

# 2021 U.S. Geothermal Power Production and District Heating Market Report

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## List of Acronyms

ATB	Annual Technology Baseline	ITC	Investment Tax Credit
AGILE	Advanced Geothermal Innovation Leadership	LCOE	levelized cost of energy
BAU	Business as Usual	LCOH	levelized cost of heat
BLM	Bureau of Land Management	MACRS	Modified Accelerated Cost Recovery System
CLG	closed-loop geothermal	MW	megawatt
CTR	Controlled Thermal Resources	MWh	megawatt-hour
DDU	deep direct use	NEPA	National Environmental Policy Act
DOE	U.S. Department of Energy	NREL	National Renewable Energy Laboratory
EIA	U.S. Energy Information Administration	ORC	Organic Rankine Cycle
EGEC	European Geothermal Energy Council	PON	Program Opportunity Notice
EGS	enhanced geothermal system	PPA	Power Purchase Agreement
FORGE	Frontier Observatory for Research in Geothermal Energy	PRDA	Program Research Development Announcement
GDH	geothermal district heating	PTC	Production Tax Credit
GEA	Geothermal Energy Association	PURPA	Public Utilities Regulatory Policies Act
GRC	Geothermal Resources Council	PV	photovoltaic
GTO	Geothermal Technologies Office	RPS	renewable portfolio standard
GW	gigawatt	TES	thermal energy storage
IEA	International Energy Association	TI	Technology Improvement
IRT	Improved Regulatory Timeline	TWh	terawatt-hour

This report provides policymakers, regulators, developers, researchers, engineers, financiers, and other stakeholders with up-to-date information and data reflecting the 2019 geothermal power production and district heating markets, technologies, and trends in the United States.

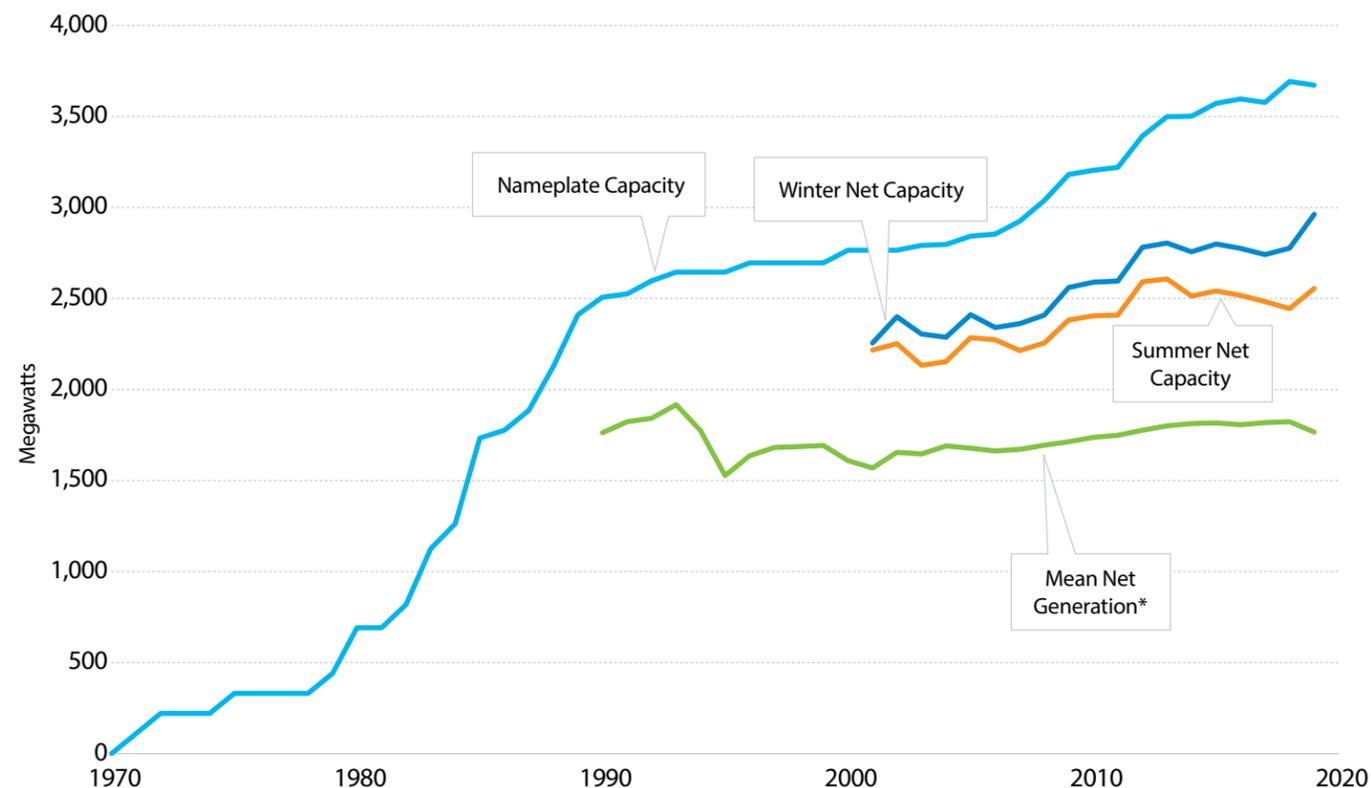
## Executive Summary

This report, the *2021 U.S. Geothermal Power Production and District Heating Market Report*, was developed by the National Renewable Energy Laboratory (NREL) and Geothermal Rising (previously the Geothermal Resources Council, or GRC), with funding support from the Geothermal Technologies Office (GTO) of the U.S. Department of Energy (DOE).

This report provides policymakers, regulators, developers, researchers, engineers, financiers, and other stakeholders with up-to-date information and data reflecting the 2019 geothermal power production and district heating markets, technologies, and trends in the United States. The report presents analysis of the current state of the U.S. geothermal market and industry for both the power production and district heating sectors, with consideration of developing power projects. Geothermal heat pumps, although a key technology in the wider use of geothermal resources, are outside the scope of this report. In addition, the report evaluates the impact of state and federal policy, presents current research on geothermal development, and describes future opportunities for the U.S. geothermal market and industry.

The following is a summary of key findings for the U.S. geothermal power generation and district heating market.

*Photo by Janet Harvey, Heidelberg University, Ladenburg Germany*



**Figure ES-1.** U.S. industry geothermal nameplate and net capacity, as well as mean net generation\*

\*Mean net generation is the effective capacity, calculated by dividing actual geothermal generation by the total hours in a year (Pettitt et al. 2020). Remaining terms are defined in Section 2.2.

Sources: Nameplate capacity is from the 2020 Geothermal Rising industry survey and Matek (2016). Net capacities and mean net generation are from the U.S. Energy Information Administration (EIA 2019a, 2019b).

## U.S. Geothermal Power Generation Market—Key Findings

The following table shows key geothermal power capacity and generation changes in the United States from the end of 2015 to the end of 2019. Note that the mean net generation

capacity for 2019 (1,766 MW, calculated from the actual generation reported by the EIA) represents a small decrease from the 1,817 MW calculated for 2015. Moreover, the 2019 power production is virtually identical to the 1,762 MW calculated for 1990, the first year the EIA published this data (EIA 2019b).

**Table ES-1.** Geothermal Power Generation Capacity and Generation in 2015 and 2019

Geothermal Power	2015 (97 power plants)	2019 (93 power plants)	Data Source
Nameplate capacity	3,627 MW	3,673 MW	GEA 2016 and the 2020 Geothermal Rising industry survey
Summer net capacity	2,542 MW	2,555 MW	EIA 2019b
Winter net capacity	2,800 MW	2,963 MW	EIA 2019a
Utility-scale power generation	15.92 TWh	15.47 TWh	EIA 2109b
Mean net generation	1,817 MW	1,766 MW	EIA 2019b (calculated)

Additional key findings include:

- **Current U.S. geothermal power generation nameplate capacity is 3,673 MW from 93 power plants.** Of this capacity, 1,300 MW are located on public lands.
- **California and Nevada contribute more than 90% of the current U.S. geothermal power generation,** with additional contributions from plants in Alaska, Hawaii, Idaho, New Mexico, Oregon, and Utah.
- **From the end of 2015 through the end of 2019, the United States brought seven new geothermal power plants online in Nevada, California, and New Mexico, adding 186 MW of nameplate capacity.** In the same time period, 11 plants were retired or classified as non-operational, subtracting 103 MW of nameplate capacity. The remaining difference in capacity from 2015 to 2019 can be attributed to the reduction of nameplate capacity at individual plants.
- **After the data for this report were collected, Ormat brought the Steamboat Hills expansion in Nevada online, increasing its generating capacity by 19 MW.** In addition, in late 2020, the Puna geothermal plant was brought back online, which should increase geothermal net-generation numbers in 2021.

- **Geothermal companies operating in the United States have a combined 58 active developing projects and prospects across nine states, with a majority located in Nevada.** Of these projects, five are in Phase IV, the phase immediately preceding project completion. Three are located in Nevada, and two are in California.
- **From November 2019 through September 2020, nine new geothermal Power Purchase Agreements (PPAs) have been signed across four states** (Figure ES-2). Included in these agreements are plans for the first two geothermal power plants to be built in California in a decade—Hell’s Kitchen and Casa Diablo IV.
- **Geothermal power provides several non-cost advantages,** including supplying continuous baseload power, ancillary grid services, resilience, environmental benefits, and a small land footprint compared to other renewable energy technologies.
- **Twenty-eight states have renewable portfolio standards (RPS) that count geothermal power as an eligible resource, seven of which include direct use.** RPSs support geothermal development by requiring a certain amount of electricity sold by utilities to come from renewable energy sources.



**Figure ES-2.** Geothermal PPAs signed from November 2019 through September 2020

In terms of policy, the United States has experienced two periods of robust federal support for geothermal exploration and development, both of which resulted in increased geothermal deployment. The first period occurred from the late 1970s into the early 1980s. The second wave of support was part of the American Recovery and Reinvestment Act of 2009.

More recently, the federal Taxpayer Certainty and Disaster Tax Relief Act of 2019, signed at the end of the year, retroactively extended the Production Tax Credit (PTC), which had expired in 2017, for geothermal projects for which construction began before January 1, 2021. The act also allows geothermal operators to elect the Investment Tax Credit (ITC) in lieu of the PTC, at a rate of 30%.

In late 2020, the Consolidated Appropriations Act passed, a year-end omnibus bill that included the Energy Act of 2020. The Act seeks to ease access to federal lands for wind, solar, and geothermal developers. It directs the Secretary of the Interior to set goals for wind, solar, and geothermal production on federal lands by 2022 and issue permits for a combined total of 25 GW of nameplate capacity for these same technologies. The act authorizes an annual budget of \$170 million for GTO's research and development activities, including advanced hydrothermal resource tools, engineered geothermal systems, and demonstration projects.

## U.S. Geothermal District Heating Market—Key Findings

- **Currently, there are 23 geothermal district heating (GDH) systems in the United States, with a capacity totaling more than 75 MW of thermal energy (MWth).** The systems range in size from 0.1 MWth to over 20 MWth.
- **Of these 23 commercial projects, 10 received DOE loan and grant support.** Federal, state, and local funding support have proven critical to develop a majority of the existing GDH projects in the United States.
- **The oldest GDH installation dates from 1892 in Boise, Idaho,** and the most recent installation was completed in 2017 in Alturas, California. The remaining systems are located in California, Colorado, Idaho, New Mexico, Nevada, Oregon, and South Dakota.
- **The majority of the GDH systems in the United States are more than 30 years old.**
- **The average U.S. levelized cost of heat (LCOH) value for GDH systems is \$54/MWh, slightly lower than the average European LCOH value of \$69/MWh.** However, this LCOH is slightly higher than the 2019 average U.S. residential natural gas LCOH. Estimated LCOH for existing U.S. systems ranges from \$15 to \$105/MWh, a range that is consistent with the range of LCOH for existing European GDH systems.
- **U.S. GDH systems tend to be smaller in size (average of 4 MWth) than European GDH systems** (continent-wide average of ~17 MWth), and orders of magnitude smaller than the average GDH system in China (~1,000 MWth).
- **U.S. GDH systems run at 23% capacity, on average.** This low utilization factor is due to frequent operation at less than full capacity and the seasonality of heating needs (i.e., the system is not needed for satisfying heating demands year-round).
- **As of 2020, few policy mechanisms intended to support GDH development are in place in the United States.**

## Emerging Opportunities and Markets

- **Significant opportunities for expanding geothermal power production and GDH exist** through cutting-edge enhanced geothermal system technology development, closed loop systems, new power plant operational

paradigms such as hybridization and thermal energy storage, harnessing vast co-production potential from existing oil and gas infrastructure, and through critical materials extraction from produced geothermal brines.

- **New public and private stakeholders such as universities and corporations are embracing geothermal** as an on-campus carbon-free heating and cooling solution for achieving decarbonization goals.
- **Industrial processes in the manufacturing sector represent an enormous market opportunity for geothermal heating and cooling.**
- **Geothermal power offers very high economic value for achieving aggressive decarbonization pathways** in states such as California, even though it may not be the lowest-cost solution on a levelized cost of energy basis. Six of the most recent geothermal PPAs signed feature California-based off-takers.
- **State-level geothermal legislation and policy development is active in California, Hawaii, Nevada, New Mexico, and Washington,** focusing on geothermal contributions to aggressive decarbonization goals as well as streamlining administrative processes and permitting authorities for developing geothermal resources.
- **Risk mitigation schemes are a promising avenue for incentivizing geothermal power deployment.** Although not currently available in the United States, risk mitigation programs incentivize the deployment of geothermal power production and GDH systems in Europe, Africa, and Asia; these types of programs were also used in the United States in the 1970s and 1980s.
- **Recent DOE-awarded Cornell and West Virginia University GDH projects represent important opportunities** to demonstrate and expand GDH deployment beyond the western United States.
- **Increasing the use of geothermal energy for U.S. heating and cooling can significantly contribute to Biden Administration decarbonization goals to cut U.S. emissions by half in 2030 and achieve a carbon-free electric sector by 2035.** For example, the GDH system in Paris, France, saves 120,000 tons of CO<sub>2</sub> annually by offsetting emissions from 170,000 buildings.
- **The international community continues to recognize the importance of geothermal resource utilization at all temperature ranges,** with active development across Europe, Africa, and Asia through the support of public and private mechanisms.



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# 1 Introduction

Between 2009 and 2016, the Geothermal Energy Association (GEA) published an annual *U.S. Geothermal Power Production and Development Report*.<sup>1</sup> These reports presented a yearly snapshot of the state of the geothermal power industry and tracked the status of geothermal power deployment, developing projects, and emerging geothermal technologies in the United States. This current report, the *2021 U.S. Geothermal Power Production and District Heating Market Report*, reevaluates the state of the industry since the final GEA report in 2016. Power production data for this 2021 report are compiled from previous GEA reports, the U.S. Energy Information Association (EIA), and from a Geothermal Rising-conducted industry survey distributed in 2020 via a questionnaire sent to all known companies operating U.S. geothermal power plants or with projects in development.

This report reevaluates the state of the geothermal industry since the final GEA report in 2016.

Unlike the GEA reports, this report also examines the status of geothermal district heating (GDH) projects in the United States. Between 1975 and 2016, the Oregon Institute of Technology Geo-Heat Center maintained a database on U.S. geothermal direct use. In 2016, the U.S. direct-use database was transferred to NREL, which has managed data maintenance and curation since (Snyder et al. 2017). Analysis on GDH systems presented in this report leverages this database.

Overall, this report considers a variety of factors that currently or soon will affect geothermal deployment. The report opens with methodology and terms (Section 2). Sections 3 and 4 present updates on U.S. geothermal power and district heating, respectively. Section 5 evaluates past and current federal policies and how they have impacted geothermal capacity over time, and reviews state policies, with a focus on RPSs. Section 6 summarizes key emerging technologies with the potential to increase geothermal deployment. Finally, the report closes with a discussion of market opportunities (Section 7), followed by conclusions and future work (Section 8). A summary of U.S. geothermal resources available online can be found in Appendix C.

<sup>1</sup> For more information and links to each year's report, visit: <https://geothermal.org/resources>. The 2016 report can be found at <https://geothermal.org/resources/2016-annual-us-global-geothermal-power-production>.

## 2 Methodology and Terms

### 2.1 Power Production Methodology

For power production, this report uses a database initially created by GEA and updated with 2019 power production data by Geothermal Rising. To collect these data, GEA—and then Geothermal Rising—sent a questionnaire (see Appendix A) to known U.S. geothermal operators and developers. The questionnaire requested information about both existing power production capacity and developing projects. The results of this survey were added to the GEA database and shared with NREL (see Appendix B). Of note, the largest geothermal operator in California, Calpine, declined to participate in Geothermal Rising's survey. As a result, this report uses a combination of data sets from the *2016 Annual U.S. & Global Geothermal Power Production Report* and EIA reports for Calpine's nameplate capacity data.

To increase the accuracy and value of information presented in its annual *U.S. Geothermal Power Production and Development Report*, the GEA developed a reporting system known as the *New Geothermal Reporting Terms and Definitions* (GEA 2010). This served as a guideline to project developers in reporting geothermal project development information to the GEA from 2010 to 2016. In the interest of continuity, Geothermal Rising elected to use the same reporting terms as the GEA in the 2020 questionnaire.

A basic understanding of the *New Geothermal Reporting Terms and Definitions* will aid the reader in fully understanding the information presented in this report. The reporting methodology ensures clarity and accuracy by providing the industry and the public with a lexicon of definitions relating to the types of different geothermal projects and a guideline for determining which phase of development a geothermal resource is in. Used with this report, this methodology helps characterize resource development by type and technology. This information also helps determine a geothermal project's position in the typical project development timeline.

To increase the accuracy and value of information presented in its annual *U.S. Geothermal Power Production and Development Report*, the GEA developed a reporting system known as the *New Geothermal Reporting Terms and Definitions* (GEA 2010).

## 2.2 Geothermal Capacity Types

Developers of geothermal resources use the following definitions to report plant capacity:

- **Generator nameplate capacity (installed):** The maximum rated output of a generator, prime mover, or other electric power production equipment under specific conditions designated by the manufacturer. Installed generator nameplate capacity is commonly expressed in megawatts and is usually indicated on a nameplate physically attached to the generator.
- **Summer capacity (installed):** The maximum output, commonly expressed in megawatts, that generating equipment can supply to the system load during peak summer demand (June 1 through September 30). This output reflects a reduction in capacity due to electricity use for station service or auxiliaries (i.e., the plant's net capacity on that day).
- **Winter capacity (installed):** The maximum output, commonly expressed in megawatts, that generating equipment can supply to the system load during peak winter demand (December 1 through February 28). Similar to summer capacity, this output reflects a reduction in capacity due to electricity use for station service or auxiliaries (i.e., the plant's net capacity on that day).

Note that the winter capacity of a geothermal power plant is generally greater than the summer capacity due to lower ambient temperatures, especially in the case of air-cooled condensers. This is because a higher differential between the ambient temperature and the working fluid yields a higher plant efficiency.

## 2.3 Geothermal Resource Types and Their Definitions

Developers of geothermal resources use the following definitions to classify projects:

- **Conventional Hydrothermal (Unproduced Resource):** The development of a geothermal resource where levels of geothermal reservoir temperature and reservoir flow capacity are naturally sufficient to produce electricity, and where development of the geothermal reservoir has not previously occurred to the extent that it supported the operation of geothermal power plant(s). This type of project is labeled "CH Unproduced" in this report.
- **Conventional Hydrothermal (Produced Resource):** The development of a geothermal resource where levels of geothermal reservoir temperature and reservoir flow capacity are naturally sufficient to produce electricity, and where development of the geothermal reservoir *has* previously occurred to the extent that it currently supports or has supported the operation of geothermal power plant(s). This type of project is labeled "CH Produced" in this report.
- **Conventional Hydrothermal Expansion:** The expansion of an existing geothermal power plant and its associated drilled area to increase the level of power that the power plant produces. This type of project is labeled "CH Expansion" in this report.
- **Geothermal Energy and Hydrocarbon Co-Production:** The utilization of produced fluids resulting from oil- and/or gas-field development to produce geothermal power. This type of project is labeled "Co-Production" in this report.
- **Enhanced Geothermal Systems:** The development of a geothermal system where the natural flow capacity of the system is not sufficient to support adequate power production, but where of the injection fluid into the system can allow production at a commercial level. This type of project is labeled "EGS" in this report.

## 2.4 Tracking Projects Through the Development Timeline

In addition to defining projects according to the above definitions, Geothermal Rising also asked developers to indicate projects' current status in the project development timeline using a four-phase system (or a classification of "Prospect" for resources that do not yet qualify for Phase I). This system captures how much and what type of work has been performed on that particular geothermal resource so far. The defined phases of project development are:

- **Prospect:** Early Resource Identification
- **Phase I:** Resource Procurement and Identification
- **Phase II:** Resource Exploration and Confirmation
- **Phase III:** Permitting and Initial Development
- **Phase IV:** Resource Production and Power Plant Construction.

Each of the four phases of project development is composed of three separate sections, each of which contains phase subcriteria. The three separate sections of subcriteria are resource development; transmission development; and external development (e.g., acquiring access to land; permitting; signing PPAs and engineering, procurement, and construction contracts; and securing a portion of project financing). For a project to be considered in any particular phase of development, a combination of subcriteria, specific to each individual project phase, must be met. If none of the criteria are met, a project is defined as a Prospect.

## 2.5 Geothermal District Heating Data

Geothermal district heating (GDH) is the use of geothermal energy to heat individual and commercial buildings, as well as for industry, through a distribution network. GDH systems range in size but typically serve heating loads between 0.5 and 50 MWth. GDH technologies rely on either hydrothermal resources for heating, or on geo-exchange (i.e., geothermal heat pumps) for heating and cooling (GeoDH N.D.). GDH systems considered in this report utilize hydrothermal resources as the energy source. This report does not consider geo-exchange systems or the rapidly evolving project development space that is highlighted in Section 6, Emerging Technologies. Data for GDH systems are sourced from the NREL geothermal direct-use database (Snyder et al. 2017) and supplemented with information obtained from news articles, publications, and interviews conducted in 2020 with project owners, operators, and other stakeholders. As mentioned, the NREL direct-use database was developed in 2016 from a database maintained by the Oregon Institute of Technology Geo-Heat Center from 1975 to 2016. Data included application type, installed capacity, well flow rates, production temperatures, and contact information, although this information was incomplete for many of the entries. Since 2017, analysts at NREL have worked to verify existing data, populate missing data, and add new data. No standardized reporting requirements are in place in the United States, which hinders maintenance of this database and increases the chance of overlooking existing sites.

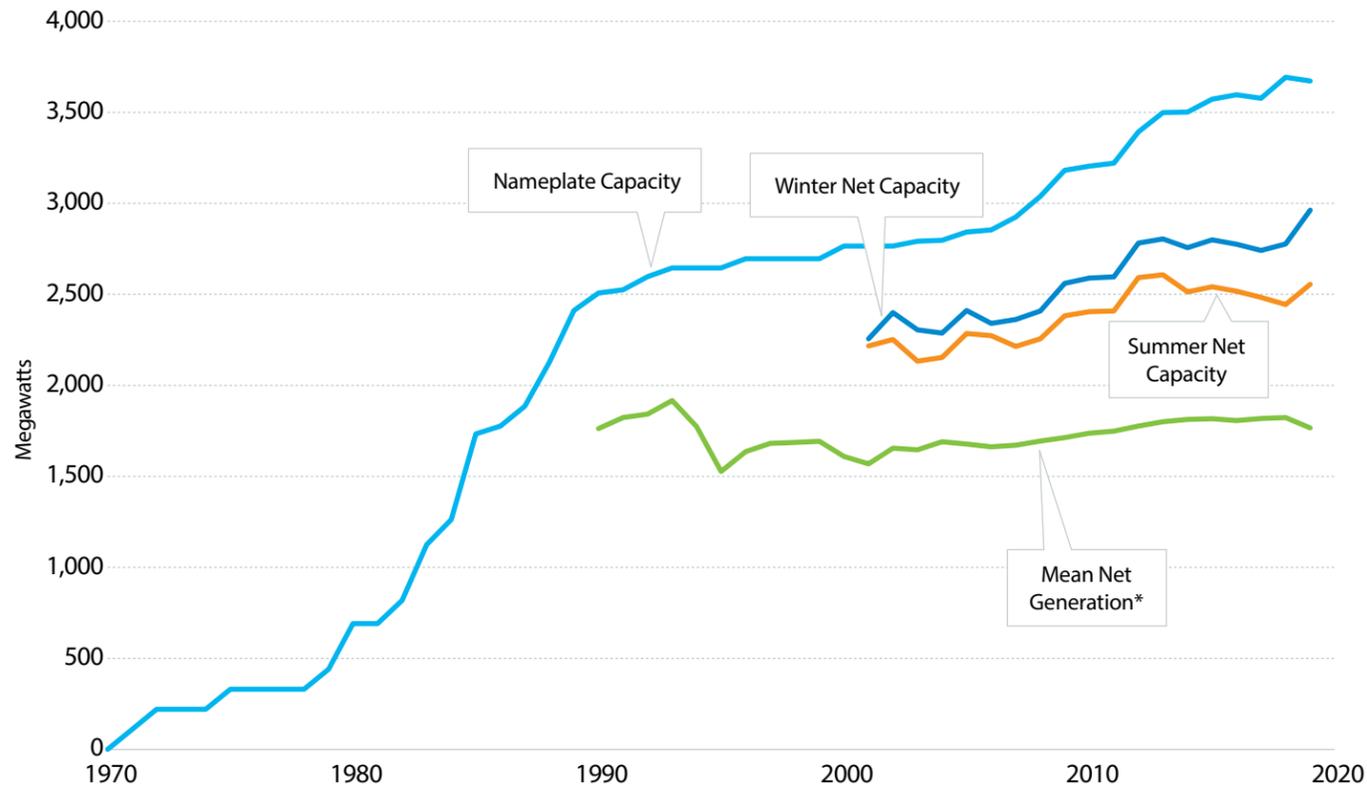
## 3 U.S. Geothermal Power Update

### 3.1 Geothermal Power Generation

The U.S. geothermal power production market has experienced limited net capacity growth since 2015. In addition, the number of developing projects has decreased. However, the addition of nine PPAs as well as recent renewable energy policy trends indicate that the sector could be ready to resume growth.

Geothermal capacity and generation in the United States have grown little since the 2016 GEA report. As seen in Figure 1, the current nameplate capacity of 3,673 MW from 93 power plants per Geothermal Rising's survey is only marginally higher than the 3,627 MW from 97 plants that the GEA reported for 2015 (GEA 2016).

The addition of nine PPAs as well as recent renewable energy policy trends indicate that the sector could be ready to resume growth.



**Figure 1.** U.S. industry geothermal nameplate and net capacity, as well as mean net generation\*

\*Mean net generation is the effective capacity calculated by dividing actual geothermal generation by the total hours in a year (Pettitt et al. 2020).

Sources: Nameplate capacity is from the 2020 Geothermal Rising industry survey and Matek (2016). Net capacities and mean net generation are from EIA (2019a, 2019b).

Also, according to the survey, from the end of 2015 through the end of 2019, the United States brought seven new geothermal power plants online, adding 186 MW of nameplate capacity (Table 1). However, in the same time period, 11 plants were retired or classified as non-operational, subtracting 103 MW of nameplate capacity (Table 2). The remaining difference in capacity from 2016 to 2020 can be attributed to gains and losses in efficiency at individual plants.

Exhibiting a similar trend, geothermal net capacities have shown only slight increases during this time, with summer net capacity increasing from 2,542 MW in 2015 to 2,555 MW in 2019, and winter net capacity increasing from 2,800 MW to 2,963 MW (EIA 2019a; EIA 2019b).

Actual utility-scale geothermal power generation has decreased since the 2016 GEA report. For the purposes of this comparison, actual generation reported by the EIA has been divided by total hours in a year to create a “mean net generation” capacity (Pettitt et al. 2020). The mean net

generation capacity calculated from the actual generation that the EIA reported for 2019 is 1,766 MW, which represents a small decrease from the 1,817 MW calculated for 2015. Moreover, the 2019 power production is virtually identical to the 1,762 MW calculated for 1990, the first year the EIA published these data. Contributing to these results is that Ormat’s Puna geothermal plant was offline for two-thirds of 2018 and the entirety of 2019 due to the eruption of the Kīlauea volcano. The Puna plant was brought back partially online in late 2020, which is likely to lead to higher numbers in 2021. Pettitt et al. (2020) examined the capacity versus production metrics in greater detail using EIA data going back to 2007.

This limited power production growth is reflected in recent drilling activity. In a paper for the 2020 World Geothermal Congress titled, “The United States of America Country Update—Electric Power Generation,” Robertson-Tait et al. noted that there have been 68 geothermal wells drilled in the United States from January 1, 2015, through the end of 2019 (Table 3). This equates to an average of only 13.6 wells drilled per year.

**Table 1.** New Plants Brought Online Since 2016

Plant Name	State	Plant Type	Resource Classification	Nameplate Capacity (MW)
Brady (Brady Complex)	Nevada	Binary	CH Produced	21.5
Elmore (ST-302)	California	Back Pressure	CH Expansion	8.41
Lightning Dock	New Mexico	Binary	CH Produced	14.5
McGinness Hills 3	Nevada	Binary	CH Produced	74
Soda Lake 3	Nevada	Binary	CH Produced	26.5
Tungsten Mountain	Nevada	Binary	CH Unproduced	37
Wabuska 3	Nevada	Binary	CH Produced	4.4
<b>Total MW:</b>				<b>186.3</b>

**Table 2.** Plants That Have Gone Offline Since 2016

Plant Name	State	Plant Type	Status	Nameplate Capacity (MW)
GEM III (Ormesa Complex)	California	Double Flash	Retired	21.6
Ormesa IH (Ormesa Complex)	California	Binary	Retired	8.8
Soda Lake I	Nevada	Binary	Retired	5.1
Steamboat (Steamboat Complex)	Nevada	Binary	Retired	2.4
Steamboat IA (Steamboat Complex)	Nevada	Binary	Retired	2
Wabuska I	Nevada	Binary	Retired	1.6
Wabuska II	Nevada	Binary	Retired	1.6
Amedee (Wendel)	California	Binary	Non-Operational	3
Bottle Rock	California	Dry Steam	Non-Operational	55
Honey Lake	California	Binary	Non-Operational	1.5
Wineagle	California	Binary	Non-Operational	0.7
<b>Total MW:</b>				<b>103.3</b>

**Table 3.** Wells Drilled for Electrical Geothermal Resources from January 1, 2015, to December 31, 2019

Source: Robertson-Tait et al. (2020)

Exploration	Production >150°C	Production 100°–150°C	Production <100°C	Injection
13	13	11	0	31

### 3.1.1 U.S. Geothermal Power Production Fleet Age

One consequence of the lack of geothermal capacity growth is that with relatively few new plants being built, the average age of the U.S. geothermal power production fleet has increased. Currently, 44% of U.S. geothermal plants are more than 30 years old, which represents 64% of the total geothermal nameplate capacity (Figure 2). This can be compared to the 4% of plants (representing 11% of the geothermal capacity)

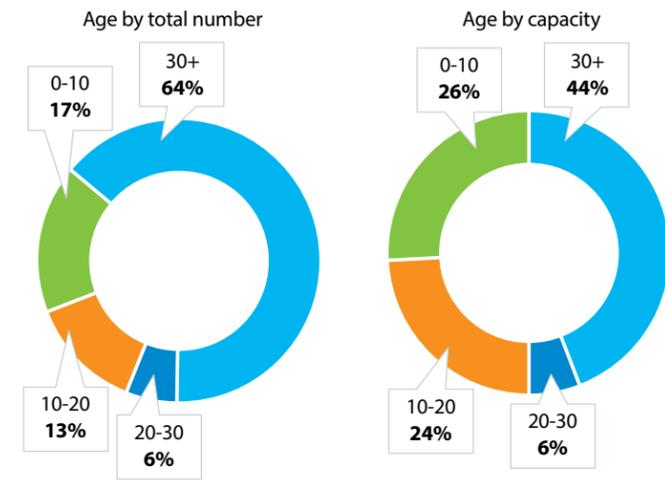


Figure 2. Age of U.S. geothermal plants by percentage of total number (left) and capacity (right)

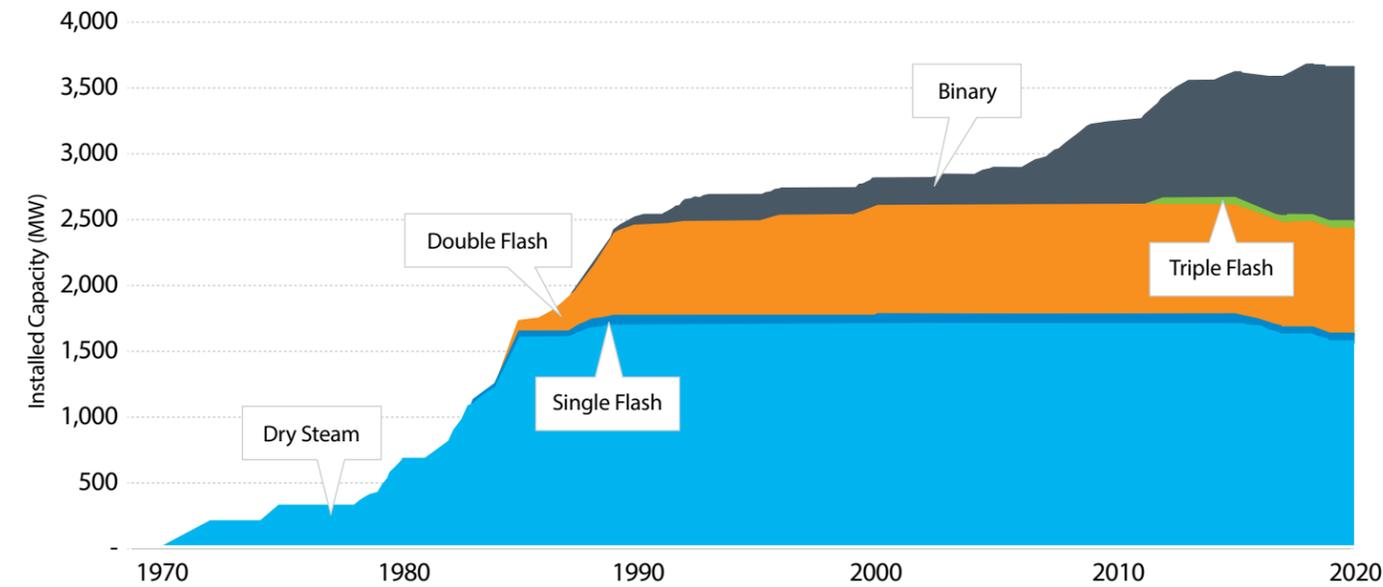


Figure 3. U.S. geothermal capacity by plant technology

that were more than 30 years old at the time of the first GEA report in 2009. As older geothermal plants and fields tend to experience a reduction in resource capacity, the relatively advanced age of the geothermal fleet (and associated fields) likely accounts for the previously noted capacity stagnation and decrease in power generation from 1990 to 2018.

### 3.1.2 U.S. Geothermal Capacity by Plant Technology Type

Figure 3 shows that high-temperature dry steam and flash technology formed the foundation of the U.S. geothermal power production capacity. However, other than one triple-flash plant in 2011, all geothermal capacity additions from 2000 through 2020 have been binary plants. This trend is expected to continue due to the flexibility of binary technology, which enables utilization of lower-temperature resources as well as being entirely emission free (Kagel et al. 2005, Eberle et al. 2017). However, the optimal capacity of a binary plant is inherently smaller than a plant using the older technologies with higher-temperature resources. These smaller binary plant capacities, along with the previously noted advanced age of the geothermal fleet, contribute to the slowing of geothermal capacity growth. Thus, beginning in 2013, essentially all capacity gains from new binary plants have been offset by decreases in the capacity of the older steam and flash plants.

### 3.1.3 U.S. Geothermal Power Production by Operator

Figure 4 and Figure 5 illustrate the extent to which the U.S. geothermal power industry is dominated by two operators, Calpine and Ormat. While they are clearly the two biggest U.S. operators, a closer look at their numbers reveals differing business models. Calpine produces 1,359 MW from only 15 power plants for an average of 91 MW per plant, whereas Ormat requires 34 plants to produce 976 MW for an average

of 29 MW per plant. This difference in electricity produced per plant can largely be explained by resource type. Calpine produces 100% of its power with dry steam plants at the Geysers, the largest single source of geothermal power in the world and the only U.S. dry steam field in production (DOE N.D.). The great majority of Ormat's power is produced by binary plants (Appendix B) with lower-temperature resources, which explains why a larger number of plants are required to produce a smaller amount of electricity.

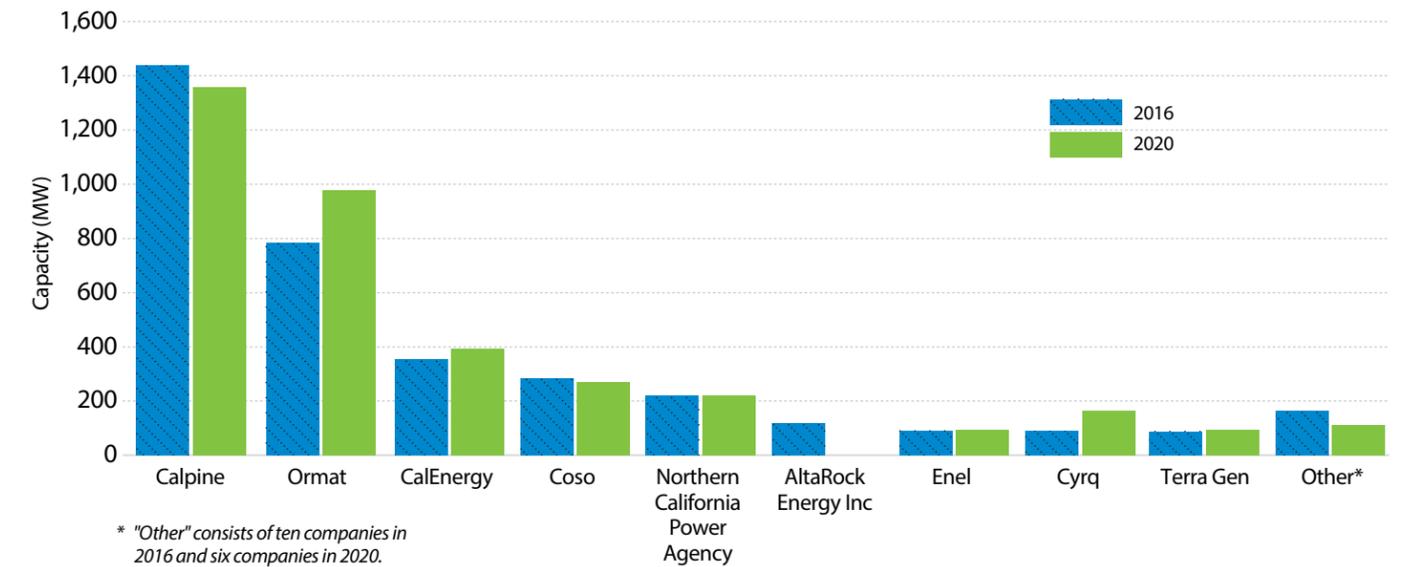


Figure 4. U.S. geothermal nameplate capacity by operator

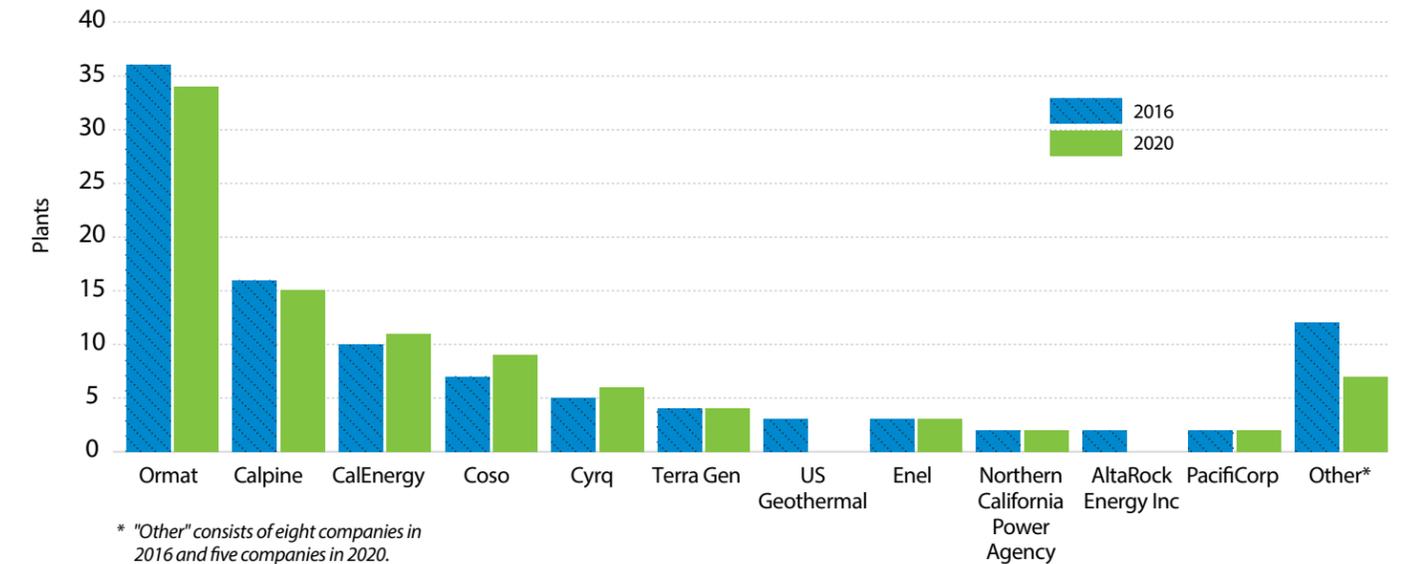


Figure 5. U.S. geothermal power plant count by operator

### 3.1.4 U.S. Geothermal Power Production by State

The interaction between resource temperature and power generation can also be seen in Figure 6 and Figure 7. Notably, California and Nevada, home to most of the highest temperature geothermal resources in the United States, are also home to the vast majority of geothermal power production. However, even between these two states there

is a clear distinction. California—where high-temperature resources at the Geysers, the Salton Sea, and Coso are located—has an installed nameplate capacity of 2,627 MW of geothermal power, which is 72% of the total U.S. geothermal power production. In addition, California is home to 51 of the 93 U.S. geothermal power plants. Nevada, which has significant identified, undiscovered, and EGS resource potential, is home to 28 power plants, which have an installed nameplate capacity of 797 MW of geothermal power.

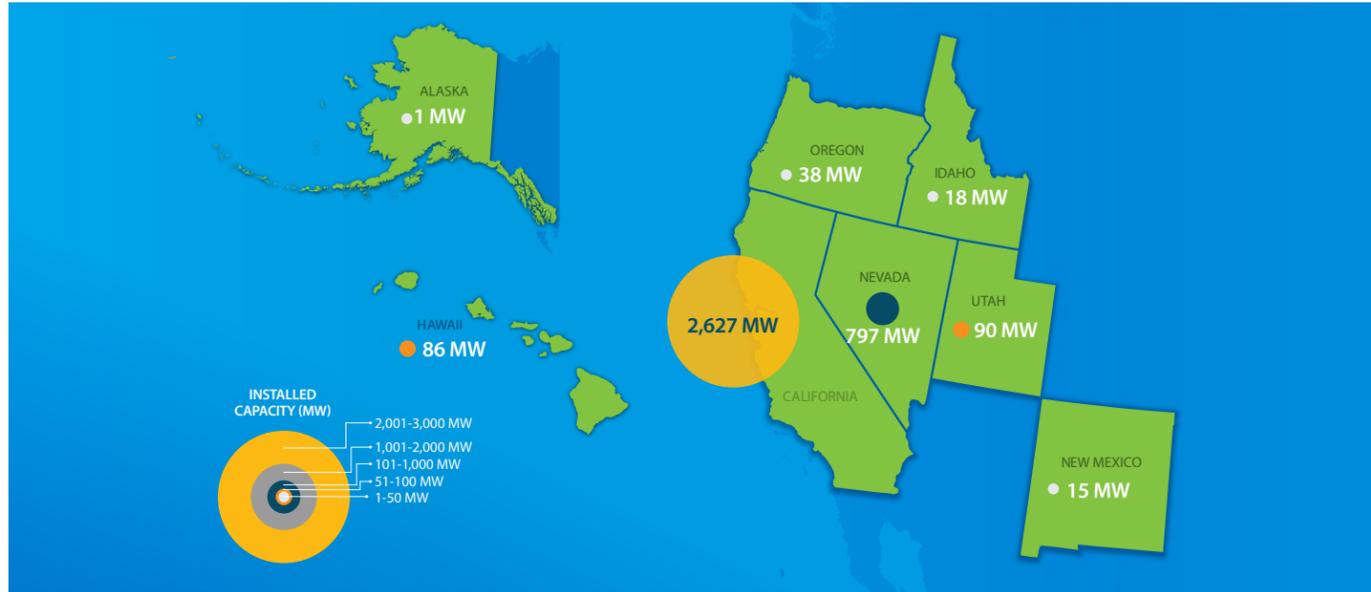


Figure 6. Geothermal nameplate capacity by state

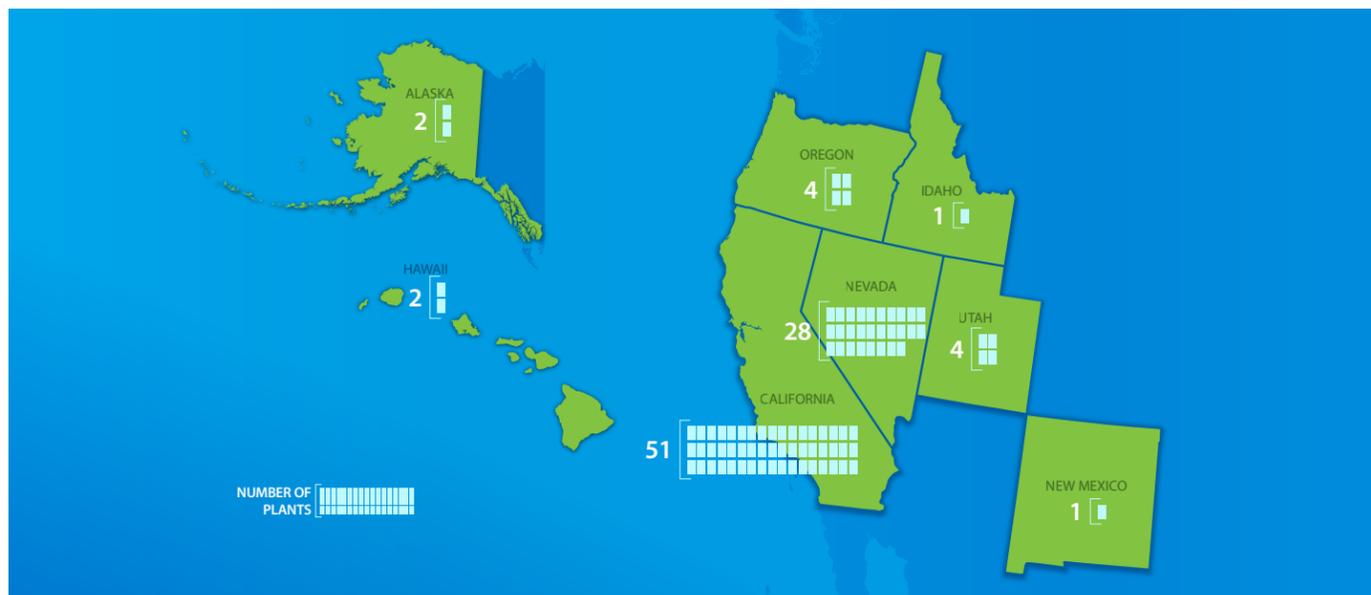


Figure 7. Geothermal power plant count by state

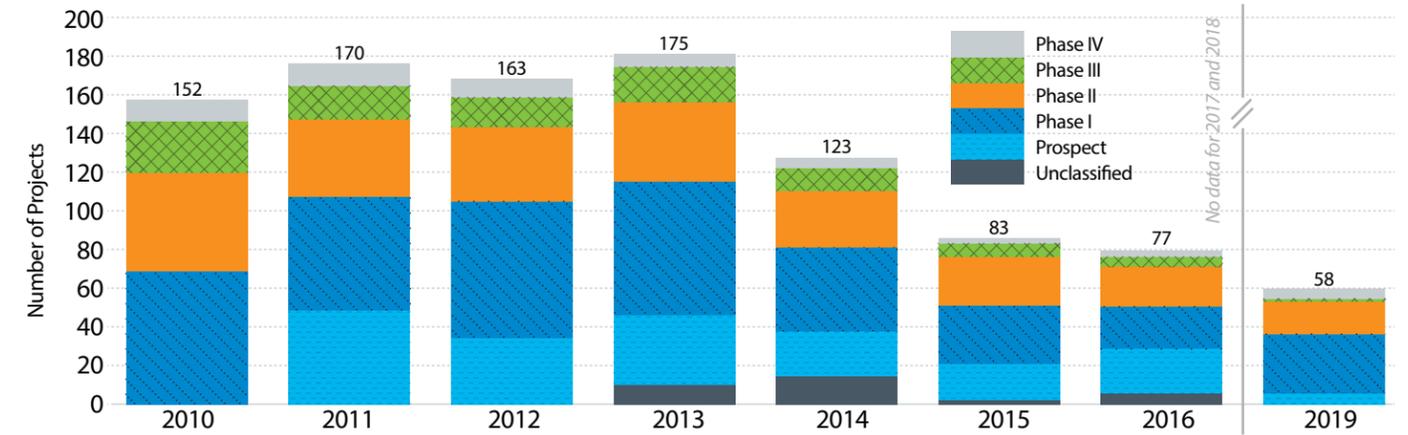


Figure 8. Developing projects by year and phase

### 3.2 Project Pipeline

#### 3.2.1 U.S. Geothermal Developing Projects Over Time

Information on geothermal projects in development was collected from Geothermal Rising’s 2020 industry survey. Survey participants were asked to classify their projects as “prospects” or in Phases I through IV (see Section 2.4). Projects categorized as “prospects” are early in development, and projects in Phase IV are nearing completion. Geothermal companies operating in the United States have a combined 58 active projects and prospects across 9 states. Of these projects, 5 are in Phase IV. As seen in Figure 8, this represents a large decrease in developing projects from 2016. In fact, of the 77 projects that were listed in various stages in the 2016 GEA report, only 2 have been completed, 25 are still active, and 50 are no longer in development (Figure 9).

