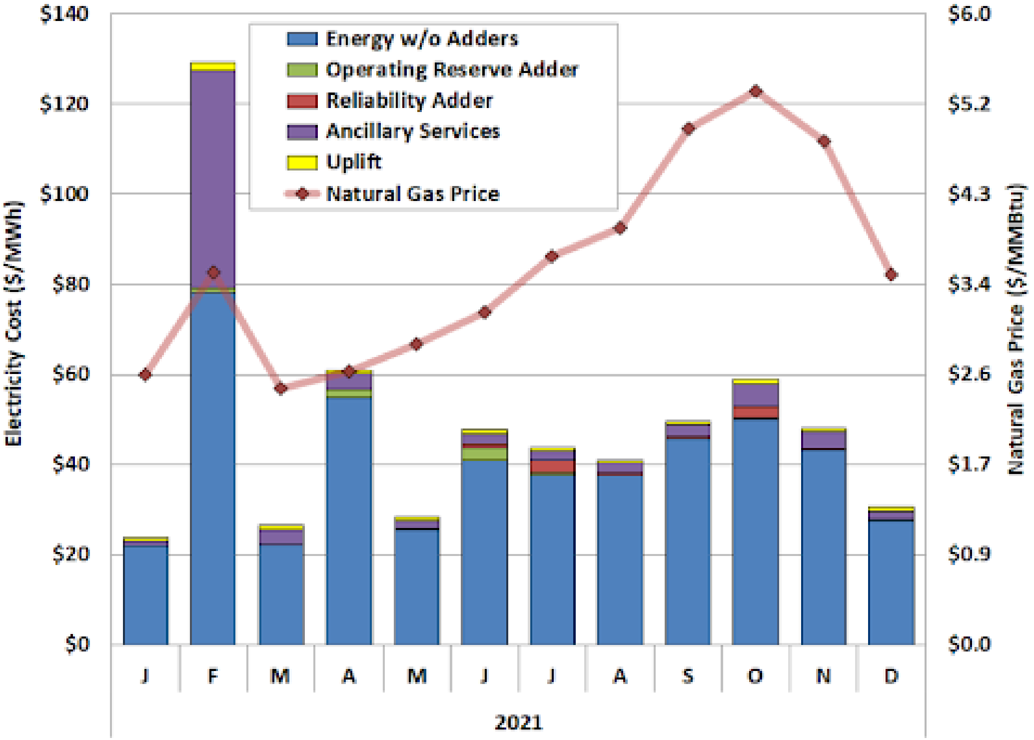


Figure 7.5. Prices by Month 2021 (without Uri). *Source: ERCOT, 2022.*

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
ERCOT $/kW.hr	$0.041	$0.027	$0.025	$0.028	$0.036	$0.047	$0.026	$0.168	$0.041
Natural Gas $/ MMBTU	$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, 2022 ;ERCOT, 2022; Future of Geothermal Energy in Texas, 2023.*

