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The United States of America Country Update 2023 – Power Generation

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ABSTRACT

The United States of America hosts a diverse and potent array of geothermal resources and plant types. High temperature dry steam or multiple flash complexes such as at The Geysers or Salton Sea in California originally occupied the larger end of the MW spectrum. Increased use of binary power plant technology has vastly extended geothermal applications into lower temperature reservoirs, such as those found in the Basin and Range province. New plant configurations are appearing such as geothermal-solar hybrids and co-production of geothermal power at oil and gas fields, and mineral recovery (primarily lithium) has become an important driver, particularly (but not exclusively) in the Salton Sea geothermal field.

For the year ending December 2021, the total installed nameplate geothermal power capacity in the United States was approximately 3.9 GWe. This is a 94 MW increase for the three-year period since the previous country update, which was based on units in operation in December 2018 (Robertson-Tait *et al.*, 2020). Geothermal power is produced in the states of Alaska, California, Hawaii, Idaho, Nevada, New Mexico, Oregon and Utah. Together, California and Nevada host the majority (3,338 MWe) of this generation, with 2,602 and 736 MWe installed in California and Nevada, respectively.

Both federal- and state-level policy and regulatory support for geothermal energy have increased during the reporting period, creating a new, positive momentum for geothermal electricity generation and heating and cooling in the United States, particularly during the past year. Highlights in the federal realm include announcing a federal 24/7 carbon-free electricity mandate, passing the historic Inflation Reduction Act of 2022, appropriating increased funds for geothermal energy research, development, and deployment (RD&D), and increased focus on facilitating permitting reform for geothermal energy projects.

Federal support from the US Department of Energy's Geothermal Technologies Office (DOE-GTO) has expanded since the prior update in 2019. DOE-GTO has maintained a strong focus on Enhanced Geothermal Systems (EGS), initiating the Enhanced Geothermal Shot in 2022, a challenge to reduce EGS costs by 90% by 2035. This is one of several recent initiatives to overcome scientific and technical barriers and enable the United States to reach the goal of net-zero emissions by 2050. The Frontier Observatory for Research in Geothermal Energy (FORGE) project in Utah (Utah FORGE, DOE-GTO's flagship EGS RD&D project) continues to make significant progress, having drilled and instrumented several monitoring wells and three deeper wells, recently completing the second well of the EGS doublet in June 2023. Injection testing in early July 2023 demonstrates a connection between the injection well and the production well. DOE-GTO has also invested in deep basin geothermal through its Geothermal Energy from Oil and Gas Demonstrated Engineering (GEODE) initiative, which was recently awarded to a broad consortium that includes deep expertise in geothermal, oil and gas, and research. Although not related to geothermal power (the focus of this paper), DOE-GTO has taken another notable step: significantly expanding its geothermal portfolio for heating and cooling at the community scale, which represents a huge decarbonization opportunity.

State support is particularly strong in California, which has a mandated renewable power requirement and a mandated cap on CO_2 emissions. This, combined with the de-stabilizing effect on the electricity grid from rooftop and utility-scale solar and the massive demand for power in California, has led the California Public Utility Commission (CPUC) to recommend the development of at least 2,000 more MW of base-load geothermal power in the near future. Although this amount may be considered modest in comparison to the potential for additional geothermal development in the United States, it is a significant turning point in terms of policy. This, like the U.S. Senate hearings on geothermal power in 2019, can be credited to work by the geothermal industry, supported by the independent technical evaluations of DOE-GTO and USGS. Legislation to support the growth of geothermal power has been introduced to streamline specific permitting processes (without undermining environmental stewardship), improve access to transmission systems and re-establish parity with tax credits provided to other renewable power sources. Together with the specific mandated requirements in the State of California (which can be served in part by sources generated outside the state), these factors will enable the continued development of geothermal power projects in the western United States.