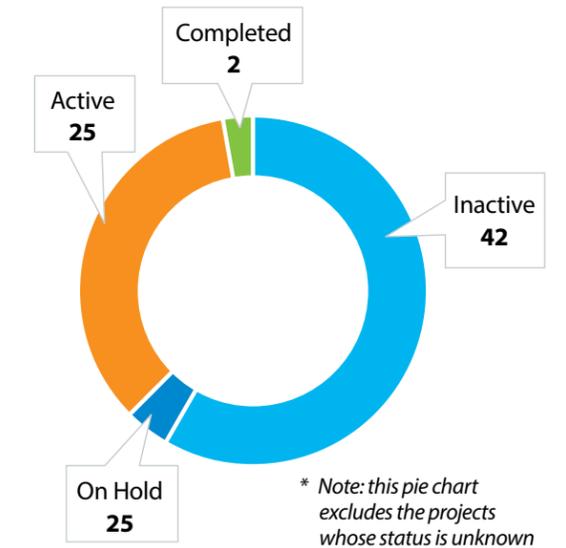


Figure 9. Status of 2016 developing projects as of 2020

In addition to stage of development, survey participants were asked to identify the developing project resource type (see Section 2.3). As seen in Figure 10, 54 of the 58 developing projects are classified as CH Unproduced, indicating that they are located in previously undeveloped hydrothermal fields. Of the seven plants brought online since the end of 2015, only one is classified as CH Unproduced. Of the remaining six, five are classified as CH Produced because they are developments

in existing hydrothermal fields or repowers. The final new plant is classified as CH Expansion because it is a back-pressure cycle plant (Table 1). These data seem to indicate that geothermal operators have largely expanded within current operations where possible and are now eyeing new fields for future growth.

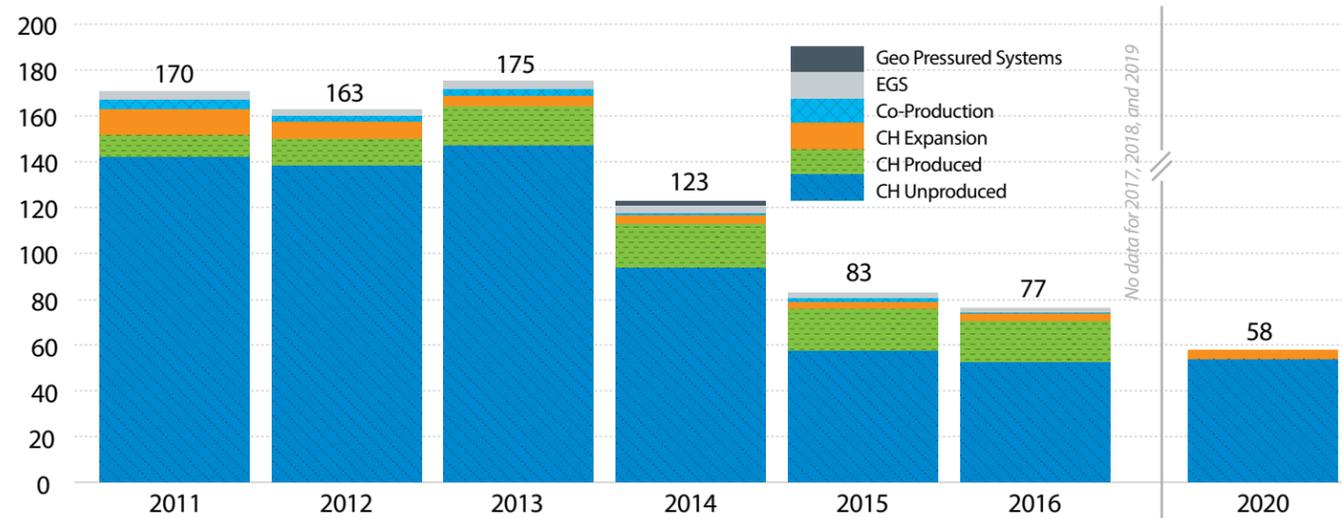


Figure 10. Developing projects resource type



Figure 11. U.S. geothermal developing projects by state and phase

### 3.2.2 U.S. Geothermal Developing Projects by State

Figure 11 shows developing projects across the western United States. Project development is moving forward faster in Nevada than other states, with 32 total projects compared to only nine in California, reflecting the maturity of the

geothermal industry in California. These data are supported by recent growth as, of the eight projects that have come online since 2015, five are located in Nevada and only two in California (Appendix B). However, as previously discussed, the largest operator in California, Calpine, declined to participate in Geothermal Rising's survey and thus this report lacks any potential developing projects from Calpine.

### 3.2.3 U.S. Geothermal Developing Projects by Operator

Since 2016, there has been a reduction in the number of U.S. geothermal operators due to industry consolidation and companies leaving geothermal or going out of business. This has contributed to the reduction in developing projects. As seen in Figure 12, Ormat is advancing the most developing projects of any operator, with 39 of the 58 total projects identified. At least part of their growth since 2016 can be explained by their acquisition of U.S. Geothermal in early 2018.<sup>2</sup> One notable addition to this operator group is Controlled Thermal Resources (CTR). Although new to geothermal, CTR has already signed a PPA for their Hell's Kitchen project in the Salton Sea.

### 3.2.4 Geothermal Power Production Levelized Cost of Electricity

Levelized cost of electricity (LCOE) is a simple and well-known metric that reflects the cost per unit of energy produced by a technology. However, it does not account for attributes in each technology that contribute to the safe and stable functioning of the electrical system. Examples include dispatch flexibility, regulation capabilities, environmental attributes, and reduced transmission congestion and demands. LCOE is helpful when quickly comparing the costs of different technologies, but it is important to understand its limitations. Per NREL's Annual Technology Baseline (ATB) analysis, LCOE is a useful metric for illustrating the primary cost and performance parameters for different energy technologies but does not reflect the value of

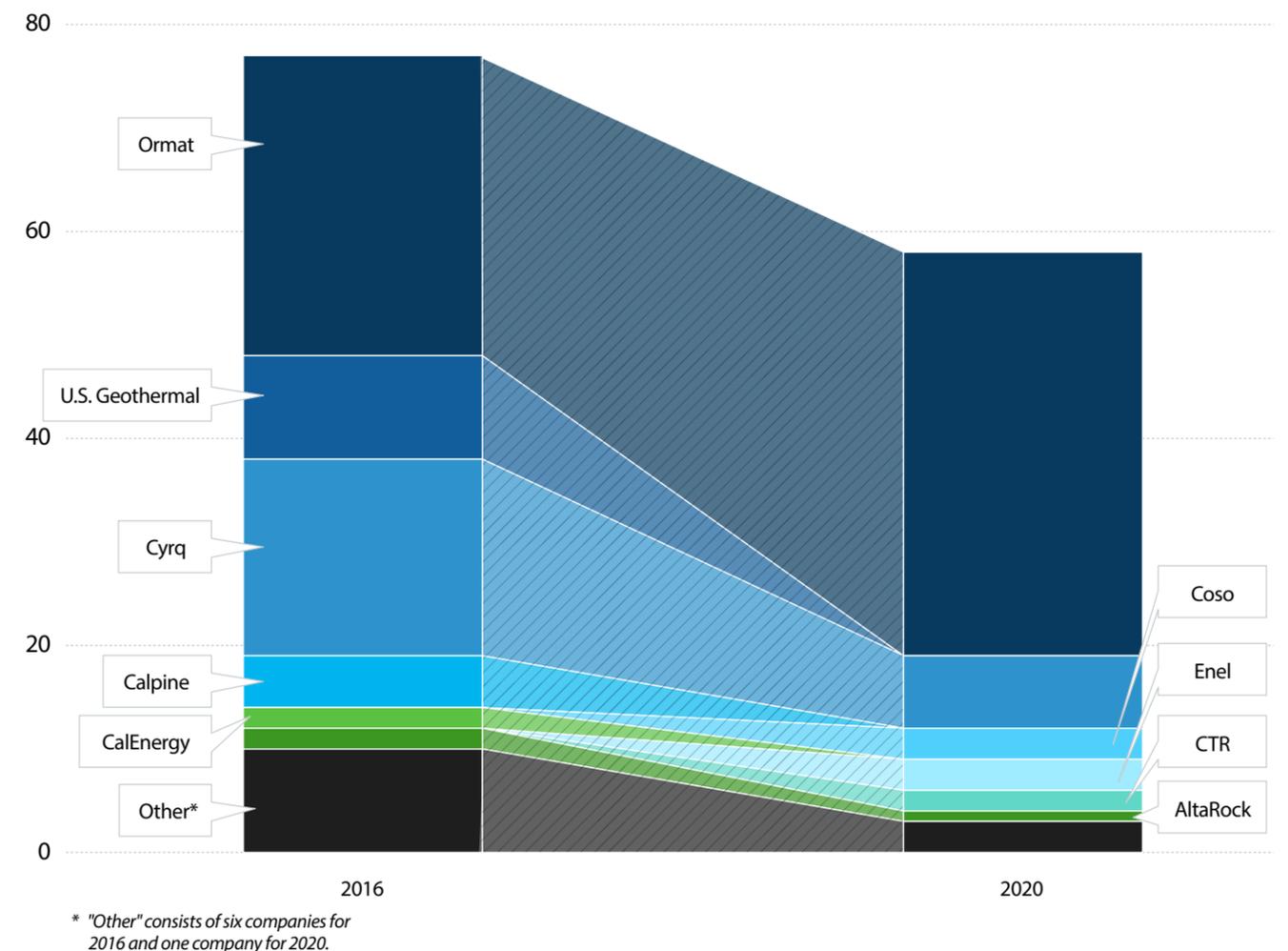


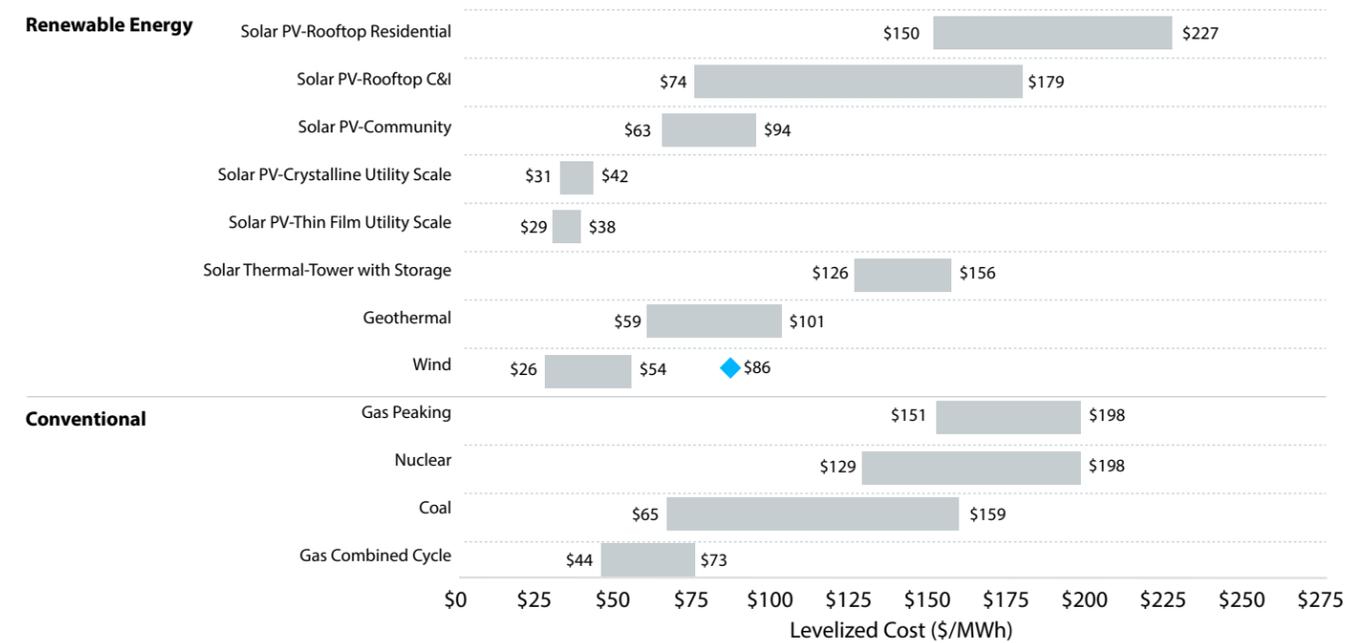
Figure 12. U.S. geothermal developing projects by operator

<sup>2</sup> For more information on the acquisition, see: <https://investor.ormat.com/news-events/news/news-details/2018/Ormat-Closes-Acquisition-Of-US-Geothermal/default.aspx>.

other grid services (NREL 2020). This limitation can undervalue baseload energy generators such as geothermal. However, LCOE is the sector standard and will be used here.

As seen in Lazard’s annual LCOE comparison, the cost of geothermal electricity production ranges between \$59 and \$101/MWh (Figure 13). This range corresponds with recent geothermal PPAs, which vary between \$67.50 and \$74. NREL’s 2020 ATB finds a similar range between \$58 and \$86, with geothermal LCOE expected to fall to between \$42 and \$77 by 2050.

Although this is competitive with conventional sources of electricity such as coal and gas peaking plants and some renewables such as rooftop solar, it exceeds the cost of gas combined-cycle plants and utility-scale solar and wind. This may explain the geothermal industry’s relative lack of growth over the past five years. Production cost models will favor the lowest-cost generators and may not value other attributes of generation sources.



**Figure 13.** Levelized cost of energy comparison—unsubsidized analysis. The blue diamond represents the estimated implied midpoint of the LCOE of offshore wind.

Source: Lazard (2020)

### 3.2.5 Barriers to Geothermal Power Production Development

A number of publications have addressed barriers to geothermal power production development in the United States, but the 2019 *GeoVision* study ably summarized the key barriers as follows:

1. **Technical barriers:**
  - A. Lack of exploration techniques required to identify and develop undiscovered geothermal resources
  - B. High upfront project costs because of expensive geothermal well drilling, which is exacerbated by relatively high exploration risks
  - C. Difficulty creating EGS reservoirs capable of sustained circulation of high flow rates of water over long periods of time.
2. **Policy/market barriers:**
  - A. Difficulty acquiring PPAs, partly because existing utility procurement practices do not value some of the benefits of geothermal power
  - B. Extended permitting timelines that can result in 7- to 10-year project development time frames
  - C. Lack of access to transmission infrastructure
  - D. Delays in obtaining project financing.
3. **Social-acceptance barriers:**
  - A. Lack of public awareness and acceptance of geothermal energy
  - B. Perception of high cost and risk by local authorities and the public.

Depending on the complexity of the project under consideration, there are several levels of NEPA review that may be used—each with its own set of requirements.

As discussed in the market barriers report and paper that accompanied the 2019 U.S. Department of Energy (DOE) *GeoVision* study (Young et al. 2017, Young et al. 2019), several factors present barriers to developers seeking to obtain PPAs, including exploration costs, upfront project risk, market demand, price of electricity, policies, and incentives. Additionally, established utility procurement practices do not always reflect the value of important benefits of geothermal power, such as supplying continuous baseload power, ancillary grid services, resilience, environmental benefits, and a small land footprint compared to other renewable energy technologies (Matek and Schmidt 2013). This PPA uncertainty can result in difficulty obtaining project financing, thus further delaying geothermal projects. Finally, the structure and duration of federal geothermal incentives when compared to extended geothermal project timelines makes these incentives difficult to rely on (*GeoVision* 2019).

Another important non-technical barrier to geothermal development is the extended permitting timeline. A variety of factors contribute to this lengthy permitting process, including lease nomination backlogs, lack of knowledge of geothermal development, under-staffed offices at regulatory agencies, and, particularly, the requirement for multiple environmental reviews under the National Environmental Policy Act (NEPA) if the project is located on federal land. Geothermal projects located on federally managed land can be subject to environmental review under NEPA up to six times throughout the development process. In addition, depending on the complexity of the project under consideration, there are several levels of NEPA review that may be used—each with its own set of requirements. Combined, these factors can result in geothermal project development time frames of up to 7 to 10 years (Young et al. 2019, *GeoVision* 2019).





### 3.3 Geothermal Development on Public Land

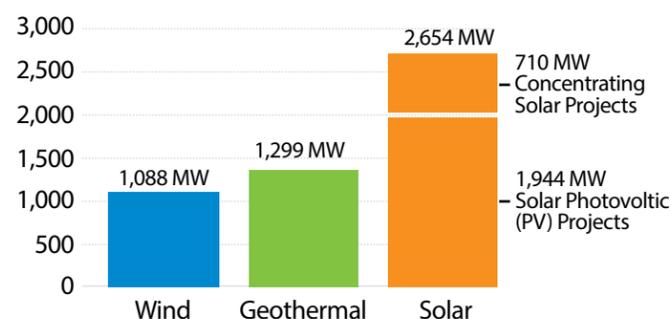
#### 3.3.1 Geothermal Generating Capacity on Public Land

U.S. public lands are an important source of renewable energy. Many geothermal projects are located on federal public land—totaling 2,439 MW of nameplate capacity—the majority of which is managed by the Bureau of Land Management (BLM). In 2019, this translated to 1,300 MW of generating capacity (Figure 14), enough to power more than 1.1 million homes.

#### 3.3.2 BLM Leasing Data Review

BLM leasing data were collected from annual BLM Public Land Statistics reports (BLM 2020). Annual lease sale results were compiled, including existing leased acres, new leased acres, and total bonus bid. Leasing policy changed to a default competitive leasing process with the Energy Policy Act of 2005 (GPO 2005), and 43 CFR 3200 leasing regulations were updated in 2007 (Federal Register 2007). The new process requires default competitive leasing, whereas the previous process only required competitive leasing for lands within a known geothermal resources area (or “KGRA”), lands from terminated, expired, or relinquished leases, or at the BLM’s discretion. However, parcels that do not receive a competitive bid are available for non-competitive leasing for two years after the lease sale.

**U.S. public lands are an important source of renewable energy. Many geothermal projects are located on federal public land—totaling 2,439 MW of nameplate capacity.**



**Figure 14.** Generating capacity of renewable energy projects operating on public lands in 2019  
Source: Springer and Daue (2020)

Under this policy, the minimum bonus bid (the dollar amount per acre that the potential lessee pays to receive a lease) is \$2/acre. In 2007, many new lease parcels were nominated for the new competitive leasing process, and there was strong competition for those parcels. The average price per acre for new competitive geothermal leases in 2007 was \$205.05/acre, increasing to \$211.12/acre in 2008. The price per acre dropped

drastically in 2009 to \$35.72/acre. Since 2010 there has been little competition for new leases, and bonus bids have remained close to the \$2/acre minimum (BLM 2020).

#### 3.3.3 Geothermal Capacity and BLM Lease Acreage

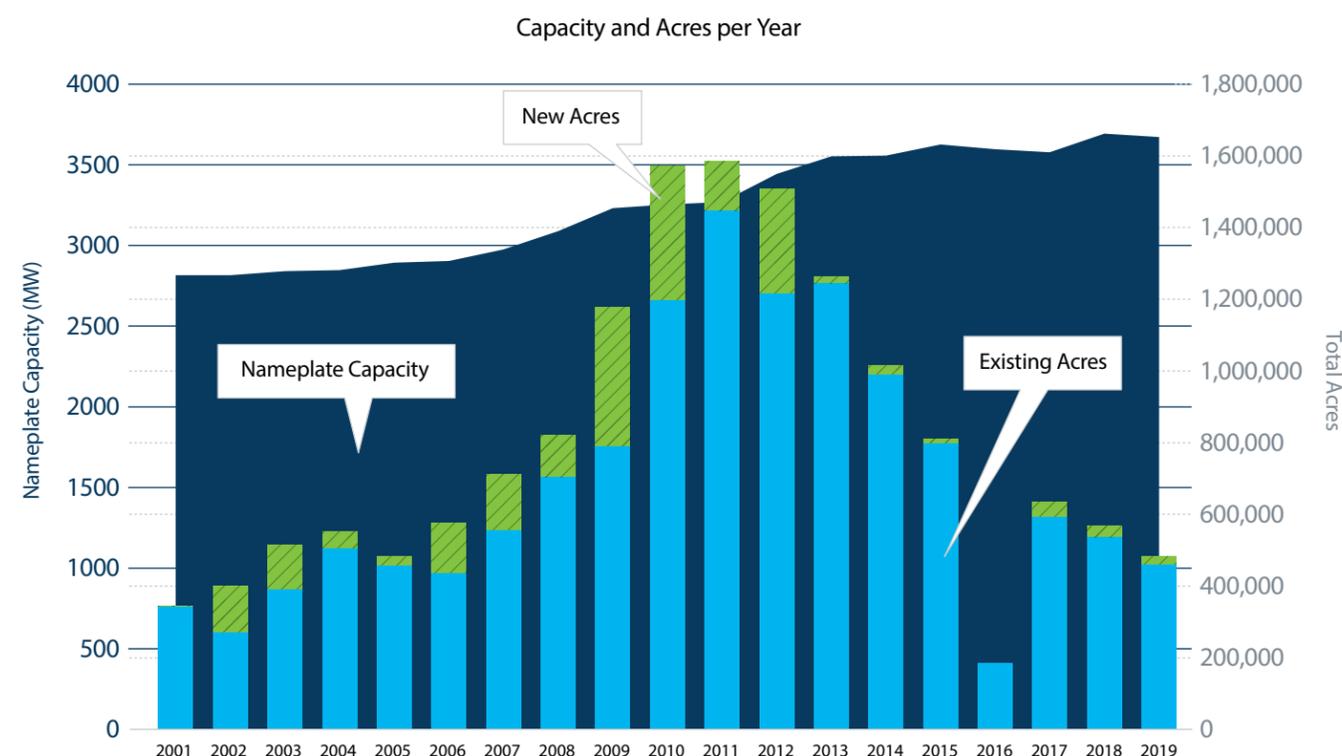
The total number of acres presented in Figure 15 includes both competitive and noncompetitive leases. The 2016 data appears to have been incorrectly reported in the Public Land Statistics report and excludes all Energy Policy Act competitive leases and new leases. The total acres in 2016 therefore only includes existing noncompetitive leases and existing pre-Energy Policy Act competitive leases.

#### 3.3.4 Wells on BLM Acreage

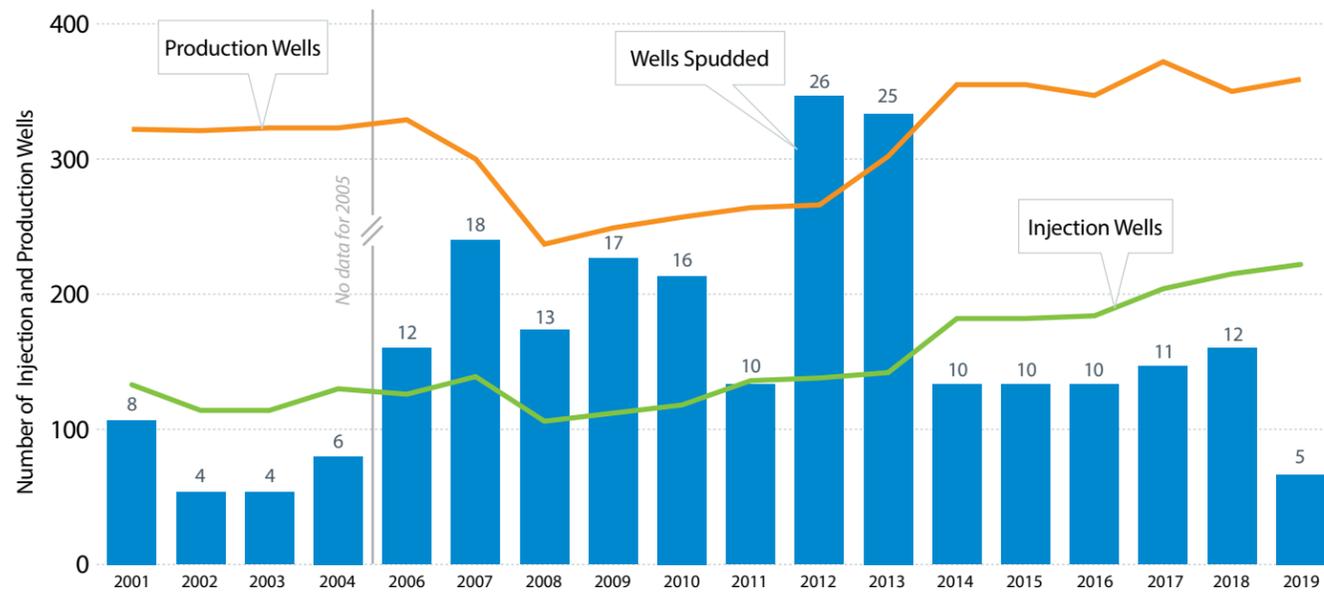
Figure 16 examines the number of production and injection wells and wells spudded on BLM leases since 2001. The

production and injection classifications are self-reported by operators and include wells that have been shut-in but not wells that have been plugged. The 2005 Public Land Statistics report had no well data and is excluded. The large number of wells spudded in 2012 and 2013 roughly coincides with the increase in new leases from 2009 through 2012, when accounting for time to receive permitting approval. The smaller number of wells spudded since 2013 concurs with the lack of growth in power production over the same time period.

Between 2006 and 2008, there is a large unexplained drop in the number of production and injection wells. This could be explained in part by decreased capacity in established geothermal fields and/or a concerted effort to reclassify wells.



**Figure 15.** U.S. nameplate capacity (dark blue), existing BLM leased acreage (light blue), and new BLM leased acreage (green)  
Source: BLM (2020)



**Figure 16.** Number of wells spudded on leased BLM acreage (blue), total number of production wells (orange), and injection wells (green) on leased BLM acreage

Source: BLM (2020)

### 3.4 Future Opportunities

#### 3.4.1 Near-Term Growth

Although the geothermal industry power generation numbers were relatively stagnant from 2015 to 2019, there is reason to expect capacity growth in the near future. Nine new geothermal PPAs have already been signed since late 2019 (Figure 17), including one each in Utah, Hawaii, and Alaska, and six in California (Howard 2020). The pricing for the PPA terms that have been made public can be found in Table 4. Also, contained in these agreements are plans for the first two geothermal power plants to be built in California in a decade—Hell’s Kitchen in the Salton Sea and Casa Diablo

IV near Mammoth Mountain (Roth 2020). In addition, after the data for this report were collected, Ormat brought the Steamboat Hills expansion online, increasing its generating capacity by 19 MW. Finally, Ormat’s Puna power plant was brought back online in late 2020, which should increase geothermal net generation in 2021 and beyond.

Nine new geothermal PPAs have already been signed since late 2019, including one each in Utah, Hawaii, and Alaska, and six in California.



**Figure 17.** Geothermal PPAs signed from November 2019 through September 2020

**Table 4.** Public Geothermal PPA Pricing

Project	State	Size (MW)	Pricing (\$/MWh)	Term (years)
Hell’s Kitchen	California	40	74	25
Whitegrass	Nevada	3	67.50	25
Star Peak	Nevada	12.5	70.25	25
Casa Diablo	California	16	68	20
Puna	Hawaii	46	70	30

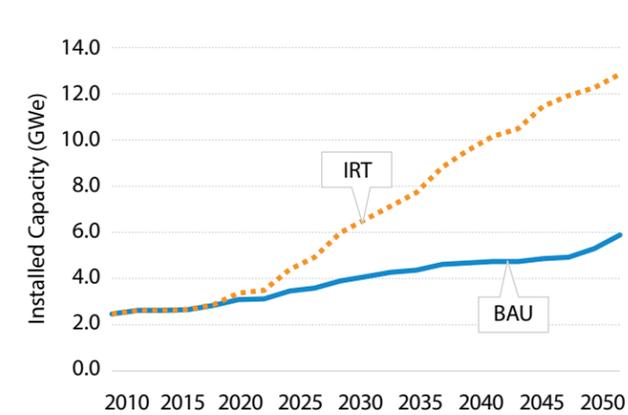
Longer-term growth potential for geothermal was addressed by DOE's landmark *GeoVision* study (*GeoVision 2019*). *GeoVision* was a comprehensive multiyear undertaking that explored the role of geothermal power production in meeting current and future energy demands in the contiguous United States.

### 3.4.2 Projections for Geothermal Power Production

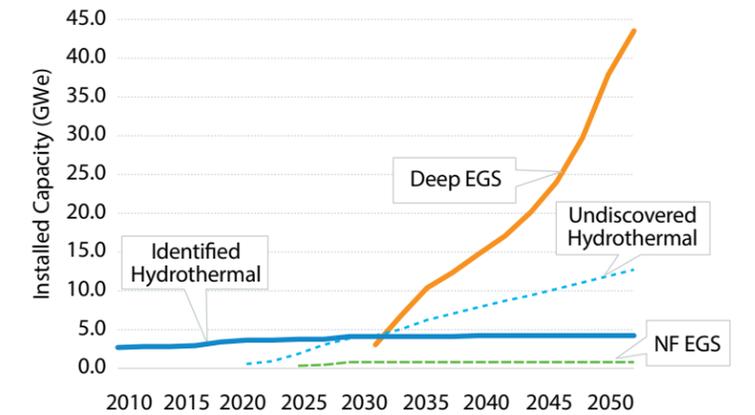
Longer-term growth potential for geothermal was addressed by DOE's landmark *GeoVision* study (*GeoVision 2019*). *GeoVision* was a comprehensive multiyear undertaking that explored the role of geothermal power production in meeting current and future energy demands in the contiguous United States. It not only examined the growth opportunities of geothermal, but also the environmental benefits of increased geothermal deployment. In addition, it created a roadmap of actionable items to guide stakeholders toward achieving the deployment levels identified in the report.

The *GeoVision* team used DOE's Geothermal Electricity Technology Evaluation Model (GETEM) and NREL's Regional Energy Deployment System (ReEDS) model to analyze the potential for geothermal deployment through 2050 under a range of scenarios. The three scenarios are: a Business as Usual (BAU) scenario, assuming status quo deployment trends; an Improved Regulatory Timeline (IRT) scenario, assuming a halving of geothermal development timelines through regulatory reform; and a Technology Improvement (TI) scenario, assuming significant technology advancements resulting in a variety of technical improvements that would enable deep EGS development. As seen in Figure 18, the *GeoVision* BAU case sees U.S. geothermal net-summer capacity increasing from 2.5 gigawatts (GW) to 6 GW by 2050. For the IRT scenario, geothermal deployment climbs to 13 GW. This IRT number is similar to the EIA Annual Energy Outlook 2021 projection, which sees 2019 utility-scale geothermal power generation increasing 311% by 2050 (EIA 2021a). Applying the same increase to this report's estimated 2019 nameplate capacity of 3.7 GW yields a capacity of 11.5 GW in 2050. Finally, the *GeoVision* TI scenario indicates the potential for 60 GW of net-summer capacity by 2050, with the majority of the increase (45 GW) coming from the deployment of deep EGS.

The *GeoVision* TI scenario indicates the potential for 60 GW of net-summer capacity by 2050, with the majority of the increase (45 GW) coming from the deployment of deep EGS.



Using existing technologies, the IRT scenario could more than double the amount of installed geothermal capacity by 2050 vs. the BAU scenario by reducing barriers to exploration and construction timelines.



EGS achieves notable deployment rates with technology improvements (capital cost reductions): 8.5% of total generation by 2050 (vs. 0.4% now)

**Figure 18.** Geothermal power production growth as predicted in *GeoVision*. Note that the figure on the right represents the TI scenario, and the capacity curves are additive.

Source: *GeoVision* (2019). Note that "NF EGS" indicates "near-field EGS."

Photo by Dennis Schroeder, NREL 48265

## 4 U.S. Geothermal District Heating Update

### 4.1 Technology Overview

Geothermal district heating (GDH) is the use of geothermal energy to heat individual and commercial buildings, as well as for heating in industry, through a distribution network.

Geothermal district heating (GDH) is the use of geothermal energy to heat individual and commercial buildings, as well as for heating in industry, through a distribution network (GeoDH 2014c). In the United States, GDH was initially developed near high-grade hydrothermal resources, but the technology is expanding to regions with moderate- to low-grade hydrothermal resources. In Europe, many GDH systems (such as in the Paris Basin) make use of hydrothermal resources in sedimentary basins, utilizing doublets (a pair of injection and production wells drilled in deviation from a single drilling pad) for heat extraction (GeoDH 2014c). Geo-exchange (i.e., geothermal heat pumps) can also be used for district-scale heating and cooling (GeoDH N.D.) GDH systems considered in this report utilize hydrothermal resources as the energy source. This report does not consider geo-exchange systems or the rapidly evolving project development space that is highlighted in Section 6, Emerging Technologies.

GDH technology is mature and has been in use for more than a century. Like geothermal power plants, GDH installations are capital-intensive, particularly in the high-risk early phases of project development (i.e., drilling). Operation and maintenance expenses, however, are relatively low compared to conventional district heating systems (GeoDH 2014c). Several countries worldwide now utilize geothermal technology as a primary source of district heating (namely China, Iceland, Turkey, and Germany). As of 2020, 29 countries have installed GDH systems (Lund and Toth 2020). As of 2019, there were 327 GDH and cooling systems in Europe, with total installed capacity of 5.5 GWth, used for buildings, industry, services, and agriculture in 25 countries (EGEC 2020a).

## 4.2 History

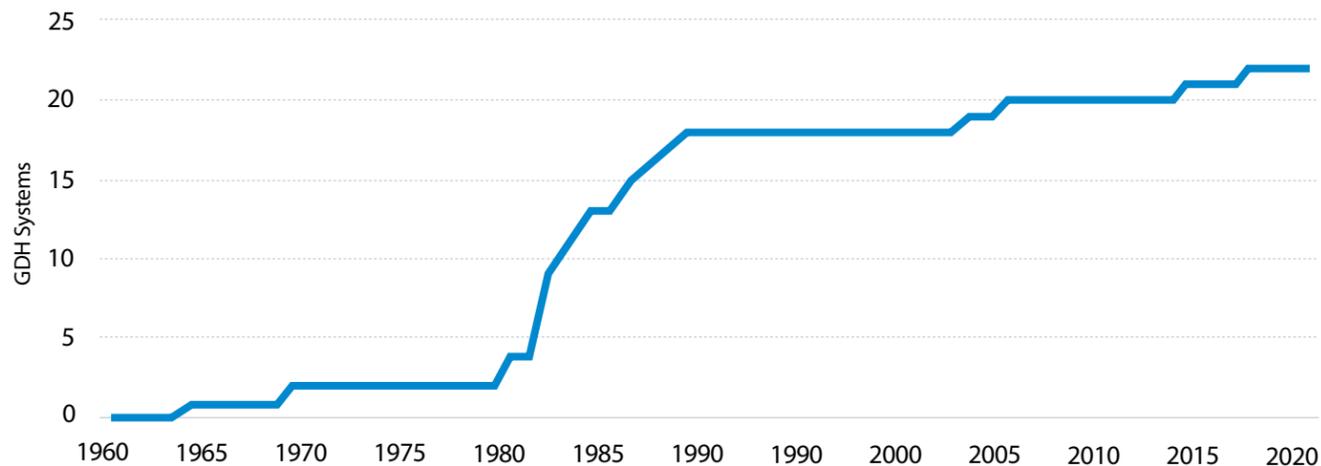
Geothermal energy has been used for district heating in the United States since the Boise, Idaho, GDH system was built in the 1890s. The original district was made up of homes and a natatorium, and the system is still operating today. In the 1980s, the City of Boise expanded the GDH system and now holds the record for the largest GDH system in the United States, supplying heat to 92 buildings in downtown Boise (King 2018).

GDH technology has been deployed in the United States for over a century, but other installations are older still. GDH in Europe dates back to Roman times, evidenced by the ruins

of city homes and baths heated via natural hot water catchments and piping. At Chaudes Aigues in France, a GDH system installed in the year 1330 is still in operation today.

The majority (15 of 23) of the existing U.S. GDH installations were installed in the

Geothermal energy has been used for district heating in the United States since the 1890s when the first GDH system was installed in Boise, Idaho.



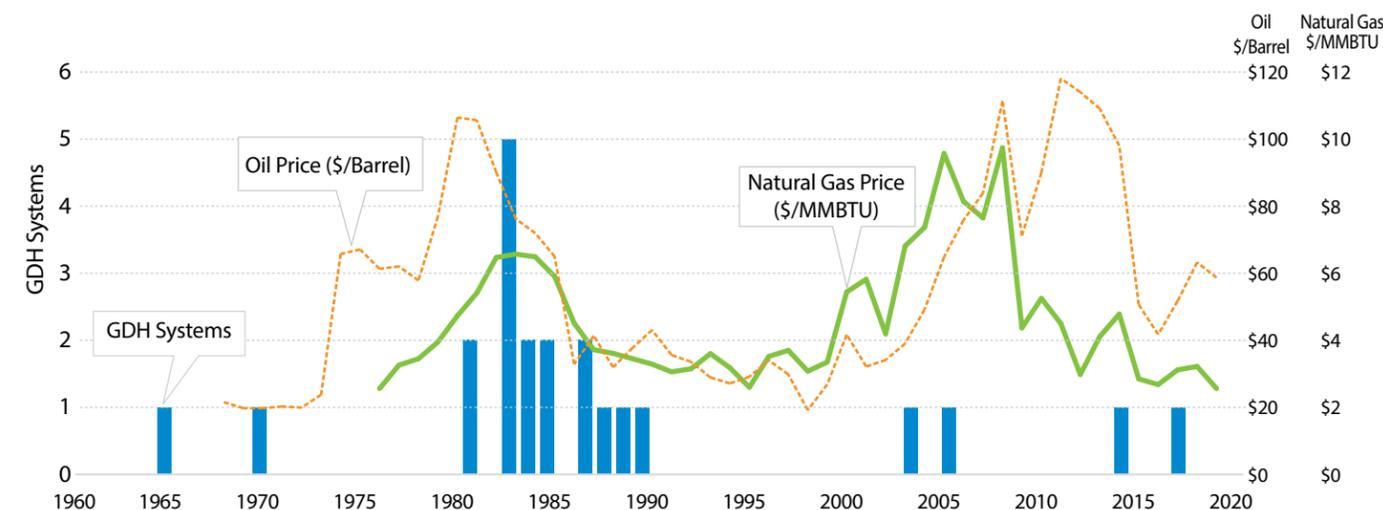
**Figure 19.** Number of U.S. GDH systems installed over time

Sources: Oregon Institute of Technology Geo-Heat Center, Snyder et al. (2017), Mattson and Neupane (2017), and 2020 operator interviews

1970s and 1980s (Figure 19). All but one of these GDH systems are still operating in 2020. The GDH system at New Mexico State University in Las Cruces, New Mexico, was installed in 1982 and removed from service in 2003.

A major factor impacting GDH development is the market price of competing heat sources. Figure 20 shows GDH

deployment over time in the United States compared to the price of competing heat sources (oil and natural gas). The boost in GDH development in the 1980s appears to have coincided with an uptick in oil and gas prices during that time period. However, similar upticks in gas prices from 2004 through 2009 and oil prices from 2011 through 2014 did not see the same increase in GDH installations.



**Figure 20.** Number of GDH installations vs. oil prices (orange) over time and natural gas prices (green) over time (adjusted for inflation)

Source: EIA (2020)



Photo from iStockphoto, 890886488

### 4.3 Current Business Environment

The GDH market in the United States is mostly undeveloped. Direct-use geothermal only provides 0.1% of the current total U.S. thermal demand (McCabe et al. 2019). This is likely due to a combination of low natural gas prices, the lack of government and incentive programs that would offset upfront GDH installation costs, and a lack of local and regional stakeholder awareness and support. Although DOE provides limited financial support for geothermal exploration, feasibility

studies, and other activities, such programs only indirectly benefit direct-use development and can exclude geothermal direct use altogether (Lund and Bloomquist 2012). As of 2020, all the DOE technical assistance programs supporting direct use have been terminated. Some states have also provided financial assistance to support development of GDH systems, though those too have also terminated in recent years, with the notable exception of California. More information on state and federal policy and programs with respect to geothermal direct use development is provided in Section 5 of this paper.

### 4.3.1 Existing GDH Systems

As of 2020, there are 23 active GDH systems in the United States (Table 5). Of the 23 existing GDH systems, four have been installed since 2000, all in California and Oregon. The most recent installation was at the Modoc County Joint Unified School District in Alturas, California, in 2017.

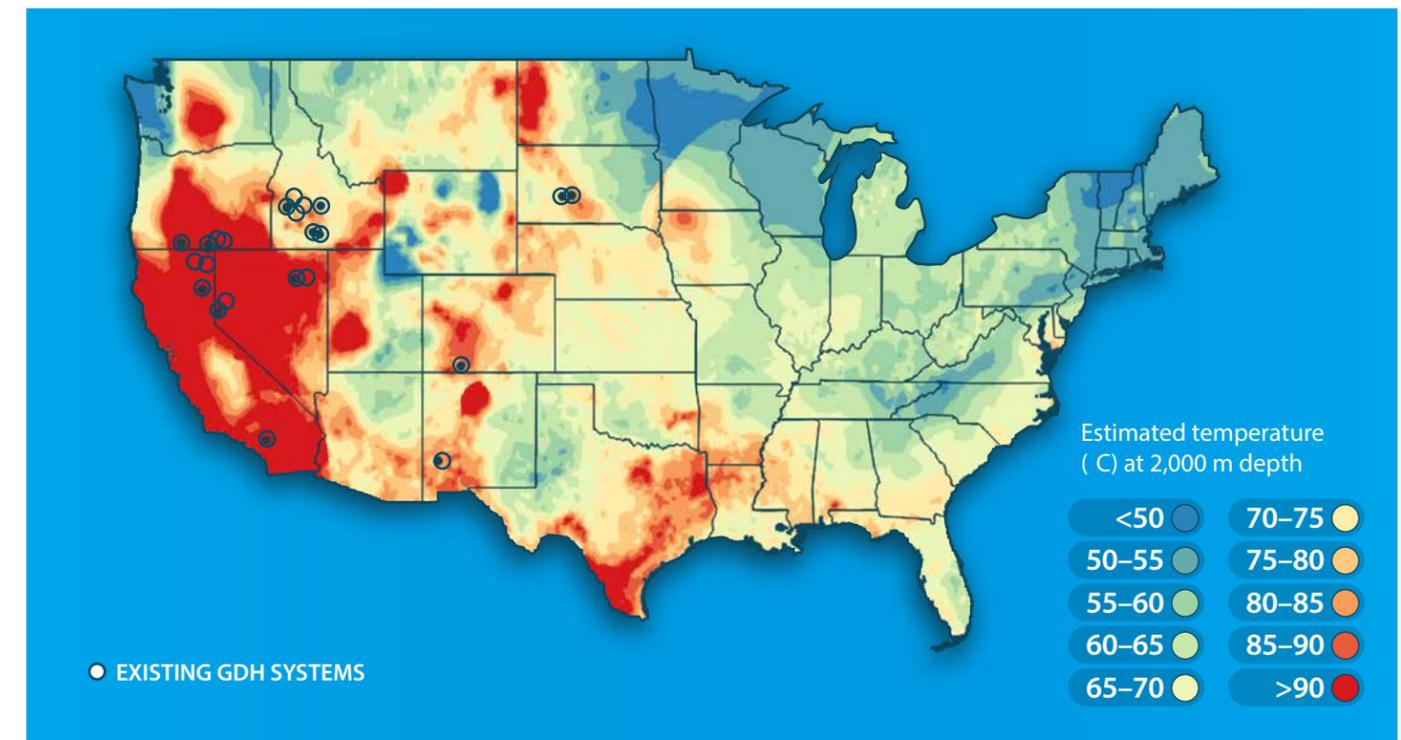
While all of the existing U.S. GDH systems are located in the western United States (Figure 21), GTO is supporting two demonstration projects looking at district heating potential in the northeast corridor of the United States (see Sections 4.5.1 and 4.6.3).

As of 2020, there are 23 active GDH systems in the United States (Table 5). Of the 23 existing GDH systems, four have been installed since 2000, all in California and Oregon. The most recent installation was at the Modoc County Joint Unified School District in Alturas, California, in 2017.