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

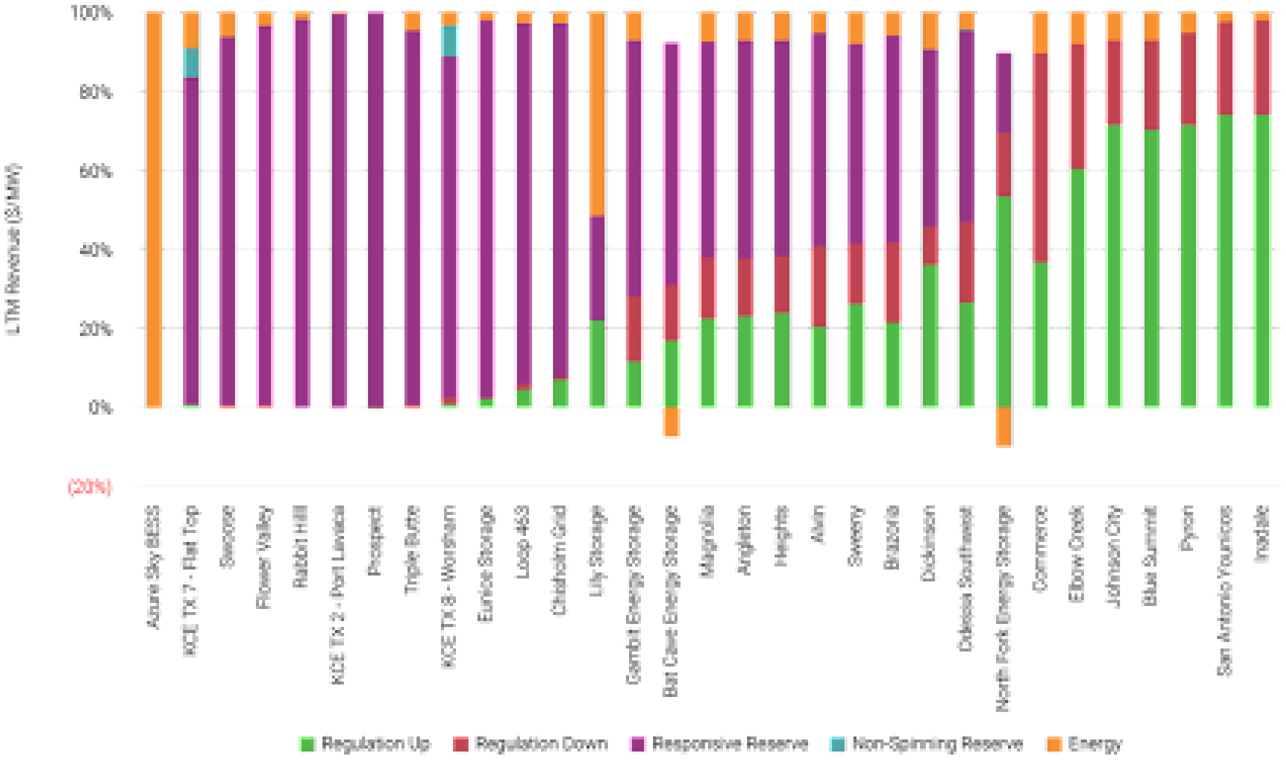


Figure 7.6. Proportion of battery storage revenue from price arbitrage ancillary services 2022. *Source: ERCOT, 2022.*

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.

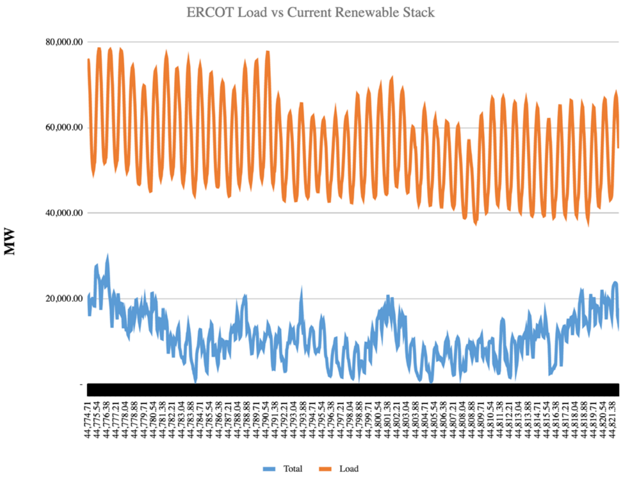


Figure 7.7. August through September 2022 actual demand vs wind and solar. *Source: ERCOT, 2022.*

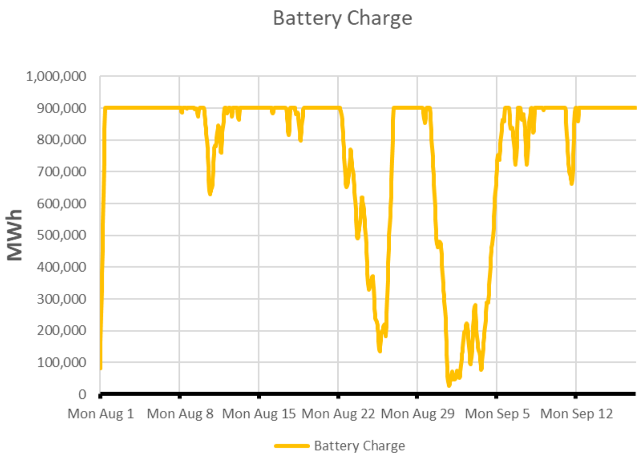


Figure 7.8. Battery capacity requirements for eight times solar and wind in ERCOT energy mix. *Source: Curry, 2020a.*

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.

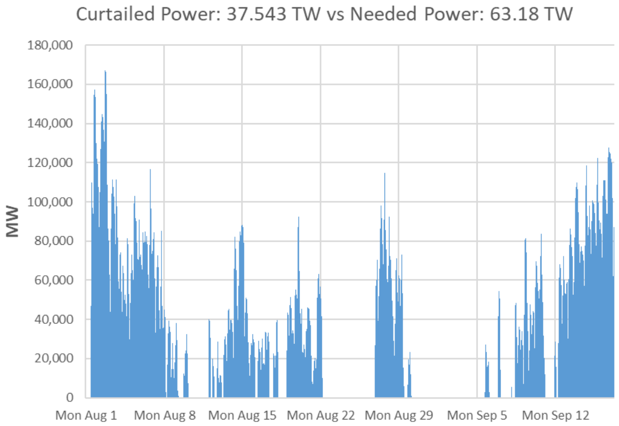


Figure 7.9. Wasted power associated with eight times that of solar and wind. *Source: Curry, 2020a.*

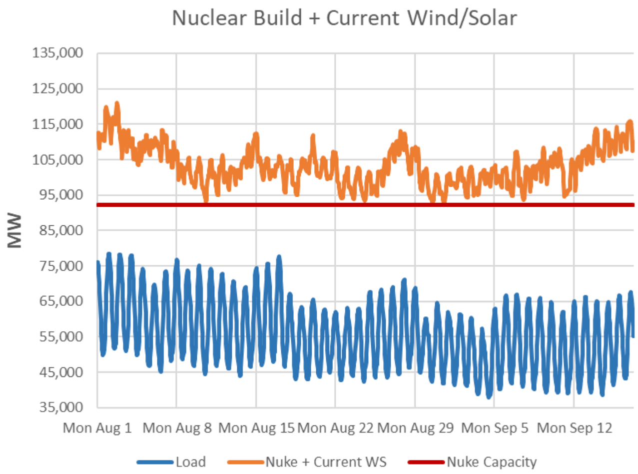


Figure 7.10. Replace fossil fuels with nuclear instead of wind. *Source: Curry, 2020a.*

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.