Significant additional geothermal power remains to be produced in the United States. DOE-GTO's 2019 GeoVision study concludes that technology improvements – many of which are the subject of active research today – could significantly increase geothermal power generation in the United States, which the GeoVision study estimates could reach 60 GWe. A significant portion of this capacity is expected to be derived from EGS. Earlier (in 2008), the United States Geological Survey (USGS) had estimated that the generation capacity of known conventional hydrothermal resources in the United States is approximately 9 GWe, of which approximately 4 GWe is already installed. Thus, another 5 GWe of conventional hydrothermal resources are available for development. The USGS estimates that there is another 30 GWe of potential from as-yet undiscovered geothermal resources, some of which are hosted in deep sedimentary basins.

As the demand for more geothermal power continues to increase in the United States, more tertiary educational institutions are offering geothermal curricula that focus on a wide range of subjects, including exploration technologies, hybrid solutions that combine geothermal with other technologies to maximize green benefits, reservoir modeling (geologic and numerical models), innovative drilling methods, power plant technology optimization, and the development of unconventional geothermal resources, including Enhanced Geothermal Systems (EGS) and closed-loop systems, now commonly referred to as Advanced Geothermal Systems (AGS).

Collaboration on specific technical topics between universities, research organizations and DOE is leading to innovation in many aspects of geothermal energy. As oil and gas companies enter or return to the geothermal market, collaboration is increasing between them and existing geothermal operators, research organizations and DOE-GTO. The focus is not only on the known reserves of traditional geothermal resources in the United States, but also deep sedimentary basins, the domain of oil and gas. This growing relationship brings another crucial element to the wholesale energy transformation that is underway today: the ability to scale-up geothermal quickly.

Although the past several years have been characterized by modest geothermal growth, current social, economic and political trends provide significant optimism for the development of additional geothermal power, particularly in the western United States. A combination of potent forces are in place to drive a new wave of geothermal power expansion in the United States, including the long-term (2024-2032) tax credits for geothermal power projects, the need for baseload generation to mitigate impacts on the grid from intermittent renewable power, the entry / re-entry of oil and gas, and accelerated policy engagement by the geothermal industry.

1. INTRODUCTION

The objective of this paper is to provide an update on the state of geothermal development in the United States. The country's overall electrical generation portfolio and market conditions are presented first, followed by the details of the currently operating geothermal assets and the potential for additional capacity. Herein we discuss trends in geothermal project development, the geothermal policy landscape in the United States, new entrants and synergies in the geothermal sector, and other initiatives that support the development of advanced geothermal technologies at the national level, including R&D.

1.1 Summary of Current Installed Power Generation Capacity (All Sources)

Table 1 provides totals for the installed capacity and annual electrical production in the United States for the years ending 2018 (which was the basis for the 2020 USA Country Update) and 2021. These years were selected as the last full years for which the U.S. Energy Information Administration (EIA) provides annual data. Note that the EIA presents generation on a net basis. The numbers presented in Table 1 are for utility-scale facilities only and do not reflect smaller installations such as residential solar. Total installed capacity (MWe) from all sources has increased by 3.8% over the 3-year period from 2018 to 2021. Net electrical generation dropped from 4,181 to 4,108 GWh/year (-1.7%), likely due to the impact of COVID-19 in 2021. Table 1 also shows the gradual shift away from fossil fuel installed capacity (-2.6%), mostly baseload, towards renewables (+27%), mostly intermittent sources such as wind and solar.