**Table 5.** U.S. Geothermal District Heating Systems, Net Capacity, and Annual Energy Use

Sources: Oregon Institute of Technology Geo-Heat Center, Snyder et al. (2017), Mattson and Neupane (2017), and 2020 operator interviews

State	GDH System	Year Opened	Capacity (MWth)	Energy Use (GWh/yr)
CA	San Bernardino	1984	12.8	22.0
CA	Susanville	1982	5.6	3.4
CA	Canby / I'SOT	2003	no data	1.2
CA	Modoc Schools / Alturas	2017	0.44	no data
CO	Pagosa Springs	1982	5.1	4.8
ID	Boise City District Heating	1983	20.6	42.3
ID	College of Southern Idaho	1980	6.3	14
ID	Fort Boise Veteran's Hospital	1988	1.8	3.5
ID	Idaho Capitol Mall	1982	3.3	18.7
ID	Kanaka Rapids Ranch	1989	1.1	2.4
ID	Ketchum District Heating	1929	0.9	1.9
ID	Warm Springs Water District	1892	3.6	8.8
NM	Gila Hot Springs Ranch	1987	0.3	0.9
NV	Elko County School District	1986	4.3	4.6
NV	Elko District Heat	1982	3.8	6.5
NV	Manzanita Estates	1986	3.6	21.2
NV	Warren Estates	1983	1.1	2.3
OR	City of Klamath Falls	1984	4.7	10.3
OR	Lakeview Prison	2005	11.7	no data
OR	Lakeview District Hospitals + Schools	2014	1.6	4.4
OR	Oregon Institute of Technology	1964	6.2	13.7
SD	Midland	1969	0.1	0.2
SD	Philip	1980	2.5	5.2



**Figure 21.** Location of 23 existing U.S. GDH systems overlaying estimated temperature at 2,000 m depth

Source: Mullane et al. (2016)

### 4.3.2 Size of U.S. GDH Systems

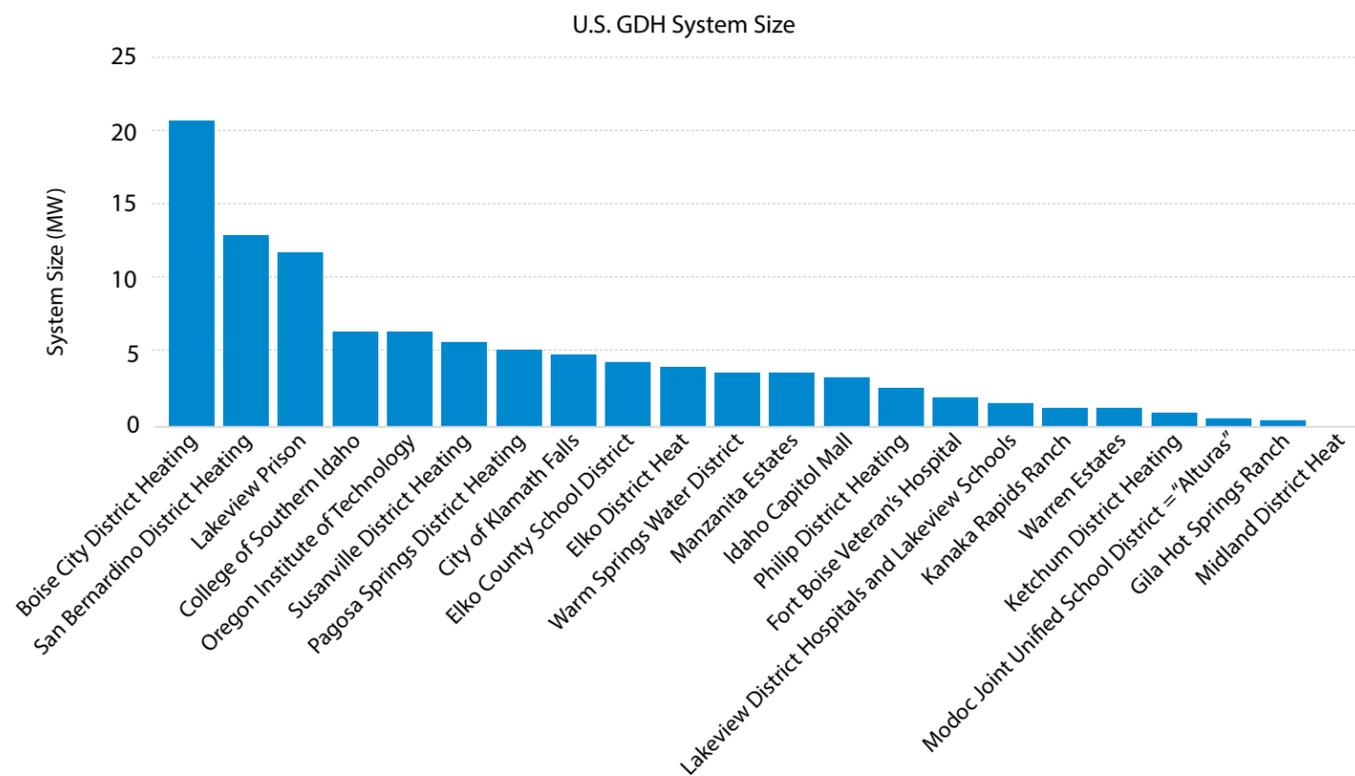
GDH systems in the United States range in size from 0.1 MWth to just over 20 MWth, with an average of 4 MWth (Figure 22). In contrast, the average size of proposed GDH systems in the United States that were the subject of recent feasibility studies on geothermal deep direct use (DDU; see Section 4.5.1 for more information about DDU projects) was 12 MWth, in line with the projected average GDH size in the 2019 *GeoVision* study (9 MWth). Compared to worldwide GDH installations, these systems are relatively small (Figure 23).

Unlike in the United States, there has been significant geothermal direct-use development in Europe recently, with between 7 and 19 geothermal heating installed online each

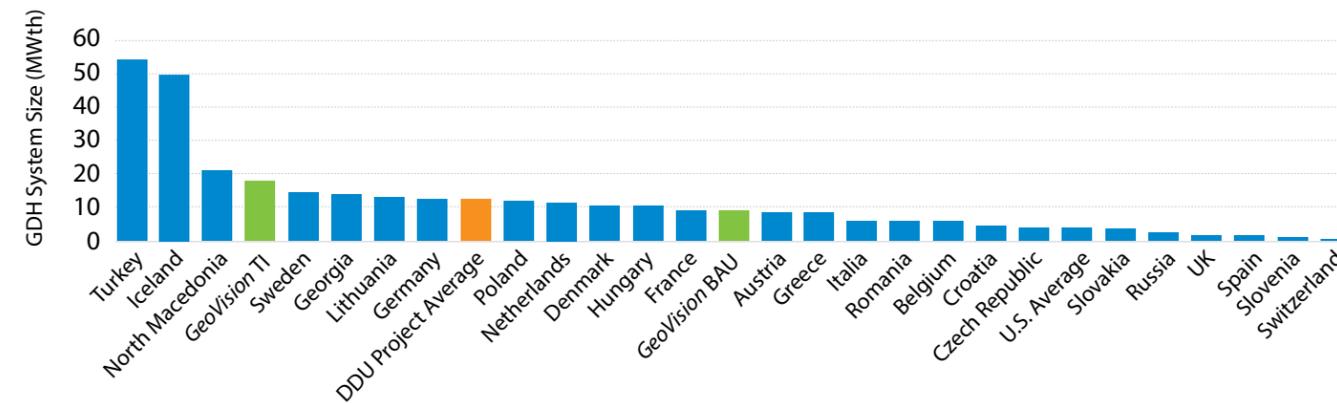
year over the last 9 years (European Geothermal Energy Council [EGEC] 2020a). The average GDH system size in Europe ranges between 1 MW (Switzerland) and 55 MW (Turkey), with a continent-wide average of about 17 MW, roughly four times larger than the average U.S. GDH system size of 4 MW (see Sections 7.4 and 7.4.1 for more discussion of European GDH deployment). For comparison, the *GeoVision* GDH average system sizes calculated with the dGeo tool are included in Figure 23—9 MW for the BAU scenario and 18 MW for the TI scenario. Also shown for comparison is the average size of six GDH systems evaluated in 2019–2020 DDU feasibility studies. China has seven large GDH systems, with an average system size of ~1,000 MWth (Figure 24), which is orders of magnitude larger than typical GDH systems worldwide (Lund and Toth 2020).



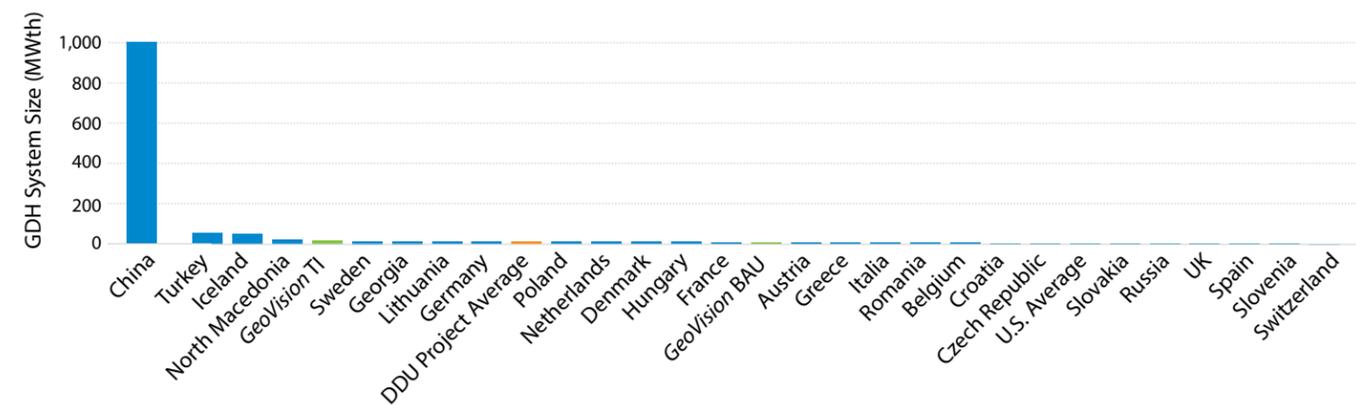
Photo courtesy of the City of Boise, Idaho



**Figure 22.** System size, in MW, of existing U.S. GDH systems  
Sources: Oregon Institute of Technology Geo-Heat Center, Snyder et al. (2017), Mattson and Neupane (2017), and 2020 operator interviews



**Figure 23.** Average GDH system size worldwide (without China)



**Figure 24.** Average GDH system size worldwide (with China)  
Data obtained from EGEC Market Report (2020a), *GeoVision* Report (2019), Lund et al. (2020), Tester et al. (2019), Lowry et al. (2020), Lin et al. (2020), and Garapati et al. (2020)

### 4.3.3 Age and Performance of U.S. GDH Systems

82% of U.S. GDH systems—representing 88% of the total U.S. geothermal heating capacity—are more than 30 years old. Of the remaining 18%, half are more than 10 years old (Figure 25).

The average utilization factor of the U.S. GDH systems—representing the slope of the blue line in Figure 26—is 23%. This means that on average the U.S. GDH systems operate 23% of the time at their nominal capacity, and the remaining 77% of the time the systems are not producing. This low utilization factor is due to frequent operation at less than full capacity and the seasonality of heating needs (i.e., the system is not needed for satisfying heating demands year-round).

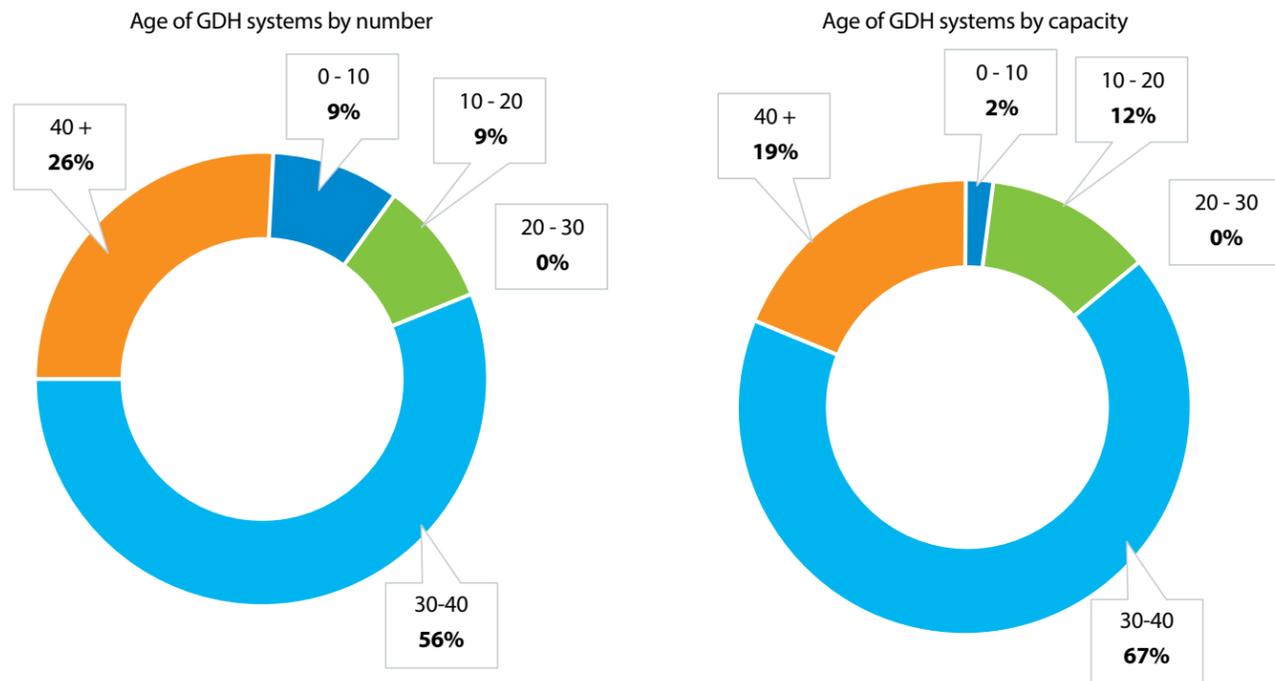
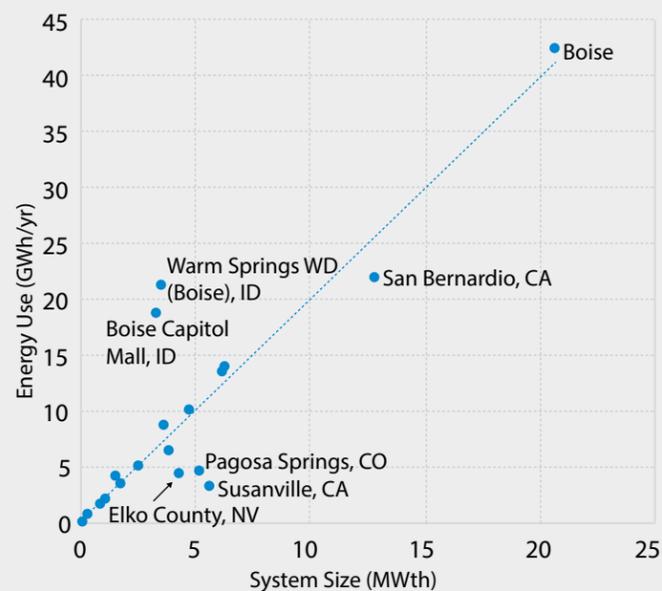


Figure 25. Age of 23 U.S. GDH systems by number (left) and capacity (right)

Figure 26. Energy use (GWh/year) versus system size (MWth) of 23 U.S. GDH systems. On average, the U.S. GDH utilization factor is 23% (slope of the blue line, which is the best linear fit of the data).



### 4.4 Costs of GDH in the United States

#### 4.4.1 Levelized Cost of Heat for U.S. GDH Systems

Levelized cost of heat (LCOH) for 19 out of the existing 23 U.S. GDH systems was calculated using the standard discounted LCOH model, as implemented in GEOPHIRES (Beckers and McCabe 2019). Inputs include the project capital cost, operation and maintenance cost, and annual heat production. These data were extracted from the NREL direct-use database as well as previous publications (e.g., Mattson and Neupane 2017); missing data were obtained

Estimated LCOH for the U.S. GDH systems ranges from \$15 to \$105/MWh, with an average of \$54/MWh.

through operator interviews. These LCOH calculations are based on a 30-year lifetime, 5% discount rate, and overnight construction. Estimated LCOH for the U.S. GDH systems ranges from \$15 to \$105/MWh, with an average of \$54/MWh (Figure 27). The fact that most of the U.S. GDH systems are older than 30 years and still operating suggests that longer project life may be a reasonable assumption when assessing project economics. Not included in this figure and in the calculation of the average is the Fort Boise Veteran's Hospital GDH, which has an estimated LCOH of \$325/MWh. This high LCOH is a result of an unusual high system cost (on the order of \$15 million). Given the very small system size of 1.8 MW, this is considered an outlier and not representative for GDH LCOH in the United States. Data were insufficient for the remaining 3 out of 23 GDH systems to perform LCOH calculations.

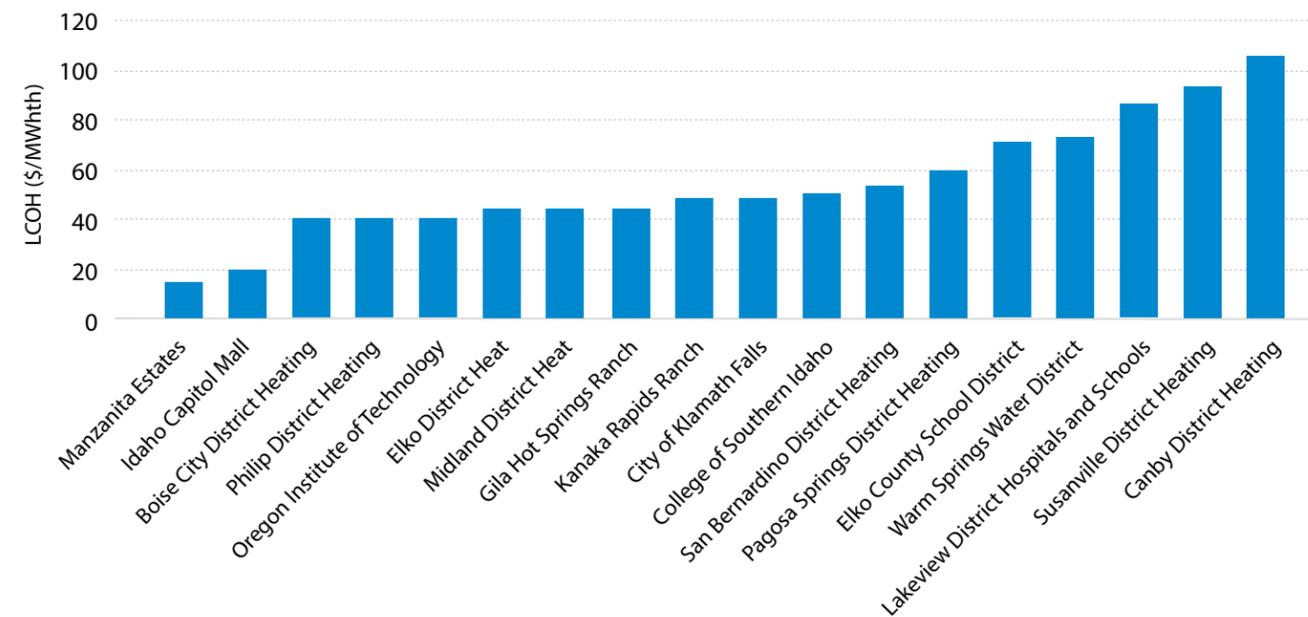
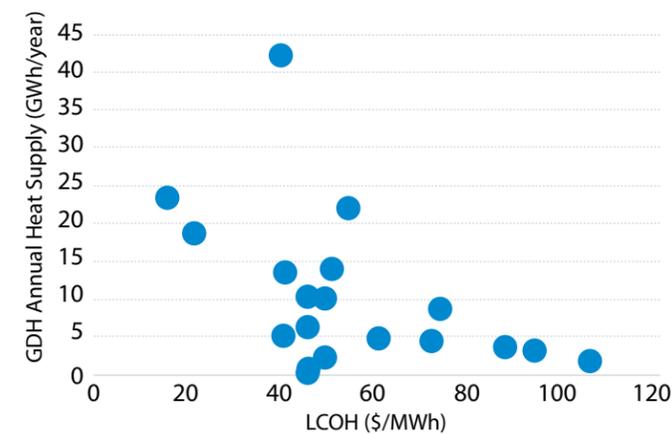


Figure 27. Estimated LCOH for U.S. GDH systems. Assuming 30-year lifetime, 5% discount rate, and overnight construction. LCOH ranges from \$15 to \$105/MWh, with average of \$54/MWh.

Figure 28 illustrates the system size (as annual heat supply) versus the LCOH of U.S. GDH systems. The graph suggests that larger systems tend to have a lower LCOH, most likely due to economies of scale.



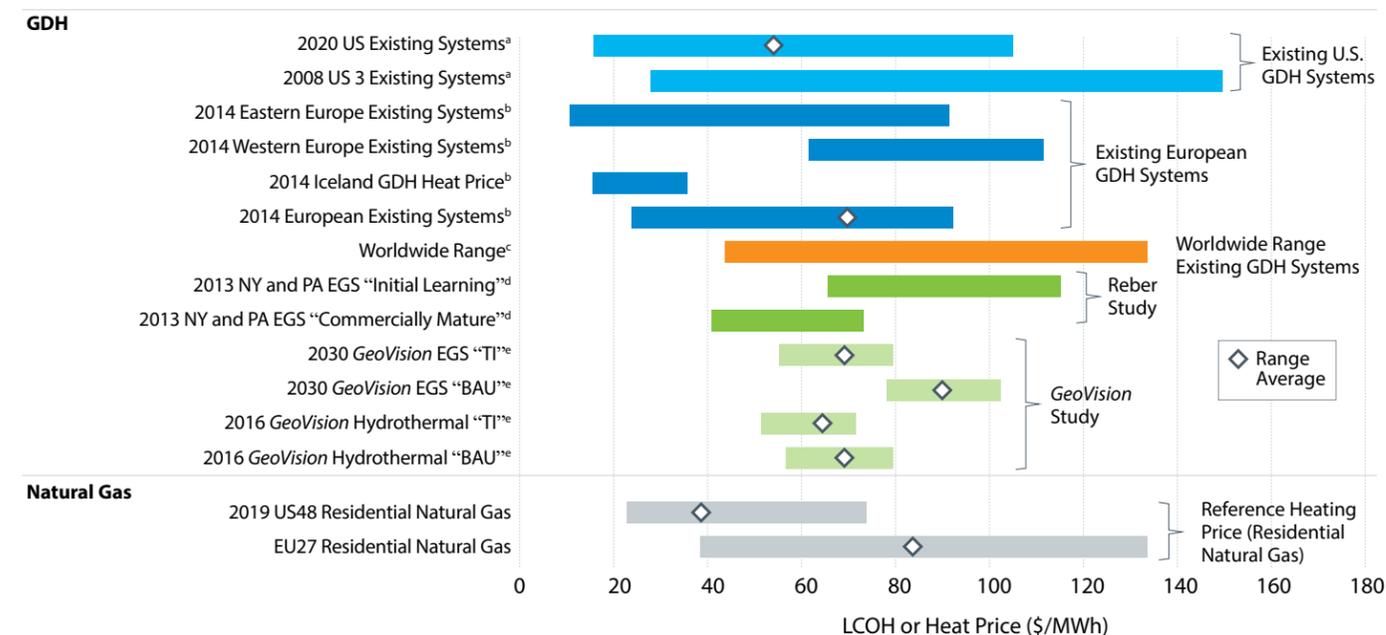
**Figure 28.** Annual heat production versus LCOH of U.S. GDH systems

LCOH calculation assumes 30-year lifetime, 5% discount rate, and overnight construction.

### 4.4.2 Comparisons of LCOH for GDH Systems: United States vs. Worldwide

Figure 29 provides a comparison of LCOH and heat prices in Europe and the United States. As mentioned, the LCOH for U.S. systems ranges between \$15 and \$105/MWh, with an average of \$54/MWh. This range is consistent with the range of LCOH for existing European GDH systems, though the average U.S. LCOH value (\$54/MWh) is slightly lower than the average European LCOH value (\$69/MWh). The U.S. range is also consistent with the range calculated in the *GeoVision* study, though again the average LCOH value is slightly lower.

On the other hand, the average LCOH for U.S. systems is higher than the average 2019 U.S. price of residential natural gas (EIA 2020a). The higher average 2019 price of residential natural gas in Europe is also provided in Figure 29 for reference. Although a variety of carbon-free and renewable heating technologies are available, such as air-source heat pumps, solar thermal heating, and biomass, natural gas prices are highlighted for comparison because most residential heating demand in the United States is met by natural gas (EIA 2015; also see Section 7.1 of this report).



<sup>a</sup>LCOH of existing U.S. GDH systems as calculated in this study and as reported by Thorsteinnsson (2008).  
<sup>b</sup>LCOH of GDH systems in Europe.  
<sup>c</sup>LCOH of worldwide GDH systems.  
<sup>d</sup>Simulated LCOH values for EGS GDH systems in New York and Pennsylvania by Reber (2013).  
<sup>e</sup>Simulated LCOH values for GDH systems nationwide using the dGeo tool in the *GeoVision* study.  
 Other Sources: EIA 2020a; EuroStat 2020

**Figure 29.** Worldwide comparison of LCOH values for GDH systems and natural gas prices

The LCOH of European systems has a wide range due to the large number of GDH systems deployed in Europe and the wide range in sizes of those systems. For example, while many systems are small in scale, the GDH system in Paris, France, has 250 MWth installed and a heat delivery of 1,500 GWhth/year for 170,000 buildings (Bertani 2016).

### 4.4.3 Capital Costs and Funding Sources for U.S. GDH Systems

Data were obtained on the original capital costs for 16 out of the 23 existing GDH systems in the United States. Of these, data on grant, loan, and tax credits supplied by state and federal agencies were obtained for 12 projects (Table 6).

**Table 6.** Capital Costs of GDH Systems, in Original Dollars, and Amount of State and Federal Support

U.S. Department of Agriculture (USDA); U.S. Department of Energy (DOE); U.S. Department of Housing and Urban Development (HUD); among others. Blank cells indicate no data.

Sources: capital costs from Mattson and Neupane (2017), the NREL direct-use database, and operator interviews; funding sources from Geo-Heat Center quarterly bulletins, news releases, project reports, and operator interviews.

State	Site	Year Opened	Original System Cost	USDA Loan	DOE Loan	DOE Grant	HUD Grant	Other Grants and Loans	State Grant	State Loan	State Energy Tax Credit	% of Project Financed Through Grants
CO	Pagosa Springs	1982	\$1,364,000		\$1.21M			\$275K				20%
ID	Boise City	1983	\$7,128,000			\$4.47M		\$355K				68%
ID	College of Southern ID	1980										
ID	Ft. Boise Vet. Hospital	1988	\$7,500,000					\$7.5M				100%
ID	Idaho Capitol Mall	1982	\$1,800,000									
ID	Kanaka Rapids Ranch	1989										
ID	Ketchum	1929										
ID	Warm Springs WD	1892										
NM	Gila Hot Springs Ranch	1987										
NV	Elko School District	1986	\$1,500,000			\$250K						17%
NV	Elko District Heat	1982	\$827,000			\$827K						100%
NV	Manzanita Estates	1986	\$1,400,000									
NV	Warren Estates	1983	Tied to above									
OR	City of Klamath Falls	1984	\$2,801,000			\$1.6M	\$300K		\$400K			82%
OR	Lakeview Prison	2005	\$1,300,000									
OR	Lakeview Hosp/Schools	2014	\$3,837,250	\$2.66M			\$200K				\$900K	29%
OR	Oregon Inst. of Tech.	1964				\$4.5M		\$3M	\$2.4M	\$6M		
SD	Midland	1969										
SD	Philip	1980	\$1,218,884			\$939K						77%
CA	San Bernardino	1984	\$6,000,000			\$60K			\$3.21M			34%
CA	Susanville	1982	\$2,400,000			\$2.04M	\$820K		\$1.52M	\$59K		77%
CA	Canby/I/SOT	2003	\$1,400,000		\$204k			\$307K	\$304K			36%
CA	Alturas	2017	\$4,963,448						\$3.97M			80%

Note that the remaining 11 projects may have received some public funding, but data were difficult to find and may be unavailable. The average percentage of the GDH projects financed through grant funding across all 23 projects is 31%. The average percentage of the GDH projects financed through grant funding across the 12 projects that have been verified to have received grant funding is 60%.

The percentages of grant funding for the GDH projects in the United States are comparable to the percentages of grant funding for recent GDH projects in Europe, which range from 19% to 80% of total project capital costs (Table 7).

**Table 7.** Capital Costs of GDH Systems and Amount of Grant Funding for Recent GDH Installations in Europe

Sources: GeoDH (2014a; 2014b) and ThinkGeoEnergy (2018a; 2018b; 2020a; 2020b; 2020c)

Project Location	Project Description	Project Status	Capital Cost	Grant Funding
Portugal	Small GDH for 25 buildings	Planned	€850K	€680K (80%)
Hungary	2.5 MW GDH	Operational	€1.43M	€0.85M (59%)
Germany	Development of geothermal well field to supply existing GDH	Under construction	€15.9M (for wells)	€9.2M (58%)
France	GDH system with 5-km district heating network	Operational	€9.7M	€5.35M (55%)
Romania	Expansion of existing GDH system	Planned	€19M (for GDH expansion)	€4M (21%)
Belgium	Development of smart heat grid with geothermal for campus heating	Under construction	€40M	€7.5M (19%)
Denmark	GDH system for 5,016 inhabitants	Operational	€12M	€2.3M (19%)

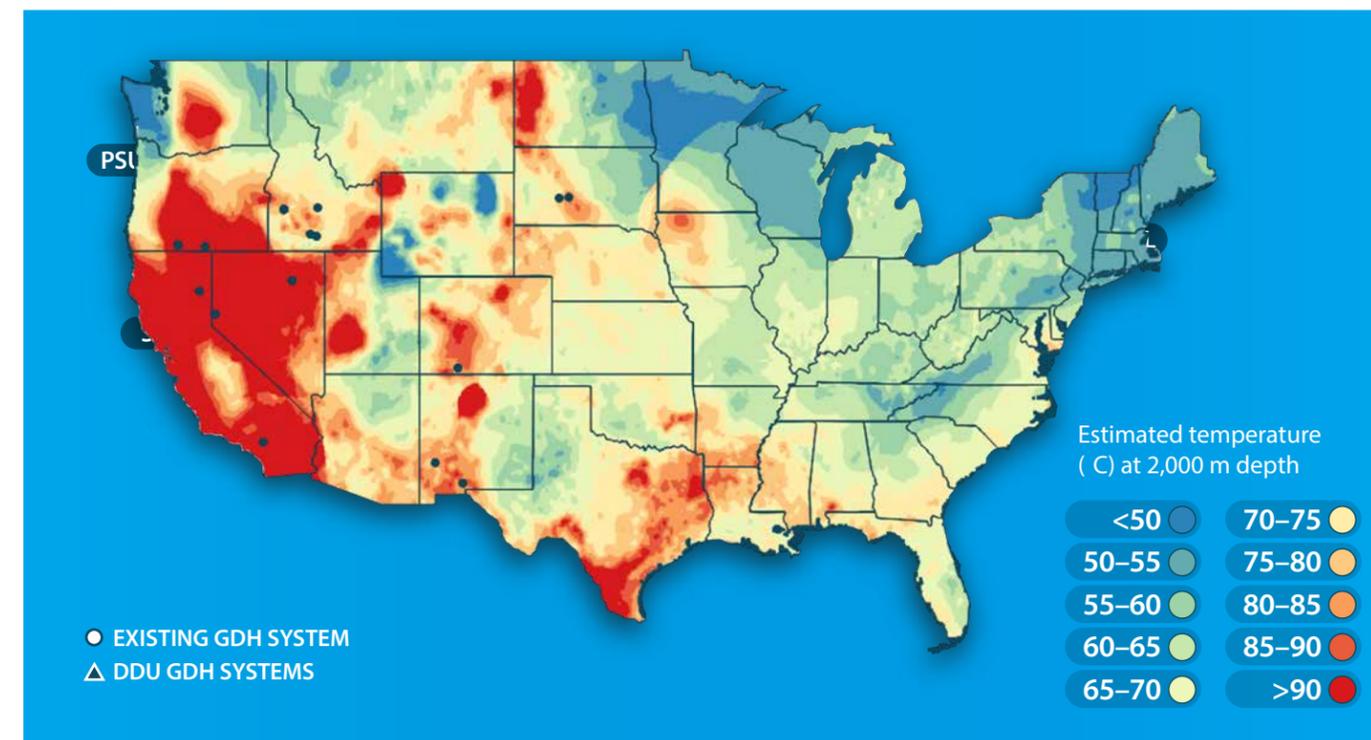
## 4.5 Developing Projects

### 4.5.1 Projects in Development

In 2017, DOE awarded approximately \$4 million of funding for geothermal deep direct-use (DDU) feasibility studies, with the objective of significantly expanding the reach of geothermal direct use outside of the western U.S. high subsurface heat flow region (Figure 30). As opposed to conventional direct use, DDU allows for development in regions with lower geothermal gradients (e.g., in the eastern United States), where deeper drilling depths are required to reach the same target temperatures (DOE 2017). Six teams were awarded funding to study large-scale low-temperature geothermal systems with annual thermal demand ranging from 2 GWh to almost 300 GWh per year. The awardees—Cornell University, NREL, Portland State University, Sandia National Laboratories,

University of Illinois, and West Virginia University—each led a team with a range of partners, who shared the cost of performing the feasibility analyses with DOE. Four out of the six projects evaluated GDH systems (Garapati and Hause 2020; Lin et al. 2019; Lowry et al. 2020; and Tester et al. 2019). The remaining two projects evaluated DDU for cooling (Turchi et al. 2020) and for thermal energy storage (TES) (Bershaw et al. 2020).

In July 2020, Cornell University was selected for a follow-on grant award from DOE to fund a deep exploratory borehole in Ithaca, New York. This borehole is intended to verify the feasibility of using deep geothermal energy for a campus GDH system that would employ innovative technologies combining heat pumps with an existing district energy infrastructure. If successful, the project could demonstrate that GDH technologies are applicable in much of the northeastern



**Figure 30.** Location of existing GDH systems and DDU projects overlaying temperature at 2,000 m depth map from Mullane et al. (2016). Locations are identified by project team leads (details on DDU teams below).

DDU projects were led by Portland State University (PSU); Sandia National Laboratories (Sandia) for Hawthorne, NV; National Renewable Energy Laboratory for E. Texas (NREL); University of Illinois (UIUC); West Virginia University (WVU); and Cornell University (Cornell)

United States (Cornell 2020). In April 2021, West Virginia University was selected to research approaches for using a year-round DDU geothermal system to generate steam for heating and cooling as well as examine the use of shallow reservoirs for TES. The planned 2027 closure of the existing coal-fired cogeneration plant that supplies steam for the West Virginia University campus’s district heating and cooling system provides the opportunity for this project (NETL 2021).

Another example of an early-stage project in development is in Cascade, Idaho. The city of Cascade has conducted feasibility studies, geophysical surveys, and other studies to evaluate the

possibility of utilizing shallow, low-temperature geothermal fluids for district heating, greenhouses, and other direct-use applications. The city currently uses its low-temperature geothermal resource of 41°C to heat an aquatic center. An existing geothermal well was originally used to heat a no-longer-operational lumber mill, and a second geothermal well heats the local school. The city is currently seeking partners and/or other sources of funding to offset the high capital costs of the project (personal communication with Scott Davenport, local business owner).

## 4.5.2 Barriers to GDH Development

A number of publications have been written in the past two decades on barriers to geothermal direct use in the United States, including Fleischmann (2007), Thorsteinsson (2008), Thorsteinsson and Tester (2010), and Snyder et al. (2017). The 2019 *GeoVision* study summarized the key barriers to GDH development as:

1. **Policy/market barriers**, including:
  - A. Competition from currently cheap alternative heating sources, especially natural gas
  - B. Lack of federal or state government incentives, such as subsidies or tax credits, in comparison with other countries or even with other renewable energy technologies
  - C. Absence of geothermal professionals, consultants, and businesses as well as the aging of the current geothermal workforce.
2. **Social-acceptance barriers**, including a lack of public involvement and knowledge of geothermal energy, which can be compounded by perceptions of high cost and risk by local authorities and the public.
3. **Technical barriers**, such as:
  - A. Limited co-location of high-grade geothermal resources (predominantly occurring in the western United States) and high heat demand (mainly in the eastern United States)
  - B. Large diversity in heating/cooling systems in the United States, which complicates and increases the costs of the retrofitting process
  - C. High upfront project costs because of expensive geothermal well drilling, which is exacerbated by relatively high exploration risks.

Currently, geothermal heating and cooling technologies in the United States do not benefit from the carbon accounting mechanisms in place in a number of states, such as emissions trading or renewable portfolio standards (RPS). A lack of a workable and clear set of accounting rules may be a barrier to deploying GDH (Zabeti et al. 2018).

Another challenge to GDH deployment concerns the financing and development of new heat grid infrastructures. Retrofitting is an alternative for developing the GDH market; however, there is a relative lack of district energy infrastructure in the

United States compared to European and Asian countries (GeoDH 2014c). Where district energy infrastructure exists in the United States, it is often steam-based, meaning that expensive retrofitting would be required for a hot-water-based distribution system for a geothermal supply. Additional barriers to GDH development include permitting issues, the need for expensive federal well-metering equipment, and royalties (Witcher et al. 2002; Fleischmann 2007).

## 4.6 Future Opportunities

From a technical and economic resource perspective, there is vast potential to rapidly deploy GDH in many parts of the United States (Mullane et al. 2016; McCabe et al. 2019). However, the U.S. GDH sector has been relatively stagnant since the 1980s, with only four new installations over the past two decades. Despite the lack of growth in the GDH sector between 2000 and 2020, there may be reasons to expect growth in the future. The following subsections point out current research or market developments that could have a positive impact on U.S. GDH deployment.

### 4.6.1 2019 *GeoVision* Forecast for Geothermal Direct Use

A task force for the *GeoVision* study (2019) explored the potential role of GDH systems in meeting current and future energy demands in the contiguous United States (McCabe et al. 2019). The Thermal Task Force developed a Distributed Geothermal Market Demand Model (dGeo) to simulate the technical, economic, and market potential for deployment of GDH systems in the residential and commercial sectors through 2050. Two scenarios were considered: a BAU scenario assuming status quo, and a TI scenario assuming significant technology advancements resulting in lower drilling and exploration costs, lower discount rates, and higher well flow rates. For known hydrothermal resources, dGeo estimated a technical, economic, and market potential of 27,000 MWth, 2,800 MWth, and 1,000 MWth in the BAU scenario and 27,000 MWth, 4,600 MWth, and 1,600 MWth in the TI scenario. When including EGS resources and technologies for district heating, the corresponding values were up to two orders of magnitude higher.

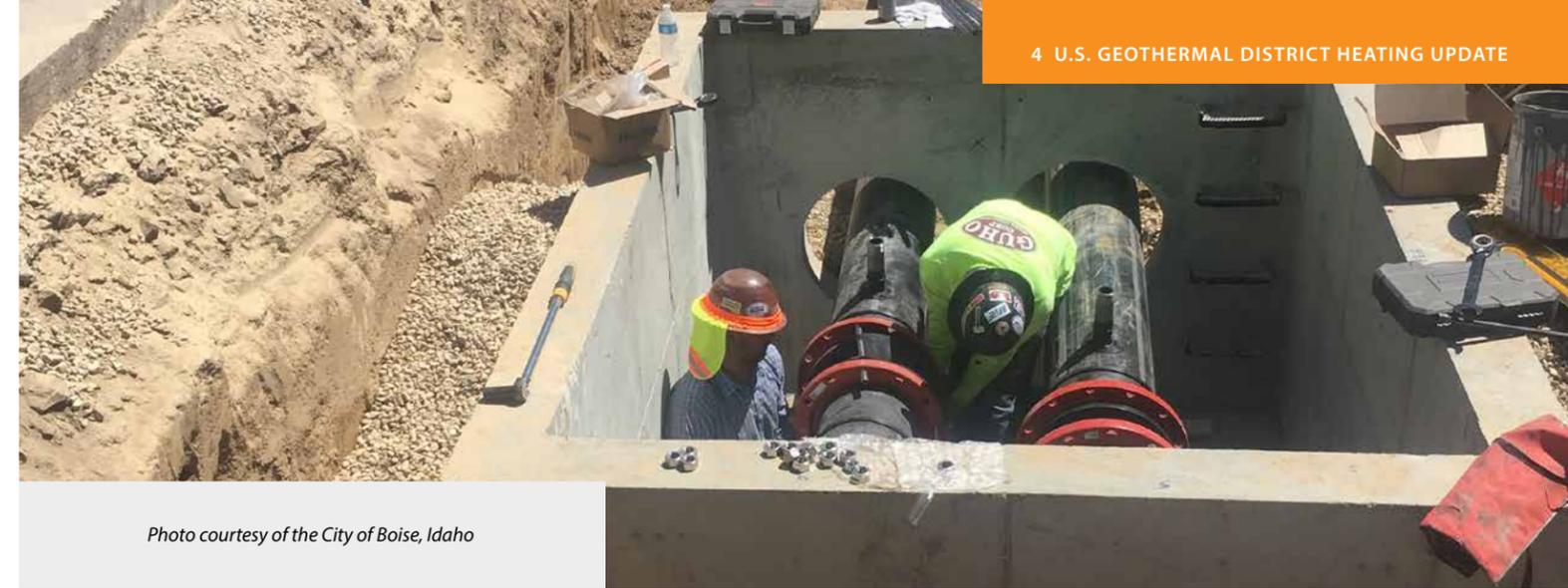


Photo courtesy of the City of Boise, Idaho

### 4.6.2 Decarbonizing the U.S. Heating and Cooling Sector

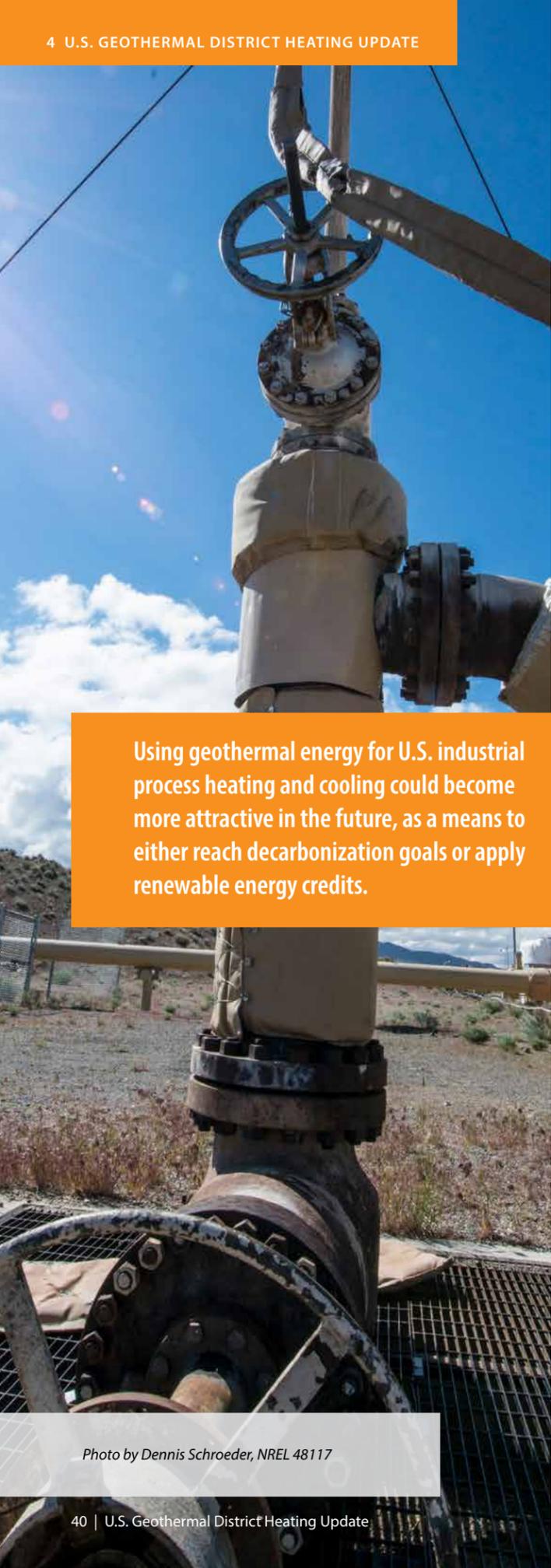
Heating and cooling account for more than 25% of total U.S. energy use across residential, commercial, and industrial sectors at an annual cost of \$270 billion. However, the use of renewable energy for heating and cooling applications has received relatively little attention compared with renewable electricity (RTC 2020). Relatedly, although greenhouse gas emission reduction accounting for the use of renewable electricity is currently well-defined, this is not the case for

Heating and cooling account for more than 25% of total U.S. energy use across residential, commercial, and industrial sectors at an annual cost of \$270 billion.

renewable heating and cooling (Zabeti et al. 2018). To meet the aggressive carbon reduction goals outlined by the Biden Administration as well as enacted by several states (White House 2021, C2ES 2020), decarbonization in the heating and cooling sector will be a critical implementation pathway. Within this space, GDH systems can play a key role in this transformation by providing low-carbon heating and cooling to entire communities and cities in support of achieving federal, state, and local decarbonization targets while also improving building energy efficiency and slashing peak electricity demand to significantly aid in rapid decarbonization scenarios. Perhaps demonstrating this potential, corporations like Microsoft and Google are installing district heating and cooling systems in their new offices (Peters 2017, Ho 2021).

### 4.6.3 University and College Campuses: Decarbonization Goals

University and college campuses are currently leading the charge in pursuit of low-carbon district energy options as a result of aggressive greenhouse gas emission reduction goals (often 100%) within the next 15 to 30 years. With many of the campus emission reduction goals nearing their intermediate 2020 and 2025 targets, campuses are actively seeking low-carbon solutions for their campus energy needs. For example, Cornell University has included GDH (called “Earth Source Heat”) in their campus’s Climate Action Plan since 2009 as a potential means of moving toward carbon neutrality on campus by eliminating fossil fuels for campus heating (Cornell 2020). The project would help eliminate Cornell’s carbon footprint while demonstrating GDH feasibility in the northeastern United States. As mentioned, for West Virginia University, the 2027 planned closure of the existing coal-fired cogeneration plant that supplies steam for the campus’s district heating and cooling system provides an opportunity to convert to a year-round DDU geothermal system as well as to examine the use of shallow reservoirs for TES. As of 2020, more than 650 university and college campuses have signed onto the Climate Leadership Network’s Carbon Commitment, Resilience Commitment, or Climate Commitment (Second Nature 2020). Many college and university campuses—such as Princeton University, Ball State University, Carleton College, and others—are currently installing or expanding district energy systems powered by geothermal heat pumps as part of their decarbonization strategies.



Using geothermal energy for U.S. industrial process heating and cooling could become more attractive in the future, as a means to either reach decarbonization goals or apply renewable energy credits.