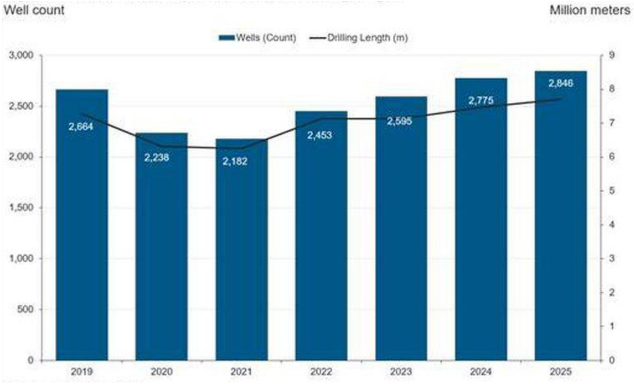


Figure 7.13. Global Number of Drilled Wells, 2019-2025. *Source: Rystad, 2020.*

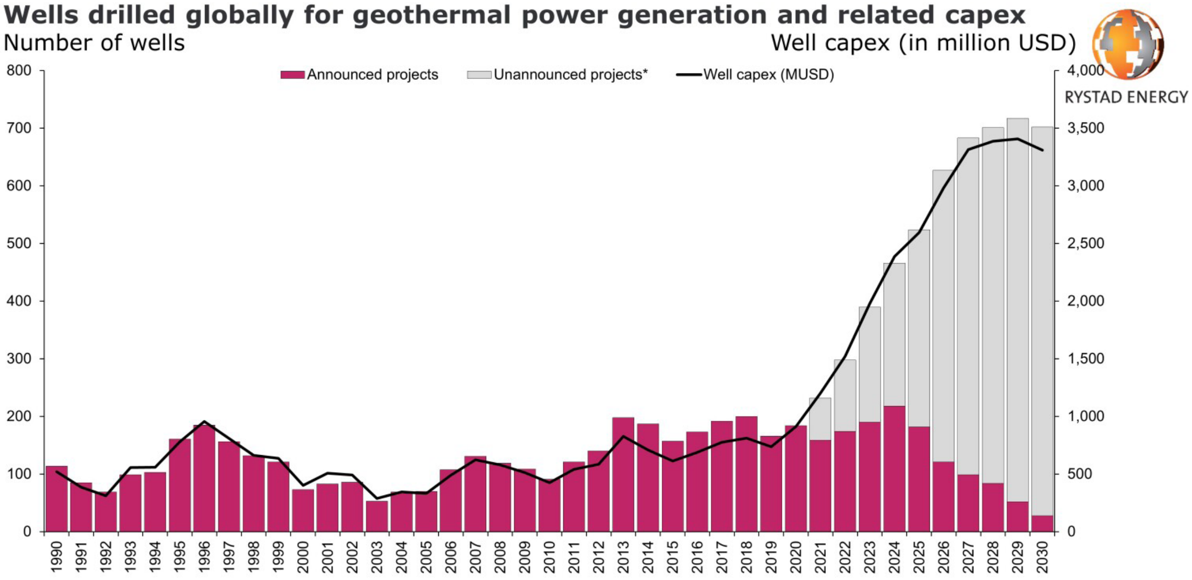
Figure 7.13 shows that roughly 60,000 to 70,000 onshore oil and gas wells are forecast to be drilled each year globally, which by comparison with Figure 7.12 would be considerably lower than in the period 2006 to 2014.

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



*Unannounced projects contain an estimated number of wells to be drilled to meet government targets on capacity addons towards 2030