Table 1: Present Production of Electricity (EIA 2022)

Energy source	Geothermal		Other Renewables (wind, utility scale solar, biomass, hydro)		Nuclear		Fossil Fuels		Other sources		Total	
	Installed Capacity (MWe)	Net Electrical generation GWh/yr	Installed Capacity (MWe)	Net Electrical generation GWh/yr	Installed Capacity (MWe)	Net Electrical generation GWh/yr	Installed Capacity (MWe)	Net Electrical generation GWh/yr	Installed Capacity (MWe)	Net Electrical generation GWh/yr	Installed Capacity (MWe)	Net Electrical generation GWh/yr
In operation in December 2018	3,806	15,967	244,555	700,911	104,270	791,117	841,288	2,660,019	2,569	12,973	**1,196,488**	**4,180,987**
In operation in December 2021	3,889	15,975	311,433	794,180	99,960	778,188	819,775	2,507,819	6,521	12,140	**1,241,578**	**4,108,302**

The installed capacity of fossil fuel power plants declined by 21.5 GW over the two-year period, offset by a 67 GW increase in other renewables. Nuclear and geothermal installed capacities and net electrical generation contributions have been relatively level.

Wind and solar (PV and thermal) have driven most of the growth in the overall renewable portfolio. Through 31 December 2021, renewables accounted for about 20% of total U.S. annual generation. Geothermal's overall generation share has stayed constant from 2018-2021 at 2% of all renewables and 0.4% of total generation.

1.2 Potential for Additional Generation (All Sources)

The EIA also provides estimates for planned generating capacity (net summer) additions across all sectors from 2022-2026. Fossil fuel plants are anticipated to continue to be retired at a net rate of -28,021 MW over this period, accompanied by nuclear (-808 MW). 105,529 MW of renewable capacity is expected to be added over this period, mainly wind (+30,012 MW) and solar (+75,251 MW). The EIA projects only 94 MW of added geothermal capacity over this period, which seems conservative compared to projects currently planned.

2. GEOTHERMAL ELECTRICITY PRODUCTION

As shown in Figure 1, the epicenter of geothermal power generation in the United States is in the western part of the country, with an array of eight states with operating geothermal plants: Alaska, California, Hawaii, Idaho, Nevada, New Mexico, Oregon and Utah, with the majority centered in the geologically favorable states of California and Nevada. In an expanding radius from these states, there has been exploration and a few small pilot projects in the states of Arizona, Colorado, Louisiana, Mississippi, Texas, Washington and Wyoming.

Information about operating geothermal fields, projects and individual generator units in the United States are presented herein using the table format specified in the IGA template, which was updated in 2020. Table 2.1 presents general information about operating geothermal fields in the United States as of 2021, all of which are hydrothermal systems. The information in Table 2.1 includes field name, field operator, the number of wells in operation and the depth of the deepest production well (where available) and the system type (hot water, two-phase liquid-dominated and two-phase steam-dominated).

2.1 Total Current Installed Capacity

Table 2.2 presents information about the power plants and individual generation units, including the unit name, type, year commissioned, operating status, turbine manufacturer, nameplate capacity, and generation. For consistent reporting year over year, the required reporting data were primarily taken from the California Energy Commission (CEC) (2022) for projects in California. The CEC data are sometimes available on a unit basis, although only net electrical production is shown. As reported in form EIA-923, EIA's annual data by plant does not show gross annual production data. For other states, data are taken from EIA (2022), which shows overall generation at each geothermal complex, but data on a unit basis is often unavailable. In selected instances, operators have provided installed capacity data that may differ from the EIA due to project upgrades such as turbine retrofits. Due to data pieced together from various sources, the values included in the tables below may not be in complete alignment with each other or the values shown in Table 1. Where data are not available, N/A is indicated.