Photo by Dennis Schroeder, NREL 48117

### 4.6.4 Industrial Process Heating Sector

Fourteen countries use deep geothermal resources for industrial process heat, led by China, New Zealand, Iceland, Russia, and Hungary (Lund and Toth 2020). The market opportunity is enormous: a Sankey diagram in Figure 31 shows that manufacturing process energy totaled about 10.4 quads in 2010, with 4.4 quads of energy losses upstream as a result of electricity generation, bringing the total process energy requirement to about 15.3 quads (1 quad = 1,000 trillion BTU or 10<sup>15</sup> BTU). Of this total, approximately 7.2 quads of energy were used for process heating, and 0.35 quads of energy were used for process cooling and refrigeration. This combined sector (more than half the process energy needs in 2010) is a large market opportunity for geothermal energy that would leverage proven heating and cooling technologies (for more information about geothermal technologies for cooling, see Section 6.8). In the manufacturing industry, for example, a significant amount of the final energy demand is in providing heating and cooling to processes and buildings (Zabeti et al. 2018).

Despite the many potential industrial uses of geothermal energy, the number of worldwide applications is relatively small (Lienau and Lund 1987). Using geothermal energy for U.S. industrial process heating and cooling could become more attractive in the future, as a means to either reach decarbonization goals or apply renewable energy credits.

### 4.6.5 Hybridizing GDH with Subsurface Thermal Energy Storage

The DDU project at Portland State University evaluated the feasibility of using a shallow subsurface reservoir for seasonal storage of solar thermal heat, with heat distributed to a hospital campus in winter months (Bershaw et al. 2020). The Portland State University reservoir TES system would deliver about 600 MWh of stored heat and cost about \$1.5 million (for more information on underground TES technology, see Section 6.6). Successful implementation of a combined GDH and underground TES system would expand and diversify the GDH paradigm in the United States, allowing the technology to enter into the rapidly expanding energy storage sector.

Successful implementation of a combined GDH and underground TES system would expand and diversify the GDH paradigm in the United States.

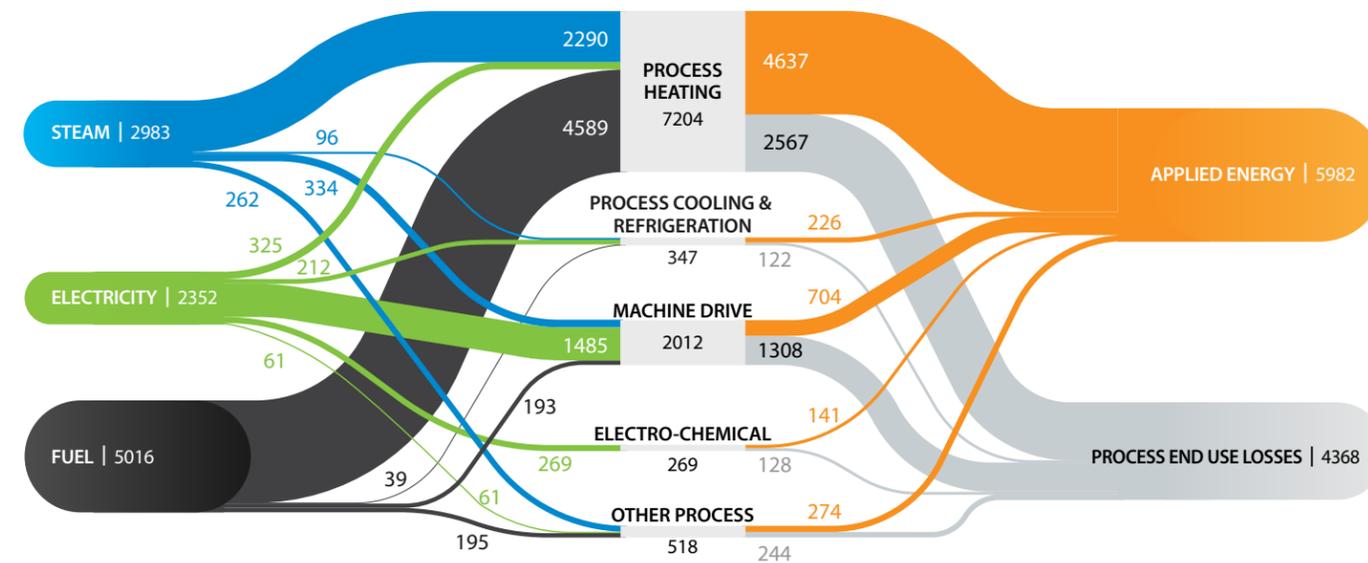


Figure 31. Sankey diagram for process energy flow in the U.S. manufacturing sector (as of 2019). Energy numbers are reported in quads (1 quad = 1,000 trillion BTU or 10<sup>15</sup> BTU).

Figure adapted from AMO (2019)



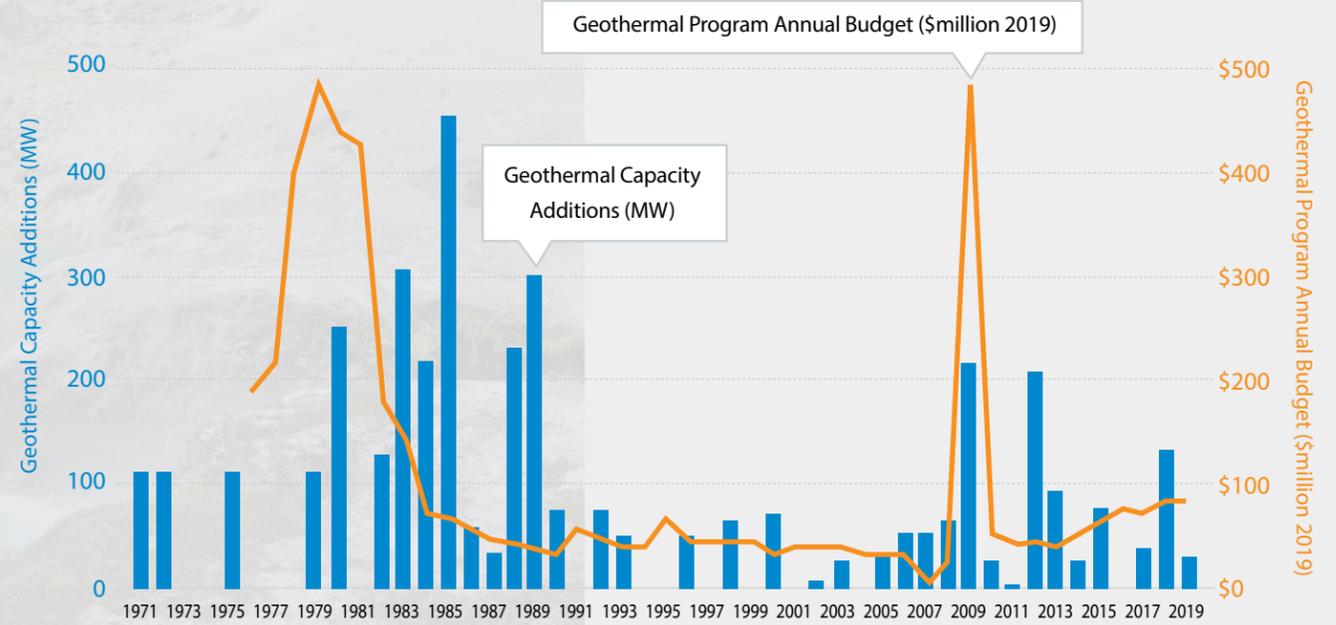
Photo by Dennis Schroeder, NREL 48302

# 5 State and Federal Policies

## 5.1 Federal Policy

This section examines in detail the policies and programs enacted since 1970 and their relationship to the expansion of the geothermal fleet in the United States.

The United States has experienced two periods of robust federal support for geothermal exploration and development. The first period occurred from the late 1970s into the early 1980s. The second wave of support was part of the American Recovery and Reinvestment Act of 2009. Figure 32 shows that during and shortly after both periods, the amount of geothermal capacity additions increased significantly compared to other years. Such correlation between support and deployment does not necessarily establish causality. This section examines in detail the policies and programs enacted since 1970 and their relationship to the expansion of the geothermal fleet in the United States.



**Figure 32.** Overlay of DOE's Geothermal Program Annual Budget and the geothermal capacity added annually in the United States

Photo by Dennis Schroeder, NREL 48144

### 5.1.1 Geothermal Steam Act of 1970

More than 40% of U.S. geothermal electricity capacity is located on leases issued by the Bureau of Land Management (BLM) (U.S. Department of the Interior 2018). Therefore, policies that regulate the leasing of federal lands are important for the geothermal industry. The Geothermal Steam Act of 1970 (30 U.S.C. § 23) governs the leasing of federal lands for geothermal resources. Under the Geothermal Steam Act (as amended), parties interested in leasing BLM lands for geothermal exploration and production can submit their nominations, and the BLM is mandated to hold a competitive auction at least once every two years. The Act also simplifies the calculation of royalties by allowing the payment of royalties based on a percentage of the value of production instead of the price of natural gas (United States Government Accountability Office 2006).

**At the time PURPA was passed into law, natural gas prices in the United States were high and trending upward. In the 10 years following the signing of PURPA, 2,086 MW of geothermal energy was installed.**

### 5.1.2 Public Utilities Regulatory Policies Act

In 1978, Congress enacted the Public Utilities Regulatory Policies Act (PURPA) (16 U.S.C. §46), which requires utilities to purchase power from small power plants at avoided cost rates. Avoided costs are the operational costs, such as fuel and maintenance, that the utility avoids by not producing the energy bought from plants that qualify under PURPA. This way, the utility does not spend more money buying energy from these plants than by producing it itself. PURPA opened the electricity market—which until that point had been regulated as a monopoly—to independent power producers (Francisco Flores-Espino 2016). PURPA also provided certainty for investors because it set the rate at which producers had to be compensated. At the time PURPA was passed into law, natural gas prices in the United States were high and trending upward. In the 10 years following the signing of PURPA, 2,086 MW of geothermal energy was installed—more than half of

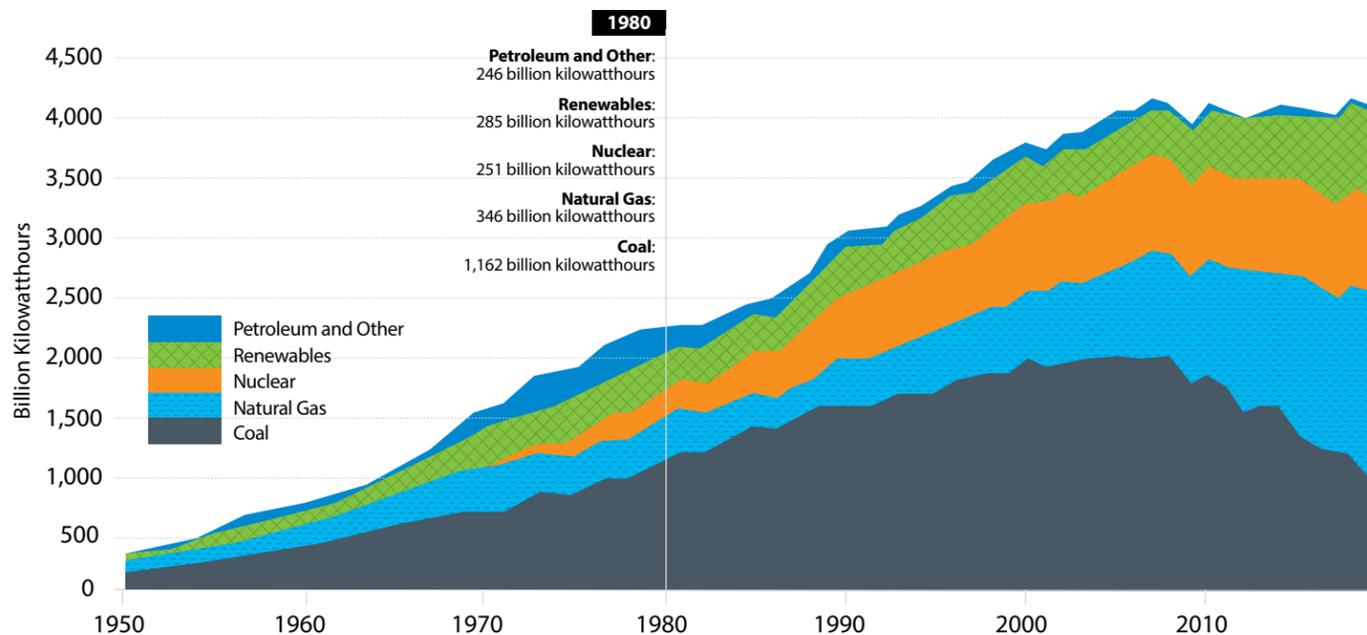


Photo from iStockphoto, 1297974434

the currently installed nameplate capacity in the United States. This period started with a sharp increase in natural gas prices that peaked in 1983 and ended with a similarly steep decline in prices. Natural gas plants only produced 10% to 18% of the total electricity produced in the United States during this time, but they were instrumental in setting the avoided cost because natural gas was used in peaking plants during hours of high demand (U.S. EIA 2020b).

PURPA, relatively high natural gas prices, government-sponsored geothermal resource studies, and other forms of government support helped the geothermal industry expand outside of California and into Nevada and Utah (Fleischmann 2007). PURPA's benefits that led to the installation of new independent power plants dwindled in the 1990s due to lower natural gas prices. In 1990, natural gas prices had fallen by 60% from the peak in 1983, and federal funding for geothermal projects was 10% of its peak in 1979. In the 15 years from 1990–2004, 403 MW of geothermal capacity came online.

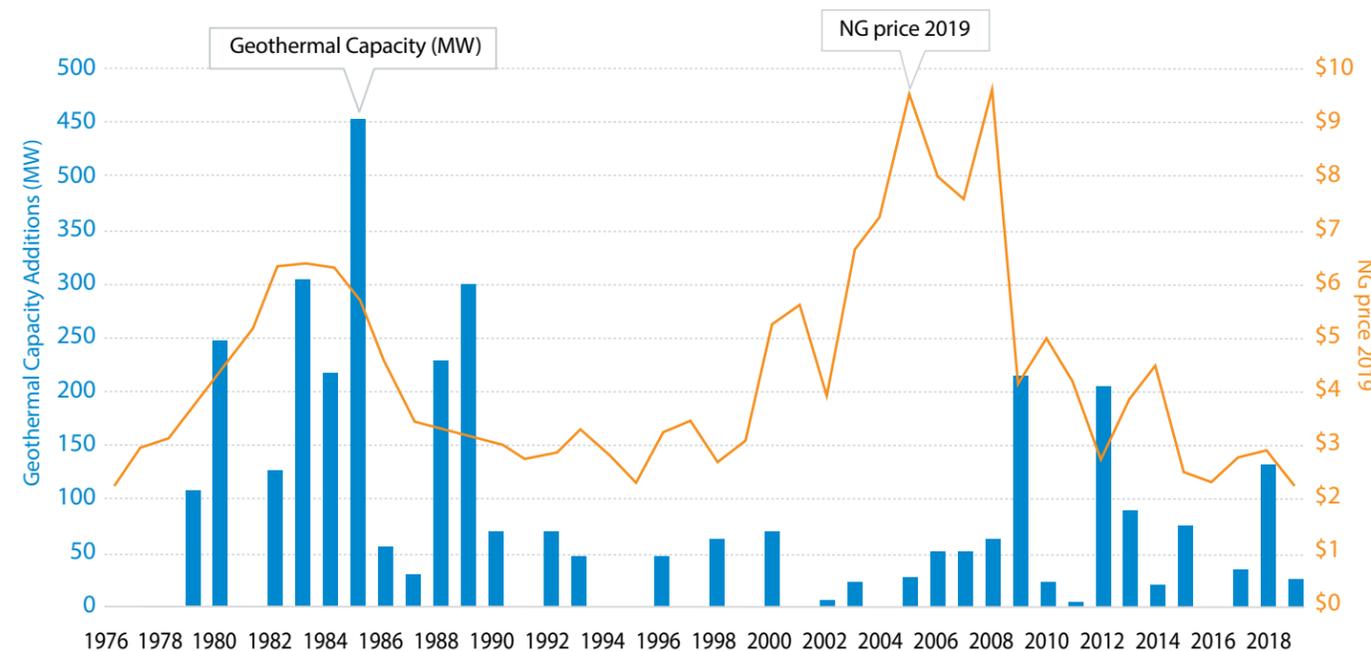
This period also coincided with an increased federal budget for geothermal activities, financial support, and programs.



Note: Electricity generation from utility-scale facilities. Source: U.S. Energy Information Administration, Monthly Energy Review, Table 7.2a, March 2020 and Electric Power Monthly, February 2020, preliminary data for 2019

**Figure 33.** U.S. electricity generation by major energy source, 1950–2019

Source: EIA (2020b)



**Figure 34.** Overlay of annual geothermal capacity additions in MW and natural gas prices in the United States (Henry Hub spot price)

Source: EIA (2021b)

### 5.1.3 Investment Tax Credit

The Energy Tax Act of 1978 (26 U.S.C. § 1) created the investment tax credit (ITC). The ITC initially provided tax incentives for energy conservation and sources of energy alternatives to oil and gas. Congress instituted the ITC to address public awareness of environmental pollution as well as the energy crisis brought about by the oil embargo of 1973 and the oil supply problems during the Iranian revolution in 1978 and 1979 (Lazzari 2008; Mormann 2016). The Act introduced accounting norms beneficial to the geothermal industry. For example, the ITC introduced the option to deduct intangible drilling costs (McDonald 1979).

**The Energy Tax Act of 1978 (26 U.S.C. § 1) created the investment tax credit (ITC). The ITC initially provided tax incentives for energy conservation and sources of energy alternatives to oil and gas.**

The Windfall Profit Tax Act of 1980 (26 U.S.C. § 1) increased the ITC from 10% to 15% for geothermal, solar, and wind, and also expanded the credit to more energy resources. The Tax Reform Act of 1986 (26 U.S.C. § 1) extended the ITC for solar and geothermal, but phased it down to 10% and set an expiration date of December 31, 1988.

The ITC was extended at the same level for geothermal for relatively short periods through the Miscellaneous Revenue Act of 1988 (26 U.S.C. § 1), the Omnibus Budget Reconciliation Act of 1989, the Omnibus Budget Reconciliation Act of 1990 (Pub. L. 101-508), and the Tax Extension Act of 1991 (26 U.S.C. § 1) (Sherlock 2018). In 1992, Congress passed the Energy Policy Act of 1992 (42 U.S.C. § 13201), which made the ITC permanent for solar and geothermal at a rate of 10% (Lund and Bloomquist 2012). The Energy Policy Act of 2005 (42 U.S.C. § 15801) increased the credit to 30% for solar, but not for geothermal.

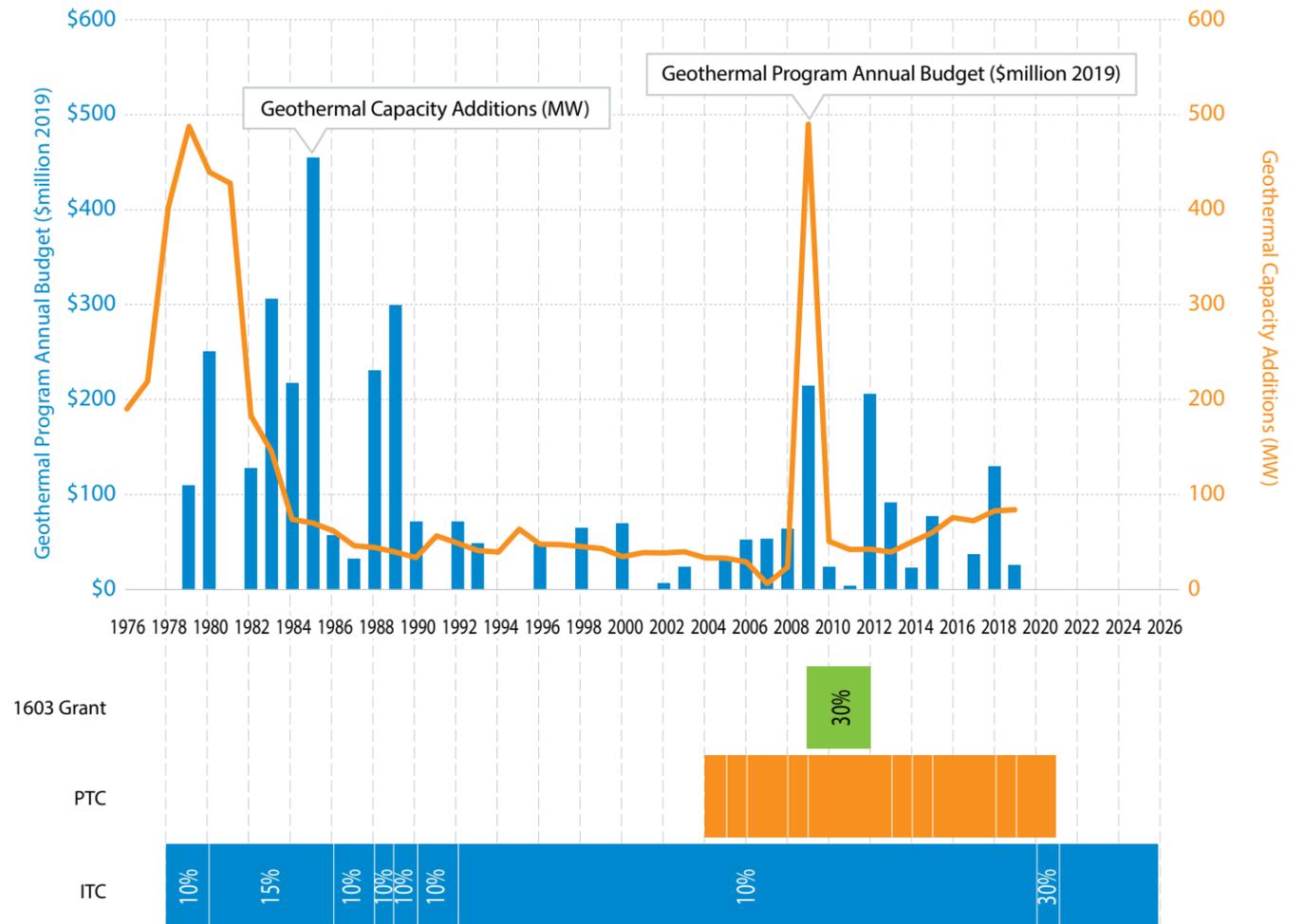
The American Recovery and Reinvestment Act (Recovery Act) of 2009 (Pub. L. 111-5) introduced the 1603 Cash Grant program. The Recovery Act kept the ITC rate at 10% for geothermal but allowed geothermal developers to claim a

30% cash grant in lieu of the Production Tax Credit (PTC) under section 1603 of the Recovery Act (the PTC is covered in Section 5.1.4). The 1603 Cash Grant program closed for applications at the end of 2011, and had an in-service requirement date of January 1, 2014 (Brown and Sherlock 2011).

Coronavirus Aid, Relief, and Economic Security Act (CARES Act) of 2020 (42 U.S. Code § 801) kept the ITC at 10% for geothermal but retroactively extended the PTC, which had expired in 2017, for projects for which construction began before January 1, 2021.

The Act allows taxpayers to elect the ITC, in lieu of the PTC, at a rate of 30% (Eliason, Weisblat, and Roessler 2020). Both the Recovery Act and the CARES Act allowed geothermal to claim either a 10% ITC or a 30% ITC, which may be counterintuitive at first glance. However, removing geothermal from qualification for the 10% ITC would have required an act of Congress to reinstate it after the 30% ITC qualification expired, which would have introduced an unnecessary risk for the industry. The Energy Act of 2020, authorized by the Consolidated Appropriations Act of 2021 (Pub. L. 116-260), extended the ITC for geothermal heat pumps through 2024 (KPMG 2020).

On the top, Figure 36 shows the comparison between geothermal power capacity additions in MW and the annual budget of DOE's geothermal program. On the bottom, a timeline shows the periods in which geothermal has been eligible for the ITC (in blue), the PTC (in yellow), and the 1603 Cash Grant. The vertical lines within the ITC and PTC bars represent the years in which the tax credit was renewed. Additionally, the ITC shows the different levels of tax break that geothermal developers were able to apply during different periods. Also, while the nominal value of the PTC has changed over time due to inflation adjustments, its actual value to developers has remained the same.



**Figure 35.** Timeline showing coincident annual data for (1) federal funding for geothermal programs (top, orange), (2) gross geothermal additions in MW (top, blue), and three federal incentives: (3) the investment tax credit as a percent of capital expenditures (blue, bottom), (4) the production tax credit (orange, bottom), and (5) the 1603 Cash Grant program (green, bottom)

### 5.1.4 Production Tax Credit

The Energy Policy Act of 1992 originally created the PTC to offer eligible wind plants tax credits in proportion to their electricity output during their first 10 years of operation. The credit originally was equivalent to \$15 per MWh of electricity, indexed to inflation, and did not include geothermal

(Mormann 2016). The American Jobs Creation Act of 2004 (Pub. L. 108–357) made geothermal energy and other qualifying resources eligible for the PTC, but only for the first 5 years of operation. The Energy Policy Act of 2005 enabled geothermal to receive credits for 10 years. Since then, the PTC has been renewed after lapsing eight times, as shown in Table 8 (Sherlock 2020).

**Table 8.** Renewable Electricity PTC Expirations and Extensions

Source: Sherlock (2020)

Legislation	Date Enacted	PTC Eligibility Window	Lapse Before Extension?
Energy Policy Act of 1992 (P.L. 102-486)	10/24/1992	1/1/1993-6/30/1999 (closed-loop biomass) 1/1/1994-6/30/1999 (wind)	—
Ticket to Work and Work Incentives Improvement Act of 1999 (P.L. 106-170)	12/17/1999	7/1/1999-12/31/2001	Yes 7/1/1999-12/17/1999
Job Creation and Worker Assistance Act (P.L. 107-147)	3/9/2002	1/1/2002-12/31/2003	Yes 1/1/2002-3/9/2002
Working Families and Tax Relief Act (P.L. 108-311)	10/4/2004	1/1/2004-12/31/2005	Yes 1/1/2004-10/4/2004
The Energy Policy Act of 2005 (P.L. 109-58)	8/8/2005	1/1/2006-12/31/2007	No
The Tax Relief and Health Care Act of 2006 (P.L. 109-432)	12/20/2006	1/1/2008-12/31/2008	No
The Emergency Economic Stabilization Act of 2008 (P.L. 110-343)	10/3/2008	1/1/2009-12/31/2010 10/3/2008-12/31/2011 (marine and hydrokinetic) 1/1/2009-12/31/2009 (wind)	No
The American Recovery and Reinvestment Act of 2009 (P.L. 111-5)	2/17/2009	1/1/2011-12/31/2013 1/1/2010-12/31/2012 (wind)	No
The American Taxpayer Relief Act of 2012 (P.L. 112-240)	1/2/2013	1/1/2013-12/31/2013 (wind)	No <sup>a</sup>
Tax Increase Prevention Act of 2014 (P.L. 113-295)	12/19/2014	1/1/2014-12/31/2014	Yes 1/1/2014-12/19/2014
Consolidated Appropriations Act, 2016 (P.L. 114-113)	12/18/2015	1/1/2015-12/31/2016 1/1/2015-12/31/2019 (wind) <sup>b</sup>	Yes 1/1/2015-12/18/2015
Bipartisan Budget Act of 2018 (P.L. 115-123)	2/9/2018	1/1/2017-12/31/2017	Yes 1/1/2017-2/9/2018 <sup>c</sup>
Further Consolidated Appropriations Act of 2020 (P.L. 116-94)	12/20/2019	1/1/2018-12/31/2020 <sup>d</sup>	Yes 1/1/2018/-12/20/2019

**Source:** Information compiled by CRS using the Legislative Information System (LIS).

**Notes:** For all lapse periods, the PTC was retroactively extended. See text for full details on qualifying technologies during different time periods.

- a. The PTC expired in January 1, 2013, before being extended on January 2, 2013.
- b. For wind facilities beginning construction in 2017, the credit is reduced by 20%. The credit is reduced by 40% for facilities beginning construction in 2018, and reduced by 60% for facilities beginning construction in 2019.
- c. The extension was fully retroactive, in that the extension only covered a time period prior to the extension's date of enactment.
- d. For wind facilities beginning construction in 2020, the credit is reduced by 40%.

In 2009, the Recovery Act extended the deadline to place projects in service to the end of 2013 for geothermal plants. The Recovery Act also allowed projects to elect a 30% ITC or Cash Grant, as discussed in the previous section (Holzman, Ciavarella, and Grant 2009). The Further Consolidated Appropriations Act of 2020 (Pub. L. 116-94), signed at the end of 2019, retroactively extended the PTC for 2018 and 2019 for geothermal and other non-wind technologies, which had expired in 2017. The Act also extended the PTC until the end of 2020 (Sherlock 2020).

The amount of the PTC was initially 1.8 cents per kWh. The amount of the credit increases each year for inflation and, as of May 2020, equals 2.5 cents per kWh (Runyon 2020).

### 5.1.5 Depreciation Acceleration and Bonus Depreciation

The Modified Accelerated Cost Recovery System (MACRS) is a depreciation system introduced in the United States by the Tax Reform Act of 1986 (26 U.S.C. § 1). MACRS allows for an accelerated depreciation of qualifying assets. MACRS establishes different depreciation schedules, depending on the type of property, ranging from 3 to 50 years. Geothermal energy projects are eligible for a 5-year depreciation schedule. If the project sponsor elects the ITC, only 85% of the projects depreciable basis can be depreciated (DSIRE 2018a). MACRS is advantageous for energy companies because the total depreciation value of the asset is used for tax deductions sooner, which means that a smaller percentage of that value is lost due to the time value of money.

Bonus depreciation was introduced for the first time to the U.S. Code in 2002 by the Job Creation and Worker Assistance Act (Pub. L. 107-147). Bonus depreciation allows businesses to deduct a large percentage of their qualifying assets in the first year of operation. The bonus depreciation available for geothermal systems has varied between 50% and 100%. The Tax Cuts and Jobs Act of 2017 (Pub. L. 115-97) increased the bonus depreciation percentage from 50% to 100% for qualified property (including geothermal systems) acquired and placed in service between September 27, 2017, and the end of 2020 (Weal 2018).

### 5.1.6 Advantages and Disadvantages of Tax-Based Incentives

Tax-based incentives can significantly lower the net cost of installation for qualifying technologies. The ITC has offered up to 30% of qualifying capital costs in tax credits. The PTC or ITC,

combined with accelerated depreciation, can lower upfront deployment costs by up to approximately 55% (Mendelsohn and Feldman 2013). However, monetizing such incentives can be difficult and expensive, unless the owner has enough tax liability. Many project owners, particularly smaller project developers, do not have adequate tax liability (Bhattacharyya 2020). The options available for project owners that do not have enough tax liability can reduce the value of the credit. One option is to carry forward the unused portion of the credit, which means losing value on that portion of unused credit due to the time value of money.

Another option is to partner with tax equity investors. These are investors with enough tax liability to take advantage of both the credits and the accelerated depreciation, such as large commercial banks. Tax equity investors require a premium over their investments, which diminishes the value of the tax credits and accelerated depreciation to the project owner. Such premiums increase according to the supply and demand and become scarce and more costly in times of economic adversity (Bandyk 2020). The Tax Cuts and Jobs Act of 2017, which reduced corporate tax liability from 35% to 21%, and the economic disruption caused by the coronavirus pandemic could reduce the pool of tax equity investment in the near term (Bhattacharyya 2020). Additionally, structuring a partnership with a tax equity investor can carry additional legal costs.

The 1603 Cash Grant program eliminated some of those barriers by providing an upfront grant that did not require tax liability, as mentioned in Section 5.1.3. This program reduced transaction costs by eliminating the need for tax equity. The payments were typically received within 60 days after application submission, which reduced the amount of value lost due to the time value of money (Brown and Sherlock 2011). A refundable ITC would also eliminate the need for tax equity when claiming the tax credit, but would increase the number of years needed to claim the full credit, thereby reducing the value of the credit.

Another disadvantage of tax-based incentives, particularly the PTC and the ITC, are the frequent cycles of expirations and extensions. This is particularly true for geothermal projects, which require several years from exploration to final commissioning. The PTC, for example, has been allowed to expire five times since its inception and has been renewed numerous times for periods of one or two years (Sherlock 2020). Such short periods do not allow the industry to depend on such incentives for planning purposes and are not helpful to the industry when seeking financing for new plants.

### 5.1.7 Energy Act of 2020

The Consolidated Appropriations Act of 2021, signed in late 2020, included the Energy Act of 2020.<sup>3</sup> The Act is an amalgamation of 37 Senate bills (included totally or partially), and it represents the first comprehensive update to national energy policies since the Energy Independence and Security Act of 2007 (42 U.S.C. § 152) (Senate Committee on Energy and Natural Resources 2020).

The Act extends tax credits for geothermal (see Sections 5.1.3 and 5.1.4), solar, wind, and energy efficiency. It seeks to ease access to federal lands for wind, solar, and geothermal developers; and includes incentives for carbon capture, energy storage, and advanced nuclear power. The bill also directs the Secretary of the Interior to set goals for wind, solar, and geothermal production on federal lands by 2022 and to issue permits for a combined total of 25 GW of nameplate capacity for these same technologies. The Department of the Interior is also required to improve federal permitting coordination for solar, wind, and geothermal projects in federal lands (Senate Committee on Energy and Natural Resources 2020; E&E News 2020; Viola et al. 2021).

Section 3002 of the Act authorizes \$170 million annually for DOE's geothermal research and development activities and modifies the definition of renewable energy in the federal code so that any energy consumption that is avoided through the use of geothermal energy is considered to be renewable energy produced (Viola et al. 2021). Research and development activities considered in the bill include advanced hydrothermal resource tools, demonstration projects in conjunction with the private industry, innovative environmental impact mitigation, reservoir TES, oil and gas technology transfer, co-production of geothermal energy and minerals, flexible operation of geothermal power plants, and the integration of geothermal power plants with other forms of energy generation and storage (Consolidated Appropriations Act 2021).

The Act authorizes up to two new Frontier Observatory for Research in Geothermal Energy (FORGE) EGS study sites, allows for the Utah FORGE site to be extended for additional years, and expands EGS and hydrothermal research and development. The Act directs the U.S. Geological Survey

to update its geothermal resource assessment by taking advantage of modern surveying techniques, with a special focus on geological formations that may also contain valuable minerals or could serve as long-duration energy storage sites (Consolidated Appropriations Act 2021).

The Act also creates a new program that intersects the Office of Fossil Energy and GTO to assist in the transfer of knowledge and techniques from the oil and gas sector to the geothermal industry. In addition, it directs the new program to investigate alternative technologies that could co-locate with geothermal development, such as minerals recovery, energy storage, and desalination (Consolidated Appropriations Act 2021).

The Act adds thermal energy to the existing definition of renewable energy in federal code, which would include geothermal direct uses and ground-source heat pumps (Consolidated Appropriations Act 2021).

## 5.2 Federal Programs

As mentioned, the two periods of robust federal support for geothermal exploration and development occurred (1) from the late 1970s into the early 1980s, and (2) as part of the American Recovery and Reinvestment Act of 2009.

Beginning in the 1970s, specific federal programs were established that benefitted geothermal power and direct-use projects. Four programs were established during this period: the Geothermal Loan Guarantee Program (GLGP, 1974), which established the first federal loan guarantee program for geothermal projects; the Program Research Development Announcement (PRDA; 1976), which provided grants for direct-use geothermal projects; the Program Opportunity Notices (PONs, 1977), which provided cost-share grants and other incentives that resulted in the development of 23 geothermal power and direct use projects between 1977 and 1978; and the User-Coupled Confirmation Drilling Program (UCDP, 1980), a cost-sharing grant program that provided government cost-share at 20% if the project was successful in the confirmation of geothermal resources and 90% if not—thus lowering exploration drilling risks. All of these programs were phased out by the mid-1980s (Sander 2012; Lund and Bloomquist 2012). Details on these programs are provided in the following subsections.

### 5.2.1 Geothermal Loan Guarantee Program

In 1974, the Geothermal Energy Research Development and Demonstration Act (30 U.S.C. § 24) established the first federal loan guarantee program for geothermal energy projects. The program benefited both electrical generation projects and direct-use applications. Additionally, loans could be used for resource evaluation, research and development, resource rights acquisition, and the construction and operation of energy facilities (Bank of Montreal (California) and Merrill Lynch, Pierce, Fenner & Smith, Inc. 1977). The program provided a loan guarantee of up to 75% of project costs and up to \$100 million per project. A single applicant could not receive more than \$200 million in loans. In case of default, the federal government guaranteed 100% of the amount of the loan (Lund and Bloomquist 2012). This program ended during the 1980s due to the cessation of appropriated funds from Congress (Bloomquist 2005).

### 5.2.2 Program Research Development Announcement

In 1976, the federal Program Research Development Announcement (PRDA) began to provide grants of between \$100,000 and \$125,000 for direct-use geothermal projects. The funds could be used by developers to complete engineering and economic feasibility studies, mainly for industrial and agricultural processes that used moderate- to low-temperature heat. Accepted applications included space, water, and soil heating; grain drying; irrigation pumping; and district heating and cooling (Sander 2012; Lund and Bloomquist 2012).

### 5.2.3 Program Opportunity Notices

Program Opportunity Notices (PONs) were cost-share grants offered by DOE that primarily provided incentives for direct-use projects, although one geothermal power project did receive funding from the program (Speer et al. 2014). Accepted applications included space and water heating and cooling as well as other agricultural and industrial processes. In total, 23 projects were funded between 1977 and the end of the program in 1978 (Lund and Bloomquist 2012).



**Figure 36.** Locations of the 23 PON projects

Source: Lund and Bloomquist (2012)

<sup>3</sup> For the full text of the bill, see: <https://rules.house.gov/sites/democrats.rules.house.gov/files/BILLS-116HR133SA-RCP-116-68.pdf>.

## 5.2.4 User-Coupled Confirmation Drilling Program

In 1980, DOE initiated the User-Coupled Confirmation Drilling Program (UCDP) cost-sharing grant program. This program was designed to financially assist geothermal power developers in the initial stages of confirming hydrothermal reservoirs. The cost-share level was 20% from UCDP if the project was successful in the confirmation of geothermal resources, and 90% from UCDP if not, with the developer paying 80% or 10%, respectively. UCDP was similar to a loan guarantee in that the government absorbed most of the financial losses from unsuccessful exploration efforts and thus lowered drillers' exploration risk. The funds could be used for drilling exploration wells, flow testing, reservoir engineering, and drilling injection wells. Funds were limited to \$3 million per application (Speer et al. 2014; Lund and Bloomquist 2012).

## 5.3 Policy at the State Level

### 5.3.1 Renewable Portfolio Standards

RPSs support geothermal development by requiring a certain amount of electricity sold by utilities to come from renewable energy sources. This creates a market for eligible technologies. Thirty states and Washington, D.C., have mandatory RPSs. Out of these states and D.C., 27 have established geothermal power as an eligible technology. Indiana also counts geothermal power toward compliance, but the RPS in this state is not mandatory. Thirteen states and D.C. count thermal technologies toward RPS compliance. Out of these jurisdictions, seven explicitly mention geothermal heat (i.e., direct use) as an eligible technology. In two of those jurisdictions, the RPS is voluntary. Although historically most of the growth associated with RPSs has benefitted wind and solar, RPSs with a 100% target may increase the demand for sources of renewable energy that are not variable, such as geothermal (Heeter et al. 2019). Currently, six states and D.C. have an RPS of 100%.

While most RPS programs are guided by generation goals, some use capacity goals, which can disadvantage baseload renewables like geothermal. However, some states use RPS multipliers to support the development of certain generation sources (GeoVision 2019). Additionally, utilities may pay financial incentives in exchange for the clean attributes associated with the generation of electricity through renewable sources.

Table 9 shows all the states that have established RPSs, both mandatory and voluntary, and also which states allow geothermal electric and/or thermal energy to count toward compliance. The "Power" column indicates whether geothermal power is eligible for compliance. The "Thermal Equivalent" column indicates whether the states have a mechanism to allow for heat-based technologies to count toward compliance. "Y" in that column means that the heat component of geothermal, including direct use, is eligible for compliance, "Heat pumps" means that only heat pumps are allowed, but not direct use, and "N" means that neither is eligible.

### 5.3.2 Relevant State-Level Incentives

States also offer other financial incentives, mainly through the provision of tax credits and grants. The following list is not meant to be comprehensive, but representative of the state-level incentives that are applicable to geothermal deployment. A comprehensive list would require resources outside of the scope of this project.

- Alaska offers the Renewable Energy Fund Grant, which provides up to \$2 million per project and requires cost-sharing. Eligible technologies include geothermal power and direct use (Alaska Energy Authority 2021).
- In Arizona, the property tax for renewable energy equipment owned by utilities and other commercial entities is assessed at 20% of its purchase value. Eligible technologies include geothermal power (Robinson + Cole 2020, DSIRE 2021a).
- In Colorado, the Enterprise Zone Refundable Renewable Energy Investment Tax Credit program offers a credit of 3% of the total qualified investment in equipment. Eligible technologies include geothermal power. Enterprise zones are areas with fewer than 115,000 people and 25% unemployment, 25% or less of the average annual growth rate of the state, or a per capita income of less than 75% of the state's average (CO State Auditor 2020).
- In 2008, Idaho enacted legislation to exempt geothermal power producers from paying taxes on real estate, fixtures, or property related to their power plants, and instead pay 3% of their annual earnings (DSIRE 2021b, Robinson + Cole 2020).
- Montana offers a personal tax credit for owners of geothermal systems equal to the cost of the system, up to \$500 per taxpayer. Eligible technologies include power systems, heat pumps, and direct use (DSIRE 2018b).

**Table 9.** RPS Details by State

Data from individual state codes

State	Target	Target Year	Mandatory	Power	Thermal Equivalent
Arizona	15%	2025	Yes	Yes	Y
California	60%	2030	Yes	Yes	
Colorado	30%	2020	Yes	Yes	
Connecticut	44%	2030	Yes	Yes	
Delaware	25%	2026	Yes	Yes	
Hawaii	100%	2045	Yes	Yes	
Illinois	25%	2026	Yes	No	
Indiana	10%	2025	No	Yes	Y
Iowa	105 MW		Yes	No	
Maine	100%	2050	Yes	Yes	
Maryland	50%	2030	Yes	Yes	Y
Massachusetts	35%	2030	Yes	Yes	Y
Michigan	35%	2025	Yes	Yes	
Minnesota	27%	2025	Yes	No	
Missouri	15%	2021	Yes	No	
Montana	15%	2015	Yes	Yes	
Nevada	100%	2050	Yes	Yes	Heat pumps
New Hampshire	25%	2025	Yes	No	Heat pumps
New Jersey	50%	2030	Yes	Yes	
New Mexico	100%	2045	Yes	Yes	
New York	70%	2030	Yes	No	
North Carolina	12.5%	2021	Yes	Yes	Y
Ohio	8.5%	2026	Yes	Yes	
Oregon	50%	2040	Yes	Yes	N
Pennsylvania	18%	2021	Yes	Yes	Case by case
Rhode Island	38.5%	2035	Yes	Yes	
South Carolina	2%	2021	No	Yes	
Texas	10 GW	2025	Yes	Yes	Heat pumps
Vermont	75%	2032	Yes	Yes	
Virginia	100%	2045	Yes	Yes	Y
Washington	100%	2045	Yes	Yes	
Wisconsin	10%	2015	Yes	Yes	
D.C.	100%	2032	Yes	Yes	N
Utah	20%	2025	No	Yes	Y
<b>Totals:</b>			<b>31</b>	<b>28</b>	<b>7</b>

In 2018, California passed Senate Bill (SB) 100, which updates the state's Renewable Portfolio Standard to require that 60% of electricity be generated by 2030 from eligible renewable energy resources.

- In Nevada, owners of geothermal power systems of at least 10-MW capacity are eligible for a 55% property tax abatement for 20 years. Additionally, the value added by a geothermal system is subtracted from the assessed value of any building for tax purposes (Robinson + Cole 2020).
- The Idaho Governor's Office of Energy and Mineral Resources has a low-interest loan program of up to \$15,000 for residential buildings and up to \$100,000 for commercial, industrial, agricultural, and multifamily loans (ID Governor's Office 2021).
- In Oregon, property equipped with an alternative energy system is exempt from ad valorem property taxation (OregonLaws.org 2020).
- Utah's Renewable Energy Systems Tax Credit provides a tax credit equal to 10% of the reasonable costs of the commercial energy system, up to \$50,000. Geothermal power, direct use, and heat pumps qualify (UT State Legislature 2019).

### 5.3.3 State-Level Legislation

In 2018, California passed Senate Bill (SB) 100, which updates the state's Renewable Portfolio Standard to require that 60% of electricity be generated by 2030 from eligible renewable energy resources. SB 100 also requires 100% zero-carbon electricity sources for the state by 2045, of which 60% must come from renewable sources and the other 40% from renewable energy or from any other sources that have zero net emissions. The cost of integrating variable energy resources—such as wind and solar—increases as their percentage of the total energy mix increases (Ginsberg et al. 2018). A goal of 100% clean energy will likely require procuring renewable energy resources that can be available 24 hours a day, such as geothermal, large-scale electricity storage, and, in the case of California, nuclear (Roberts 2018). SB 100 may create, in the medium and long term, a larger market for geothermal in California, a state rich in geothermal resources exploitable with current technology.

In 2016, the Geothermal Resources Development Act (NM Stat § 71-9-1-1 through 71-9-11) was enacted in New Mexico. The bill transfers the responsibility of overseeing the development of geothermal resources to the Energy Conservation and Management Division, previously in the hands of the Energy, Minerals, and Natural Resources Department's Oil Conservation Division. The goal was to assign the responsibility to an agency that had experience providing assistance to developers of renewable energy in the state (Conservation Voters New Mexico 2016). Another result from the bill was that in 2018, the Energy Conservation and Management Division adopted new regulations for the

development and permitting of high-temperature geothermal wells and geothermal facilities. Previous rules were based in oil and gas development and were not suitable for geothermal energy (Renewable Energy World 2016).

Other state-level legislation includes:

- SB 5470 was enacted in Washington in 2017 to improve the permitting process for geothermal resource exploration in the state (WashingtonVotes.org 2017).
- HB 1170 was enacted in Hawaii in 2015 to allow the lease of public lands for geothermal use without public auction (Capitol Hawaii 2016).
- SCR 1 was enacted in Nevada in 2019 and mandated a study of the potential economic impacts of renewable energy development in the state, as well as finding ways to provide relevant education to students and training for workers related to promoting the use of renewable energy in the state (LegiScan 2019).

Policy mechanisms to price and reduce carbon emissions, such as cap and trade systems, have not had a noticeable impact on geothermal deployment in the United States thus far.

### 5.3.4 Cap and Trade

Policy mechanisms to price and reduce carbon emissions, such as cap and trade systems, have not had a noticeable impact on geothermal deployment in the United States thus far. There are two active U.S. cap and trade systems, both managed at the state level. The first is in California, and the second is the Regional Greenhouse Gas Initiative, which operates in 10 states in the northeast (C2ES 2021a). The Regional Greenhouse Gas Initiative sets a cap on power plant emissions (RGGI 2020). California's cap and trade system applies emission caps not only to power plants but to participants in other sectors of the economy, such as natural gas suppliers, and oil and gas producers (C2ES 2021a, CARB 2021). Revenues from the program fund the Greenhouse

Gas Reduction Fund and from there flow to other programs administered by state agencies to lower greenhouse gas emissions (C2ES 2021b). As of yet, heating and cooling are not included in these programs.