Source: Rystad Energy Geothermal Analysis Dashboard

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-

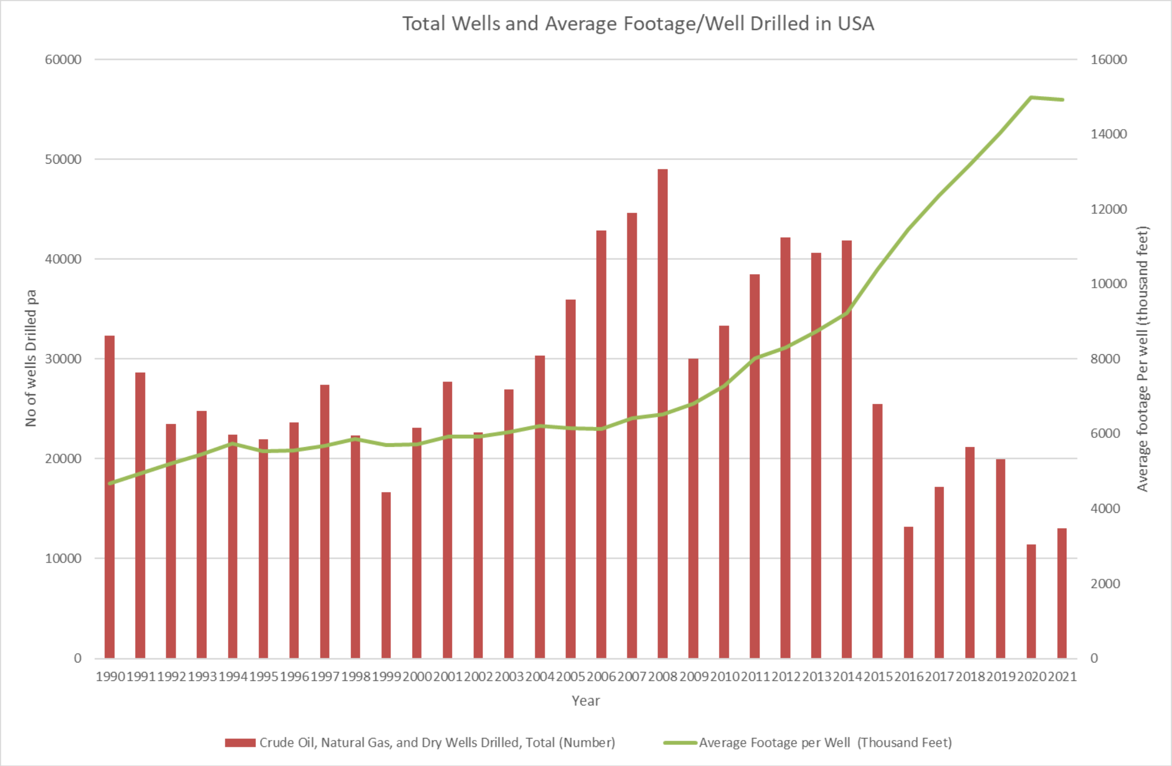


Figure 7.12. Total Wells and Average Footage Per Well drilled in the USA. *Source: EIA, 2022.*

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-Tcold/Thot} where T is in absolute temperature - after Carnot;
- The conversion plant design and fluid selection (Rankine, Brayton, Single Flash, Double Flash / organic fluid, water, sCO2 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 Tsink is 71 °C (160 °F)). **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'ed rock permeabilities is a much greater

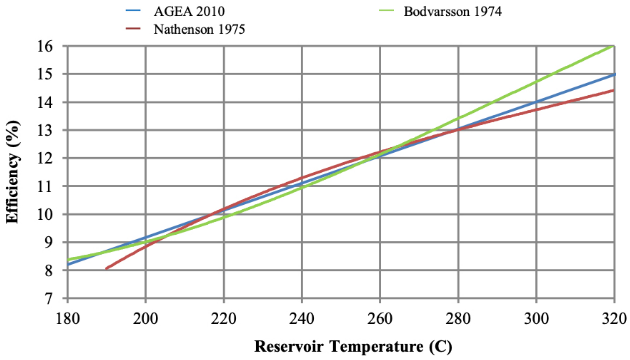


Figure 7.14. Conversion efficiency from heat to electricity. *Source: Moon & Zarrouk, 2012.*

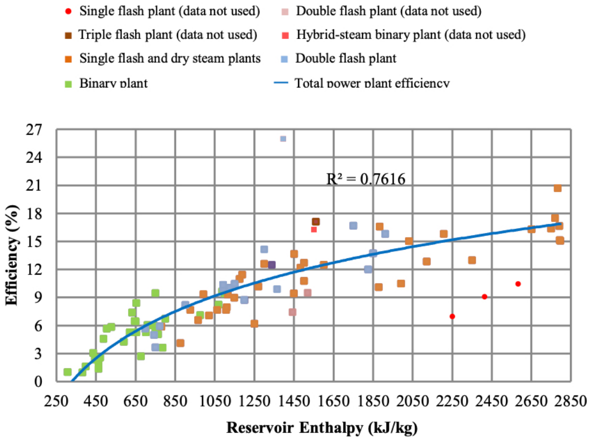


Figure 7.15. Geothermal power plant conversion efficiency. *Source: Moon & Zarrouk, 2012.*

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 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