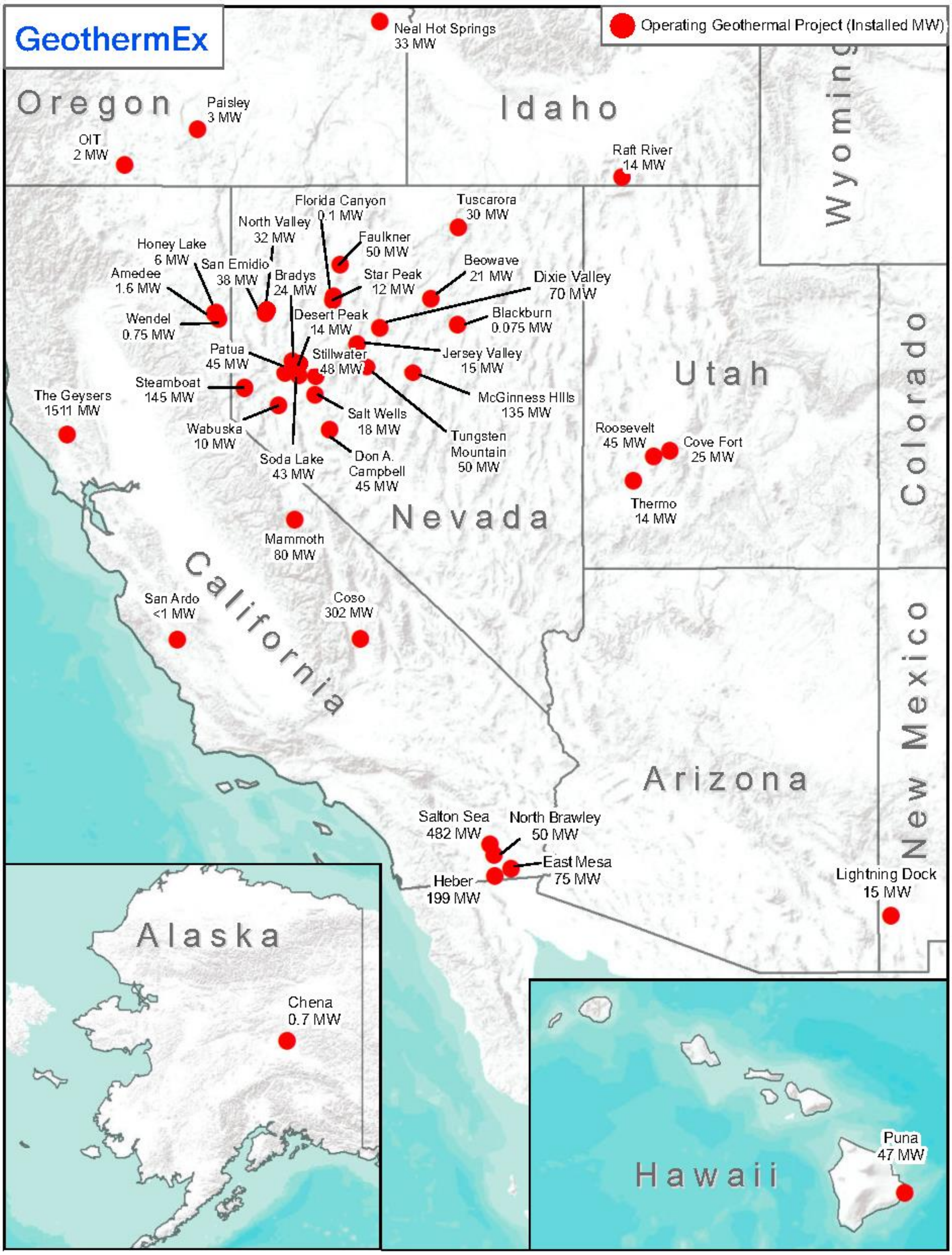

Figure 1: Locations and installed capacities at geothermal fields developed for power generation in the United States

Total installed (generator nameplate) geothermal capacity at the end of year 2021, as stated by EIA (2022), is approximately 3.9 GW. As noted above, depending on the data source, MW ratings differ. In addition, some plants have been re-rated due to turbine modifications, or evolution of their fields or power plant equipment, and that information may not be perfectly synchronized across data reported by owners, the CEC or EIA. The EIA data in Table 1, for total net geothermal generation in the year ending December 2021, was 15.98 TWh. The sum of data in Table 2.2 indicates a 2021 total net geothermal generation of 15.77 TWh.