## 6 Emerging Technologies

### 6.1 Enhanced Geothermal Systems

It is estimated that only 2% of the earth's geothermal resources are located in regions with accessible conventional geothermal resources (Geiser et al. 2016). These are sites that contain the right combination of heat, water, and permeability, and many have already been developed. There are untapped resources in hot, dry rock with little or no permeability, which are now accessible (but not yet fully exploitable) due to recent technological advancements. These advancements include capability and cost improvements in deep well drilling, logging, and construction, as well as improvements in materials (cement and well casing) that enable completions in hard-rock and high-temperature formations (Van Horn et al. 2020).

Enhanced or engineered geothermal systems (EGS) create hydraulic linkages between two or more boreholes to allow fluid circulation. This allows heat stranded in low-permeability rocks to be utilized for geothermal energy production. Permeability can be increased with hydraulic (or mechanical) stimulation, which acts by shear dilation through injection of water at pressure. Permeability can also be increased with chemical stimulation, which dissolves secondary minerals that are sealing natural fractures (Genter et al. 2010), or simply by thermal stimulation (injection of cooler water into hot rock, creating permeability by thermal contraction (Rose et al. 2017)).

There have been several EGS demonstration projects over recent decades. Ormat's Desert Peak and Brady field demonstration projects are located in Churchill County, Nevada. Formerly owned by U.S. Geothermal, Ormat's Raft River EGS demonstration project is located in Raft River, Idaho. AltaRock Energy's EGS demonstration project at Newberry Volcano is located in Bend, Oregon, and Calpine's EGS demonstration is in Middletown, California (EERE N.D.). The Bottle Rock geothermal facility, also operated by AltaRock Energy, attempted to use EGS in the past to counteract decreased capacity, and now is using EGS for an R&D project to build and test a new field-scale thermoelectric generator (Li et al. 2020b). Of these projects, Desert Peak, Raft River, and Geysers EGS operations are commercially active. The longest operating commercial EGS project currently generating power is the Soultz experimental EGS project in Alsace, France. After decades of scientific drilling and research at Soultz, a pilot

Enhanced or engineered geothermal systems (EGS) create hydraulic linkages between two or more boreholes to allow fluid circulation. This allows heat stranded in low-permeability rocks to be utilized for geothermal energy production.

power plant began operations in 2009 with an installed gross capacity of 1.7 MWe (Koelbel and Genter 2017, Mouchot et al. 2018). The project has two stimulated reservoirs within fractured granite, one at 3.5 km depth and the other at 5 km. For the last 30 years, this project has provided data useful for further EGS development (Genter et al. 2010).

The flagship EGS initiative supported through DOE is the Fronter Observatory for Research in Geothermal Energy (FORGE). The FORGE site is located near Milford, Utah, and aims to accelerate EGS research and development by focusing on field-scale reservoir testing and monitoring with the goal of creating a replicable process for developing EGS resources. The associated FORGE Roadmap identified critical research areas for EGS: stimulation planning and design, fracture control, and reservoir management (McKittrick et al. 2019). The Utah FORGE team recently completed drilling the project's first highly deviated deep well in less than half of the originally anticipated drilling schedule. This well will serve as the injector or producer for an injection-production well pair, with temperatures at depth close to 226°C (Utah FORGE 2020a). The FORGE site currently includes a pilot well and three seismic monitoring wells (Utah FORGE 2020b).

In July 2020, GTO selected Cyrq Energy, Inc., Ormat Nevada, Inc., and the University of Oklahoma under the Geothermal Wells of Opportunity (WOO) FOA to conduct cutting-edge research for improving tools, technologies, and methodologies for exploring, identifying, accessing, creating, and managing EGS resources at existing geothermal fields in Nevada and California.

DOE also funds the EGS Collab project, which is an in-situ field laboratory located at the Sanford Underground Research Facility in Lead, South Dakota, where a collaborative team is performing tests focused on EGS reservoir creation and model validation. Other DOE EGS funding opportunities include: "Zonal Isolation for Manmade Reservoirs" for technologies that allow command and control of fractures during stimulation, "Machine Learning for Geothermal Energy" to improve exploration and operation processes, "Waterless Stimulation" to advance waterless methods to create and sustain fracture networks, and "Efficient Drilling for Geothermal Energy (EDGE)" for technologies to drill wells faster and more efficiently (McKittrick et al. 2019).

## 6.2 Closed-Loop Geothermal

Closed-loop geothermal (CLG) energy systems use sealed wells to circulate a heat transport fluid through the subsurface, which eliminates the need for geothermal fluid flow from permeable rock formations. However, permeability might still be needed to overcome limited heat replenishment near the wellbore in tight rocks. CLG may be able to produce heat and power within a wide range of temperature and rock conditions, including low-temperature sedimentary zones and high-temperature dry rock formations (Van Horn et al. 2020). CLG also increases the number of viable geothermal projects because it can be used in previously unproductive geothermal wells. Geothermal wells may start out or become unproductive for a variety of reasons due to reservoir thermo-hydro-chemical changes over time (Higgins et al. 2019). CLG can also be deployed in depleted oil and gas wells in hot strata (Van Horn et al. 2020). Retrofitting existing wells instead of drilling new ones would decrease the drilling risk and costs that are inherently high for geothermal projects. Because no fluid is lost to the surrounding formations, the environmental permitting process can be simplified and alternative heat transport fluids (e.g., supercritical CO<sub>2</sub>) can be used, which may be superior to water under certain conditions (Scherer et al. 2020).

Although CLG is not yet commercial, there are ongoing demonstration projects. One is at the Coso Geothermal Field, where GreenFire Energy, Inc. installed a downbore heat exchanger in a field-scale closed-loop system where the target well had several megawatts of potential, but was not used due to high non-condensable gas content. The downbore heat exchanger consisted of vacuum-insulated tubing inside of a liner that was plugged at the bottom, in which water and supercritical carbon dioxide were successfully used as heat transport fluids. The water produces steam that does not contain non-condensable gas, and the supercritical carbon dioxide is heated to make power directly (Scherer et al. 2020, Higgins et al. 2019, Amaya et al. 2020). Eavor Technologies, Inc. recently completed its Eavor-Lite Demonstration Project, located in Alberta, Canada. Eavor-Lite is a full-scale prototype closed-loop system. Drilling and construction began in August 2019, and the facility was commissioned in December 2019 (ThinkGeoEnergy 2020e).

CLG technologies are not a new concept (Horne 1980, Morita et al. 1985, Oldenburg et al. 2016), but there is renewed interest in CLG from new commercial developers that is creating an active development landscape. However, this technology remains very much in development, and more research is needed. Research needs include techno-economic analyses, field-scale demonstration in diverse settings, and optimization of materials and wellfield design (Amaya et al. 2020).

## 6.3 Dispatchable Geothermal

Historically, geothermal energy has been primarily used as a baseload renewable energy resource. With the recent growth of variable renewable energy resources, there is an increased need for dispatchable power resources. Utilities use computerized automatic generation control systems to control multiple generators that are connected to the grid. A dispatchable geothermal plant is able to participate in the grid's automatic generation control, which allows the utility to remotely dispatch the facility any time of day (Nordquist et al. 2013).

Dispatchable geothermal is technologically feasible and has been demonstrated at the Puna Joint Venture in Hawaii. Geothermal plants can operate flexibly to provide ancillary and grid reliability services (e.g., grid support, regulation, load following, spinning reserve, non-spinning reserve, replacement or supplemental reserve). Geothermal plants at the Geysers used to offer flexible modes, but this ceased in the early 1990s due to low demand, high operations and maintenance costs from the additional stresses placed on equipment, and the lower costs of generation from hydroelectric, coal, and natural gas. Because geothermal plant economics are dominated by capital costs and have relatively low operating costs, operators favor baseload power production to maximize revenue. Geothermal plants can act as dispatchable resources (i.e., holding some capacity in reserve) if contracts sufficiently monetize the value of that service. Operators need well-structured and appropriately priced contracts that include payments for flexible operations that deliver grid reliability and ancillary services as well as pricing structures that can account for the unique capital structure of geothermal (GEA 2015). Hence, deployment of dispatchable geothermal is more of an economic question than a technical problem. Further research is needed to evaluate the economic parameters of flexible geothermal operations and the requirements of future electricity grids with respect to baseload versus dispatchable geothermal power plants.

The value of geothermal as a dispatchable resource may increase with high penetrations of variable renewable energy resources; for example, on isolated or island grids, there is a need for flexible renewable energy resources. In Hawaii, the Puna Geothermal Venture plant represents the first fully dispatchable geothermal plant. An 8-MW expansion agreement was reached in 2011 between Puna Geothermal Venture and Hawaii Electric Light Company, and the plant has since expanded to 38 MW, with 16 MW of flexible capacity (Nordquist et al. 2013, Gomes 2020). There are also examples of flexible geothermal in Europe, with five flexible plants in Munich, Germany, three of which also supply heat to district heating networks (EGEC 2020b).

An alternative way to offer flexibility is to couple power production with energy storage so that power can be stored and released to the grid as needed. See Section 6.6 for an explanation of underground TES systems.

## 6.4 Hybrid Geothermal

Hybrid energy systems combine two or more energy sources (e.g., geothermal and solar) or produce two or more products (e.g., electricity and minerals from brines). This section focuses on systems that combine two or more energy sources. See Section 6.5 for more information on mineral extraction from geothermal brines.

When carefully designed, a system with two energy sources may have many advantages over a system with single energy source. Hybrid geothermal systems provide power output that can more easily match electricity demand because baseload geothermal is paired with a more flexible energy source. By using a secondary energy source during peak hours, the impacts of resource productivity decline can be offset. In addition, hybrid technologies could decrease costs of geothermal power generation and increase the viability of low-temperature geothermal resources (Wendt et al. 2018).

The *GeoVision* analysis identified a number of hybrid technologies that may become a part of the future geothermal industry. Thermo-electric power generation technologies were a main focus, including solar thermo-electric, coal thermo-electric, and natural gas thermo-electric hybrid power generation systems. Geothermal energy can also be used for process heat applications, such as carbon dioxide capture from fossil thermo-electric plants and thermal desalination, and compressed air energy storage can be augmented with geothermal energy (Wendt et al. 2018).

Lithium extraction is the geothermal mineral process closest to commercialization. The path to commercialization runs through the Salton Sea in California, where the highest geothermal lithium concentrations in the United States occur (up to 400 mg/L).

A main focus of research to date has been solar thermo-electric power generation, specifically the hybridization of geothermal with concentrating solar power. This combination is promising because the two systems can have a shared thermodynamic cycle, so the same power block equipment can be used for each system, thereby decreasing capital costs. Both systems have operating strengths and weaknesses that can be minimized in combination (Angelos and Zhu N.D., Sharan et al. 2020). Solar can be used to increase the temperature of geothermal brine, improving the efficiency of geothermal power generation and making low-temperature geothermal resources accessible for power generation. Geothermal fluid can serve as storage for power generated by solar, which counters problems such as weather dependence and instability. Photovoltaic (PV) panels in a geothermal power plant can supplement geothermal energy for peak power demand during daytime, which can extend the lifespan of geothermal fluids (Li et al. 2020a).

There are many locations worldwide with abundant geothermal and solar resources. However, hybrid systems are a relatively new concept, and their performance and economics need to be demonstrated under various geographical and economic scenarios before significant deployment of physical hybrid geothermal power plants can occur. For now, most studies focus on modeling hypothetical systems instead of real-world hybrid plants (Li et al. 2020a).

There are a few commercial-scale or demonstration-scale solar thermo-electric hybrid systems. The Enel Green Power hybrid geo-solar Stillwater power plant features a large solar PV array and solar thermal preheating of the brine in a binary geothermal plant (Wendt et al. 2018). In 2017, Cyrq added a 14.5-MW solar PV array to its Patua geothermal plant (EnergyCentral.com 2017). In 2019, Ormat Technologies Inc. added a 7-MW solar PV system to their Tungsten Mountain power plant, completing the company's first hybrid project (Ormat 2020). Additionally, Solar Augmented Geothermal Energy (SAGE) was patented in 2006 and is an integrated approach to using solar with geothermal energy. Renewable Geothermal and Unified Collective Won have obtained federal and state approvals to begin testing the technology (RenewGeo 2020).

## 6.5 Mineral Extraction (Lithium)

Demand for lithium and rare earth elements has been driven by emerging green technologies. These minerals and metals, which are used in wind turbines, solar panels, and electric vehicle (EV) batteries, can be found in concentrations and total resource quantities that make them economically recoverable from geothermal brines. If economically extracted, revenue from these minerals could offset the high development costs of geothermal power plants, making geothermal energy more economical for developers. Most lithium imported by the United States is extracted from dried lakebeds (salars) in Argentina, Chile, and Bolivia through the use of evaporation ponds with large operational footprints (Ventura et al. 2020, Jeffers et al. 2017, Saevarsdottir et al. 2015). Hot geothermal fluids can dissolve lithium and minerals from underground rock formations, and although concentrations are low (a few hundred parts per million), the large volumes of brine that are processed by geothermal plants make brines a valuable resource (Ventura et al. 2020). Having a domestic source of lithium that has been quickly and efficiently extracted would greatly diversify U.S. mineral resources.

There are a wide variety of methods to extract lithium and other minerals from geothermal brine. Southern Research has developed a method that uses high-capacity selective sorbents to extract lithium from low-temperature brine, while also using thermoelectric generation for energy production (Rajterowski et al. 2015, Jeffers et al. 2017). Other methods include bioengineered rare earth-adsorbing bacteria (Jiao et al. 2017), solid-phase extraction with nanocomposite sorbent (Ventura et al. 2018), Integrated Lithium Adsorption Desorption (ILiAD) developed by EnergySource Minerals, electro dialysis (Mroczek et al. 2015), and others.

Lithium extraction is the geothermal mineral process closest to commercialization. The path to commercialization runs through the Salton Sea in California, where the highest geothermal lithium concentrations in the United States occur (up to 400 mg/L). EnergySource has a lithium extraction pilot plant (project ATLiS) set to begin construction in 2021 in this area (EnergySource 2020). Additionally, Berkshire

Hathaway Energy secured funding from the California Energy Commission in late 2020 to demonstrate lithium extraction at pilot scale using lithium-selective sorbent. CTR has recently secured a PPA for power sales from a planned 49.9-MW hybrid power-lithium extraction operation at the Salton Sea. CTR also secured funding from the California Energy Commission to develop brine pre-treatment processes supporting lithium extraction. Prior efforts at the Salton Sea have demonstrated the technical feasibility of lithium extraction and extraction of other metals, including zinc and manganese.

DOE has supported mineral extraction technologies via GTO's Low Temperature Geothermal Mineral Recovery Program Funding Opportunity Announcement (FOA), which began in 2014 (Thomas et al. 2015, 2016). The methods developed for this FOA include empirical methods for extraction and modification of previously developed methods to extract lithium from salars. The use of chemical and process modeling may help screen possible lithium extraction methods with respect to technical feasibility and cost (Porse 2020). A complete retrospective report detailing the results of the Mineral Recovery FOAs is available in Stringfellow and Dobson (2020), and a review of the various methods of lithium recovery from geothermal brines are provided in Stringfellow and Dobson (2021).

Although projected revenues from various minerals at several sites look promising, there are still several technological, financial, market, and site-specific challenges (Neupane and Wendt 2017). Current research needs include improving mineral extraction technologies, lowering costs of mineral extraction, and demonstration of extraction technologies at scale. Research needs also extend beyond technical focus to include analyses of benefits (economic, social, and environmental), economic viability, market drivers, and regulatory barriers (Climo et al. 2015). Current DOE research efforts are focused on the critical material supply chain. Studies include technology benchmarking (process steps, cost inputs, operational efficiency) and techno-economic analysis, as well as supply chain and life-cycle analysis (Porse 2020, Warren 2021, Stringfellow and Dobson 2020, 2021).

## 6.6 Underground Thermal Energy Storage

Underground TES uses the natural heat capacity of the subsurface to store thermal energy for later use. Underground TES can be subgrouped into closed-loop and open-loop technologies. Open-loop technologies include aquifer TES, reservoir TES, and others. Closed-loop technologies include borehole TES and others (Kallesøe and Vangkilde-Pedersen 2019).

Aquifer TES stores thermal energy at modest temperatures in subsurface aquifers (Nordell et al. 2015). The majority of aquifer TES systems are in the Netherlands, with wells typically 10–150 m deep (Bloemendal and Hartog 2018, Fleuchaus et al. 2018). These aquifers can be hosted within unconsolidated sedimentary units, porous sedimentary rocks like sandstone or limestone, or fractured hard rock formations. There are three different types of aquifer TES, divided by their applicable temperature ranges: high-temperature storage is possible in deep aquifers with temperatures in excess of 60°C. Medium-temperature storage ranges from 30°–60°C. Low-temperature storage in the upper few hundred meters of the subsurface is typically restricted to less than 30°C (Kallesøe and Vangkilde-Pedersen 2019). Aquifer TES systems have been installed worldwide, with many successful systems in Europe (Bloemendal and Hartog 2018, Fleuchaus et al. 2018, Todorov et al. 2020, Schüppler et al. 2019). Aquifer TES is much more limited in the United States, but there is an aquifer TES project at Richard Stockton College in New Jersey. There have also been feasibility studies for aquifer TES in Minnesota, Ohio, and Maryland (Underground Energy 2020).

Reservoir TES uses permeable zones in the subsurface to store thermal energy. Stored temperatures can range from 70° to 100°C, though reservoir TES is a novel technology and

there are very few systems currently installed. The reservoirs used are typically deeper and hotter than those used for aquifer TES and are characterized by little to no flow, making TES easier to control (Pepin et al. 2021). The efficiency of reservoir TES increases over time as the rate of heat loss to the surrounding rock decreases, and reservoir TES has been shown to be a feasible source of heating energy for large buildings (Burns et al. 2020).

Borehole TES heats and cools by circulating fluid within plastic pipes installed in closely spaced closed-loop boreholes. This type of system can be used to store temperatures up to approximately 90°C. There is great potential for borehole TES to store excess heat from industrial processes, incineration plants, and heat from renewable sources such as solar thermal. However, this type of system does not react very quickly due to a relatively low heat transfer coefficient, so a buffer such as a water tank is needed for faster reaction times (Kallesøe and Vangkilde-Pedersen 2019). Drake Landing Solar Community is a borehole TES demonstration project in Alberta, Canada, that was commissioned in 2007. The project uses a solar district heating system combined with borehole TES to store energy seasonally. The project has achieved conventional fuel savings of more than 90% (Mesquita et al. 2017).

Other TES technologies include the utilization of excavated spaces in the subsurface, either of natural or anthropogenic origin such as pits, mines, and caves. These are not widely used, but are currently moving from the R&D phase into the deployment phase (Kallesøe and Vangkilde-Pedersen 2019; Hahn et al. 2019). Pit TES consists of storing water in lined excavated basins with an insulated lid. Mine TES uses mine water or flooded mines as a low-temperature heat source to heat buildings, but only a few plants operate in Europe (Kallesøe and Vangkilde-Pedersen 2019). Geologic TES is a geothermal energy storage system that is combined with

concentrating solar power to create a hybrid renewable energy system. This system uses concentrating solar power to produce hot water that is injected into an aquifer, creating a synthetic geothermal reservoir. The geothermal heat stored in the subsurface can then be dispatched when needed (Wendt et al. 2019, Sharan et al. 2020). Other technologies, such as geothermal battery energy storage systems, are currently under development, but studies suggest that nearly all of the stored heat can be practically recovered in these types of systems (Green et al. 2020). See Section 6.4 for more information on hybrid energy systems.

## 6.7 Sedimentary Geothermal and Co-Production

The possibility of using sedimentary basin resources and/or existing oil and gas wells for geothermal energy would remove substantial risk and expense from the early phases of geothermal development (MEET 2020).

### 6.7.1 Sedimentary Geothermal

Sedimentary geothermal basins are defined as “thermal sedimentary aquifers overlain by low thermal-conductivity lithologies [that] contain trapped thermal fluid and have flow rates sufficient for production without stimulation” (Mullane et al. 2016). The *GeoVision* study estimated that the accessible resource contained in U.S. sedimentary basins is 28,000 EJ, or 7.5 million GWhth of beneficial heat. This is more than 150 times the amount of usable energy in isolated springs and wells (*GeoVision* 2019). To put this in perspective, in 2008 the total U.S. thermal demand (from 0 to 260°C) was 33.5 EJ (Fox et al. 2011).

Notable advantages of sedimentary geothermal basins over conventional geothermal settings include easier well targeting and drilling, flat topography, significant existing infrastructure, and proximity to large population centers. Many sedimentary basins in the United States have been drilled for oil and gas, leaving behind extensive well records and characterization of geological formations, temperature gradients, and other reservoir properties that can be leveraged to conduct low-cost and low-impact geothermal

Notable advantages of sedimentary geothermal basins over conventional geothermal settings include easier well targeting and drilling, flat topography, significant existing infrastructure, and proximity to large population centers.

exploration. Because heat flow in sedimentary reservoirs is dominated by conduction and not convection, and their geometry is more predictable, exploration and drilling risk is lower. On the other hand, encountering adequate resource temperatures in sedimentary basins requires deeper drilling compared to convective geothermal reservoirs (Porro and Augustine 2012), often >3 km (Moeck 2014). In addition, the relatively high permeabilities required for sustainable energy production over lifetimes of multiple decades is at the high end of those found in sedimentary formations. This important variable—permeability—is largely unknown because the geologic formations that are good candidates for geothermal production have not generally been penetrated and/or tested by oil and gas wells.



The feasibility of using sedimentary basin resources for *electricity generation* is controversial. Augustine (2014) found that few basins in the United States displayed evidence of high permeability at depths where temperatures were high enough for electricity generation. Allis et al. (2013) determined that electricity production from sedimentary geothermal settings was feasible (LCOE <10c/kWh) if the reservoirs met the following requirements: heat flow >80 mW/m<sup>2</sup>, reservoir temperatures >175°C, at depths of <4 km. Other studies have shown that reservoir permeability must be >50 millidarcies (mD) to sustain productivity (Anderson 2012). Project examples include Munich, Germany, where a small power plant is co-located with a large-scale district heating system, and in Saskatchewan, Canada, where the first successful geothermal test well was drilled in a sedimentary basin (bottom-hole temperatures exceeding 125°C at 3.5 km and “positive” permeability) (Groenewoud and Marcia 2020). Using EGS development approaches could expand this resource opportunity.

The feasibility of using sedimentary basin resources for direct use (heat) is well proven. The GDH network in Paris, France, has the largest concentration of wells in the same sedimentary aquifer in the world. During a period of over 40 years, more than 120 wells have been drilled into the Paris basin to supply a large district heating system with fluids at temperatures about 70°C. First installed in the 1970s, the system continues to expand, with several new projects at different stages of planning and realization. Several additional large-scale GDH systems exist in sedimentary basins around the globe (e.g., Germany, Hungary, China).

### 6.7.2 Co-Production and Conversion of Oil and Gas Wells for Geothermal Energy

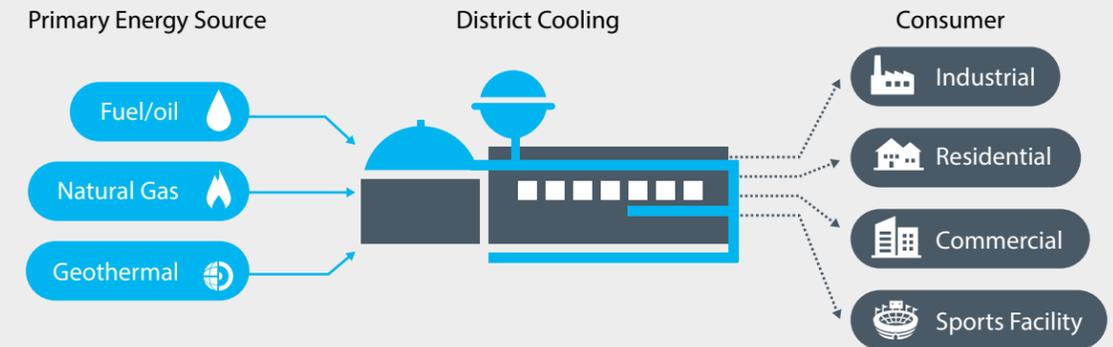
Warm and even hot water is often produced during oil and gas extraction at volumes and temperatures that vary as a function of geologic formation, well depth, well age, and other factors. Often, the ratio of produced water to hydrocarbons increases over time, meaning that wells in declining oil and gas reservoirs may be good candidates for geothermal co-production or conversion. There are two ways to produce geothermal energy with oil and gas wells. First, the wells can be repurposed for exclusive geothermal production (conversion). Second, the wells can produce hydrocarbons and heat simultaneously (co-production). In both cases,

reusing existing wells avoids expensive drilling costs for new wells, and would improve social acceptance for industrial surface installations (MEET 2020). To facilitate these uses, the Energy Act of 2020 allows for non-competitive geothermal leases to co-produce out of federally managed and approved oil and gas wells.

The concept of utilizing co-produced geothermal fluids with hydrocarbons is not new (e.g., McKenna et al. 2005). The technical feasibility was demonstrated through a project at the Rocky Mountain Oilfield Testing Center in Wyoming, where co-produced geothermal water from oil wells was used to power a 250-kW Organic Rankine Cycle (ORC) plant (Reinhardt et al. 2011). Then, Augustine and Falkenstern (2014) simulated the electricity generation potential of geothermal fluids produced as a byproduct of oil and gas production from existing fields in the United States. That study found a significant number of active oil and gas wells with geothermal temperatures and flow rates sufficient for energy production but estimated only a modest near-term market potential of ~300 MWe of electrical output from known formations, with marginal economics.

From a techno-economic standpoint, deepening or repurposing oil and gas wells for exclusive geothermal energy use (“conversion”) may be more feasible than co-production. A recent study of the Williston basin in North Dakota did not find co-production of geothermal fluids and hydrocarbons in the Bakken field to be commercially feasible for power production (due to excessive heat loss during slow transit of fluids in wells), but the study did suggest that water-rich, hotter carbonate rocks underlying the Bakken could generate several megawatts of power (Gosnold et al. 2020). Hence, the study proposed recompleting (including deepening) marginally economic existing oil wells for water production rather than co-production. That study also recommended installing ORCs on the many water flood projects in the basin.

Vermilion Energy, an oil producer in France, currently supplies co-produced geothermal heat to an eco-village, a high school, and to geothermal greenhouses in southwest France. As part of the “Multidisciplinary and multi-context demonstration of Enhanced Geothermal Systems exploration and Exploitation Techniques” (MEET) H2020 Research Project, Vermilion Energy and other partners will demonstrate the feasibility of electricity production from co-produced geothermal fluids in France by testing an ORC turbine connected to an oil well (MEET 2020).



**Figure 37.** Principles of a district cooling system

Source: Kreuter (2012)

## 6.8 Geothermal for Cooling

In addition to heating, geothermal resources can provide cooling for buildings. Making cold air or ice out of hot water is a mature technology, invented in the 1850s, that relies on enthalpy changes in absorption/desorption processes. Using geothermal energy through absorption chiller technology to provide district cooling, space cooling, or refrigeration has advantages over conventional systems, such as reducing electricity demand and greenhouse gas emissions (Liu et al. 2015). Moderate-temperature geothermal resources have the temperature ranges required to drive an absorption cycle (Erickson and Holdmann 2005).

In district cooling systems, chilled water or air is produced in a central unit driven by a primary energy source (fossil heat source, waste heat, or geothermal) and distributed to consumers via a network of insulated pipes and/or stored as chilled water or ice (Kreuter 2012; see Figure 37).

Chiller technologies compatible with low-temperature geothermal heat sources include absorption and adsorption chilling (Liu et al. 2015). For geothermal heat sources between 60°C and 90°C, typical chiller technology is based on ammonia-water or lithium-bromide-water brines. Lithium-bromide-water absorption chillers are an important part

of “comprehensive geothermal utilization” in China, which includes heating, cooling, and power generation when resources are adequate (Ma et al. 2010). There are currently two such operational systems in the Guangdong and Xiqing provinces of China (RTC 2018). In the United States, lithium-bromide-water absorption chillers were used to provide cooling to the Oregon Institute of Technology campus using geothermal heat. However, that system was decommissioned in 1999 after 19 years of operation due to high water use and low efficiencies.

An ammonia-water-based absorption chiller was installed in 2005 at the Aurora Ice Museum at Chena Hot Springs, Alaska. Chena Hot Springs is a remote off-grid community near Fairbanks, with a number of operating geothermal power and direct-use installations (see Section 6.10: Geothermal Microgrids). The chiller runs on 73°C geothermal heat and provides 15 tons of -29°C chilling, allowing the Ice Museum to stay frozen year-round. The chill brine (a CaCl<sub>2</sub> solution) circulates through an air handler, which cools an annular space in the ice hotel between the ice walls and the external insulation (Erickson and Holdmann 2005).

A proposed expansion to an existing GDH system in Munich, Germany, would provide heat as well as district cooling using absorption chillers to more than 80,000 residents. District

cooling is already generated centrally and distributed to customers via an extensive piping network in Munich. The additional cooling capacity provided by geothermal-fired absorption chillers will add additional users and piping to the current city network (ThinkGeoEnergy 2020d).

In addition to district cooling, geothermally driven chillers could also be used for industrial processes in the United States that require ice, process cooling, refrigeration, and related applications. A recent study conducted by NREL investigated the techno-economic feasibility of using geothermal-sourced absorption chillers to produce chilled water for a chemical plant in East Texas. The proposed cooling system generates about 11 MW of chilled water, or 86 GWh of cooling per year (Turchi et al. 2020). A 2015 study led by Oak Ridge National Laboratory proposed the development of a geothermal-sourced cooling system that would provide off-site space conditioning (up to 100 miles from geothermal resources). The proposed technology decouples the production and regeneration of the conventional absorption cycle into a two-step process: first, “regeneration” takes place near the geothermal resource, wherein a binary fluid is concentrated using geothermal heat and then allowed to cool to ambient temperatures. Then, the concentrate is transported to users, where it provides space conditioning via evaporation-absorption cycles using on-site water and the concentrated solution. The hydrated solution is then transported back to the geothermal site to regenerate. However, transportation costs appeared to be prohibitive in that study (Liu et al. 2015).

Whether for cooling or ice production, **geothermally driven absorption chilling is a feasible technology** despite its limited uptake in the United States. In much of the United States, there is a greater need for chilling than heating. At Chena Hot Springs in Alaska, the absorption chiller running off geothermal heat has operational costs of less than a third of the backup system (Erickson and Holdmann 2005). A summary of the potential market sectors for geothermal cooling applications is given in Table 10.

## 6.9 Supercritical Geothermal

Pure water reaches a supercritical state at temperatures and pressures above 374°C and 221 bar, respectively. Supercritical conditions are often found at the roots of volcanic-hosted hydrothermal systems, and reservoir fluids in supercritical states could be used as unconventional geothermal resources (Reinsch et al. 2017). Supercritical geothermal systems should occur at conditions corresponding with the transition from brittle to ductile behavior of rocks, which can occur at shallow crustal depths in magmatic settings (Stimac et al. 2017). Ogawa (2014) hypothesized that large amounts of fluid may be trapped in the supercritical state in certain geologic settings.

Supercritical geothermal resources encompass both fluids and rocks at supercritical conditions. The energy potential of supercritical geothermal resources has been estimated at the gigawatt scale for at least one resource area (Okamoto et al. 2019), and at up to 10 times more energy per well than conventional hydrothermal resources (Friðleifsson et al. 2014).

Because exploration and production of supercritical geothermal resources carries high risk but a higher reward, the risk/reward ratio of this resource type bears more similarity to oil and gas than conventional geothermal.

More than 25 geothermal wells have encountered temperatures above 374°C, and in some cases have encountered magma (Reinsch et al. 2017). Even when fluids were encountered, however, none of these wells have successfully been produced for geothermal energy. Whether permeability can be maintained at supercritical conditions is unproven. Wells drilled to temperatures greater than 370°C have historically encountered little permeability (Fournier 1999), but experimental work conducted by Watanabe et al. (2017) refutes previous hypotheses about permeability reductions at the brittle-ductile transition zone based on silica solubility and other factors (Saishu et al. 2014). Coordinated research efforts are underway in Japan, Italy, Iceland, Mexico, the United States, and New Zealand to better characterize supercritical systems and their utilization as geothermal energy sources.

Conventional drilling and well completion techniques, downhole tools, and surface equipment are not suitable for the extreme temperatures and aggressive fluid chemistry compositions of these systems (Reinsch et al. 2017). The first supercritical well drilled in Iceland (IDDP-1) produced extremely corrosive and abrasive fluids. Nonetheless, and despite encountering magma at ~2 km depth, the well was flow tested for more than 1 year and shown to be capable of producing more than 36 MW (Friðleifsson et al. 2014). Iceland’s second supercritical well, IDDP-2, was not tested due to casing damage that likely occurred as a result of the corrosive nature of the fluid. However, the well was drilled to 4.7 km depth, with an estimated bottom hole temperature of 535°C. This confirms that the supercritical domain was reached even for fluids with seawater compositions (Friðleifsson and Elders 2017). The third deep well of the Iceland Deep Drilling Project, IDDP-3, is planned in the next few years.

Active research programs are also investigating the investment and economic development opportunities related to supercritical fluid production, such as material processing, industrial scale forestry, dairy, and other uses in New Zealand.<sup>4</sup> Other studies are focused on the feasibility of the application of innovative technologies in supercritical settings, such as EGS and CLG (e.g., Cladouhos et al. 2018).

## 6.10 Geothermal Microgrids

Although geothermal power is almost exclusively produced for large, grid-scale projects in the United States, geothermal technology is also capable of providing power at the microgrid scale. Many small projects, both grid-connected and isolated, have successfully operated for years. They provide an alternative to the diesel generators typically used for remote power generation. Several changing market conditions are improving the competitiveness of geothermal-powered microgrids, including carbon accounting, technological improvements in small-scale geothermal power generation (particularly in ORC turbine efficiency, wellhead generation, and design optimization), and the availability of mass-produced modular systems.

ORC design continues to improve, particularly with respect to modularization and optimization for lower temperatures (70°–120°C). Some companies are mass producing ORC units, which lowers costs through economies of scale; increases reliability, resale value, and part availability; and enables lower financing rates (Havsed and Skog 2018). The smaller the system, the more drastic the decrease in capital costs with manufacturing volume. Compared to using custom designs, using mass-produced standardized designs yields potential increases in net present value of \$1.4 million for a given 5-MWe ORC system (Akar et al. 2018). Optimization of whole-system design has also improved the economics for smaller systems (e.g., sizing a low-enthalpy geothermal plant to thermal degradation considerations [Gabbrielli 2012]).

Traditionally, in a geothermal project with multiple wellheads, drilling and power plant installation are performed in series. Newer projects with smaller power plants use the “wellhead method,” wherein modular ORC units are installed on each well in parallel with continued drilling. This approach has several advantages, including reduced time until energy production begins, more efficient exploitation of wells at varying temperatures and pressures, resilience due to modularity, transportability, the elimination of large steam-gathering systems, and utilization of remote wells. Disadvantages include longer transmission lines, higher cost/kW per unit, more electrical equipment, a separation station for each plant, and reinjection during drilling. Overall, wellhead plants could increase system power and net present value by up to 5% and 16%, respectively (Geirdal et al. 2015). In addition, reduced flowrate requirements for newer-generation units could take advantage of slimholes rather than traditional large-diameter geothermal wells. Slimholes can theoretically supply more than 1 MWe with optimized slimhole casing designs to

**Table 10.** Market Sectors for Geothermal Cooling Applications

Cooling Application	Market Sectors
District Cooling (“Central Cooling”)	Air conditioning for cities, campuses, military bases, etc.
Process Cooling and Refrigeration	Manufacturing sector Agricultural sector (food processing, storage) Data centers Tourist sites and other miscellaneous uses (e.g., Ice Hotel in Alaska)
Turbine Inlet Cooling	Power sector, utilities
Ice Production	Agricultural/fishing sector Cold storage

<sup>4</sup> For more information, see [www.geothermalnextgeneration.com](http://www.geothermalnextgeneration.com).



Photo by Dennis Schroeder, NREL 48106

increase discharge (Garg et al. 2000). This could mean that a 300-kW plant with a 120°C resource could produce power at 11c/kWh, which is competitive in many remote markets (Combs et al. 1997). The slimhole concept is untested, but proposed projects include one in Indonesia (Aalten et al. 2018) with an estimated 7–8 year payback period, and one in Vietnam (Do et al. 2018).

Successful small geothermal plants occur in both isolated and grid-connected settings, typically coupled with cascaded direct-use projects to improve project economics. The grid-connected Fang geothermal system near Chang Mai, Thailand, utilizes a low-temperature source (116°C) with an ORC system in continuous operation since 1989. The plant produces 150–250 kWe, with seasonal variation, with an LCOE of \$0.06–0.09/kWh. Waste heat is used for cold storage, crop drying, and a spa. A 680-kW isolated geothermal microgrid has been operating in Chena, Alaska, since 2006. The geothermal plant offsets diesel generation, and the first year of operation saved more than \$650,000 in diesel fuel, and reduced electricity cost from \$0.30 to \$0.05/kWh (Holdmann 2007). The plant utilizes the lowest-temperature geothermal electricity source in the world, 71°C, with power generation enabled by the availability of near-freezing river water and seasonal subzero air temperatures for power cycle heat rejection. Overall, the plant has operated successfully, with some modifications over the years (related to the cold-water supply and issues with the geothermal resource, leading to the deepening of a well and revision of the injection scheme). Waste heat is used for district heating, greenhouses, seasonal cooling using absorption chilling (see Section 6.8: Geothermal for Cooling), a spa, and other uses.

Other geothermal microgrid installations have been less successful. The Nagqu geothermal power plant in Tibet, now offline, is another isolated geothermal microgrid utilizing low-temperature fluids (110°C). That system, commissioned in 1993, had setbacks related to pump failures and other maintenance issues, but was reported as providing far cheaper power than the diesel generators it replaced. The failure of that system due

**Geothermal microgrids for power and heat are technically and economically feasible in both remote and grid-connected settings.**



Photo by Dennis Schroeder, NREL 48116

to operation and maintenance issues highlights the need for proper maintenance support to enable rural operation. A study looking at social impacts of small-scale off-grid geothermal energy systems in rural Indonesia emphasized similar points about the importance of a well-trained, dedicated local workforce—as well as cascaded uses of the geothermal heat—to project success (Brotheridge et al. 2000).

In 2016, an Indonesian and Dutch partnership was formed to develop and deploy MiniGeo, a prototype small-scale (<1 MW) geothermal power plant designed for remote communities. The team is currently installing a pilot MiniGeo on a small island in the eastern part of Indonesia (Richter 2016). Compared to other types of off-grid conventional and renewable energy solutions, the MiniGeo plants may prove

very competitive, running at \$0.1–0.2/kWh according to the energy company ENI (compared to \$0.3/kWh for off-grid solar panels and \$0.5/kWh for diesel generators in remote Indonesia [ENI 2020]).

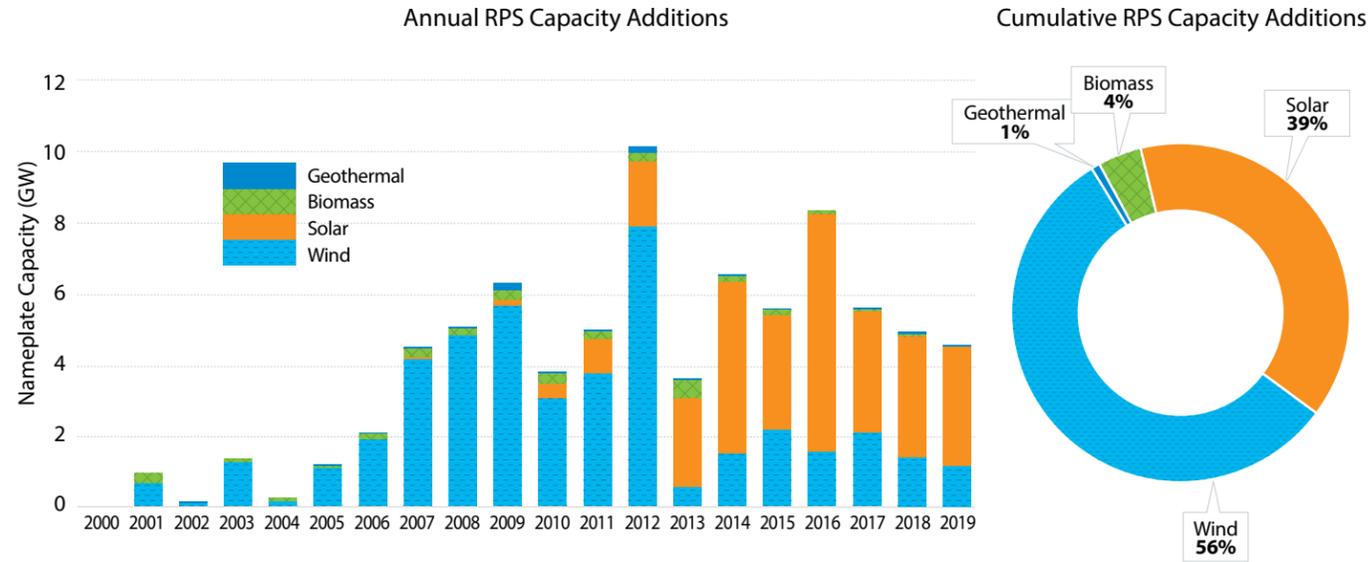
In short, geothermal microgrids for power and heat are technically and economically feasible in both remote and grid-connected settings. Operational problems relate mainly to infrastructure and maintenance, although as in all geothermal operations, reservoir and well field management must be properly addressed (Kaplan and Shilon 1999). In addition to often attractive economics compared to alternatives, geothermal microgrids offer local power that improves system resiliency in the face of potential weather events or fuel-supply constraints.

## 7 Market Opportunities for Geothermal Energy

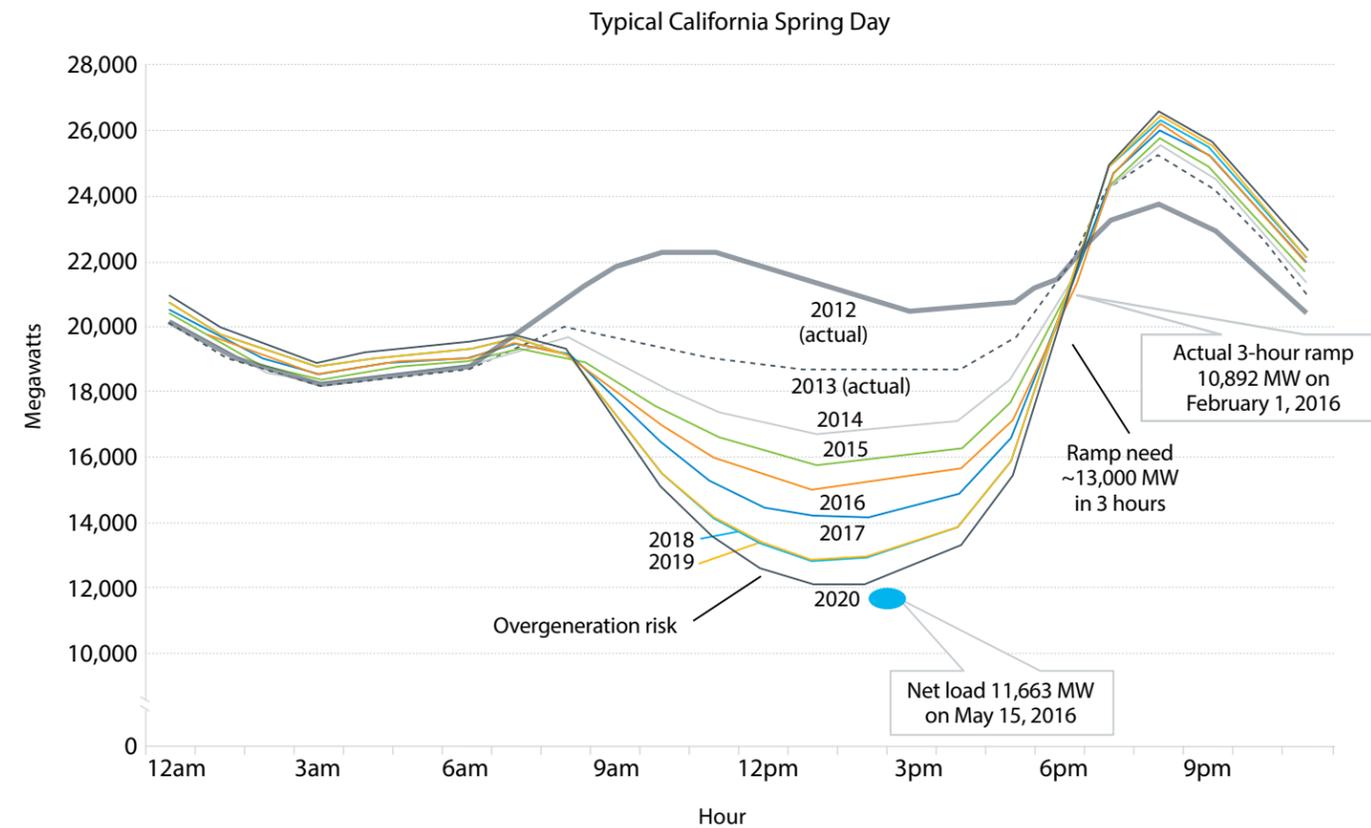
### 7.1 Market for Geothermal Energy in the United States

*GeoVision* projects a possible future whereby geothermal capacity could reach up to 60 GW by 2050. This is primarily through improvements in the regulatory process and technology advances that enable the deployment of deep EGS for power production.

As previously discussed, *GeoVision* projects a possible future whereby geothermal capacity could reach up to 60 GW by 2050. This is primarily through improvements in the regulatory process and technology advances that enable the deployment of deep EGS for power production. However, considering the limited development over the last five years, geothermal power deployment will need to accelerate to meet those projections. One potential mechanism that may benefit low-carbon baseload electricity generation methods, such as geothermal, is the implementation of greenhouse gas limits.



**Figure 38.** Annual and cumulative RPS capacity additions in the United States by technology  
Source: Barbose (2021)



**Figure 39.** The duck curve shows steep ramping needs and overgeneration risk  
Source: CAISO (2020)

While the use of RPSs to this point has primarily increased deployment of wind and solar (Figure 38), there is some evidence that the combination of an RPS and greenhouse gas limits can increase the demand for baseload power. The most illustrative current example is SB 100 in California. As mentioned in Section 5.3.3, this legislation mandates 60% renewable power by 2030 and 100% zero-carbon electricity sources by 2045. As more ambitious clean energy targets such as these are adopted, states need an energy mix that provides resiliency, reliability, and stability in addition to low costs (Pettitt et al. 2020). As California has increased variable energy resource deployment and enacted stricter decarbonization targets, the so-called “duck curve” has become more pronounced (Figure 39). This figure shows how an increasing oversupply of solar power during daylight hours has led to shorter and steeper late-afternoon ramps when additional electricity resources must be brought online as the sun sets. In addition, during a heat wave in the summer of 2020, California was hit with a string of rolling blackouts. Initial evaluations indicated that this was partly due to a poorly planned transition from fossil fuels to variable energy resources as well as a lack of baseload power (Penn 2020).