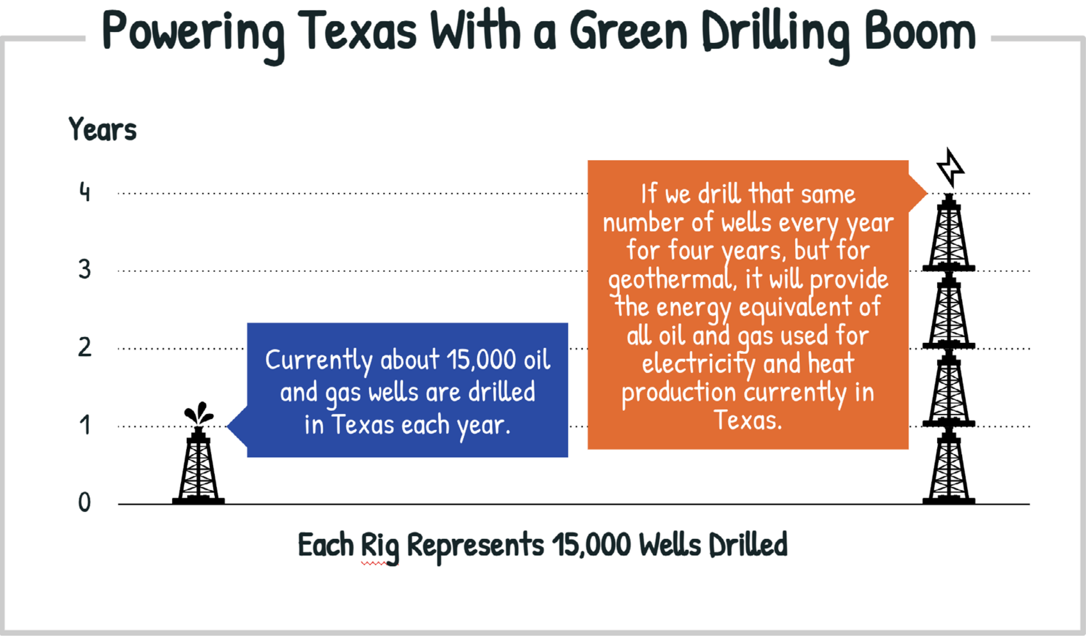


Figure 7.16. A graphic illustration of the potential for a geothermal drilling boom in Texas. It would take approximately four years of drilling at the rate Texas currently drills for oil and gas to produce the equivalent energy of all oil and gas used for electricity and heat production currently in 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 unconventionals 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.**

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

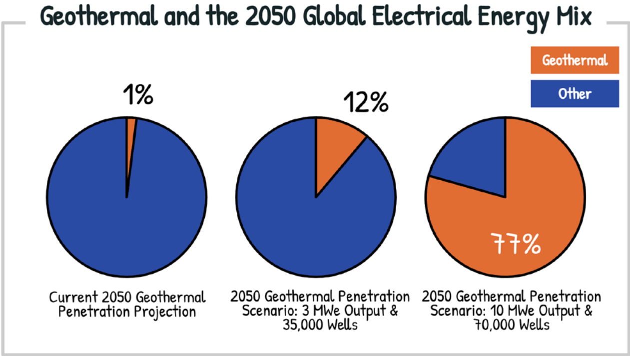


Figure 7.17. 2050 geothermal electrical energy contribution to the global energy mix under three calculated scenarios: 1) current IEA projection (left), 2) scenario of 35,000 geothermal wells drilled per year from 2030-2050, having three megawatts electric per well output (middle), and 3) scenario of 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.*

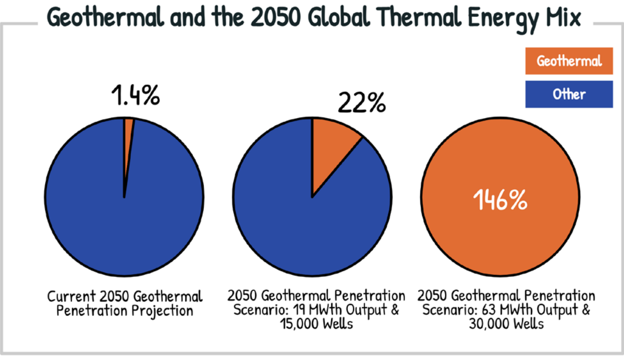


Figure 7.18. 2050 geothermal thermal energy contribution to the global energy mix under three calculated scenarios: 1) current IEA projection (left), 2) scenario of 15,000 geothermal wells drilled per year from 2030-2050, having 19 MWth per well output (middle), and 3) scenario of 30,000 geothermal wells 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.*

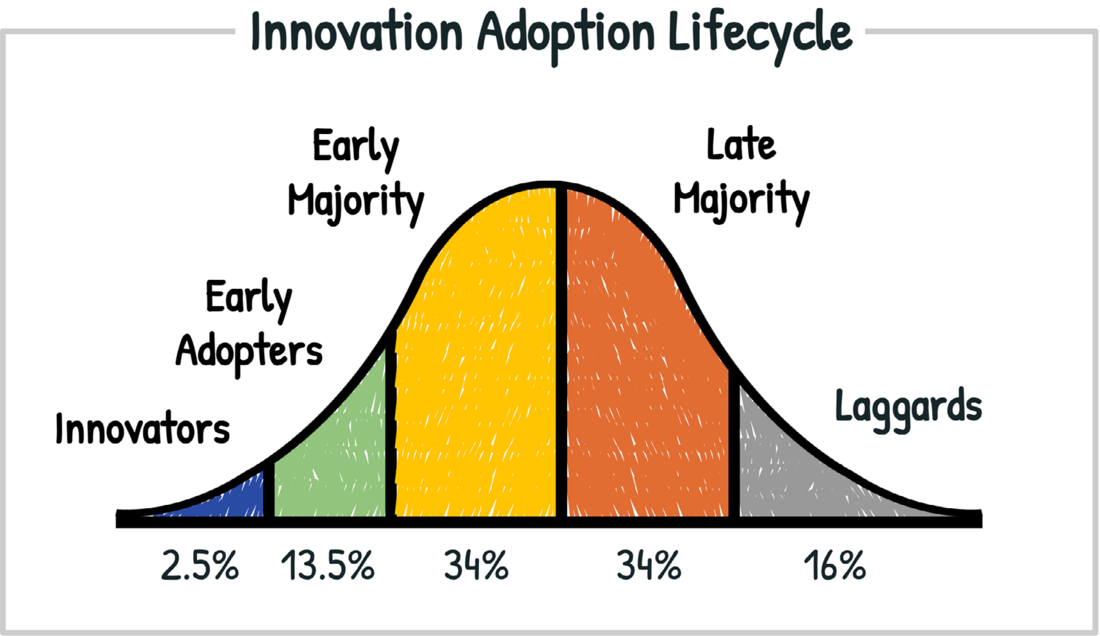


Figure 7.19. Rogers diffusion of innovations. *Source: Rogers, et al., 2014.*

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 CO2 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.