Table 2.1 Operating geothermal fields in the United States

Geothermal Field					
(1) Field Name	(2) Field operator	(3) Wells in operation	(4) Depth of deepest production well (m)	(6) System type	(7) Plant Name or number
AK - Chena	Chena Hot Springs	N/A	N/A	Hot water	Chena Unit 1
					Chena Unit 2
					Chena Unit 3
CA - Coso	Coso Operating Company	50	3375	Two-phase, liquid-dominated: High enthalpy	Navy I
		39	3200	Two-phase, liquid-dominated: High enthalpy	Navy II
		43	3438	Two-phase, liquid-dominated: High enthalpy	BLM
CA - Wendel	Baseload Power US	1	400	Hot water	Wendel
CA - Amedee	Amedee Geothermal Venture	N/A	N/A	Hot water	Amedee
CA - Honey Lake	HL Power	N/A	N/A	Hot water	Honey Lake
CA - Mammoth	Mammoth Pacific (Ormat)	N/A	N/A	Hot water	G-1 (MP-1)
					G-1 (MP-1)
					G-2 (MP-2)
					G-2 (MP-2)
					G-2 (MP-2)
					G-3 (PLES-1)
					G-3 (PLES-1)
					G-3 (PLES-1)
					Casa Diablo IV
CA - Ormesa	Ormat	N/A	N/A	Hot water	OG I (Ormesa I)
					OG II (Ormesa II)
					Ormesa IE
					Ormesa IH
					GEM 2
					GEM 3
					GEM Bottoming Unit
					Ormesa III
CA - Heber	Ormat	N/A	N/A	Two-phase, liquid-dominated: Low enthalpy	Heber
					Heber
					Heber
					Heber
					Heber
					Heber
					Heber
					Heber
					Heber
CA - North Brawley	Ormat	N/A	N/A	Hot water	North Brawley
CA - Salton Sea - CalEnergy	BHER/CalEnergy	1	2438	Two-phase, liquid-dominated: High enthalpy	Salton Sea 1
		5			Salton Sea 3
		1			Salton Sea 2
		1			Salton Sea 2
		1			Salton Sea 2
		4			Salton Sea 4
		6			Salton Sea 5
		4	2134		Vulcan
		1			Vulcan
		5			Del Ranch (Hoch)
		1			CE Turbo
		8	2783		Elmore
		1			Elmore Backpressure
		11	2652		Leathers
CA - Salton Sea - Cyrq	Cyrq Energy	8	2622	Two-phase, liquid-dominated: High enthalpy	John L. Featherstone
CA - The Geysers	Calpine	323 (production) N/A (injection)	3932	Two-phase, vapour-dominated	McCabe (5&6)
					McCabe (5&6)
					Ridgeline (7&8)
					Ridgeline (7&8)
					Eagle Rock (11)
					Cobb Creek (12)
					Big Geysers (13)
					Sulphur Springs (14)
					Lake View (17)
					Socrates (18)
					Sonoma (3)
					Calistoga (19)
					Calistoga (19)
					Quicksilver (16)
					Grant (20)
					Aidlin (1)
					Aidlin (1)
					West Ford Flat (4)
					Bear Canyon (2)
CA - The Geysers	NCPA	75	3343	Two-phase, vapour-dominated	NCPA I (Geothermal 1)
					NCPA I (Geothermal 1)
					NCPA II (Geothermal 2)
					NCPA II (Geothermal 2)
CA - The Geysers	Open Mountain Energy	N/A	N/A	Two-phase, liquid-dominated: Low enthalpy	Bottle Rock