**While geothermal may not be the lowest-cost solution on an LCOE basis, it can be argued that it has the highest economic value of renewable resources operating in California.**

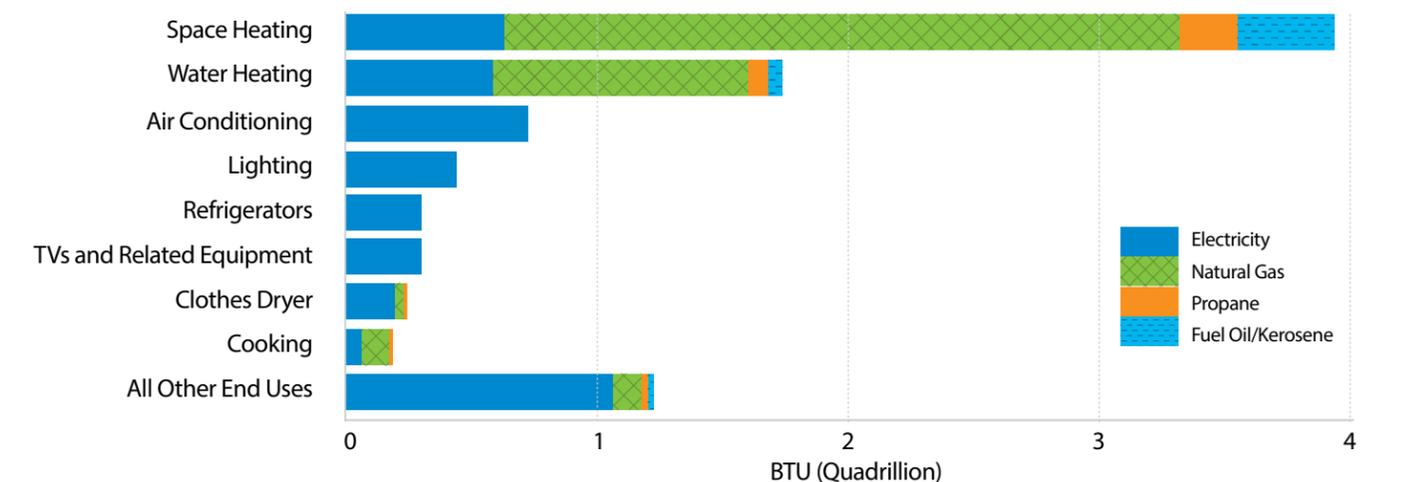
This potential for overgeneration of solar reduces its relative value and increases the relative value of resources, such as geothermal, that can provide reliable system capacity. One recent analysis showed that by 2018, geothermal electricity had a wholesale market value of \$8–\$9/MWh more than solar PV in California (Thomsen 2018). Thus, while geothermal may

not be the lowest-cost solution on an LCOE basis, it can be argued that it has the highest economic value of renewable resources operating in California (Bartosz and Thomsen 2020). Recent events support this analysis, as six of the recently signed PPAs feature off-takers located in California. Currently, a total of 28 states have enacted RPSs in some form or another. As stricter greenhouse gas limits are added to the regulatory mix and variable energy resource deployment increases, the market for clean baseload electricity such as geothermal should continue to grow.

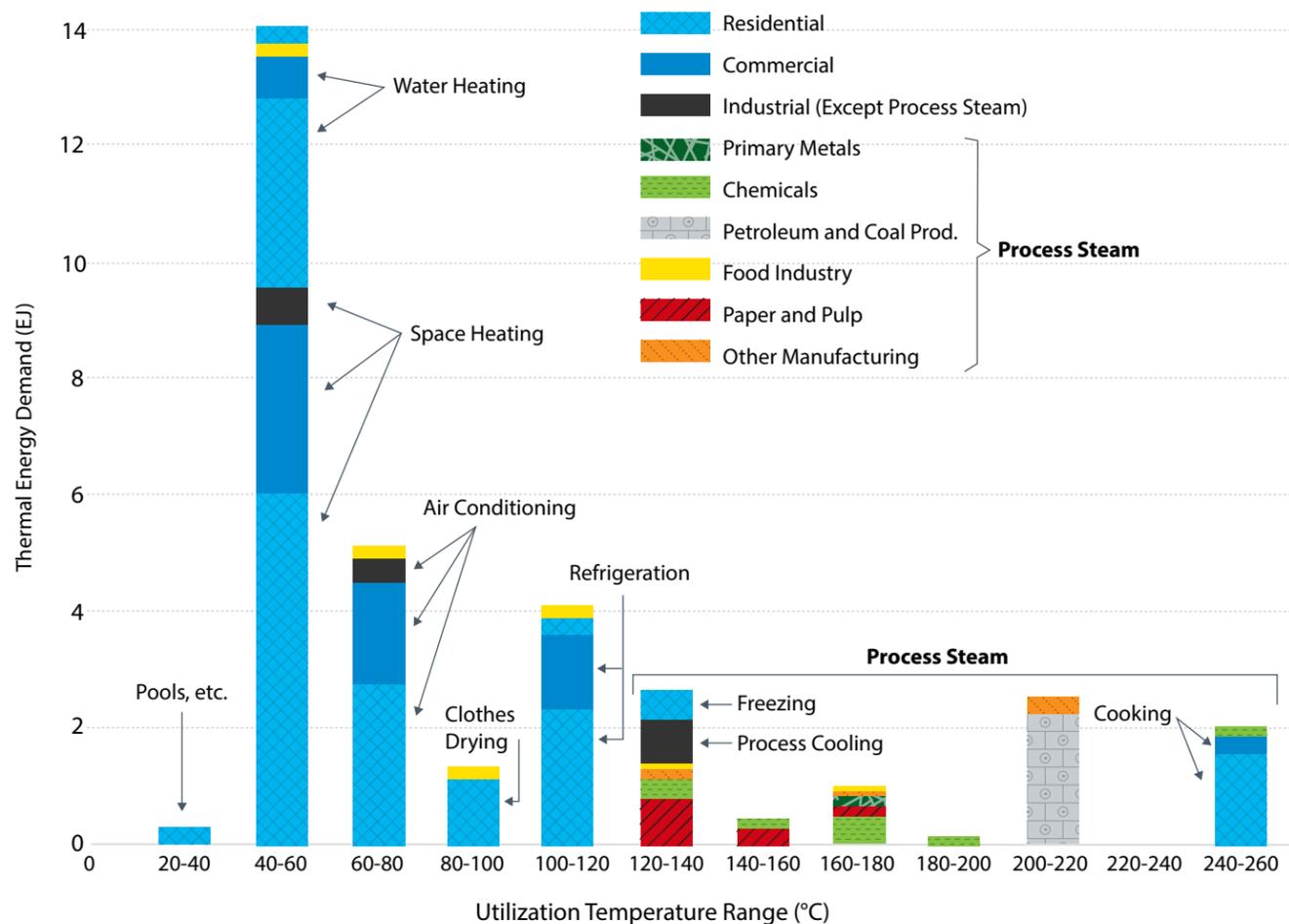
Demand for low-temperature heating and cooling in the United States is also significant. Space heating and water heating account for nearly two-thirds of U.S. residential energy

use (Figure 40). Most of that combined residential heating demand was met by natural gas in 2015. Fox et al. (2011) calculated that in 2008 in the U.S. residential, commercial, and industrial sector, about 14 EJ (1 EJ = 10<sup>18</sup> J = 0.9478 quad) of primary energy was used for space and water heating and 5

EJ for air conditioning (Figure 41). In comparison, total U.S. annual primary energy demand is about 100 EJ. Space heating and cooling demand vary seasonally and depend significantly on building type. The seasonality of heating loads results in a low utilization factor of the geothermal supply, which is a challenge for GDH economics. Supplying cooling with geothermal energy is more challenging than simply supplying heating, as additional equipment is required (i.e., absorption chiller), and higher geothermal temperatures are preferred



**Figure 40.** EIA's latest Residential Energy Consumption Survey (RECS)  
Source: EIA (2015)



**Figure 41.** 2008 U.S. thermal energy demand as function of utilization temperature (includes electrical system energy losses)

Source: Fox et al. (2011)

(see also Section 6.8: Geothermal for Cooling). Increasing the use of geothermal energy for heating and cooling in the United States can significantly contribute to Biden Administration decarbonization goals to cut U.S. greenhouse gas emissions by half in 2030 and achieve a carbon-free electric sector by 2035. The GDH system in Paris, France, saves 120,000 tons of carbon dioxide per year by offsetting emissions from 170,000 buildings (Bertani 2016).

## 7.2 Outlook for Geothermal Growth in the United States

Geothermal power production provides several non-cost advantages. Importantly, geothermal plants operate 24 hours a day regardless of weather, and so they do not experience the variability and associated voltage swings that energy resources, such as solar and wind, can exhibit. This makes

geothermal an appropriate baseload replacement for retiring fossil fuel plants and a complement to variable energy resources. In addition, geothermal plants are potentially dispatchable and able to act as a flexible power source (see Section 6.3). Power flexibility could mean providing a range of services, including grid support, regulation, load following, spinning reserve, non-spinning reserve, and replacement or supplemental reserve. As variable energy resource deployment increases, supplying these ancillary services will become more important to grid stability. The wide range of operational conditions offered by geothermal can help address this challenge (Matek and Schmidt 2013).

Geothermal power also offers environmental advantages over other electricity sources. Compared to fossil fuel plants of comparable size, geothermal plants emit 97% less sulfur compounds and 99% less carbon dioxide (EIA 2020c). In fact, as discussed earlier, almost all geothermal plants built since 2000 use binary technology, which emits almost no

greenhouse gases at all (EIA 2020d). Additionally, geothermal plants require a much smaller land footprint than renewables such as solar, wind, and biomass (Matek and Schmidt 2013). Currently, geothermal power projects on BLM land require an average of 1.6 acres per MW of nameplate capacity (Cruce et al. 2020). This compares favorably to solar (3–6 acres per MW) or wind (30–45 acres per MW) (NREL N.D.).

Due to these advantages, there is some indication that geothermal growth may soon accelerate. As mentioned, the 2019 *GeoVision* report concluded that there is a path to 60 GW of installed geothermal power production capacity by 2050 (*GeoVision* 2019). Improvements in the regulatory process (with no technological improvement) are thought to result in 13 GW of geothermal capacity deployed by 2050. However, the bulk of the 60-GW deployment comes from technology advances and cost reductions that enable the deployment of EGS for power production. In addition, analyses including policy considerations that are favorable for geothermal power and heat increased deployment levels dramatically. In conclusion, *GeoVision* presented a roadmap of actionable items to guide stakeholders toward achieving the deployment levels identified in the report.

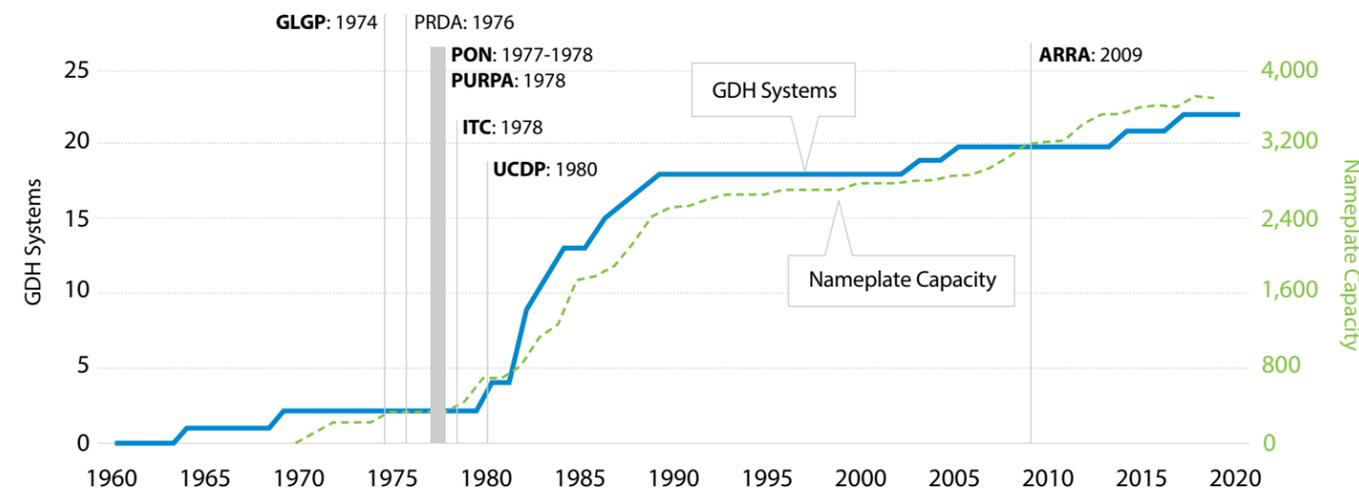
While there are currently 23 GDH systems in operation in the United States, *GeoVision* concluded that there is the potential for 17,500 GDH systems to be operating in the United States by 2050. Much of this sharp uptick in deployment

was foreseen as a result of commercial EGS technology advancements that can enable geothermal direct use. Similar optimism was expressed in another recent study, but for different reasons (Fry 2020). That study suggested that rapid GDH deployment may not need to wait for EGS to become cost-effective; rather, conventional hydrothermal geothermal resources in rural and suburban settings have significant scalable direct-use potential.

## 7.3 Impact of Policy on Geothermal Growth

As discussed in Section 5, beginning in the mid-1970s, a number of DOE financial assistance and risk mitigation programs, along with state incentives, were available to support geothermal deployment by offsetting the high-risk exploration drilling phase, as well as the high capital costs of system installation. Since the 1980s, these programs have been more limited, and so have geothermal power and GDH deployment (Figure 42).

At the state level, a few western states have also provided financial assistance to support development of GDH systems, most notably Oregon and California. These programs have supported the three most recent GDH developments in Lakeview, Oregon (2005), Canby, California (2003), and Alturas, California (2017).



**Figure 42.** Availability of financial incentives and risk mitigation schemes for geothermal energy projects vs. number of GDH installations and geothermal nameplate capacity in the United States over time

Risk mitigation schemes include GLGP = Geothermal Loan Guarantee Program; PRDA = Program Research and Development Announcement; and UCDP = The User-Coupled Confirmation Drilling Program. Financial incentives include PON = Program Opportunity Notice; ITC = Investment Tax Credit; and ARRA = American Recovery and Reinvestment Act. For more details, see Section 5 of this report, as well as Lund and Bloomquist (2012).

Figure 42 suggests that federal policy may have had an impact on geothermal development. The support for both direct-use geothermal and power production in the late 1970s and early 1980s was substantial compared to any other period analyzed in this report. In the decades after this period, the number of programs supporting geothermal energy focused mostly on power production rather than GDH. Other factors may have also influenced the decline in the number of new direct-use projects since the early 1980s, such as the emergence of alternate technologies (e.g., heat pumps) and competition from natural gas (Lund et al. 2020).

Geothermal power capacity additions increased the most during the 1980s. This decade was preceded by a period of significantly increased funding for the geothermal program annual budget at the federal level. A lag between the two periods of approximately five years may be explained by number of years that it takes to develop a geothermal power plant, from exploration to commissioning. The geothermal program used its funding to reduce the risk of geothermal development in its initial stages, to promote the mapping of the resource nationwide, and to fund exploration and development of power plants.

The American Recovery and Reinvestment Act (ARRA), enacted in 2009, also substantially increased federal geothermal funding, but did not focus on direct use. The funding was shared between conventional hydrothermal and newer technologies like EGS. Between 2009 and 2014, 561 MW of new geothermal power capacity, but no GDH installations, were added nationally.

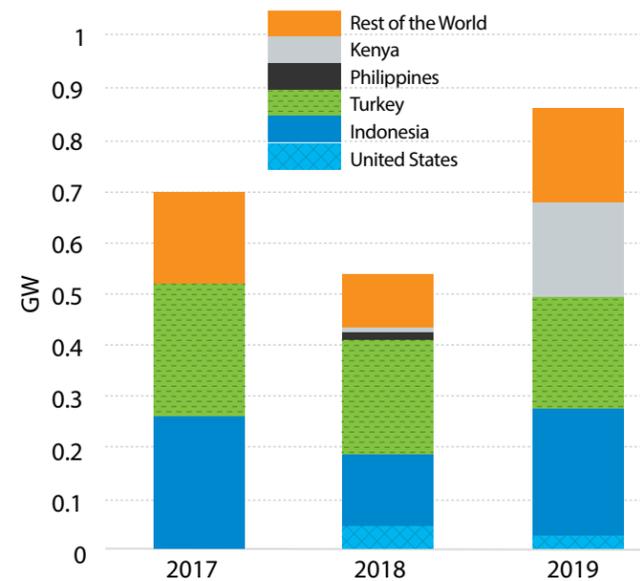
Given the number of variables that can influence the deployment of geothermal, it is not possible to prove causation for geothermal growth from any particular variable. However, there does seem to be a correlation between a few variables and annual geothermal capacity additions. Those variables include significant increases in federal funding for geothermal technologies (positive correlation), tax incentives (positive correlation), natural gas prices (negative correlation), and the flow of incentives for renewable energy to other types of clean energy, mostly solar and wind (negative correlation) (see the discussion on RPS capacity additions in Section 7.1).

Policy mechanisms to price and reduce carbon emissions, such as cap and trade systems, have not had a noticeable impact on geothermal development in the United States thus far.

However, if other states follow California’s lead in accounting for emissions not only from power plants but also from participants in other sectors of the economy—particularly in the heating and cooling sector—this could spur more interest in decarbonizing heating and cooling technologies.

### 7.4 International Programs for Accelerating Geothermal Deployment

While geothermal power production growth in the United States has been flat, growth worldwide has been more robust. According to the International Energy Association (IEA), Indonesia, Turkey, and Kenya have seen the largest amount of geothermal power production growth from 2017 through 2019 (Figure 43). The growth in these countries is thought to be heavily linked to their policy choices. All three countries employ risk mitigation schemes of some kind (GEORISK 2020, Ngugi 2014, World Bank 2020). Kenya built the vast majority of its geothermal industry via public financing. Projects are



**Figure 43.** Geothermal capacity additions in selected countries, 2017–2019  
Source: IEA (2020a)

generally supported by the government in early stages via direct financing and in later stages via equity and loans. In 2019, the New Energy Act in Kenya created additional fiscal incentives such as duty waivers on equipment, tax holidays, and letters of support, which act as a political guarantee (Omenda et al. 2020).

In addition, Turkey and Indonesia have both implemented feed-in tariffs with the express purpose to boost geothermal deployment. In 2011, Turkey implemented a 10.5c/kWh geothermal feed-in tariff that currently runs through mid-2021 (Richter 2020a). Turkey has seen its geothermal nameplate capacity grow by almost 1,500 MW during that time (Mertoglu et al. 2020). Indonesia has also had a feed-in tariff in place since 2012, with a new scheme to accelerate growth currently

in development (Hasan and Wahjosudibjo 2014, Richter 2020b). Indonesia’s geothermal power capacity has grown by 1,000 MW during that time (Darma et al. 2020).

Like geothermal power production, GDH growth has been flat in the United States, but has seen more deployment worldwide. As of 2020, 29 countries have installed GDH systems (Lund and Toth 2020). As of 2019, there were 327 GDH and cooling systems in Europe, with total installed capacity of 5.5 GWth, used for buildings, industry, services, and agriculture in 25 countries (EGEC 2020a). More than 1.2 GWth of additional GDH capacity is planned to be installed in Europe (EGEC 2020a). China currently has seven large-scale GDH systems for a total installed capacity of about 7 GWth (Lund and Toth 2020).

**Table 11.** Examples of Barriers for GDH Development and Policies Implemented in Europe to Mitigate the Barriers  
Information from EGEC (2013) and GeoDH (2014c)

Barrier	Example of Policies in Europe That Address Barrier
High upfront cost reduces competitiveness of geothermal heat and power	<p>Various funding opportunities are available at European, national, and regional levels to provide grants and low-cost loans for development of GDH. Examples include the European Investment Bank, the European Investment Fund, and the “Heat Fund” in France.</p> <p>Some countries (e.g., Italy, Netherlands, U.K.) have feed-in tariffs for geothermal heat</p> <p>Some countries (e.g., France, Hungary, Italy, Netherlands) have tax rebates and tax reductions for providing geothermal heat</p>
High upfront risk	<p>Some countries (e.g., France, Germany, Belgium, Netherlands) have government risk insurance funds in place to mitigate short-term risk (e.g., failed well) and long-term risk (e.g., resource depletion)</p> <p>Upfront risk may hinder securing attractive financing. Low- or zero-interest loans at European and country level (e.g., France, Germany, Hungary) are available for GDH projects</p> <p>Geologic data from drilling becomes publicly available in some countries (e.g., the Netherlands), benefiting future projects</p>
Lack of public involvement and knowledge of geothermal energy	European-wide geothermal agencies in place (e.g., EGEC, GeoDH, RHC-Platform) that promote GDH in Europe and increase awareness of GDH potential
Slow permitting process	European-wide agencies (e.g., EGEC, GeoDH, RHC-Platform) with mission to streamline policies, remove administrative and financial barriers, and provide recommendations (administrative, legal, financial and managerial) to assist developers
Absence of geothermal professionals, consultants and businesses	Geothermal training programs in place (e.g., by RHC-Platform, GeoTrainet) to assist with training authorities and workforce
Low-carbon energy sources not prioritized over high-carbon energy sources	CO <sub>2</sub> tax exists in some countries (e.g., Finland, Sweden, Denmark), benefiting low-carbon heat production (e.g., geothermal).

There appears to be a strong correlation between policy and GDH development. Currently, a wide spectrum of policy and market factors make GDH development more favorable in Europe than in the United States. These include financial incentives, insurance schemes, and national and European-wide programs for promoting GDH and streamlining the permitting process. A list of barriers to GDH development and policies in Europe that address these barriers is provided in Table 11.

Based on this table, there are several policy-related impediments to GDH development in the United States beyond the barriers listed in Section 4.5.2, such as the lack of risk mitigation schemes (e.g., insurance) for geothermal energy, lack of carbon pricing schemes, leasing difficulties and the extended timeline for leasing on federal lands (Lund and Bloomquist 2012), and others.

### 7.4.1 Geothermal Risk Mitigation Schemes

One key to worldwide geothermal growth has been the multitude of risk mitigation systems employed. As previously discussed, risk insurance or risk mitigation funds for power production projects exist in Turkey, Indonesia, and Kenya. In addition, the Geothermal Risk Mitigation Facility for Eastern Africa<sup>5</sup> is intended to spur geothermal development by encouraging public and private investors and private partnerships. To accomplish this, the Geothermal Risk Mitigation Facility provides grants to conduct surface studies for reservoir confirmation and for drilling and testing of geothermal exploration and confirmation wells. In Latin America, the Inter-American Development Bank offers a variety of financial products and risk mitigation instruments for both publicly and privately backed projects with the goal of jumpstarting geothermal deployment in the region (Inter-American Development Bank 2014). The risk mitigation solutions on offer from the bank include technical assistance grants, direct loans to governments, private development loans, lines of credit for development banks, and access to international concessional finance.

As discussed in Section 5.2, the United States employed several risk mitigation schemes in the 1970s and early 1980s

to accelerate geothermal growth. The Geothermal Loan Guarantee Program, the PRDA, PONs, and the User-Coupled Confirmation Drilling Program all contributed to the initial development of the U.S. geothermal industry. From the mid-1970s through the late 1980s, U.S. nameplate capacity increased by approximated 2,000 MW, and 15 additional GDH systems were installed (Figure 42).

Recent GDH deployment in Europe has been driven by several de-risking tools put in place (GEORISK 2020). Other more power-focused risk mitigation systems exist in Turkey, Indonesia, Kenya (as well as Africa as a whole), and Latin America. Schemes for de-risking geothermal development include:

- Grants
- Convertible grants
- Payable grants (loans)
- Public insurance
- Public financing
- Public private partnership
- Private insurance
- Direct government investment.

Risk insurance funds for GDH projects exist in France, Germany, Iceland, the Netherlands, and Switzerland. In France, funding mechanisms to help accelerate GDH development have been in place since the 1980s. The financing system addresses short-term risk (well drilling) and long-term risk (resource sustainability and the potential risk of resource depletion). This system is influenced by the fact that GDH drilling in the Paris Basin is relatively low risk (78% full success,

18% partial success, 4% total failure), but outside Paris, the risk is higher (25% failure) (GEORISK 2020). In Switzerland, the 2050 energy strategy was established in 2017 and promotes the use of geothermal energy for heat and power. As such, projects are eligible to receive a large range of public support, including risk mitigation but also feed-in tariffs, exploration subsidies paid throughout the life of the project, and other incentives (Swiss Energy Office 2020).

**Risk insurance funds for GDH projects exist in France, Germany, Iceland, the Netherlands, and Switzerland. In France, funding mechanisms to help accelerate GDH development have been in place since the 1980s.**

### 7.4.2 Alternative Business Models for Geothermal

As discussed in Section 3.2.4, geothermal power's LCOE is higher than some competing renewable electricity sources (Figure 13). One potential solution is to augment geothermal project economics with additional revenue streams. As introduced in Section 6.4, hybrid plants and/or co-location is a currently viable solution. Several projects in Nevada, including Stillwater (Enel), Patua (Cyrq), and Tungsten Mountain (Ormat) have added solar PV to their geothermal power plants. Time-of-day pricing can further boost these projects' economics (Robertson-Tait et al. 2020).

Another promising hybrid revenue stream is mineral extraction, especially lithium, from geothermal brine. As discussed in Section 6.5, lithium and rare earth elements are increasingly in demand for use in technologies such as wind turbines, solar panels, and batteries used in phones, electric vehicles, and other electronics. There are a host of extraction methods currently being researched, though none have been proven to be economical as of yet. However, both CTR and EnergySource are currently developing projects in the Salton Sea area to pursue lithium extraction. CTR's Hell's Kitchen project is a combined geothermal power and lithium extraction plant and, as seen in Section 3.4.1, has already secured a PPA. CTR estimates the revenue potential from lithium to be 15 times that of selling electricity. EnergySource's project ATLiS, to be built adjacent to its 60-MW Featherstone geothermal plant, is anticipated to produce around 16,500 tonnes of lithium per year beginning in 2023 (Trabish 2020).

There are other hybrid models that are early in development but promising, nonetheless. Section 6.6 covered a myriad of underground TES types. These emergent technologies seek to use shallow aquifers, deeper reservoirs, boreholes, pits, or mines for thermal storage. These technologies allow the seasonal storage of heat during times of abundant sun and can be utilized for electricity generation at night or during the winter. Hybridizing geothermal energy with seasonal energy storage could greatly improve the value proposition of an integrated subsurface energy system. Using geothermal power for hydrogen production is another idea that would add value to an integrated geothermal energy proposition. In this concept, during times of abundant electricity, geothermal energy is used to generate hydrogen through electrolysis and then employed in electrolytic cells to help balance the grid. However, this concept has yet to be proven and may require the development of new resources (e.g., supercritical geothermal fluids). Both underground TES and hydrogen production would allow flexibility by utilizing geothermal energy for grid balancing (Elders et al. 2019).

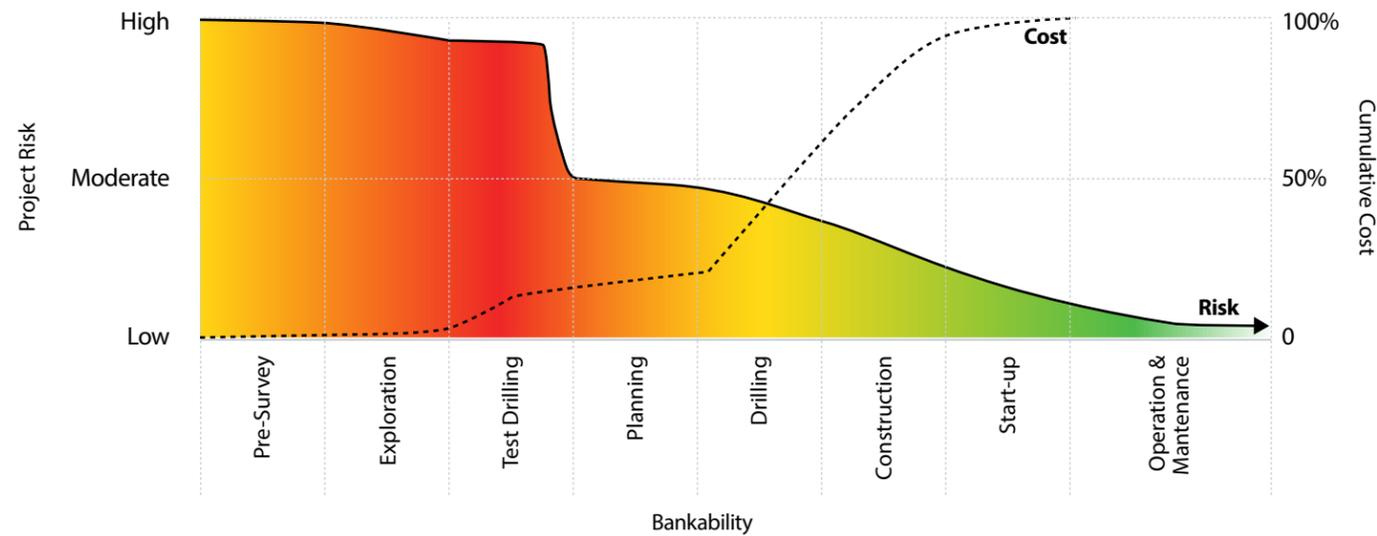
Alternate financial models are another potential solution for increasing the competitiveness of geothermal projects. There are three frequently used financing models for GDH in Europe (GEORISK 2020): (1) public investment undertaken by the local or regional authority; (2) private sector investment, which ultimately sells the heat directly to the grid-connected subscribers over a long duration (20–30 years); and (3) a hybrid public-private approach, which entails the creation of companies dedicated to GDH development with investment shared by both public and private entities. Within this financing framework, two business models are most common: (1) the case of a district heating company decarbonizing its heat supply, with a marketing strategy combining sustainable heat supply and energy saving services; and (2) the case of a dedicated GDH project developer (public or private) aiming to propose a new district heating system supplied by geothermal energy (GeoDH 2014c). A third business model is available, featuring cascaded use of geothermal heat from a power plant.

## 7.5 Potential Avenues for Growth

### 7.5.1 The Emergence of an Oil-and-Gas-to-Geothermal Transition in the United States

One potential avenue for geothermal industry growth that has received recent attention is from the oil and gas industry. Other than in the early days of geothermal exploration, U.S. oil and gas operators have been only minimally involved in U.S. geothermal development. The historic 2020 downturn in oil and gas prices has prompted speculation about oil and gas operators taking another look at geothermal. Per the IEA's *Renewables 2020* report, "geothermal power is also receiving greater interest from oil companies, which recognise opportunities to diversify their activities while capitalising on their drilling expertise" (IEA 2020b). This is largely because of the many similarities between the industries. Geothermal and oil and gas use much of the same equipment, contractors, and expertise for drilling wells (Finlay 2020). There is also significant overlap of the subsurface geologic skills needed to explore for geothermal and oil and gas, as well as the engineering skills to produce it from the ground. The two industries even have similar risk and spend profiles (Figure 44). In addition, some oil and gas operators are already investing in renewable energy sources such as solar and wind (Finlay 2020). Finally, tens of thousands of oil and gas workers have been laid off and may be looking to transition into a new industry where their subsurface skills are valued (Aranoff 2020).

<sup>5</sup> For more information, see: <https://grmf-eastafrica.org/about-grmf/objectives/>.



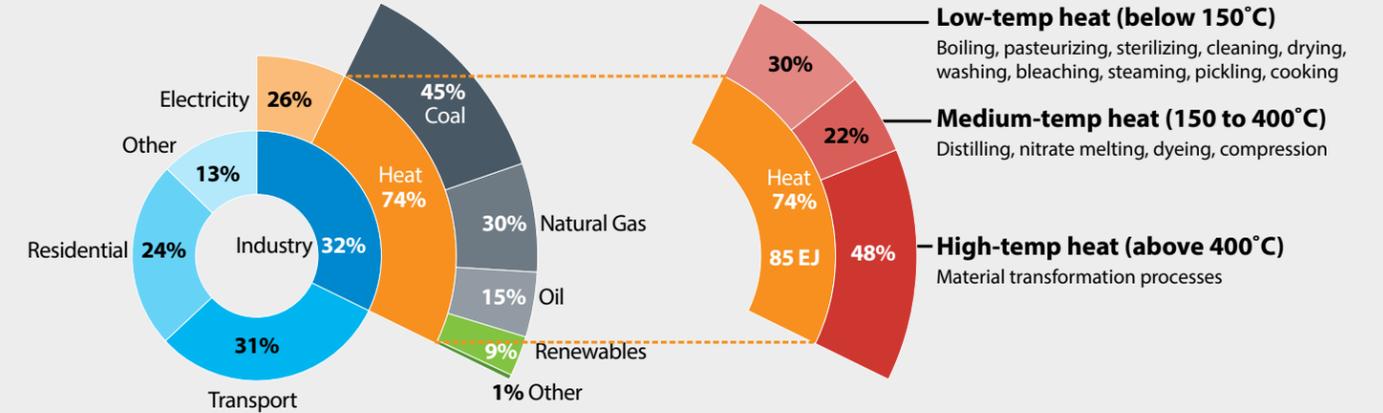
**Figure 44.** Geothermal project risk

Source: ESMAP (2012)

However, there are significant barriers to the transition. For one, there is a large difference in the current scale of geothermal development compared to oil and gas. Whereas oil and gas are global commodities, geothermal energy operates locally with local customers (Finlay 2020). In addition, oil and gas projects can be permitted and drilled relatively quickly, but geothermal projects have significant regulatory and financial barriers and can take 7–10 years to bring online (Young et al. 2014). Though many technologies in the exploration, characterization, and production of geothermal reservoirs at depth are similar to those used in oil and gas, there are also many differences in application and process that will require significant knowledge transfer. This can also be an advantage as opportunities for innovation can be accelerated by these synergies. Finally, to be successful in geothermal development, oil and gas operators must accept that short-term return on investments are relatively low for geothermal compared with their current business models, and instead will have to focus on the long-term returns and advantages associated with a constant, consistent, and unlimited resource.

**Oil and gas projects can be permitted and drilled relatively quickly, but geothermal projects have significant regulatory and financial barriers and can take 7–10 years to bring online.**

There is some evidence that some oil and gas companies are beginning to pivot to geothermal projects. In Canada, several oil and gas groups have recently created an alliance to promote geothermal development and to create jobs for displaced oil and gas workers. This new group believes that “geothermal power generation and direct heat opportunities will provide a significant opportunity for new industries and new long-term job creation, while helping Canada reduce greenhouse gas emissions and address climate change” (Richter 2020c). Although this is not a U.S. group, the issues are similar in both countries, and Canada’s geothermal industry is small. Therefore, it is reasonable to expect the formation of similar agreements in the United States. Indeed, as discussed in Section 5.1.7, the AGILE section of the Energy Act of 2020 creates a new program that intersects the Office of Fossil Energy and GTO to assist in the transfer of knowledge and techniques from the oil and gas sector to the geothermal industry.



**Figure 45.** Global industrial heat demand

Source: Philibert (2017)

### 7.5.2 Emerging Technologies

The development of “geothermal anywhere” technologies such as EGS would significantly increase the amount of geothermal economic potential. *GeoVision* models a mid-case EGS projection of 45 GW of geothermal electricity generation capacity by 2050, but *GeoVision* did not include CLG or supercritical geothermal in its calculations. The effects of the successful demonstration and deployment of either or both of those technologies could be considerable.

**The development of “geothermal anywhere” technologies such as EGS would significantly increase the amount of geothermal economic potential.**

Another potential area of growth is direct use of geothermal heat. For example, there is an enormous global demand for heat (85 EJ) from the industrial sector alone (Figure 45). Currently, the vast majority of this heat is provided by fossil fuels and only 9% from renewables. 30% of the total heat required is low temperature, or below 150°C, and 22% is medium temperature, or 150–400°C. Thus, a large part of this demand matches the available supply temperatures from geothermal resources.

This report is intended to provide policymakers, regulators, developers, researchers, engineers, financiers, and other stakeholders with up-to-date information and data reflecting the 2019 geothermal power production and district heating markets, technologies, and trends in the United States.

## 8 Conclusions

This report is intended to provide policymakers, regulators, developers, researchers, engineers, financiers, and other stakeholders with up-to-date information and data reflecting the 2019 geothermal power production and district heating markets, technologies, and trends in the United States. Geothermal Rising collected U.S. geothermal power production data via a questionnaire sent to all known U.S. geothermal operators and developers. This questionnaire requested information about both existing power production capacity and developing projects, which was then added to an existing GEA database and shared with NREL. For GDH systems, an NREL geothermal direct-use database was updated with information obtained from news articles, publications, and interviews conducted in 2020 with project owners, operators, and other stakeholders.

### 8.1 U.S. Geothermal Power Sector

The U.S. power sector saw little capacity growth from 2015 through 2019 as installed nameplate capacity went from 3,627 MW to 3,673 MW. In that time, 7 new geothermal power plants with 186 MW of nameplate capacity were brought online, most of which were field expansions or repowers. However, that was mostly offset by the retirement of 11 plants with 103 MW of capacity and a loss of efficiency at some remaining plants. Actual utility-scale power generation decreased from 15,917,575 MWh to 15,472,717 MWh over the same time period.

Developing projects saw a significant reduction from 77 in early 2016 to 58 in 2019. Of the 58 projects, 5 are in Phase IV, the phase closest to completion. The overall decrease was not due to projects being brought online, as only 2 of the projects catalogued in 2016 were fully developed and are currently operational. Some of the decline is likely due to industry reductions and consolidation, as the total number of geothermal developers dropped from 12 to 7.

Geothermal power production growth is likely hindered by its LCOE, which, although lower than coal and gas peaking plants, remains higher than utility-scale solar PV and wind and combined-cycle gas plants. However, geothermal plants offer several non-cost advantages such as 24 hours-a-day electricity production regardless of weather, dispatchability, minimal emissions, and a small footprint.

California's SB 100, which requires 100% zero-carbon electricity by 2045, could increase the value of geothermal power as a clean source of energy capable of adding stability to the grid in periods of overgeneration.

Recent regulatory changes may work in the geothermal industry's favor. The use of RPSs has primarily increased the deployment of wind and solar. However, California's SB 100, which requires 100% zero-carbon electricity by 2045, could increase the value of geothermal power as a clean source of energy capable of adding stability to the grid in periods of overgeneration.

There have been nine new geothermal PPAs signed since late 2019, indicating a renewed interest in geothermal power. After the data for this report were collected, Ormat brought the Steamboat Hills expansion online, increasing its generating capacity by 19 MW, and Ormat's Puna power plant was brought back online in 2020, both of which should increase geothermal net-generation in 2021 and beyond.

The geothermal power sector also looks ready to benefit from technological innovation. Three solar thermal hybrid plants are currently operational in Nevada. Two projects focused on lithium extraction from geothermal brine are in development near the Salton Sea. There is great interest in CLG systems, with successful tests at Coso and in Canada. Finally, and perhaps most importantly, the FORGE project continues to advance development of EGS in pursuit of the geothermal electricity growth forecasted in *GeoVision*.

## 8.2 U.S. Geothermal District Heating Sector

GDH technology is mature, and GDH installations are currently cost-competitive in Europe and parts of Asia. The competitiveness of GDH in the United States is questionable in 2020 due to the combination of inexpensive natural gas (2020 saw prices at a historic low of \$2/MMBTU), lack of carbon accounting, lack of incentives focused on renewable heating/cooling, and other factors.

Although there are only 23 U.S. GDH systems in operation today, the barriers to expansion of this sector are primarily political, social, and economic—not technical. The majority of the 23 GDH systems have been in continuous operation for more than 30 years, with relatively low operation and maintenance costs. An adequate subsurface resource exists to rapidly deploy GDH in many parts of the United States, whether through better use of conventional hydrothermal and sedimentary basin resources or through using EGS in direct-use systems.

Like geothermal power plants, GDH systems are capital-intensive, particularly in the high-risk early phases of project development (e.g., drilling). Operations and maintenance

expenses, however, are relatively low compared to conventional DH systems. Due to this cost structure, the majority of U.S. GDH systems have benefitted from some source of grant or loan financing available in the past, and almost all the current GDH installations worldwide (particularly in Europe) currently benefit from similar programs. A large percentage of the GDH projects in the United States were developed as part of the Program Opportunity Notice (PON) in the early 1980s. GDH installations may be too capital-intensive for cities or municipalities to undertake alone, and the current policy incentives such as ITC do not appear to be sufficient to accelerate U.S. GDH deployment. This is either because the incentives are not substantial enough or enduring enough, or because municipalities interested in installing GDH systems would not benefit because they are not tax liable.

## 8.3 Future Work

Periodic updates to the data and analyses presented in this paper for 2021 would help keep the geothermal energy sector—and outside stakeholders—updated on market trends. Having such updates will be important going into what many in the industry are calling the “geothermal decade” to benchmark progress and understand market dynamics.

Other topics not covered in this report but that may warrant future consideration include:

1. Inclusion of the entire U.S. direct-use sector, and/or expanding to include analysis of geothermal heat pump technologies, hybrid and thermal energy storage technologies, and other emerging geothermal technologies.

2. Collaboration with international geothermal market reporting organizations. The geothermal industry is currently experiencing more international growth than in the United States. To truly understand the direction of the industry, it is beneficial to consider both domestic and international focuses for the electricity and GDH sectors.
3. Additional information on national and international R&D activities that have the potential to impact the national and international geothermal market.
4. Increased focus on specific growth markets such as the industrial/commercial landscape, venture capital investment, and oil and gas investment, among other topics.

A comprehensive list of state-level geothermal policies and incentives does not exist and would require resources outside of the scope of this report. A thorough review would require investigating the available incentives (tax credits, financial incentives, grants, etc.), but also reading deeply into the terms and conditions of each incentive to understand the eligibility of geothermal technologies for all 50 states.

Finally, whereas carbon accounting rules for the use of renewable electricity are generally well-defined and widely accepted, this is not the case for renewable heating and cooling technologies. The lack of a workable and clear set of accounting rules may be a barrier to deployment of renewable heating and cooling technologies such as geothermal (Zabeti et al. 2018). Future research can identify mechanisms for including renewable heating and cooling in carbon accounting schemes such as RPSs, cap and trade, and other programs.

# References

- Aalten, T., Willemsen, N., Kleinlengenbelt, J., and Pittens, B. 2018. "Small scale direct use of geothermal energy in sedimentary basins using slimhole drilling techniques, Indonesia." Report to GEOCAP, Publication #GEOCAP/2018/REP/IF Technology/WP2.03/1. <https://www.geocap.nl/.uc/f048a0187010242d11f004cd712044559a149324b782d00/October%202018%20-%20IF%20Technology%20-%20Geocap%20-%20Small%20scale%20direct%20use%20of%20geothermal%20ene.pdf>.
- Akar, S., Augustine, C., Kurup, P., and Mann, M. 2018. *Global Value Chain and Manufacturing Analysis on Geothermal Power Plant Turbines*. National Renewable Energy Laboratory: Golden, CO. <https://doi.org/10.2172/1471556>.
- Alaska Energy Authority. 2021. "Renewable Energy Fund." <http://www.akenergyauthority.org/Portals/0/Fact%20Sheets/2020.02.11%20Renewable%20Energy%20Fund%20Fact%20Sheet.pdf?ver=2021-02-11-160112-237>.
- Allis, R., Moore, J., Anderson, T., Deo, M., Kirby, S., Roehmer, R., and Spencer, T. 2013. "Characterizing the Power Potential of Hot Stratigraphic Reservoirs in the Western U.S. Proceedings," Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford CA SGP-TR-198. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2013/Allis.pdf>.
- Amaya, Alvaro, Joseph Scherer, John Muir, Mehul Patel, and Brian Higgins. 2020. "GreenFire Energy Closed-Loop Geothermal Demonstration using Supercritical Carbon Dioxide." *Proceedings*, 45<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020. SGP-TR-216. <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2020/Higgins.pdf>.
- AMO. 2019. "Static Sankey Diagram of Process Energy in U.S. Manufacturing Sector (2010 MECS)." U.S. Department of Energy Advanced Manufacturing Office. <https://www.energy.gov/eere/amo/static-sankey-diagram-process-energy-us-manufacturing-sector-2010-meecs>.
- Anderson, T.C., 2012. "Review of permeability characteristics in drilled, sediment-hosted geothermal systems." Report submitted as part of DE-EE5128 "Novel Geothermal Development of Deep Sedimentary Systems in the United States." Energy and Geoscience Institute, 66.
- Angelos, Audrey and Guangdong Zhu. Forthcoming. *Geothermal Energy*. National Renewable Energy Laboratory: Golden, CO.
- Aronoff, K. 2020. "The Oil Crash Could Be Geothermal's Big Break." *The New Republic*. May 2020. <https://newrepublic.com/article/157646/oil-crash-geothermals-big-break>.
- Augustine, C., 2014. "Analysis of Sedimentary Geothermal Basins Using an Analytical Reservoir Model." *GRC Transactions*, v. 38. <http://pubs.geothermal-library.org/lib/grc/1033602.pdf>.
- Augustine, C., and Falkenstern, D. 2014. "An Estimate of the Near-Term Electricity-Generation Potential of Co-Produced Water from Active Oil and Gas Wells." *Society of Petroleum Engineers Journal*, June 2014, pp 530-541. <https://onepetro.org/SJ/article-abstract/19/03/530/205877/An-Estimate-of-the-Near-Term-Electricity?redirectedFrom=fulltext>.
- Bandyk, Matthew. 2020. "Tax Equity Financing for Renewables Remains Robust, but Deal Delays Likely, Morgan Stanley, Others Agree." 2020. <https://www.utilitydive.com/news/tax-equity-financing-for-renewables-remains-robust-but-deal-delays-likely/578551/>.
- Bank of Montreal (California), and Merrill Lynch, Pierce, Fenner & Smith, Inc. 1977. "Geothermal Loan Guaranty Program." Rogers Engineering Co., Inc., San Francisco, CA. <https://doi.org/10.2172/883317>.
- Barbose, Galen. 2021. 17. *U.S. Renewables Portfolio Standards: 202117 Status Update: Early Release Annual Status Report*. Lawrence Berkeley National Laboratory: Berkeley, CA. <https://emp.lbl.gov/publications/us-renewables-portfolio-standards-3>. <http://eta-publications.lbl.gov/sites/default/files/2017-annual-rps-summary-report.pdf>.
- Bartosz, A. and P. Thomsen. 2020. "The Value of Geothermal in California." *GRC Bulletin*, Vol. 49, No. 3.
- Beckers, Koenraad, and Kevin McCabe. 2019. "GEOPIRES v2.0: updated geothermal techno-economic simulation tool." *Geothermal Energy*. 7(5). <https://geothermal-energy-journal.springeropen.com/articles/10.1186/s40517-019-0119-6>.
- Bershaw, J. et al. 2020. *An Integrated Feasibility Study of Reservoir Thermal Energy Storage (RTES) in Portland, OR, USA*. Portland State University. U.S. Department of Energy, Geothermal Technologies Program Final Technical Report.
- Bertani, R. 2016. "Deep geothermal energy for heating and cooling." Book chapter: *Renewable Heating and Cooling*. Elsevier Ltd. <http://dx.doi.org/10.1016/B978-1-78242-213-6.00004-7>.
- Bhattacharyya, Bidisha. 2020. "Renewable Energy Tax Credits: The Case for Refundability." Center for American Progress. <https://cdn.americanprogress.org/content/uploads/2020/05/27054658/Refundable-Energy-Tax-Credits.pdf>.
- BLM. 2020. "Public Land Statistics." U.S. Department of the Interior. <https://www.blm.gov/about/data/public-land-statistics>.
- Bloemendal, Martin, and Niels Hartog. 2018. "Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATEs systems." *Geothermics*, 71: 306-319. <https://doi.org/10.1016/j.geothermics.2017.10.009>.
- Bloomquist, R. Gordon. 2005. "The Evolution of U.S. Policy Designed to Encourage Geothermal Development Provision of Access and Encouraging Project Development." <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/2201.pdf>.
- Brotheridge, J., Leniston, M., and Christyono. 2000. "Potential environmental and social impacts of small-scale, rural geothermal development." *Proceedings*, World Geothermal Congress, Kyushu—Tohoku, Japan. <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2000/R0267.pdf>.
- Brown, Phillip, and Molly F. Sherlock. 2011. "ARRA Section 1603 Grants in Lieu of Tax Credits for Renewable Energy: Overview, Analysis, and Policy Options." Congressional Research Service. [https://www.everycrsreport.com/files/20110208\\_R41635\\_bc79f44cf92fc1305699f4d19a90602ab635fbc4.pdf](https://www.everycrsreport.com/files/20110208_R41635_bc79f44cf92fc1305699f4d19a90602ab635fbc4.pdf).
- Burns, Erick R., John Bershaw, Colin F. Williams, Ray Wells, Matt Uddenberg, Darby Scanlon, Trenton Cladouhos, and Boz van Houten. 2020. "Using saline or brackish aquifers as reservoirs for thermal energy storage, with example calculations for direct-use heating in the Portland Basin, Oregon, USA." *Geothermics*, 88. <https://www.sciencedirect.com/science/article/pii/S0375650519304729>.
- C2ES. 2020. "U.S. State Greenhouse Gas Emissions Targets." Center for Climate and Energy Solutions. <https://www.c2es.org/document/greenhouse-gas-emissions-targets/>.
- C2ES. 2021a. "Market-Based State Policy." Center for Climate and Energy Solutions. <https://www.c2es.org/content/market-based-state-policy/>.
- C2ES. 2021b. "California Cap and Trade." Center for Climate and Energy Solutions. <http://www.c2es.org/content/california-cap-and-trade/>.
- CAISO. 2020. "Fast Facts." California Independent System Operator. [https://www.caiso.com/documents/flexibleresourceshelprenewables\\_fastfacts.pdf](https://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf).
- Capitol Hawaii 2016. "HB 1170, HD2: Relating to Land Resources." [https://www.capitol.hawaii.gov/Session2016/Testimony/HB1170\\_HD2\\_TESTIMONY\\_TRE-WLA\\_03-22-16.PDF](https://www.capitol.hawaii.gov/Session2016/Testimony/HB1170_HD2_TESTIMONY_TRE-WLA_03-22-16.PDF).
- CARB. 2021. "Allowance Allocation: Cap-and-Trade Program." California Air Resources Board. <https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/allowance-allocation>.
- Cladouhos, T., Petty, S., Bonneville, A., Schultz, A., Sorlie, C. 2018. "Super Hot EGS and the Newberry Deep Drilling Project." Proceedings of the 43<sup>rd</sup> Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, 2018. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2018/Cladouhos.pdf>.
- Climo, M., E. Mroczek, B. Carey, A. Hill, and B. Barton. 2015. "Extraction from New Zealand's Geothermal Brines: Where to Next?" New Zealand Geothermal Conference, Taupo, New Zealand. [https://www.researchgate.net/publication/290003979\\_Mineral\\_Extraction\\_from\\_New\\_Zealand's\\_Geothermal\\_Brines\\_Where\\_to\\_Next](https://www.researchgate.net/publication/290003979_Mineral_Extraction_from_New_Zealand's_Geothermal_Brines_Where_to_Next).
- CO State Auditor. 2020. "Enterprise Zone Refundable Renewable Energy Investment Tax Credit." [http://leg.colorado.gov/sites/default/files/images/2020-te3\\_enterprise\\_zone\\_refundable\\_renewable\\_energy\\_investment\\_tax\\_credit\\_0.pdf](http://leg.colorado.gov/sites/default/files/images/2020-te3_enterprise_zone_refundable_renewable_energy_investment_tax_credit_0.pdf).
- Combs, J., Garg, S., and Pritchett, J. 1997. "Geothermal slim holes for small off-grid power projects." *Renewable Energy*, v10, issue 2, p389-402. [https://doi.org/10.1016/0960-1481\(96\)00096-1](https://doi.org/10.1016/0960-1481(96)00096-1).
- Conservation Voters New Mexico. 2016. "Conservation Group Disappointed In Failure To Renew New Mexico Solar Tax Credit." <https://cvnm.org/in-the-news/conservation-group-disappointed-in-failure-to-renew-new-mexico-solar-tax-credit/>.
- Cornell University. 2020. "7.2M grant funds exploratory research into Earth Source Heat." <https://news.cornell.edu/stories/2020/08/72m-grant-funds-exploratory-research-earth-source-heat>.