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.

Chapter 7 References

Arctic Green. (2022). Retrieved on October 16, 2022, from https://arcticgreen.com/projects/.

Beckers, K. F., & McCabe, K. (2019). GEOPHIRES v2. 0: updated geothermal techno-economic simulation tool. Geothermal Energy, 7(1), 1-28.

Bianchi, G., Panayiotou, G. P., Aresti, L., Kalogirou, S. A., Florides, G. A., Tsamos, K., ... & Christodoulides, P. (2019). Estimating the waste heat recovery in the European Union Industry. Energy, Ecology and Environment, 4(5), 211-221.

Bošnjaković, M., Stojkov, M., & Jurjević, M. (2019). Environmental impact of geothermal power plants. Tehnički vjesnik, 26(5), 1515-1522.

California Climate Investments - CCI. (2020). Using Cap and Trade Auction Proceeds. Retrieved on December 23, 2022, from http://ww2.arb.ca.gov/sites/default/files/auction-proceeds/2020_cci_annual_report.pdf.

Chevron. (2022). Chevron and Baseload Capital create join venture to explore geothermal development opportunities. Retrieved on December 22, 2022, from https://www.chevron.com/newsroom/2022/q4/chevron-and-baseload-capital-create-joint-venture-to-explore-geothermal-development-opportunities.

Coker, A. K. (Ed.). (2022). Petroleum Refining Design and Applications Handbook, Volume 3: Mechanical Separations, Distillation, Packed Towers, Liquid-Liquid Extraction, Process Safety Incidents. John Wiley & Sons.

Compton, A., Kim, W., Grossman, G., Sosa, P. (2022). Climate Change Progress: The Inflation Reduction Act. Retrieved on October 22, 2022, from https://www.linklaters.com/en/knowledge/publications/alerts-newsletters-and-guides/2022/august/23/climate-change-progress-the-inflation-reduction-act#:~:text=Investment percent20Tax percent20Credits percent20(Section percent2048,projects percent20until percent20January percent201 percent2C percent202035.

Curry, J. A. (2020a). ERCOT Load vs. Renewables. Retrieved on October 22, 2022, from https://judithcurry.com/wp-content/uploads/2022/10/ERCOT-Load-vs-Renewables.xlsx.

Curry, J. A. (2020b). ERCOT Renewable Energy: Reality Check. Retrieved on October 22, 2022, from https://judithcurry.com/2022/10/31/ercot-renewable-energy-reality-check/#:~:text=Battery%20percent20cost%20percent20%20percent24385%20percent2C000%20percent2FMWh.

Dhar, A., Naeth, M. A., Jennings, P. D., & Gamal El-Din, M. (2020). Geothermal energy resources: potential environmental impact and land reclamation. Environmental Reviews, 28(4), 415-427.

DiPietro, J. A. (2013). Keys to the interpretation of geological history. Landscape evolution in the United States, 3-95.

Dumitru, A., Kölbl, B., Wijffelaars, M. (2021). The Carbon Border Adjustment Mechanism Explained. Retrieved on December 23, 2022, from https://economics.rabobank.com/publications/2021/july/cbam-carbon-border-adjustment-mechanism-eu-explained/.

DNV. (2021), World Energy Transition Outlook. Retrieved on December 23, 2022, https://www.dnv.com/energy-transition-outlook/index.html.

Electric Reliability Council of Texas - ERCOT. (2022). December 2022 Fact Sheet. Retrieved on December 23, 2022, from https://www.ercot.com/files/docs/2022/02/08/ERCOT_Fact_Sheet.pdf.

Enverus Intelligence Research - EIR. (2022). ERCOT Storage: Hunting for New opportunities. Retrieved on December 23, 2022, from https://www.enverus.com/newsroom/ercot-storage-hunting-for-new-opportunities/.

European Union - EU. (2022). EU climate action: provisional agreement reached on Carbon Border Adjustment Mechanism. Retrieved on December 23, 2022, from https://www.consilium.europa.eu/en/press/press-releases/2022/12/13/eu-climate-action-provisional-agreement-reached-on-carbon-border-adjustment-mechanism-cbam/.

Franco, A., & Villani, M. (2009). Optimal design of binary cycle power plants for water-dominated, medium-temperature geothermal fields. Geothermics, 38(4), 379-391.

Friedman, L. (2021). Democrats Propose a Border Tax Based on Countries' Greenhouse Gas Emissions. Retrieved on December 23, 2022, from https://www.nytimes.com/2021/07/19/climate/democrats-border-carbon-tax.html.

German Incentive. (2017). "Opportunities geothermal (sic) energy in Germany." Infra News. Retrieved on January 4, 2023, from https://www.nortonrosefulbright.com/en/knowledge/publications/3e005a80/opportunities-geothermal-energy-in-germany#:~:text=The%20German%20Renewable%20Energy%20Sources,25.20%20cents%20per%20kilowatt%20hour.

Croatia Incentive. (2020). "Goverment (sic) adopts decree to introduce premiums for renewables in Croatia." Balkan Green Energy News. Retrieved on January 4, 2023, from https://balkangreenenergynews.com/goverment-adopts-decree-to-introduce-premiums-for-renewables-in-croatia/.

Hartford. (2022). When to Use Investment Tax Credits. Retrieved on October 22, 2022, from https://www.thehartford.com/business-insurance/strategy/business-tax-credits/investment-tax-credits.

Holloway, M. D., & Holloway, E. (2020). Dictionary of Industrial Terminology. John Wiley & Sons.

Huttrer, G. W. (2020). Geothermal power generation in the world 2015-2020 update report. In Proceedings world geothermal congress (Vol. 1).

Inflation Reduction Act of 2022 - IRA. (2022). Retrieved on November 14, 2022, from https://www.govinfo.gov/content/pkg/PLAW-117publ169/uslm/PLAW-117publ169.xml.

International Energy Agency - IEA. (2022). World Energy Outlook 2022. Retrieved on November 18, 2022, from https://www.iea.org/reports/world-energy-outlook-2022.

International Renewable Energy Agency - IRENA. (2021). Renewable Power Generation Costs in 2020. Retrieved on November 6, 2022, from https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020.

International Renewable Energy Agency - IRENA. (2022).Renewable Capacity Statistics 2022. Retrieved on November 6, 2022, from https://www.irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022.

Jennings 2022. HeatFlow.org: A repository for data and models related to thermal studies of the Earth by Sam Jennings and Derrick Hasterok, University of Adelaide

Lawless, J. (2010). "Geothermal Lexicon For Resources and Reserves Definition and Reporting" Retrieved on December 14, 2022, from http://www.dmp.wa.gov.au/Documents/Geological-Survey/Geothermal_Lexicon_2010.pdf.

Lund, J. W., & Toth, A. N. (2021). Direct utilization of geothermal energy 2020 worldwide review. Geothermics, 90, 101915.

Moon, H., & Zarrouk, S. J. (2012). Efficiency of geothermal power plants: a worldwide review. In New Zealand Geothermal Workshop (pp. 19-21).

Murray, C. (2022). "New IPP REX orders first tranche of US$400 million ERCOT BESS pipeline from Stem Inc." Energy Storage. Retrieved on December 14, 2022, from https://www.energy-storage.news/new-ipp-rex-orders-first-tranche-of-us400-million-ercot-bess-pipeline-from-stem-inc/.

National Conference of State Legislatures - NCSL. (2021). State Renewable Portfolio Standards and Goals. Retrieved on November 14, 2022, from https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx.

National Law Review - NLR. (2022). Relief Arrives for Renewable Energy Industry - Inflation Reduction Act of 2022. Retrieved on October 22, 2022, from https://www.natlawreview.com/article/relief-arrives-renewable-energy-industry-inflation-reduction-act-2022.

National Renewable Energy Laboratory - NREL. (2022). Utility-Scale Battery Storage. Retrieved on November 30, 2022, from https://atb.nrel.gov/electricity/2022/utility-scale_battery_storage.

NLOG. (2016). DoubletCalc 2D v1.0. Retrieved on October 16, 2022, from https://www.nlog.nl/en/nieuws/doubletcalc-2d-v10.

North Carolina State University Clean Energy Technology Center - NCCETC. (2022). Renewable Generation Requirement. Retrieved on November 14, 2022, from https://programs.dsireusa.org/system/program/detail/182.

Nuclear Energy Institute - NEI. (2022). Nuclear Costs in Context. Retrieved on October 16, 2022, from https://www.nei.org/resources/reports-briefs/nuclear-costs-in-context.

Oil and Gas Clearing House - OGCH. (2022). Retrieved on October 16, 2022, from https://www.ogclearinghouse.com/company.

O'Neill, R., Rohner, E., Kaden, M., Blitman, J., McClure, K. (2022). An Overview of Clean Energy Tax Legislation in the Inflation Reduction Act. Retrieved on November 14, 2022, from https://www.mossadams.com/articles/2022/08/inflation-reduction-act-clean-energy-credits#section-45.

Organization for Economic Co-operation and Development - OECD. (2021). Supplement to Effective Carbon Rates, United States. Retrieved on October 16, 2022, from https://www.oecd.org/tax/tax-policy/effective-carbon-rates-2021-0e8e24f5-en.htm.

Organization for Economic Co-operation and Development - OECD. (2022). Pricing Greenhouse Gas Emissions, United States Country Notes. Retrieved on October 16, 2022, from https://www.oecd.org/tax/tax-policy/carbon-pricing-united-states.pdf.

Potomac Economics. (2022). Executive Summary 2021 State of the Market Report. Retrieved on November 3, 2022, from https://www.potomaceconomics.com/wp-content/uploads/2022/05/2021-State-of-the-Market-Report.pdf.