- Cruce, Jesse R., Jeff Cook, and Tim Larsen. 2020. "Streamlining Energy Sprawl: Assessment of Geothermal Impacts on Public Lands." *GRC Transactions*, Vol. 44, 2020. <https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1034273>.
- Dacey, Connor. 2021. "Energizing the Nation: The Energy Act of 2020 Becomes Law." Speaking of Geoscience (blog). January 28, 2021. <https://speakingofgeoscience.org/2021/01/28/energizing-the-nation-the-energy-act-of-2020-becomes-law/>.
- Darma, S., Y. Imami, M. N. A. Shidqi, T. D. Riyanto, M. Y. Daud. 2020. "Country Update: The Fast Growth of Geothermal Energy Development in Indonesia." Proceedings of the World Geothermal Congress 2020. <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01073.pdf>.
- Do, Q., Doan, T., Hoang, T., Nguyen, T., and Tran, T. 2019. "Potential Application of Slimhole Drilling Technology to Geothermal Wells in Vietnam." In *Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering*, pp 239–244. [https://doi.org/10.1007/978-981-13-2306-5\\_32](https://doi.org/10.1007/978-981-13-2306-5_32).
- DOE. 2017. "Energy Department Announces up to \$4 Million for Geothermal Deep Direct-Use Feasibility Studies." <https://www.energy.gov/eere/articles/energy-department-announces-4-million-geothermal-deep-direct-use-feasibility-studies>.
- DOE. 2020. Office of Energy Efficiency and Renewable Energy. "Past and Present EERE Budget" <https://www.energy.gov/eere/budget/past-and-present-eere-budget> and "EERE Budget Search" [https://www7.eere.energy.gov/office\\_eere/program\\_budget\\_formulation.php](https://www7.eere.energy.gov/office_eere/program_budget_formulation.php).
- DOE. N.D. "Geothermal: Electricity Generation." U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. <https://www.energy.gov/eere/geothermal/electricity-generation>.
- DSIRE. 2018a. "Modified Accelerated Cost-Recovery System (MACRS)." <https://programs.dsireusa.org/system/program/detail/676>.
- DSIRE. 2018b. "Residential Alternative Energy System Tax Credit." <https://programs.dsireusa.org/system/program/detail/366>.
- DSIRE. 2021a. "Property Tax Assessment for Renewable Energy Equipment." <https://programs.dsireusa.org/system/program/detail/2984>.
- DSIRE. 2021b. "Property Tax Exemption for Wind, Solar, and Geothermal Energy Producers." <https://programs.dsireusa.org/system/program/detail/2786>.
- E&E News. 2020. "CONGRESS: 13 Ways the Massive Omnibus Hits Energy." <https://www.eenews.net/stories/1063721401>.
- Eberle, Annika, Heath Garvin, Scott Nicholson, and Alberta Carpenter. 2017. "Systematic Review of Life Cycle Greenhouse Gas Emissions from Geothermal Electricity." National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy17osti/68474.pdf>.
- EERE. N.D. "Enhanced Geothermal Systems Demonstration Projects." U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. <https://www.energy.gov/eere/geothermal/enhanced-geothermal-systems-demonstration-projects>.
- EGEC. 2013. *Financing Geothermal Energy*. <https://www.egec.org/wp-content/uploads/2017/05/EGEC-policy-paper-on-financing-geothermal-Fin.pdf>.
- EGEC. 2020a. *2019 EGEC Geothermal Market Report*. Ninth Edition.
- EGEC. 2020b. *Smart Sectoral Integration: The multiple benefits of geothermal energy*. <https://www.egec.org/wp-content/uploads/2020/04/Smart-Sectoral-Integration.pdf>.
- EIA. 2015. "Space heating and water heating account for nearly two thirds of U.S. home energy use." U.S. Energy Information Administration. <https://www.eia.gov/todayinenergy/detail.php?id=37433>.
- EIA. 2019a. "Annual Electric Generator data." U.S. Energy Information Administration. <https://www.eia.gov/electricity/data/eia860/>.
- EIA. 2019b. "Electric Power Annual 2019." U.S. Energy Information Administration. <https://www.eia.gov/electricity/annual/pdf/epa.pdf>.
- EIA. 2020a. "Natural Gas Prices." U.S. Energy Information Administration. [https://www.eia.gov/dnav/ng/ng\\_pri\\_sum\\_a\\_EPG0\\_PRS\\_DMcf\\_a.htm](https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm)
- EIA. 2020b. "Electricity explained: Electricity in the United States." U.S. Energy Information Administration. <https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php>.
- EIA. 2020c. "Geothermal explained: Geothermal energy and the environment." U.S. Energy Information Administration. <https://www.eia.gov/energyexplained/geothermal/geothermal-energy-and-the-environment.php>.
- EIA. 2020d. "Most U.S. utility-scale geothermal plants built since 2000 are binary-cycle plants." U.S. Energy Information Administration. <https://www.eia.gov/todayinenergy/detail.php?id=44576>.
- EIA. 2021a. "Annual Energy Outlook 2021." U.S. Energy Information Administration. <https://www.eia.gov/outlooks/aeo/electricity/sub-topic-03.php>.
- EIA. 2021b. "Henry Hub Natural Gas Spot Price (Dollars per Million Btu)." 2021. U.S. Energy Information Administration. <https://www.eia.gov/dnav/ng/hist/rngwhhdA.htm>.
- Elders, W., W. Osborn, A. Raju, and A. Martinez-Morales. 2019. "The Future Role of Geothermal Resources in Reducing Greenhouse Gas Emissions in California and Beyond." Proceedings of the 44th Workshop on Geothermal Reservoir Engineering, Stanford University. <https://www.semanticscholar.org/paper/The-Future-Role-of-Geothermal-Resources-in-Reducing-Elders-Osborn/704ea414c0beb1a614999e582dcaef355dc65f1e>
- Eliason, John A., David B. Weisblat, and Tori Roessler. 2020. "Production Tax Credit Extended for Renewable Projects Beginning Construction in 2020." Foley & Lardner LLP. <https://www.foley.com/en/insights/publications/2020/01/production-tax-credit-renewable-projects-2020>.
- EnergyCentral.com. 2017. "Cyrq Energy adds solar plant to its Patua geothermal power plant in Nevada." <https://energycentral.com/news/cyrq-energy-adds-solar-plant-its-patua-geothermal-power-plant-nevada-0>.
- EnergySource. 2020. "EnergySource Minerals." Presented at CEC's Presentations of California's Lithium Recovery Initiative – Symposium, February 12, 2020.
- ENI. 2020. "Mini-geothermal energy gains ground." <https://www.eni.com/en-IT/low-carbon/mini-geothermal-energy-gains-ground.html>.
- EPA. 2020. "Renewable Space Cooling." U.S. Environmental Protection Agency. <https://www.epa.gov/rhc/renewable-space-cooling>.
- Erickson, D., Kyung, I., and Holdmann, G. 2005. "Geothermal Powered Absorption Chiller for Alaska Ice Hotel." *Transactions: Geothermal Resources Council* 29: 57-59.
- ESMAP. 2012. *Geothermal Handbook: Planning and Financing Power Generation*. Energy Sector Management Assistance Program. <https://openknowledge.worldbank.org/bitstream/dle/10986/23712/728280NWP0Box30k0TR0020120Optimized.pdf?sequence=1&isAllowed=y>.
- EuroStat. 2020. "Natural gas prices for household consumers, second half of 2019." [https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural\\_gas\\_price\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics).
- Federal Register. 2007. "Part 3200—Geothermal Resource Leasing." Part II: Department of the Interior: Bureau of Land Management: 43 CFR Parts 3000, 3200, and 3280 Geothermal Resource Leasing and Geothermal Resources Unit Agreements; Final Rule. <https://www.govinfo.gov/content/pkg/FR-2007-05-02/pdf/E7-7991.pdf#page=44>.
- Finlay, K. 2020. "Oil collapse sparks new interest in geothermal energy." REN21. <https://www.ren21.net/geothermal-energy/>.
- Fleischmann, D. J. 2007. "An assessment of geothermal resource development needs in the western United States." Geothermal Energy Association. Report prepared for the U.S. Department of Energy. <http://www.sustentabilidad.uai.edu.ar/pdf/energia/StatesGuide.pdf>.
- Fleischmann, Daniel J. 2007. "An Assessment of Geothermal Resource Development Needs in the Western United States." Geothermal Energy Association. <http://www.sustentabilidad.uai.edu.ar/pdf/energia/StatesGuide.pdf>.
- Fleuchaus, Paul, Bas Godschalk, Ingrid Stober, and Philipp Blum. 2018. "Worldwide application of aquifer thermal energy storage – A review." *Renewable and Sustainable Energy Reviews*, 94: 861-876. <https://doi.org/10.1016/j.rser.2018.06.057>.
- Flores-Espino, Francisco, Tian Tian, Ilya Chernyakhovskiy, Megan Mercer, and Mackay Miller. 2016. *Competitive Electricity Market Regulation in the United States: A Primer*. <https://www.nrel.gov/docs/fy17osti/67106.pdf>.
- Fournier R. 1999. "Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment." *Econ Geol.* 1999; 94(8):1193–211. Doi:10.2113/gsecongeo.94.8.1193. <https://pubs.geoscienceworld.org/segweb/economicgeology/article-abstract/94/8/1193/21899/Hydrothermal-processes-related-to-movement-of?redirectedFrom=fulltext>.

- Fox, D. B., Sutter, D., and Tester, J. W. 2011. "The thermal spectrum of low-temperature energy use in the United States." *Energy & Environmental Science*, 4(10), 3731-3740. <https://es.stanford.edu/ERE/pdf/IGAstandard/SGW/2011/fox.pdf>.
- Friðleifsson G., and Elders W. 2017. "The Iceland Deep Drilling project geothermal well at Reykjanes successfully reaches its supercritical target." *Geothermal Resources Council Bull.* 46:30-3. <https://eseries.geothermal.org/PDFs/Articles/17MarchApril.pdf>.
- Friðleifsson G., Elders, WA, and Albertsson A. 2014. "The concept of the Iceland Deep Drilling project." *Geothermics*. 49:2-8. <https://www.sciencedirect.com/science/article/pii/S0375650513000217>.
- Fry, Nicholas. 2020. Rapid Geothermal District Heating Assessments For Municipal Utility Planners in the USA. *Transactions: Geothermal Rising* 44: p1307. <https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1034314>
- Gabbrielli, R. 2012. "A Novel Design Approach for Small Scale Low Enthalpy Binary Geothermal Power Plants." *Energy Conversion and Management*, v64, pp263-272. <https://doi.org/10.1016/j.enconman.2012.04.017>.
- Garapati, N., Hause, J. et al. 2020. "Feasibility of Deep Direct-Use Geothermal on the West Virginia University Campus-Morgantown, WV." West Virginia University. U.S. Department of Energy, Geothermal Technologies Program Final Technical Report.
- Garg, S., Combs, J., and Livesay, B. 2000. "Optimizing Casing Designs of Slim Holes for Maximum Discharge of Geothermal Fluids from Liquid Feedzones." *Proceedings, World Geothermal Congress, Kyushu—Tohoku, Japan*. <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2000/R0152.PDF>.
- GEA. 2010. "New Geothermal Terms and Definitions." [https://archive.geothermal.org/Policy\\_Committee/Documents/Geothermal\\_Terms\\_and\\_Definitions.pdf](https://archive.geothermal.org/Policy_Committee/Documents/Geothermal_Terms_and_Definitions.pdf).
- GEA. 2015. "Geothermal Energy Association Issue Brief: Firm and Flexible Power Services Available from Geothermal Facilities." [https://archive.geothermal.org/Policy\\_Committee/Documents/Firm\\_and\\_Flexible\\_Power\\_Services\\_from\\_Geothermal.pdf](https://archive.geothermal.org/Policy_Committee/Documents/Firm_and_Flexible_Power_Services_from_Geothermal.pdf).
- GEA. 2016. "2016 Annual U.S. & Global Geothermal Power Production Report." <https://geothermal.org/resources/2016-annual-us-global-geothermal-power-production>.
- Geirdal, C., Gudjonsdottir, M., and Jensson, P. 2015. "Economic Comparison of a Well-Head Geothermal Power Plant and a Traditional Geothermal Power Plant." *Proceedings, 38th Workshop on Geothermal Reservoir Engineering*. Stanford University. Stanford, California, February 11-13, 2013 SGP-TR-198. <https://www.sciencedirect.com/science/article/pii/S0375650514000406>.
- Geiser, Peter, Bruce D. Marsh, Markus Hilpert. 2016. "Geothermal: The Marginalization of Earth's Largest and Greenest Energy Source." *Proceedings, 43rd Workshop on Geothermal Reservoir Engineering*. Stanford University, Stanford, California, February 22-24, 2016. SGP-TR-209. [https://www.researchgate.net/publication/297471727\\_Geothermal\\_The\\_Marginalization\\_of\\_Earth's\\_Largest\\_and\\_Greenest\\_Energy\\_Source](https://www.researchgate.net/publication/297471727_Geothermal_The_Marginalization_of_Earth's_Largest_and_Greenest_Energy_Source).
- Genter, Albert, Keith Evans, Nicolas Cuenot, Daniel Fritsch, and Bernard Sanjuan. 2010. "Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS)." *Comptes Rendus Geoscience* 342: 502-516. <http://dx.doi.org/10.1016/j.crte.2010.01.006>.
- GeoDH. 2014a. "Boly." <http://geodh.eu/project/boly/>.
- GeoDH. 2014b. "Plessis Robinson." <http://geodh.eu/project/plessis-robinson/>.
- GeoDH. 2014c. "Developing Geothermal District Heating in Europe." [https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/geodh\\_final\\_publishable\\_results\\_oriented\\_report.pdf](https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/geodh_final_publishable_results_oriented_report.pdf).
- GeoDH. N.D. <http://geodh.eu/about-geothermal-district-heating/>
- GEORISK. 2020. "Developing Geothermal Projects by Mitigating Risks with Financial Instruments." <https://www.georisk-project.eu/>.
- GeoVision. 2019. *GeoVision: Harnessing the Heat Beneath Our Feet*. U.S. Department of Energy. DOE/EE-1306. <https://www.energy.gov/eere/geothermal/geovision>.
- Ginsberg, Michael, Shahar Goeta, and Vasilis Fthenakis. 2018. "Grid Flexibility and the Cost of Integrating Variable Renewable Energy: Toward a Renewable Energy Integration Adder for San Diego Gas and Electric Service Territory and the California Electric Grid." 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion. Waikoloa, HI. <https://ieeexplore.ieee.org/document/8547842>.
- Gomes, Andrew. 2020. "Puna Geothermal Venture primed for restart." *West Hawaii Today*. <https://www.westhawaii.com/2020/09/08/hawaii-news/pgv-primed-for-restart/>.
- Gosnold, W., Ballesteros, M., Wang, D., and Crowell, J. 2020. "Using Geothermal Energy to Reduce Oil Production Costs." *GRC Transactions*, Vol. 44. <https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1034249>.
- GPO. 2005. "Energy Policy Act of 2005." Public Law 109-58. August 8, 2005. <https://www.congress.gov/109/plaws/publ58/PLAW-109publ58.pdf>.
- Green, Sidney, John McLennan, Palash Panja, Kevin Kitz, Rick Allis and Joseph Moore. 2020. "Geothermal Battery Energy Storage." *Large-scale Subsurface Seasonal Solar Heat Storage for Future Value*. <https://www.sciencedirect.com/science/article/pii/S0960148120315081>
- Groenewoud, L., and Marcia, K. 2020. "The DEEP Geothermal Power Project: Wildcat Drilling for The Earth's Heat, Williston Sedimentary Basin (Canada)." *GRC Transactions*, Vol. 44, 2020. <https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1034255>.
- Hahn, Florian, Felix Jagert, Gregor Bussman, Isabella Nardini, Rolf Bracke, Torsten Seidel, and Timo König. 2019. "The reuse of the former Markgraf II colliery as a mine thermal energy storage." *European Geothermal Congress 2019, Den Haag, The Netherlands, 11-14 June 2019*. <http://europeangeothermalcongress.eu/wp-content/uploads/2019/07/64.pdf>.
- Hasan, M. and A. Wahjosudibjo. 2014. "Feed-In Tariff for Indonesia's Geothermal Energy Development, Current Status and Challenges." *Proceedings, 39th Workshop on Geothermal Reservoir Engineering*. Stanford University. February 24-26, 2014. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2014/Hasan.pdf>.
- Havsed, R., and Skog, G. 2018. "The Case for Small, Scalable and Standardized Geothermal Power Plants." *GRC Transactions*, Vol. 42. <http://pubs.geothermal-library.org/lib/grc/1033945.pdf>.
- Heeter, Jenny, Bethany Speer, and Mark Glick. 2019. *International Best Practices for Implementing and Designing Renewable Portfolio Standard (RPS) Policies*. National Renewable Energy Laboratory: Golden, CO. TP-6A20-72798. <https://www.nrel.gov/docs/fy19osti/72798.pdf>.
- Higgins, Brian, John Muir, Joe Scherer, and Alvaro Amaya. 2019. "GreenFire Energy Closed-Loop Geothermal Demonstration at the Coso Geothermal Field." *GRC Transactions*, 43. <http://pubs.geothermal-library.org/lib/grc/1033761.pdf>.
- geothermal-library.org/lib/grc/1034139.pdf.
- Ho, Vanessa. 2021. "Unusual 'machine in the woods' taps clean energy deep underground for new Microsoft campus." *Microsoft Features*. <https://news.microsoft.com/features/unusual-machine-in-the-woods-taps-clean-energy-deep-underground-new-microsoft-campus/>.
- Holdmann, G. 2007. "The Chena Hot Springs 400kW Geothermal Power Plant: Experience Gained During the First Year of Operation." Unpublished report to Chena Power, 9p. <http://citeseerx.ist.punasu.edu/viewdoc/download?doi=10.1.1.532.6994&rep=rep1&type=pdf>.
- Holzman, Ruth N., Angelo Ciavarella, and Arnold E. Grant. 2009. "The American Recovery and Reinvestment Act: Tax Incentives for Business." Reed Smith LLP. <https://www.lexology.com/library/detail.aspx?g=7b27732d-14f0-4ce9-9310-241cd29af3d9>.
- Horne, Roland N. 1980. "Design Considerations of a Down-Hole Coaxial Geothermal Heat Exchanger." *Geothermal Resources Council, Transactions*, Vol. 4, September 1980. <https://publications.mygeoenergynow.org/grc/1000656.pdf>.
- Howard, K. 2020. "Geothermal Power Purchase Agreements on the Rise." *Geothermal Resources Council Bulletin*, Vol. 49, No. 3. June 2020. <https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1040017>.
- ID Governor's Office. 2021. "State Energy Loan Program." Idaho Governor's Office of Energy and Mineral Resources. <https://oemr.idaho.gov/loan-program/>.
- IEA. 2020a. "Geothermal capacity additions in selected countries, 2017-2025." <https://www.iea.org/data-and-statistics/charts/geothermal-capacity-additions-in-selected-countries-2017-2025>.
- IEA. 2020b. "Renewables 2020: Analysis and forecast to 2025." <https://www.iea.org/reports/renewables-2020/hydropower-bioenergy-csp-and-geothermal#abstract>.
- Inter-American Development Bank 2014. "Promoting Geothermal Development." <https://publications.iadb.org/publications/english/document/Promoting-Geothermal-Development.pdf>.
- Jeffers, Ken, Jay Renew, Andrew Muto, and Kevin McCabe. 2017. "Lithium Extraction from Low Temperature Geothermal Brines with Integrated Thermoelectric Generation." *GRC Transactions*, 41. <http://pubs.geothermal-library.org/lib/grc/1033761.pdf>.

- Jiao, Yongqin, Dan M. Park, Aaron Brewer, Congwang Ye, Laura Lammers, Tianyi Kou, and Yat Li. 2017. "A Biotechnology Application for Rare Earth Extraction from Geothermal Brines." *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering*. Stanford University, Stanford, California, February 13-15, 2017. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2017/Jiao.pdf>.
- Johnson, Scott K. 2020. "The Omnibus Bill Was Packed with Energy and Environment Policy." *Ars Technica*. December 23, 2020. <https://arstechnica.com/science/2020/12/heres-the-energy-and-environment-policy-passed-with-the-relief-bill/>.
- Kagel, A., D. Bates, and K. Gawell. 2005. *A Guide to Geothermal Energy and the Environment*. Geothermal Energy Association. <https://www.osti.gov/biblio/897425-q5NDer/>.
- Kallesøe, Anders Juhl and Thomas Vangkilde-Pedersen (eds). 2019. "Underground Thermal Energy Storage (UTES)—state-of-the-art, example cases and lessons learned." HEATSTORE project report, *GEOTHERMICA – ERA NET Cofund Geothermal*. [https://www.heatstore.eu/documents/HEATSTORE\\_UTES%20State%20of%20the%20Art\\_WP1\\_D1.1\\_Final\\_2019.04.26.pdf](https://www.heatstore.eu/documents/HEATSTORE_UTES%20State%20of%20the%20Art_WP1_D1.1_Final_2019.04.26.pdf).
- Kaplan, U., and Shilon, Y. 1999. "Small Scale Geothermal Power Plants with Less than 5.0 MW Capacity." *Bulletin d'Hydrogeologie* No. 17, Neuchatel, Switzerland.
- Khanh, D., Doan, T., Hoang, T., Nguyen, T., and Tran, T. 2018. "Potential Application of Slimhole Drilling Technology to Geothermal Wells in Vietnam." In book: *Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering*. DOI: [10.1007/978-981-13-2306-5\\_32](https://doi.org/10.1007/978-981-13-2306-5_32).
- King, M. 2018. "An inside look at the largest geothermal heat system in the US." Featured article for WCPO Cincinnati: <https://www.wcpo.com/news/national/an-inside-look-at-the-largest-geothermal-heat-system-in-the-us>.
- Koelbel, Thomas and Albert Genter. 2017. "Enhanced Geothermal Systems: The Soultz-sous-Forêts Project." *Springer Proceedings in Energy: Towards 100% Renewable Energy*. [https://doi.org/10.1007/978-3-319-45659-1\\_25](https://doi.org/10.1007/978-3-319-45659-1_25).
- KPMG. 2020. "Favorable Tax Provisions for Renewable Energy Industry Enacted." KPMG. 2020. <https://home.kpmg/us/en/home/insights/2020/12/tnf-favorable-tax-provisions-renewable-energy-industry-enacted.html>.
- Kreuter H. 2012. "Geothermal Applications: Geothermal Cooling." *Proceedings of the Renewable Energy Training Program*, 10 July 2012, ESMAP – IFC, Washington DC.
- Lazard. 2020. "Lazard's Levelized Cost of Energy Analysis—Version 14.0." <https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf>.
- Lazzari, Salvatore. 2008. "Energy Tax Policy: History and Current Issues." Congressional Research Service. <https://fas.org/sgp/crs/misc/RL33578.pdf>.
- LegiScan. 2019. "Nevada Senate Concurrent Resolution 1." Nevada State Legislature. <https://legiscan.com/NV/bill/SCR1/2019>.
- Li, Kewen, Changwei Liu, Shanshan Jiang, and Youguang Chen. 2020a. "Review on hybrid geothermal and solar power systems." *Journal of Cleaner Production*, 250. <https://www.sciencedirect.com/science/article/pii/S0959652619343513>.
- Li, Kewen, Geoffrey Garrison, Michael Moore, Yuhao Zhu, Changwei Liu, Jay Hepper, Larry Bandt, Roland Horne, and Susan Petty. 2020b. "Field Test of Thermoelectric Generators at Bottle Rock Geothermal Power Plant." *Proceedings, 45th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, February 10-12, 2020. SGP-TR-216.
- Lienau, Paul J., and John W. Lund. 1987. *Industrial Application Geothermal Direct Use Engineering and Design Handbook*. pp. 297-317. <https://www.osti.gov/etdweb/servlets/purl/895133>.
- Lin, Y.F., A. Stumpf, S. Frailey, R. Okwen, Y. Lu, F. Holcomb, J. Tinjum, et al. 2020. "Geothermal Heat Recovery Complex: Large-Scale, Deep Direct-Use System in a Low-Temperature Sedimentary Basin." Champaign, IL: Illinois State Geological Survey. DOE-DE-EE0008106 Final Report. <https://www.ideals.illinois.edu/handle/2142/108977>.
- Liu, X., Gluesenkamp, K., and Momen, A. 2015. *Overview of Available Low-Temperature/Coproduced Geothermal Resources in the United States and the State of the Art in Utilizing Geothermal Resources for Space Conditioning in Commercial Buildings*. Oak Ridge National Laboratory: Oak Ridge, TN. <https://info.ornl.gov/sites/publications/Files/Pub54942.pdf>.
- Lowry, T., Ayling, B., Hinz, N. et al. 2020. *Deep Direct-Use Geothermal Feasibility Study for Hawthorne, NV*. Sandia National Laboratories. U.S. Department of Energy. <https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2020/203210.pdf>.
- Lund, J. and Bloomquist, G. 2012. "Development of Geothermal Policy in the United States: What Works and What Doesn't Work." *Proceedings, 37th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, January 30–February 1, 2012. SGP-TR-194. <https://www.osti.gov/servlets/purl/1209222>.
- Lund, J. W. and Toth, A.N. 2020. "Direct utilization of geothermal energy 2020 worldwide review." *Proceedings, World Geothermal Congress 2020*. <https://www.sciencedirect.com/science/article/pii/S0375650520302078>.
- Lund, John W., Alex Sifford, Susan G. Hamm, and Arlene Anderson. 2020. "The United States of America Direct Utilization Update 2019." *Proceedings World Geothermal Congress 2020*. <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01011.pdf>.
- Lund, John W., and R. Gordon Bloomquist. 2012. "Development of Geothermal Policy in the United States-What Works and What Doesn't Work." *Proceedings, 37th Workshop on Geothermal Reservoir Engineering*. Stanford, California. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2012/Lund.pdf>.
- Ma, Wei-bin, Chao Luo, and Yu-lie Gong. 2010. "An Absorption Refrigeration System Used for Exploiting Mid-low Temperature Geothermal Resource." *Proceedings, World Geothermal Congress 2010*. Bali, Indonesia, 25–29 April 2010. <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/2911.pdf>.
- Martin, R. Neal. 2020. "Energy & Sustainability Washington Updates — July 2020." Mintz.com. <https://www.mintz.com/insights-center/viewpoints/2151/2020-06-30-energy-sustainability-washington-updates-july-2020>.
- Matek, B. 2016. *2016 Annual U.S. & Global Geothermal Power Production Report*. Geothermal Energy Association. [https://www.geothermal.org/Policy\\_Committee/Documents/2016\\_Annual\\_US\\_Global\\_Geothermal\\_Power\\_Production.pdf](https://www.geothermal.org/Policy_Committee/Documents/2016_Annual_US_Global_Geothermal_Power_Production.pdf).
- Matek, B., and B. Schmidt. 2013. *The Values of Geothermal Energy: A Discussion of the Benefits Geothermal Power Provides to the Future U.S. Power System*. GRC and GEA. <http://pubs.geothermal-library.org/lib/grc/1030701.pdf>.
- Mattson, Earl D., and Ghanashyam Neupane. 2017. "LCOH Estimated from Existing Geothermal District Heating Systems in the U.S." *Geothermal Resources Council Annual Meeting*, October 2017. <https://www.osti.gov/servlets/purl/1402044>.
- McCabe et al. 2019. *GeoVision Analysis Supporting Task Force Report: Thermal Applications—Quantifying Technical, Economic, and Market Potential of Geothermal District Heating Systems in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71715. <https://www.nrel.gov/docs/fy19osti/71715.pdf>.
- McClurg, C., Schiller, C., and Keuhn, P. 2017. *Mapping a Pathway to Low-Carbon Campuses: Insights for Developing an Effective Campus Action Plan*. Rocky Mountain Institute Report. [https://rmi.org/wp-content/uploads/2017/03/CampusGuide\\_Digital-V6.pdf](https://rmi.org/wp-content/uploads/2017/03/CampusGuide_Digital-V6.pdf).
- McDonald, S. L. 1979. "Energy Tax Act of 1978." *Nat. Resour. J.*; 19:4. <https://www.osti.gov/biblio/5625890-energy-tax-act>.
- McKenna, J., Blackwell, D., Moyes, C. et al. 2005. "Geothermal Electric Power Supply Possible from the Gulf Coast, Midcontinent Oil Field Waters." *Oil & Gas J.*, 103 (33): 34-40.
- McKittrick, Alexis, Leslie Abrahams, Christopher Clavin, Robert Rozansky, and Daniel Bernstein. 2019. "Frontier Observatory for Research in Geothermal Energy: A Roadmap." *IDA Science and Technology Policy Institute*. <https://www.ida.org/-/media/feature/publications/f/fo/forge/d-10474.ashx>.
- MEET. 2020. <https://www.meet-h2020.com/project-results/outreach-articles/how-can-we-do-geothermal-from-oil-wells/>.
- Mendelsohn, M., and D. Feldman. 2013. *Financing U.S. Renewable Energy Projects Through Public Capital Vehicles: Qualitative and Quantitative Benefits*. NREL/TP-6A20-58315. National Renewable Energy Laboratory (NREL), Golden, CO. <http://www.osti.gov/scitech/biblio/1076663>.
- Mertoglu, O., S. Simsek, and N. Basarir. 2020. "Geothermal Energy Use: Projections and Country Update for Turkey." *Proceedings, World Geothermal Congress 2020*. [https://www.researchgate.net/publication/334599464\\_Geothermal\\_Energy\\_Use\\_Country\\_Update\\_for\\_Turkey](https://www.researchgate.net/publication/334599464_Geothermal_Energy_Use_Country_Update_for_Turkey).
- Mesquita, Lucio, Doug McClenahan, Jeff Thornton, Jarrett Carriere and Bill Wong. 2017. "Drake Landing Solar Community: 10 Years of Operation." *ISES Solar World Congress 2017*. <http://proceedings.ises.org/paper/swc2017/swc2017-0033-Mesquita.pdf>.
- Moeck, I., 2014. "Catalog of geothermal play types based on Geologic Controls." *Renewable and Sustainable Energy Reviews*, v. 37, pp. 867-882. <https://www.sciencedirect.com/science/article/pii/S1364032114003578>.
- Morita, Koji, Osamu Matsubayashi, and Ken-ichi Kusunoki. 1985. "Down-Hole Coaxial Heat Exchanger Using Insulated Pipe for Maximum Heat Extraction." *Geothermal Resources Council, Transactions*, Vol 9, Part 1, August 1985. <https://publications.mygeoenergynow.org/grc/1001239.pdf>.

Mormann, Felix. 2016. "Fading into the Sunset: Solar and Wind Energy Get Five More Years of Tax Credits with a Phase-Down." American Bar Association. [https://www.americanbar.org/groups/environment\\_energy\\_resources/publications/trends/2015-2016/may-june-2016/fading\\_into\\_the\\_sunset/](https://www.americanbar.org/groups/environment_energy_resources/publications/trends/2015-2016/may-june-2016/fading_into_the_sunset/).

Mouchot, Justine, Albert Genter, Nicolas Cuenot, Julia Scheiber, Olivier Seibel, Clio Bosia, and Guillaume Ravier. 2018. "First Year of Operation from EGS geothermal Plants in Alsace, France: Scaling Issues." *Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, Stanford*. February 12–14, 2018. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2018/Mouchot.pdf>.

Mroczek, Ed, Gaetano Dedual, Duncan Graham, and Lew Bacon. 2015. "Lithium Extraction from Wairakei Geothermal Fluid using Electrodialysis." *Proceedings, World Geothermal Congress, Melbourne, Australia, 19–25 April 2015*. <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1059.8400&rep=rep1&type=pdf>.

Mullane, M., M. Gleason, K. McCabe, M. Mooney, T. Reber, and K.R. Young. 2016. "An Estimate of Shallow, Low-Temperature Geothermal Resources of the United States." Presented at the 40th GRC Annual Meeting, Sacramento, California, October 23–26. NREL/CP-6A20-66461. <http://www.nrel.gov/docs/fy17osti/66461.pdf>.

Neupane, Ghanashyam, and Daniel S. Wendt. 2017. "Potential Economic Values of Minerals in Brines of Identified Hydrothermal Systems in the US." *GRC Transactions*, 41. <https://www.osti.gov/servlets/purl/1402042>.

NETL. 2021. *Initial Report to the President on Empowering Workers Through Revitalizing Energy Communities*. Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization. Produced in cooperation with the U.S. Department of Energy's National Energy Technology Laboratory (NETL). [https://netl.doe.gov/sites/default/files/2021-04/Initial%20Report%20on%20Energy%20Communities\\_Apr2021.pdf](https://netl.doe.gov/sites/default/files/2021-04/Initial%20Report%20on%20Energy%20Communities_Apr2021.pdf).

Ngugi, P. K. 2014. "Risks and Risk Mitigation in Geothermal Development." Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization," organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23–29, 2014. <https://orkustofnun.is/gogn/unu-gtp-sc/UNU-GTP-SC-18-41.pdf>.

Nordell, B., A. Snijders, and L. Stiles. 2015. "The use of aquifers as thermal energy storage (TES) systems." *Advances in Thermal Energy Storage Systems*: 87-115. <https://doi.org/10.1533/9781782420965.1.87>.

Nordquist, Josh, Tom Buchanan, and Michael Kaleikini. 2013. "Automatic Generation Control and Ancillary Services." *GRC Transactions*, 37: 761-766. <http://pubs.geothermal-library.org/lib/grc/1030656.pdf>.

NREL. 2020. "2020 Annual Technology Baseline. 2020. Golden, CO: National Renewable Energy Laboratory. <https://atb.nrel.gov/>.

NREL. N.D. "Land Use by System Technology." Golden, CO: National Renewable Energy Laboratory. <https://www.nrel.gov/analysis/tech-size.html>.

Ogawa, Y., Ichiki, M., Kanda, W., Mishina, M., and Asamori, K. 2014. "Three-dimensional magnetotelluric imaging of crustal fluids and seismicity around Naruko volcano, NE Japan." *Earth Planets Space*, 66, 158. <https://earth-planets-space.springeropen.com/articles/10.1186/s40623-014-0158-y>.

Okamoto, Kyosuke, Hiroshi Asanuma, Takuya Ishibashi, Yusuke Yamaya, Hanae Saishu, Norio Yanagisawa, Toru Mogi, et al. 2019. "Geological and engineering features of developing ultra-high-temperature geothermal systems in the world." *Geothermics*, Volume 82, Pages 267-281. <https://doi.org/10.1016/j.geothermics.2019.07.002>.

Oldenburg, Curtis M., Lehua Pan, Mark P. Muir, Alan D. Eastman, and Brian S. Higgins. 2016. "Numerical Simulation of Critical Factors Controlling Heat Extraction from Geothermal Systems Using a Closed-Loop Heat Exchange Method." *Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford, California, SGP-TR-209*. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2016/Oldenburg2.pdf>.

Omenda, P., P. Mangi, C. Ofwona, and M. Mwangi. 2020. "Country Update Report for Kenya 2015-2019." *Proceedings, World Geothermal Congress 2020*. <https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01055.pdf>.

OregonLaws.org. 2020. "ORS 307.175 Alternative energy systems." <https://www.oregonlaws.org/ors/307.175>.

Ormat. 2020. "Global Projects: Tungsten Mountain." <https://www.ormat.com/en/projects/all/main/>.

Penn, I. 2020. "Climate Change and Poor Planning Are Blamed for California Blackouts." *The New York Times*. October 6, 2020. <https://www.nytimes.com/2020/10/06/business/energy-environment/california-blackout-cause-report.html>

Pepin, J., Burns, E., Dickinson, J., Duncan, L., Kuniansky, E., and Reeves, H. 2021. "National-Scale Reservoir Thermal Energy Storage Pre-Assessment for the United States." *Proceedings, 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-218*. <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2021/Pepin.pdf>.

Peters, Adele. 2017. "Google's New Office Will Be Heated And Cooled By The Ground Underneath." *Fast Company*. <https://www.fastcompany.com/40484709/googles-new-office-will-be-heated-and-cooled-by-the-ground-underneath>.

Pettitt, W., B. Schmidt, and J. Robins. 2020. "Baseline Geothermal Power Capacity in the USA and California." *Geothermal Resources Council Transactions*, Vol. 44, 2020. <https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1034214>.

Philibert, C. 2017. *Renewable Energy for Industry*. IEA Insights Series 2017. [https://webstore.iea.org/download/direct/1025?fileName=Insights\\_series\\_2017\\_Renewable\\_Energy\\_for\\_Industry.pdf](https://webstore.iea.org/download/direct/1025?fileName=Insights_series_2017_Renewable_Energy_for_Industry.pdf).

Porro, C., and Augustine, C., 2012. "Estimate of Geothermal Energy Resource in Major US Sedimentary Basins." NREL/PR-6A20-55017.

Porse, Sean. 2020. "GTO Efforts in Geothermal Energy and Critical Materials." Presented at CEC's Presentations of California's Lithium Recovery Initiative – Symposium, February 12, 2020.

Rajterowski, Jacob, Jay E. Renew, and Ryan Melsert. 2015. "Modular Solid-State Thermoelectric Power Generation and High-Value Lithium Recovery From Low-Temperature Geothermal Brines." *GRC Transactions*, 39: 1025-1028. <http://pubs.geothermal-library.org/lib/grc/1032249.pdf>.

Reber. 2013. "Evaluating Opportunities for Enhanced Geothermal System-Based District Heating in New York and Pennsylvania." MS thesis, Cornell University, Ithaca, New York, United States. <https://ecommons.cornell.edu/handle/1813/34090>.

Reinhardt, T., Johnson, L., and Popovich, N. 2011. "Systems for Electrical Power from Corproduced and Low Temperature Geothermal Resources." *Proceedings of the 36th Workshop on Geothermal Reservoir Engineering, Stanford University, California*. <http://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2011/reinhardt.pdf>.

Reinsch, T., Dobson, P., Asauma, H., Huenges, E., Poletto, F., and Sanjuan, B. 2017. "Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities." *Geotherm Energy*. 5:16 DOI 10.1186/s40517-017-0075-y. <https://geothermal-energy-journal.springeropen.com/articles/10.1186/s40517-017-0075-y>

Renewable Energy World. 2016. "New Mexico House, Senate Pass Geothermal Legislation." <https://www.renewableenergyworld.com/baseload/new-mexico-house-senate-pass-geothermal-legislation/>.

RenewGeo. 2020. "SAGE." <http://www.renewgeo.com/>.

RGGI. 2020. "The Investment of RGGI Proceeds in 2018." Regional Greenhouse Gas Initiative. [https://www.rggi.org/sites/default/files/Uploads/Proceeds/RGGI\\_Proceeds\\_Report\\_2018.pdf](https://www.rggi.org/sites/default/files/Uploads/Proceeds/RGGI_Proceeds_Report_2018.pdf).

Richter, Alexander. 2016. "Dutch IF technology is developing a small-scale geothermal power plant system aimed at supplying power from geothermal resources in remote areas of Indonesia, called MiniGeo." *Think Geoenergy*. May 24, 2016. <https://www.thinkgeoenergy.com/minigeo-a-small-scale-off-grid-geothermal-power-plant-for-remote-areas/>.

Richter, Alexander. 2020a. "Turkey extends feed-in-tariff scheme for geothermal to mid-2021." *Think Geoenergy*. September 18, 2020. <https://www.thinkgeoenergy.com/turkey-extends-feed-in-tariff-scheme-for-geothermal-to-mid-2021/>.

Richter, Alexander. 2020b. "Indonesia still trying to find balance between geothermal tariffs and investor expectations." *Think Geoenergy*. August 5, 2020. <https://www.thinkgeoenergy.com/indonesia-still-trying-to-find-balance-between-geothermal-tariffs-and-investor-expectations/>.