Railroad Commission, Texas - RCC. (2021). Texas Oil & Gas Producers by Rank. Retrieved on October 16, 2022, from https://www.rrc.texas.gov/oil-and-gas/research-and-statistics/operator-information/texas-oil-and-gas-producers-by-rank-2021/.

Railroad Commission, Texas - RCC. (2022). Oil and Gas Well Records. Retrieved on October 16, 2022, from https://www.rrc.texas.gov/oil-and-gas/research-and-statistics/obtaining-commission-records/oil-and-gas-well-records/.

Railroad Commission, Texas - RCC. (2021). Summary of Drilling Permits, Completions and Plugging Reports Processed. Retrieved on December 17, 2022, from https://www.rrc.texas.gov/media/xp1ls32u/december-2021.pdf.

Ray, R. (2015). Combined Cycle: The Preferred Option. Power Engineers. Retrieved on November 3, 2022, from https://www.power-eng.com/coal/combined-cycle-the-preferred-option/#gref.

Febrianto, R., Bydder, J., Hochwimmer, A., Ussher, G., & Libbey, R. (2019). Developing low temperature Geothermal projects in Indonesia using pumped well technology. In IOP Conference Series: Earth and Environmental Science (Vol. 254, No. 1, p. 012021). IOP Publishing.

Robins, J. C., Kolker, A., Flores-Espino, F., Pettitt, W., Schmidt, B., Beckers, K., ... & Anderson, B. (2021). 2021 US Geothermal Power Production and District Heating Market Report (No. NREL/TP-5700-78291). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Rogers, E. M., Singhal, A., & Quinlan, M. M. (2014). Diffusion of innovations. In An integrated approach to communication theory and research (pp. 432-448). Routledge.

Rystad Energy. (2021). Rystad Energy Geothermal Analysis Dashboard. Retrieved on December 17, 2022, from https://www.rystadenergy.com/services/wells-and-seismic-solution.

Sage Geosystems - Sage. (2022). November 3, 2022, from https://www.sagegeosystems.com/.

Smith, A. and Tassone, C. (2022). How the Inflation Reduction Act Changes the Way Energy Tax Credits Are Calculated and Monetized. Retrieved on October 22, 2022, from https://www.taftlaw.com/news-events/law-bulletins/how-the-inflation-reduction-act-changes-the-way-energy-tax-credits-are-calculated-and-monetized.

Smith, S. (2021). Rystad Energy: Geothermal power on the rise. Retrieved on October 22, 2022, from https://www.energyglobal.com/other-renewables/17092021/rystad-energy-geothermal-power-on-the-rise/.

Sonoma Clean Power - SCP. (2022). GeoZone Pre-project Stakeholder Input. Retrieved on December 22, 2022, from https://sonomacleanpower.org/uploads/documents/GeoZone_PreProject_Stakeholder_Input_2022_Jun_28.pdf.

Sutter, K.R. (2022). May brings another record auction for the Western Climate Initiative, as California considers how to ramp up climate action. Environmental Defense Fund. Retrieved on December 23, 2022, from https://blogs.edf.org/climate411/2022/05/26/may-brings-another-record-auction-for-the-western-climate-initiative-as-california-considers-how-to-ramp-up-climate-action/.

United Nations Supplementary Specifications for the application of the United Nations Framework Classification for Resources (Update 2019) to Geothermal Energy Resources, Geneva, 25 October 2022, from https://unece.org/sed/documents/2022/12/standards/supplementary-specifications-application-united-nations-framework.

U.S. Department of Energy - DOE. (2022). Transformative Power Systems. Office of Fossil Energy and Carbon Management. Retrieved on October 16, 2022, from https://www.energy.gov/fecm/transformative-power-systems.

U.S. Department of Justice - DOJ. (2018). Herfindahl–Hirschman Index. Retrieved on October 16, 2022, from https://www.justice.gov/atr/herfindahl-hirschman-index#:~:text=The percent20agencies percent20generally percent20consider percent20markets,points percent20to percent20be percent20highly percent20concentrated.

U.S. Energy Information Administration - EIA. (2020).Capital Cost and Performance

Characteristic Estimates for Utility Scale Electric Power Generating Technologies. Retrieved on December 23, 2022, from https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2020.pdf.

U.S. Energy Information Administration - EIA. (2022a). Carbon Dioxide Emissions Coefficients. Retrieved on December 23, 2022, from https://www.eia.gov/environment/emissions/co2_vol_mass.php.

U.S. Energy Information Administration - EIA. (2022b). Glossary, distillate fuel oil. Retrieved on December 23, 2022, from https://www.eia.gov/tools/glossary/index.php?id=distillate%20fuel%20oil.

U.S. Energy Information Administration - EIA. (2022c). International Electricity Capacity. Retrieved on December 23, 2022, from https://www.eia.gov/international/data/world/electricity/electricity-capacity.

Watson, M. (2022). Battery storage leads 400-MW addition to Texas power grid's commercially operating resources. Retrieved on December 22, 2022, from https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/110222-battery-storage-leads-400-mw-addition-to-texas-power-grids-commercially-operating-resources.

World Energy & Climate Statistics - WECS. (2021). Yearbook 2021, Breakdown by Country. Retrieved on October 16, 2022, from https://yearbook.enerdata.net/crude-oil/world-production-statistics.html.

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%
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%
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%

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%

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%

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%