- Richter, Alexander. 2020c. "Canadian Oil Service Sector joins forces to support emerging Canadian geothermal industry." Think Geoenergy. April 2020. <https://www.thinkgeoenergy.com/canadian-oil-service-sector-joins-forces-to-support-emerging-canadian-geothermal-industry/>.
- Richter, Alexander. 2020x. "Geothermal heat to also fuel district cooling network in Munich, Germany." Think Geoenergy. April 18, 2020. <https://www.thinkgeoenergy.com/geothermal-heat-to-also-fuel-district-cooling-network-in-munich-germany/>.
- Richter, Alexander. 2020x. "The Top 10 Geothermal Countries 2019 – based on installed generation capacity (MWe)." Think Geoenergy. January 2020. <https://www.thinkgeoenergy.com/the-top-10-geothermal-countries-2019-based-on-installed-generation-capacity-mwe/>.
- Robertson-Tait, A., W. Harvey, S. Hamm, and L. Boyd. 2020. "The United States of America Country Update 2020—Electric Power Generation." Proceedings, World Geothermal Congress 2020. <https://pangea.stanford.edu/ERE/db/WGC/Abstract.php?PaperID=4459>.
- Roberts, David. 2018. "California just adopted its boldest energy target yet: 100% clean electricity." Vox.com. <https://www.vox.com/energy-and-environment/2018/8/31/17799094/california-100-percent-clean-energy-target-brown-de-leon>.
- Robinson + Cole. 2020. "Green Tax Incentive Compendium: Federal and State Tax Incentives for Renewable Energy and Energy Efficiency." <http://www.rc.com/newsletters/upload/RC-Garciano-Green-Tax-Incentive-Compendium-January-2020.PDF>.
- Rose, Peter E., Joseph M. Moore, Jacob Bradford, Michael Mella, Bridget Ayling, and John McLennon. 2017. "Tracer Testing to Characterize Hydraulic Stimulation Experiments at the Raft River EGS Demonstration Site." *GRC Transactions*, Vol. 41. <http://pubs.geothermal-library.org/lib/grc/1033775.pdf>.
- Roth, S. 2020. "California needs clean energy after sundown. Is the Answer under our feet?" *Los Angeles Times*. <https://www.latimes.com/environment/story/2020-01-22/california-needs-clean-energy-after-sundown-geothermal-could-be-the-answer>.
- RTC. 2018. "Sustainable Options for Reducing Emissions from Thermal Energy: Showcasing Successful Outcomes from Six Case Studies." Report to the Renewable Thermal Collaborative by the Center for Climate and Energy Solutions. <https://www.c2es.org/site/assets/uploads/2018/10/sustainable-options-for-reducing-emissions-from-thermal-energy.pdf>.
- RTC. 2020. "The Thermal Opportunity." Renewable Thermal Collaborative. <https://www.renewablethermal.org/our-strategy/>.
- Rules Committee. 2020. "Text of the House Amendment to the Senate Amendment to H.R. 133." <https://rules.house.gov/sites/democrats.rules.house.gov/files/BILLS-116HR133SA-RCP-116-68.pdf>.
- Runyon, Jennifer. 2020. "US Treasury Says It May Modify Tax Credit Rules for Wind and Solar Energy." Renewable Energy World. May 11, 2020. <https://www.renewableenergyworld.com/2020/05/11/us-treasury-says-it-may-modify-tax-credit-rules-for-wind-and-solar-energy/>.
- Saevarsdottir, Gudrun, Pai-Chun Tao, Hlynur Stefansson, and William Harvey. 2015. "Potential Use of Geothermal Heat in Lithium-Ion Battery Production." Proceedings, World Geothermal Congress 2015. Melbourne, Australia. April 19–25, 2015.
- Saishu, H., A. Okamoto, and N. Tsuchiya. 2014. "The significance of silica precipitation on the formation of the permeable-impermeable boundary within Earth's crust," *Terra Nova*, vol. 26, no. 4, pp. 253–259. <https://onlinelibrary.wiley.com/doi/full/10.1111/ter.12093>.
- Sander, Marietta. 2012. "Lessons Learnt From Geothermal-Friendly Regulatory Frameworks in Iceland, Kenya, New Zealand, Philippines and The United States of America." *GRC Transactions*. <http://pubs.geothermal-library.org/lib/grc/1030390.pdf>.
- Scherer, Joseph A., Brian Higgins, John R. Muir, and Alvaro Amaya. 2020. "Closed-Loop Geothermal Demonstration Project: Confirming Models for Large-Scale, Closed-Loop Geothermal Projects in California." *California Energy Commission Consultant Report*. <https://ww2.energy.ca.gov/2020publications/CEC-300-2020-007/CEC-300-2020-007.pdf>.
- Schüppler, Simon, Paul Fleuchaus, and Phillip Blum. 2019. "Techno-economic and environmental analysis of an Aquifer Thermal Energy Storage (ATES) in Germany." *Geothermal Energy*, 7(11). <https://geothermal-energy-journal.springeropen.com/articles/10.1186/s40517-019-0127-6>.
- Second Nature. 2020. "Second Nature Reporting Platform." <https://reporting.secondnature.org/>.
- Senate Committee on Energy and Natural Resources. 2020. "ICYMI: What They're Saying About the Energy Act of 2020." U.S. Senate Committee on Energy and Natural Resources. December 29, 2020. <https://www.energy.senate.gov/2020/12/icymi-what-they-re-saying-about-the-energy-act-of-2020>.
- Senate Committee on Energy and Natural Resources. 2020. "Murkowski, Manchin, House Colleagues Reach Agreement on Energy Package for Year-End Appropriations Bill." U.S. Senate Committee on Energy and Natural Resources. December 21, 2020. <https://www.energy.senate.gov/2020/12/murkowski-manchin-house-colleagues-reach-agreement-on-energy-package-for-year-end-appropriations-bill>.
- Sharan, Prashant, Kevin Kitz, Daniel Wendt, Joshua McTigue, and Guangdong Zhu. 2020. "Using Concentrating Solar Power to Create a Geological Thermal Energy Reservoir for Seasonal Storage and Flexible Power Plant Operation." *Journal of Energy Resources Technology*, 143. <https://asmedigitalcollection.asme.org/energyresources/article/143/1/010906/1085944/Using-Concentrating-Solar-Power-to-Create-a>.
- Sherlock, Molly F. 2018. "The Energy Credit: An Investment Tax Credit for Renewable Energy." Congressional Research Service. <https://crsreports.congress.gov/product/pdf/IF/IF10479>.
- Sherlock, Molly F. 2020. "The Renewable Electricity Production Tax Credit: In Brief." Congressional Research Service. <https://fas.org/sgp/crs/misc/R43453.pdf>.
- Snyder, D. M., Beckers, K. F., and Young, K. R. 2017. "Update on Geothermal Direct-Use Installations in the United States." In *Proceedings*, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University. Stanford California, February 13-15, 2017, SGP-TR-212. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2017/Snyder.pdf>.
- Speer, Bethany, Ryan Economy, Travis Lowder, Paul Schwabe, and Scott Regenthal. 2014. *Geothermal Exploration Policy Mechanisms: Lessons for the United States from International Applications*. National Renewable Energy Laboratory: Golden, CO. NREL/TP-6A20-61477. <https://www.nrel.gov/docs/fy14osti/61477.pdf>.
- Springer, N. and A. Daue. 2020. "Key Economic Benefits of Renewable Energy on Public Lands." The Yale Center for Business and the Environment. <https://cbey.yale.edu/renewable-energy-on-public-lands-report>.
- Stimac, Jim, Maxwell Wilmarth, Petronila Esther Mandeno, Patrick Dobson, and Jeff Winick. 2017. "Review of Exploitable Supercritical Geothermal Resources to 5 km at Geysers-Clear Lake, Salton Sea, and Coso." <http://pubs.geothermal-library.org/lib/grc/1033767.pdf>.
- Stringfellow, William T. and Patrick F. Dobson. 2020. *Retrospective on Recent DOE-Funded Studies Concerning the Extraction of Rare Earth Elements & Lithium from Geothermal Brines LBNL-2001359 (Final Report)*. Lawrence Berkley National Laboratory, Energy Geosciences Division. <https://escholarship.org/content/qt2j7688zb/qt2j7688zb.pdf>.
- Stringfellow, William T. and Patrick F. Dobson. 2021. "Technology for Lithium Extraction in the Context of Hybrid Geothermal Power." Lawrence Berkley National Laboratory, Energy Geosciences Division. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2021/Stringfellow.pdf>.
- Swiss Energy Office. 2020. *2050 Energy Strategy in Switzerland*. <https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050.html>.
- Tester, J., Jordan, T., and Beyers, S. 2019. *DE-EE0008103 Earth Source Heat: A Cascaded Systems Approach to DDU of Geothermal Energy on the Cornell Campus*. Final Project Report. Cornell University. U.S. Department of Energy Geothermal Technologies Program.
- ThinkGeoEnergy. 2018a. <https://www.thinkgeoenergy.com/work-kicked-off-on-geothermal-district-heating-project-for-pharmaceutical-company-in-flanders-belgium/>.
- ThinkGeoEnergy. 2018b. <https://www.thinkgeoenergy.com/municipality-in-romania-plans-extension-of-geothermal-district-heating-system/>.
- ThinkGeoEnergy. 2020a. <https://www.thinkgeoenergy.com/a-new-large-geothermal-district-heating-network-being-established-in-chaves-portugal/>.
- ThinkGeoEnergy. 2020b. <https://www.thinkgeoenergy.com/towards-carbon-neutrality-with-geothermal-district-heating-city-of-schwerin/>.
- ThinkGeoEnergy. 2020c. <https://www.thinkgeoenergy.com/e-on-plans-geothermal-district-heating-project-in-malmo-sweden/>.

- ThinkGeoEnergy. 2020d. <https://www.thinkgeoenergy.com/geothermal-heat-to-also-fuel-district-cooling-network-in-munich-germany/>.
- ThinkGeoEnergy. 2020e. <https://www.thinkgeoenergy.com/eavor-technology-reports-validation-of-its-eavor-loop-scalable-geothermal-technology/>.
- Thomas, Holly, Timothy P. Reinhardt, and Brittany Segneri. 2015. "Low Temperature Geothermal Mineral Recovery Program." *Proceedings*, 40th Workshop on Geothermal Reservoir Engineering. Stanford University. Stanford, California, January 26-28, 2015. SGP-TR-204.
- Thomas, Holly, Timothy P. Reinhardt, Arlene Anderson, and Brittany Segneri. 2016. "Critical and Strategic Materials and Potential Importance for Geothermal Projects." *Proceedings*, 41st Workshop on Geothermal Reservoir Engineering. Stanford University. Stanford, California, February 22-24, 2016. SGP-TR-209.
- Thomsen, P. 2018. "The Increasing Comparative Value of Geothermal in California—2018 Edition." *GRC Transaction*, Vol. 42. <http://pubs.geothermal-library.org/lib/grc/1033948.pdf>.
- Thorsteinsson H. H. 2008. "US geothermal district heating: barriers and enablers." Master thesis, Massachusetts Institute of Technology. <https://dspace.mit.edu/handle/1721.1/42932>.
- Thorsteinsson, H. H., and Tester, J. W. 2010. "Barriers and enablers to geothermal district heating system development in the United States." *Energy Policy*, 38(2), 803-813. <https://www.sciencedirect.com/science/article/pii/S0301421509007721>.
- Todorov, Oleg, Kari Alanne, Markku Virtanen, and Risto Kosonen. 2020. "A method and analysis of aquifer thermal energy storage (ATES) system for district heating and cooling: A case study in Finland." *Sustainable Cities and Society*, 53. <https://www.sciencedirect.com/science/article/pii/S2210670719319237>.
- Trabish, H. K. 2020. "Geothermal's Surprise: Cheap renewables could keep states from achieving climate goals." *Utility Dive*. <https://www.utilitydive.com/news/geothermals-surprise-cheap-renewables-could-keep-states-from-achieving-cl/569807/>.
- Turchi, C., McTigue, J., Akar, S., Beckers, K., Richards, M., Chickering, C., Batir, J., Schumann, H., Tillman, T., and Slivensky, D. 2020. *Geothermal Deep Direct Use for Turbine Inlet Cooling in East Texas*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-74990. <https://www.nrel.gov/docs/fy20osti/74990.pdf>.
- U.S. Department of the Interior. 2018. "BLM FACT SHEET, Renewable Energy: Geothermal." <https://www.blm.gov/sites/blm.gov/files/Geothermal%20Fact%20Sheet.pdf>.
- U.S. Government Accountability Office. 2006. "Increased Geothermal Development Will Depend on Overcoming Many Challenges." <https://www.gao.gov/assets/260/250183.pdf>.
- Underground Energy, LLC. 2020. "Case Studies." <https://underground-energy.com/case-studies/>.
- Utah FORGE. 2020a. "Drilling Progress of Well 16A(78)-32." <https://utahforge.com/2020/11/09/drilling-progress-of-well-16a78-32/>.
- Utah FORGE. 2020b. "Current and Planned Activities." <https://utahforge.com/data-dashboard/current-and-planned-activities/>.
- UT State Legislature. 2019. "59-7-614 Renewable energy system tax credits." <https://le.utah.gov/xcode/Title59/Chapter7/59-7-S614.html>.
- Van Horn, Andrew, Alvaro Amaya, Brian Higgins, John Muir, Joe Scherer, Robert Pilko and Malcolm Ross. 2020. "New Opportunities and Applications for Closed-Loop Geothermal Energy Systems." *GRC Transactions*, 44.
- Ventura, Susanna, Srinivas Bhamadi, Marc Hornbostel, and Anoop Nagar. 2020. "Selective Recovery of Lithium from Geothermal Brines." *California Energy Commission Final Project Report*.
- Ventura, Susanna, Srinivas Bhamadi, and Marc Hornbostel. 2018. "Selective Recovery of Lithium from Brines." *Proceedings*, 43rd Workshop on Geothermal Reservoir Engineering. Stanford University. Stanford, California, February 12–14, 2018. <https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2018/Ventura.pdf>.
- Viola, Beth A., Tait R. McDonald, Sydney Lauren Bopp, and Isabel C. Lane. 2021. "Energy Policy Act Signals Inclusive, Innovation-Focused Future for DOE | Insights | Holland & Knight." 2021. <https://www.hklaw.com/en/insights/publications/2021/01/energy-policy-act-signals-inclusive-innovation-focused-future-for-doe>.
- Warren, I. 2021. "Techno-Economic Analysis of Lithium Extraction From Geothermal Brines." NREL/TP-5700-79178.
- WashingtonVotes.org. 2017. "Senate Bill 5470: Advancing the development of renewable energy by improving the permitting process for geothermal resources exploration." <https://www.washingtonvotes.org/2017-SB-5470>.
- Watanabe N., T. Numakura, K. Sakaguchi, H. Saishu, A. Okamoto, S.E. Ingebritsen, and N. Tsuchiya. 2017. "Potentially exploitable supercritical geothermal resources in the ductile crust." *Nat Geosci*. 2017;10(2):140–4. doi:10.1038/NGEO2879. <https://www.nature.com/articles/ngeo2879>.
- Weal, Brett. 2018. "Tax Reform: New 100% Bonus Depreciation and Renewable Energy." CohnReznick. <https://www.cohnreznick.com/insights/tax-reform-new-bonus-depreciation-and-renewable-energy>.
- Wendt, D. S., G. Neupane, C. L. Davidson, R. Zheng, and M. A. Bearden. 2018. *GeoVision Analysis Supporting Task Force Report: Geothermal Hybrid Systems*. Idaho National Laboratory and Pacific Northwest National Laboratory.
- Wendt, Daniel, Hai Huang, Guangdong Zhu, Prashant Sharan, Kevin Kitz, Sidney Green, John McLennan, Josh McTigue, and Ghanashyam Neupane. 2019. *Flexible Geothermal Power Generation utilizing Geologic Thermal Energy Storage: Final Seedling Project Report*. Idaho National Laboratory. <https://doi.org/10.2172/1524048>.
- White House. 2021. "Executive Order on Tackling the Climate Crisis at Home and Abroad." Presidential Action. <https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/>.
- Witcher, James C., John W. Lund, and Damon S. Seawright. 2002. "Lightning Dock KGRA: New Mexico's Largest Geothermal Greenhouse, Largest Aquaculture Facility, and First Binary Electrical Power Plant." *Geo-Heat Center Bulletin*, 23: 37-41.
- World Bank. 2020. "Indonesia Geothermal Resource Risk Mitigation Project (GREM)." <https://projects.worldbank.org/en/projects-operations/project-detail/P166071?lang=en>.
- Young, K., K. Witherbee, A. Levine, A. Keller, J. Balu, and M. Bennett. 2014. "Geothermal Permitting and NEPA Timelines." *GRC Transactions*, Vol. 38. <http://pubs.geothermal-library.org/lib/grc/1033639.pdf>.
- Young, K., A. Levine, J. Cook, D. Heimiller, and J. Ho. 2017. "Crossing the Barriers: An Analysis of Market Barriers to Geothermal Development and Potential Improvement Scenarios." *GRC Transactions*, Vol. 41. <https://publications.mygeoenergynow.org/grc/1033868.pdf>.
- Young, K., A. Levine, J. Cook, D. Heimiller, and J. Ho. 2019. *GeoVision Analysis Supporting Task Force Report: Barriers—An Analysis of Non-Technical Barriers to Geothermal Deployment and Potential Improvement Scenarios*. Golden, CO: National Renewable Energy Laboratory. NREL/PR-6A20-71641. <https://www.nrel.gov/docs/fy19osti/71641.pdf>.
- Zabeti, M., Alberici, S., de Beer J., Eggink, E., Goes, M., and Noach C. 2018. "Renewable Heating and Cooling for Industrial Applications: Guidance for Carbon Accounting." Report to the Renewable Thermal Collective, Navigant Consulting, Reference No.: SISNL17392. <https://www.renewablethermal.org/wp-content/uploads/2018/06/Navigant-2018-Renewable-Heating-and-Cooling-for-Industrial-Applications.pdf>.

# Appendix A. Industry Questionnaire

Dear Geothermal Market Report Participant,

This survey lists our (NREL and GRC's) current knowledge of your company's developing and existing projects. We will use this information in our 2021 U.S. Geothermal Power Production and District Heating Market Report, and we ask that you verify/confirm the information we have provided.

- (1) For clarification, the first section, "Definitions," provides terms and definitions relevant to different types of geothermal development projects.
- (2) The following sections contain several templates with the information we collected about your current project(s). This information is gathered from publicly available information and past survey responses. **We ask that you double check this information and please fill in the blanks where information is missing.**
- (3) **If your organization has developing projects that are not included in this document, please add additional information for those projects.**
- (4) **We (NREL and GRC) will not include specific information or proprietary information regarding your projects in the 2021 report, and will keep this information confidential.** It is left to your organization to confirm the information we currently have on record.
- (5) Don't hesitate to reach out to us if you have any comments, questions, or concerns.

Thank you and we look forward to working with you,

Jody Robins, Senior Geothermal Drilling Engineer, NREL

Will Pettitt, Executive Director, GRC

## Geothermal Resource Types

**Conventional Hydrothermal (Unproduced Resource, CH Unproduced):** the development of a geothermal resource where levels of geothermal reservoir temperature and reservoir flow capacity are naturally sufficient to produce electricity and where development of the geothermal reservoir has not previously occurred to the extent that it supported the operation of geothermal power plant(s).

**Conventional Hydrothermal (Produced Resource, CH Produced):** the development of a geothermal resource where levels of geothermal reservoir temperature and reservoir flow capacity are naturally sufficient to produce electricity and where development of the geothermal reservoir has previously occurred to the extent that it currently supports or has supported the operation of geothermal power plant(s).

**Conventional Hydrothermal Expansion (CH Expansion):** the expansion of an existing geothermal power plant and its associated drilled area so as to increase the level of power that the power plant produces.

**Geothermal Energy and Hydrocarbon Co-production (Coproduct):** the utilization of produced fluids resulting from oil and/or gas-field development for the production of geothermal power.

**Enhanced Geothermal Systems (EGS):** the development of a geothermal system where the natural flow capacity of the system reservoir is not sufficient to support adequate electric or thermal power production but where hydraulic stimulation of the system can enable production at a commercial level.

## Geothermal Capacity Types

**Generator nameplate capacity (installed):** The maximum rated output of a generator, prime mover, or other electric power production equipment under specific conditions designated by the manufacturer. Installed generator nameplate capacity is commonly expressed in megawatts (MW) and is usually indicated on a nameplate physically attached to the generator.

**Summer capacity (installed):** The maximum output, commonly expressed in megawatts (MW), that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30.) This output reflects a reduction in capacity due to electricity use for station service or auxiliaries.

**Winter capacity (installed):** The maximum output, commonly expressed in megawatts (MW), that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of peak winter demand (period of December 1 through February 28). This output reflects a reduction in capacity due to electricity use for station service or auxiliaries.

Developing Project Information

Operating Facilities Basic Information										
Field Name	Plant Name	Nameplate Capacity (MW)	Summer Capacity (MW)	Winter Capacity (MW)	Net Generation (MWh)	Year Completed	Decommissioned? Y/N	Year Decommissioned	Turbine Type	Plant Type
<b>Total company employees:</b>										
<b>Instructions: Please double check this information and fill in the blanks where information is missing.</b>										
<b>Nameplate Capacity:</b>	The maximum rated output of a generator, prime mover, or other electric power production equipment under specific conditions designated by the manufacturer. Indicated on a nameplate physically attached to the generator. Installed generator nameplate capacity is commonly expressed in megawatts (MW) and is usually indicated on a nameplate physically attached to the generator.									
<b>Summer Capacity:</b>	The maximum output, commonly expressed in megawatts (MW), that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30.) This output reflects a reduction in capacity due to electricity use for station service or auxiliaries.									
<b>Winter Capacity:</b>	The maximum output, commonly expressed in megawatts (MW), that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of peak winter demand (period of December 1 through February 28). This output reflects a reduction in capacity due to electricity use for station service or auxiliaries.									
<b>Net Generation:</b>	The amount of gross generation less the electrical energy consumed at the generating station(s) for station service or auxiliaries. Note: Electricity required for pumping at pumped-storage plants is regarded as electricity for station service and is deducted from gross generation. E.g., Dry Steam, Binary, Single Flash, Double Flash,									
<b>Plant Type:</b>	Co-production, EGS									

Basic Information	
	Project Name
	Developer
	Estimated Nameplate Capacity (MW)
	Estimated Resource Capacity (MW)
	Project Type (see Project Type Definitions)
	Power Plant Type (Binary, Single, Double, or Triple Flash, Dry Steam, other)
	Estimated Year of Completion or Year Completed
	Location (State, County)
	Project Phase I, II, III, IV (See Below) or Prospect
	Estimated Date to reach the next Phase?

**Phase I Project**

**Resource Development: at least two of the following Resource Development criteria must be met.**

- Literature Survey Complete
- Geologic Mapping Completed, Geophysical and Geochemical Sites Identified
- Geochemical and Geophysical Surveys in Progress

**Transmission Development: all of the following Transmission Development criteria must be met.**

- Internal Transmission Analysis Complete

**External to Resource Development: all of the following criteria must be met.**

- Land or Lease Acquired
- Permitting Process for Exploration Drilling (TGH and/or Slimholes) Underway

**Phase II Project**

**Resource Development: at least one of the following Resource Development criteria must be met.**

- Temperature Gradient Holes Drilled
- Slim Hole Drilled
- One Full Size Discovery Well Drilled

**Transmission Development: at least one of the following Transmission Development criteria must be met.**

- Interconnection Application Submitted and Queue Position Established
- Transmission Feasibility Studies Underway

**External to Resource Development: at least one of the following External to Resource Development criteria must be met.**

- Permit for Slimhole Drilling Applied for or Approved
- Permit for Production Well Drilling Submitted
- Permit for Production Well Drilling Approved

**Phase III Project**

**Resource Development: at least two of the following Resource Development criteria must be met.**

- At Least One Full Size Production Well Drilled and Operational
- At Least One Full Size Injection Well Drilled and Operational
- Reservoir Characterization Completed and Sustainable Reservoir Capacity Determined

**Transmission Development: at least two of the following Transmission Development criteria must be met.**

- Interconnection Feasibility Study Complete
- System Impact Study (SIS) Underway or Complete
- Interconnection Facility Study Underway
- Transmission Service Request Submitted

**External to Resource Development: at least two of the following External to Resource Development criteria must be met.**

- Power Plant Permit Application Complete or in Process
- Power Purchase Agreement Secured or in Negotiation
- Financing Secured, or Being Secured, for Portion of Project Construction

**Phase IV Project**

**Resource Development: at least two of the following Resource Development criteria must be met.**

- Power Plant Equipment on Order
- Power Plant Construction Underway
- Production and Injection Drilling Underway

**Transmission Development: for a project to be considered a Phase IV development project the Large Generator Interconnection Agreement must be signed.**

If the transmission of power from the project to the end user requires point-to-point service through one or more utility networks then all of the below criteria must be met for the project to be considered a Phase IV development project.

- Large Generator Interconnection Agreement Signed
- Transmissions System Service Request Studies Complete

**External to Resource Development: all of the following Resource Development criteria must be met.**

- Power Plant Permit(s) Approved
- EPC Contract Signed
- PPA Secured

**Project Online and in Operation**

# Appendix B. Survey Results

This appendix details results from the industry survey. Blue rows indicate that the source is new since the final GEA report in 2016, whereas dark gray indicates that the plant has since been retired. A single blue cell indicates that the capacity of an existing plant has been increased.

Plant Name	Field Name	Company	Nameplate Capacity (MW)	Operational Year	Primary Plant Type	Turbine	Status	Decommission Date	EIA Plant ID
Aidlin Unit 1	CA - The Geysers	Calpine	11.2	1989	Dry Steam	Fuji	Operational	N/A	52158
Aidlin Unit 2	CA - The Geysers	Calpine	11.2	1989	Dry Steam	Fuji	Operational	N/A	52158
Amedee (Wendel)	CA - Honey Lake	Amedee Geothermal Venture (Oski Energy)	Non-operational	1988	Binary	Barber Nichols	Non-operational		50964
Beowawe	NV - Beowawe	Terra Gen	17	1985	Double Flash	Mitsubishi	Operational	N/A	10287
Beowawe 2	NV - Beowawe	Terra Gen	3.6	2011	Binary	TAS Energy	Operational	N/A	10287
Big Geysers	CA - The Geysers	Calpine	95	1980	Dry Steam	General Electric	Operational	N/A	286F
BLM East Unit 1	CA - Coso	Navy	30	1988	Double Flash	Fuji	Operational	N/A	10875
BLM East Unit 2	CA - Coso	Navy	30	1988	Double Flash	Fuji	Operational	N/A	10875
BLM West Unit 1	CA - Coso	Navy	30	1988	Double Flash	Fuji	Operational	N/A	10875
Blundell 1	UT - Roosevelt	PacifiCorp	30.7	1984	Single Flash	General Electric	Operational	N/A	299
Blundell 2	UT - Roosevelt	PacifiCorp	14.1	2007	Binary	Ormat	Operational	N/A	299
Bottle Rock	CA - The Geysers	Altarock/Cyrq	Non-operational	1985	Dry Steam	Fuji	Non-operational		902
Brady (Brady Complex)	NV - Brady Hot Spring	Ormat	21.5	2018	Binary	Ormat	Operational	N/A	55991
Brady Hot Spring (Brady Complex)	NV - Brady Hot Spring	Ormat	26.1	1992	Double Flash	Ormat	Retired	2019	55991
Calistoga	CA - The Geysers	Calpine	97	1984	Dry Steam	Toshiba	Operational	N/A	50066
CE Turbo	CA - Salton Sea	CalEnergy	10.35	2000	Single Flash	GE Rotoflow	Operational	N/A	55984
Chena Unit 1	AK - Chena Hot Springs	Chena Hot Springs	0.7	2006	Binary	Turboden	Operational	N/A	None found
Chena Unit 2	AK - Chena Hot Springs	Chena Hot Springs	0.4	2013	Binary		Operational	N/A	None found
Cobb Creek	CA - The Geysers	Calpine	110	1979	Dry Steam	Toshiba	Operational	N/A	286E
Cove Fort	UT - Cove Fort	EneI	30.8	2013	Binary	Ormat	Operational	N/A	58570
Del Ranch (Hoch)	CA - Salton Sea	CalEnergy	45.5	1989	Double Flash	Fuji	Operational	N/A	10632
Desert Peak II (Brady Complex)	NV - Brady Hot Spring	Ormat	26	2007	Binary	Ormat	Operational	N/A	10018
Desert Peak II EGS (Brady Complex)	NV - Brady Hot Spring	Ormat	Non-operational		EGS	Ormat	Non-operational		
Dixie Valley	NV - Dixie Valley	Terra Gen	64.7	1988	Double Flash	Fuji	Operational	N/A	52015
Dixie Valley (Binary)	NV - Dixie Valley	Terra Gen	6.2	2012	Binary	TAS Energy	Operational	N/A	52015
Don A. Campbell (Wild Rose)	NV - Deadhorse Wells (Wild Rose)	Ormat	25	2014	Binary	Ormat	Operational	N/A	58533
Don A. Campbell II	NV - Deadhorse Wells (Wild Rose)	Ormat	25	2015	Binary	Ormat	Operational	N/A	60419
Eagle Rock	CA - The Geysers	Calpine	110	1975	Dry Steam	Toshiba	Operational	N/A	286D
Elmore	CA - Salton Sea	CalEnergy	45.5	1989	Double Flash	Fuji	Operational	N/A	10634
Elmore (ST-302)	CA - Salton Sea	CalEnergy	8.41	2019	Back Pressure	GE	Operational	N/A	54111
Faulkner	NV - Blue Mountain	Cyrq	49.5	2009	Binary	Ormat	Operational	N/A	56982
Galena I (Richard Burdette) (Steamboat Complex)	NV - Steamboat	Ormat	30	2006	Binary	Ormat	Operational	N/A	56321
Galena II (Steamboat Complex)	NV - Steamboat	Ormat	13.5	2007	Binary	Ormat	Operational	N/A	56540
Galena III (Steamboat Complex)	NV - Steamboat	Ormat	30	2008	Binary	Ormat	Operational	N/A	56541
GEM II (Ormesa Complex)	CA - East Mesa	Ormat	21.6	1989	Double Flash	Ormat	Operational	N/A	54038
GEM III (Ormesa Complex)	CA - East Mesa	Ormat	21.6	1989	Double Flash	Ormat	Retired	2020	10763
GEM Bottoming Unit (Ormesa Complex)	CA - East Mesa	Ormat	8	2007	Binary	Ormat	Operational	N/A	10763
Goulds I (Heber Complex)	CA - Heber	Ormat	29.5	2006	Binary	Ormat	Operational	N/A	49748
Goulds II (Heber Complex)	CA - Heber	Ormat	16	2006	Binary	Ormat	Operational	N/A	54111

Plant Name	Field Name	Company	Nameplate Capacity (MW)	Operational Year	Primary Plant Type	Turbine	Status	Decommission Date	EIA Plant ID
Grant	CA - The Geysers	Calpine	120	1985	Dry Steam	Toshiba	Operational	N/A	286K
Heber I (Heber Complex)	CA - Heber	Ormat	52	1985?	Double Flash	Ormat	Operational	N/A	54689
Heber II (Heber Complex) Second Imperial	CA - Heber	Ormat	48	1993	Binary	Ormat	Operational	N/A	54111
Heber South (Heber Complex) Second Imperial	CA - Heber	Ormat	16	2008	Binary	Ormat	Operational	N/A	54111
Honey Lake	CA - Honey Lake	HL Power Company		1989	Binary	General Electric	*Non-operational		
Jersey Valley	NV - Dixie Valley	Ormat	23.5	2011	Binary	Ormat	Operational	N/A	57376
John L. Featherstone	CA - Salton Sea	Energy Source	55	2012	Triple Flash	Fuji	Operational	N/A	57475
Lake View	CA - The Geysers	Calpine	120	1982	Dry Steam	Toshiba	Operational	N/A	286I
Leathers	CA - Salton Sea	CalEnergy	45.5	1990	Double Flash	Fuji	Operational	N/A	10631
Lightning Dock (Old)	NM - Lightning Dock	Cyrq	4.4	2013	Binary	Kaishan	Retired	2017	58629
Lightning Dock	NM - Lightning Dock	Cyrq	14.5	2018		Kaishan	Operational	N/A	58629
Mammoth GI Repowering (Mammoth Complex)	CA - Mammoth	Ormat	10	2013	Binary	Ormat	Operational	N/A	10480
Mammoth GII (Mammoth Complex)	CA - Mammoth	Ormat	15	1990	Binary	Ormat	Operational	N/A	10481
Mammoth GIII Repowering (Mammoth Complex)	CA - Mammoth	Ormat	15	1990		Ormat	Operational	N/A	10479
McCabe	CA - The Geysers	Calpine	110	1971	Dry Steam	Toshiba	Operational	N/A	286A
McGinness Hills 1 & 2	NV - McGinness Hills	Ormat	100	2012 and 2015	Binary	Ormat	Operational	N/A	57446
McGinness Hills 3	NV - McGinness Hills	Ormat	74	2018	Binary	Ormat	Operational	N/A	61912
Navy I Unit 1	CA - Coso	Navy	30	1987	Double Flash	Fuji	Operational	N/A	10873
Navy I Unit 2	CA - Coso	Navy	30	1987	Double Flash	Fuji	Operational	N/A	10873
Navy I Unit 3	CA - Coso	Navy	30	1987	Double Flash	Fuji	Operational	N/A	10873
Navy II Unit 1	CA - Coso	Navy	30	1989	Double Flash	Fuji	Operational	N/A	10874
Navy II Unit 2	CA - Coso	Navy	30	1989	Double Flash	Fuji	Operational	N/A	10874
Navy II Unit 3	CA - Coso	Navy	30	1989	Double Flash	Fuji	Operational	N/A	10874
NCPA I No. 2	CA - The Geysers	Northern California Power Agency	110	1983	Dry Steam	Fuji	Operational	N/A	7368
NCPA II	CA - The Geysers	Northern California Power Agency	110	1985	Dry Steam	Toshiba	Operational	N/A	7369
Neal Hot Springs	OR - Neal Hot Springs	Ormat	33	2012	Binary	U.S. Geothermal	Operational	N/A	58022
North Brawley	CA - North Brawley	Ormat	50	2010	Binary	Ormat	Operational	N/A	56832
OIT	OR - Klamath Falls	OIT	0.28	2009	Binary	Pratt & Whitney	Operational	N/A	
OIT	OR - Klamath Falls	OIT	1.75	2014	Binary	Pratt & Whitney	Operational	N/A	
Ormesa I (Ormesa Complex)	CA - East Mesa	Ormat	26.4	2003	Binary	Ormat	Operational	N/A	50766
Ormesa IH (Ormesa Complex)	CA - East Mesa	Ormat	8.8	1989?	Binary	Ormat	Retired	Post 2015	50762
Ormesa II (Ormesa Complex)	CA - East Mesa	Ormat	24		Double Flash	Ormat	Retired	2007	
Ormesa II Upgrade (Ormesa Complex)	CA - East Mesa	Ormat	24	2007	Binary	Ormat	Operational	N/A	54724
Paisley Geothermal	OR - Surprise Valley	Surprise Valley Electric Corp.	3.1	2014	Binary	TAS Energy	Operational	N/A	
Patua Phase 1	NV - Hazen (Black Butte)	Cyrq	48	2013	Binary	TAS Energy	Operational	N/A	58319
Puna	HI - Puna	Ormat	35	1993	Binary	Ormat	Operational	N/A	52028
Puna Expansion	HI - Puna	Ormat	51	2012	Binary	Ormat	Operational	N/A	52028
Quicksilver	CA - The Geysers	Calpine	120	1985	Dry Steam	Toshiba	Operational	N/A	286H
Raft River	ID - Raft River	Ormat	18	2008	Binary	U.S. Geothermal	Operational	N/A	56317
Ridgeline	CA - The Geysers	Calpine	110	1982	Dry Steam	Toshiba	Operational	N/A	286B
San Emidio Repower	NV - San Emidio (Empire)	Ormat	11.75	2012	Binary	U.S. Geothermal	Operational	N/A	57456
Salt Wells	NV - Salt Wells (Eight Mile Flat)	EneI	27.6	2009	Binary	Atlas Copco/Mafi Trench	Operational	N/A	57213
Salton Sea I	CA - Salton Sea	CalEnergy	10.25	1982	Single Flash	Fuji	Operational	N/A	10878
Salton Sea II	CA - Salton Sea	CalEnergy	19.7	1990	Double Flash	Mitsubishi	Operational	N/A	10879
Salton Sea III	CA - Salton Sea	CalEnergy	54	1989	Double Flash	Mitsubishi	Operational	N/A	10759
Salton Sea IV	CA - Salton Sea	CalEnergy	55	1996	Double Flash	GE	Operational	N/A	54996
Salton Sea V	CA - Salton Sea	CalEnergy	58.32	2000	Double Flash	Fuji	Operational	N/A	55983
Socrates	CA - The Geysers	Calpine	120	1983	Dry Steam	Toshiba	Operational	N/A	286J

Plant Name	Field Name	Company	Nameplate Capacity (MW)	Operational Year	Primary Plant Type	Turbine	Status	Decommission Date	EIA Plant ID
Soda Lake 1	NV - Soda Lake	Cyrq	5.1	1987	Binary	Ormat	Retired	Post 2015	52174
Soda Lake 2	NV - Soda Lake	Cyrq	9	1991	Binary	Ormat	Operational	N/A	52174
Soda Lake 3	NV - Soda Lake	Cyrq	26.5	2019	Binary	Ormat	Operational	N/A	
Sonoma	CA - The Geysers	Calpine	78	1983	Dry Steam	Mitsubishi	Operational	N/A	510
Steamboat 1 (Steamboat Complex)	NV - Steamboat	Ormat	2	1985?	Binary	Ormat	Retired	2018	
Steamboat IA (Steamboat Complex)	NV - Steamboat	Ormat	2.4	1985?	Binary	Ormat	Retired	2018	52138
Steamboat 2 (Steamboat Complex)	NV - Steamboat	Ormat	18.2	2008	Binary	Ormat	Operational	N/A	54665
Steamboat 3 (Steamboat Complex)	NV - Steamboat	Ormat	18.2	2008	Binary	Ormat	Operational	N/A	54666
Steamboat Hills Bottoming	NV - Steamboat	Ormat	5.5	2007	Single Flash	Ormat	Operational	N/A	50654
Steamboat Hills STG	NV - Steamboat	Ormat	16.3	1988	Binary	Ormat	Operational	N/A	50654
Stillwater	NV - Stillwater	Enel	33.1	2009	Binary	Atlas Copco/Mafi Trench	Operational	N/A	50765
Sulphur Spring	CA - The Geysers	Calpine	117.5	1980	Dry Steam	Toshiba	Operational	N/A	2866
Thermo Hot Spring	UT - Thermo Hot Spring	Cyrq	14.5	2009	Binary	Turboden	Operational	N/A	57353
Tungsten Mountain	NV - Tungsten Mountain	Ormat	37	2017	Binary		Operational	N/A	60785
Tuscarora	NV - Hot Sulphur Springs	Ormat	32	2012	Binary	Ormat	Operational	N/A	57451
Vulcan	CA - Salton Sea	CalEnergy	39.72	1986	Double Flash	Mitsubishi	Operational	N/A	50210
West Ford Flat	CA - The Geysers	Calpine	28.8	1988	Dry Steam	Mitsubishi	Operational	N/A	10199
Wineagle	CA - Honey Lake	Wineagle Development	Non-operational	1985	Binary	Barber Nichols	*Non-operational		
Wabuska 3	NV - Wabuska	Open Mountain Energy	4.4	2018	Binary		Operational	N/A	

# Appendix C. U.S. Geothermal Online Resources

## C.1 Federal Government Resources

### Bureau of Land Management (BLM)

#### BLM General Land Office (GLO) Records

The BLM GLO Records Automation website provides live access to Federal land conveyance records for the Public Land States, including image access to more than 5 million Federal land title records issued between 1788 and the present. <https://glorerecords.blm.gov/>

#### BLM Geothermal Guidance

This page serves as a central point of reference and as a repository of reading material and information for the BLM's geothermal program. <https://www.blm.gov/programs/energy-and-minerals/renewable-energy/geothermal-energy/geothermal-guidance>

### Department of Energy (DOE)

#### Geothermal Technologies Office (GTO)

The GTO website gives a general description of geothermal technologies as well as an overview of some of the office's programs. <https://www.energy.gov/eere/geothermal/geothermal-energy-us-department-energy>

#### Deep Direct Use (DDU)

This web page summarizes DDU geothermal research and applications and provides links to other direct use and low-temperature resources. <https://www.energy.gov/eere/geothermal/downloads/energy-department-explores-deep-direct-use>

#### EGS Collab

This web page describes the GTO-funded EGS Collab project, which aims to establish a collaborative experimental and model comparison initiative for longer-term, transformational enhanced geothermal systems (EGS). <https://www.energy.gov/eere/geothermal/egs-collab>

### Frontier Observatory for Research in Geothermal Energy (FORGE)

This website has a variety of resources related to the FORGE project, which aims to create a dedicated site where scientists and engineers will be able to develop, test, and accelerate breakthroughs in EGS technologies and techniques. <https://www.energy.gov/eere/forge/forge-home>

### GeoVision: Harnessing the Heat Beneath Our Feet

This report summarizes and discusses the many opportunities that geothermal energy offers in both electric and non-electric uses. The report also highlights the outcomes the United States could realize from increased geothermal deployment and outlines a range of activities necessary to reach this deployment. <https://www.energy.gov/eere/geothermal/geovision>

### Play Fairway Analysis (PFA)

This page describes DOE's investments in adapting play fairway analysis to geothermal exploration. <https://www.energy.gov/eere/geothermal/play-fairway-analysis>

### National Renewable Energy Laboratory (NREL)

#### Annual Technology Baseline (ATB)

The ATB is a populated framework to identify technology-specific cost and performance parameters or other investment decision metrics across a range of fuel price conditions as well as site-specific conditions for electric generation technologies at present and with projections through 2050. <https://atb.nrel.gov/>

#### GEOPHIRES v2.0

GEOPHIRES is a free and open-source geothermal techno-economic simulator that combines reservoir, wellbore, surface plant, and economic models to estimate the capital as well as operation and maintenance costs, instantaneous and lifetime energy production, and overall levelized cost of energy of a geothermal plant. <https://github.com/NREL/GEOPHIRES-v2>

### Geothermal Electricity Technology Evaluation Model (GETEM)

GETEM is a downloadable document that estimates the levelized cost of electricity using user-input data and a set of default information that is based on several resource scenarios that GTO has defined and evaluated. <https://www1.eere.energy.gov/geothermal/getem/DownloadTools.aspx>

### Geothermal Prospector

This interactive map contains information on known geothermal resource areas and exploration regions, geothermal potential for EGS, low-temperature geothermal resources, identified hydrothermal sites, hot spring and well analyses, and FORGE project sites, as well as geothermal infrastructure and leasing information. <https://maps.nrel.gov/geothermal-prospector/>

### Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT)

The GeoRePORT Protocol can assist in evaluating project risk and return, identifying gaps in reported data, evaluating research and design impacts, and gathering insights on successes and failures. It helps to compare project potential more objectively and quantitatively in geological, technical, and socio-economic areas. <https://openei.org/wiki/GeoRePORT>

### Geothermal Technologies Group

NREL's Geothermal Technologies page summarizes some of the program's activities, including impact and market research, technological development and organizational partnerships, and provides access to the group's research and publications. <https://www.nrel.gov/geothermal/>

### United States Forest Service (USFS)

#### Geothermal Resource Management on National Forest System Lands

This web page describes the U.S. Forest Service's role in geothermal development and provides general information regarding USFS geothermal leases. <https://www.fs.usda.gov/science-technology/geology/energyminerals/geothermal>

### United States Geological Survey (USGS)

#### Geothermal Resources Program

The USGS website holds a collection of resources aimed at characterizing and assessing geothermal energy resources in the United States. [https://www.usgs.gov/energy-and-minerals/energy-resources-program/science/geothermal?qt-science\\_center\\_objects=0#qt-science\\_center\\_objects](https://www.usgs.gov/energy-and-minerals/energy-resources-program/science/geothermal?qt-science_center_objects=0#qt-science_center_objects)

## C.2 State Government Resources

### Alaska Department of Natural Resources, Geological and Geophysical Surveys: Geothermal Energy

This web page houses a collection of geoscience resources related to geothermal production in Alaska. <https://dggs.alaska.gov/energy/geothermal.html#:~:text=Alaska%20is%20geothermally%20active%20with,and%20began%20operation%20in%202006>

### California Department of Conservation: Geothermal Resources

This web page provides information on California geothermal usage, including Geologic Energy Management Division (CalGEM) dynamic, statewide maps. <https://www.conservation.ca.gov/calgem/geothermal>

### California Energy Commission

The CEC website houses a collection of reports and resources covering all aspects of energy production in California. <https://www.energy.ca.gov/>

### California Geothermal Energy Statistics and Data

This web page provides geothermal power plant and power generation figures for the state of California. [https://ww2.energy.ca.gov/almanac/renewables\\_data/geothermal/index cms.php](https://ww2.energy.ca.gov/almanac/renewables_data/geothermal/index cms.php)

### Hawaii State Energy Office

This website provides a summary of geothermal activities in Hawaii. <https://energy.hawaii.gov/renewable-energy/geothermal>

### Idaho Energy and Mineral Resources: Geothermal

This web page provides a summary of geothermal activities in Idaho, including description of the Boise district heating system. <https://oemr.idaho.gov/sources/re/geothermal/#:~:text=Idaho%20uses%20its%20geothermal%20resources,aquatic%20species%2C%20and%20for%20recreation.&text=A%20well%20is%20drilled%20into,power%20plant%20or%20individual%20home>

### Nevada Division of Minerals

This website contains a summary of geothermal activities in the state of Nevada. <http://minerals.nv.gov/Programs/Geo/Geo/>

### New Mexico Energy Conservation and Management Division: Geothermal

This web page provides a summary of geothermal policy and activities in the state of New Mexico. <http://www.emnrd.state.nm.us/ECMD/RenewableEnergy/geothermal.html>

### Oregon Department of Energy: Geothermal

This web page provides a summary of geothermal activities in the state of Oregon. <https://www.oregon.gov/energy/energy-oregon/Pages/Geothermal.aspx#:~:text=Geothermal%20Energy%20in%20Oregon,-In%202018%3A&text=It%20makes%20up%20less%20than,were%20used%20to%20create%20electricity>

### Utah Geological Survey: Geothermal

This web page provides a summary of geothermal production in the state of Utah. <https://geology.utah.gov/resources/energy/geothermal/>

## C.3 Universities

### Southern Methodist University Geothermal Lab

An active research facility, the SMU Geothermal Lab provides access to a variety of resources, including the Geothermal Map of North America. <https://www.smu.edu/Dedman/Academics/Departments/Earth-Sciences/Research/GeothermalLab>

### Stanford Geothermal Program

The Stanford Geothermal Program's website provides access to geothermal research as well as information and publications related to Stanford's Geothermal Workshop. <https://geothermal.stanford.edu/>

### University of Illinois

This web page provides links to documents related to the University of Illinois' geothermal projects, including the in-development Campus Instructional Facility (CIF). <https://icap.sustainability.illinois.edu/project/geothermal-campus>

### University of Nevada, Reno: Great Basin Center for Geothermal Energy (GBCGE)

GBCGE is a research facility focused on collecting and synthesizing geodata to map the geothermal potential of the Great Basin. <https://gbcge.org/>

### University of Utah Energy and Geoscience Institute (EGI)

The Applied Geothermal Research page of the EGI website provides basic and applied geoscientific research for the geothermal, petroleum, and mining industries, government agencies, and international organizations. <https://egi.utah.edu/research/geothermal/>

## C.4 Non-Governmental Organizations

### ClearPath

ClearPath is an organization dedicated to developing and advancing conservative policies that accelerate clean energy innovation. <https://clearpath.org/policy/geothermal/>

### Geothermal Entrepreneurship Organization (GEO)

GEO is an organization which aims to leverage the legacy of oil and gas research and development to enable drilling for geothermal energy anywhere in the world. Its website contains a variety of resources, including information on the PIVOT2020 event. <https://www.texasgeo.org>

### Geothermal Rising (formerly the Geothermal Resources Council)

A geothermal industry association that advocates for the use of geothermal energy, the Geothermal Rising website houses information on all aspects of Earth's most plentiful and sustainable energy source. <https://geothermal.org/>

### International Geothermal Association (IGA)

The IGA website hosts global data on geothermal use, as well as information relating to the World Geothermal Congress. <https://www.geothermal-energy.org/>

### Women in Geothermal (WING)

WING is a global network that aims to promote the education, professional development, and advancement of women in the geothermal community. Join us in making waves in the geothermal industry. <https://womeningeothermal.org/>

## C.5 Publication and Data Catalogs

### Geothermal Data Repository (GDR)

This database provides access to reports and data related to Department of Energy sponsored projects, such as FORGE and EGS Collab. <https://gdr.openei.org>

### Geothermal Rising Online Library

Geothermal Rising's library database (formerly the GRC Geothermal Library) contains over 42,000 records on all aspects of geothermal energy, including article-level citations to: all GRC Transactions (1977 to present), all GRC Special Reports, numerous feature articles and news briefs from the GRC Bulletin (1973 to present), corporate and academic technical reports, journals, and books. <https://geothermal-library.org/>

### IGA Library

The IGA paper database includes scientific geothermal papers presented during geothermal conferences and events, including the World Geothermal Congress. <https://www.geothermal-energy.org/explore/our-databases/conference-paper-database/>

### National Geothermal Data System (NGDS)

The NGDS is a collaborative repository of geothermal data and publications. <https://geothermaldata.org>

### OnePetro

The OnePetro database provides access to a variety of papers and conference proceedings related to the oil and gas industry. <https://www.onepetro.org/>

### Office of Scientific and Technical Information

The OSTI database contains over 70 years of energy-related research results and citations collected by OSTI, consisting of nearly 3 million citations. <https://www.osti.gov/>

### Stanford/IGA Conference Database

This database contains papers and proceedings from a variety of geothermal-focused conferences, including the World Geothermal Congress, the Stanford Geothermal Workshop, and the New Zealand Geothermal Workshop, among others. <https://pangea.stanford.edu/ERE/db/IGAstandard/search.php>

## C.6 Commercial Resources

### Lazard's Levelized Cost of Energy and Levelized Cost of Storage

An annual report that compares the levelized costs of various power production technologies. <https://www.lazard.com/perspective/lcoe2019>

### ThinkGeoEnergy

A collection of news stories and other resources related to geothermal energy. <https://www.thinkgeoenergy.com/>



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