Geothermal Field					
(1) Field Name	(2) Field operator	(3) Wells in operation	(4) Depth of deepest production well (m)	(6) System type	(7) Plant Name or number
CA - San Ardo	Chevron	N/A	N/A	Hot water	San Ardo
HI - Puna	Ormat	N/A	N/A	Two-phase, liquid-dominated: High enthalpy	Puna Geothermal Venture I
					Puna Expansion
ID - Raft River	Ormat	N/A	N/A	Hot water	Raft River
NM - Lightning Dock	Cyrq Energy	N/A	N/A	Hot water	Lightning Dock
		9	882		Lightning Dock Repowering
NV - Beowawe	Ormat	N/A	N/A	Two-phase, liquid-dominated: Low enthalpy	Beowawe
				Hot water	Beowawe 2
NV - Blue Mountain	Cyrq Energy	10	1345	Hot water	Blue Mountain I
NV - Brady	Ormat	N/A	N/A	Hot water	Brady
NV - Desert Peak	Ormat	N/A	N/A	Hot water	Desert Peak 2
NV - Don A. Campbell	Ormat	N/A	N/A	Hot water	Don A. Campbell
NV - Dixie Valley	Ormat	N/A	N/A	Two-phase, liquid-dominated: Low enthalpy	Dixie Valley
				Hot water	
NV - Jersey Valley	Ormat	N/A	N/A	Hot water	Jersey Valley
NV - Florida Canyon	Florida Canyon	N/A	N/A	Hot water	Florida Canyon Mine
NV - North Valley	Ormat	N/A	N/A	Hot water	North Valley
NV - Patua	Cyrq Energy	8	2962	Hot water	Patua
NV - Tuscarora	Ormat	N/A	N/A	Hot water	Tuscarora
NV - McGinness Hills	Ormat	N/A	N/A	Hot water	McGinness Hills
NV - Salt Wells	ENEL Green Power North America	N/A	N/A	Hot water	Salt Wells
NV - San Emidio	Ormat	N/A	N/A	Hot water	San Emidio Repower
					North Valley
NV - Soda Lake	Cyrq Energy	7	2742	Hot water	Soda Lake 1
					Soda Lake 2
					Soda Lake 3 (Repower)
NV - Star Peak	OME	N/A	N/A	Hot water	Star Peak
NV - Steamboat	Ormat	N/A	N/A	Two-phase, liquid-dominated: Low enthalpy	Steamboat Hills
					Steamboat Hills Repower
					Steamboat II
					Steamboat III
					Galena 1 (Richard Burdette)
					Galena 2
					Galena 3
NV - Stillwater	ENEL Green Power North America	N/A	N/A	Hot water	Stillwater 2
NV - Tungsten Mountain	Ormat	N/A	N/A	Hot water	Tungsten Mountain
NV - Wabuska	OME	N/A	N/A	Hot water	Wabuska 1
					Wabuska 2
					Whitegrass No. 1
					Whitegrass No. 2
NV - Blackburn	Grant Canyon Oil and Gas	1	N/A	Hot water	Pilot
OR - OIT	Oregon Institute of Technology	3	1612	Hot water	OIT Unit 1
		N/A	N/A		OIT Unit 2
OR - Neal Hot Springs	Ormat	N/A	N/A	Hot water	Neal Hot Springs
OR - Paisley	Surprise Valley Electrification Corp.	N/A	N/A	Hot water	Paisley
UT - Cove Fort	ENEL Green Power North America	N/A	N/A	Hot water	Cove Fort 3
UT - Blundell	Pacificorp	N/A	N/A	Two-phase, liquid-dominated: Low enthalpy	Blundell Unit 1
				Hot water	Blundell Unit 2
UT - Thermo	Cyrq Energy	N/A	N/A	Hot water	Thermo 1
		8	2122	Hot water	Thermo 1 Repower

2.2 Details of Existing Geothermal Generation Facilities

The intent of this section is not to provide a detailed description of all existing plants in each state, but rather to comment on recent trends or development activities within the past several, which may overlap with commentary in the previous (2020) update.

2.2.1 Alaska

The Chena Hot Springs project continues to deliver both electrical and thermal power, displacing costly diesel fuel consumption in this remote area.

The most sizable new project under development in the state is the 36 MW Unalaska geothermal power plant, located on an island in the Aleutians. The project is a joint development between Chena Power and Ounalaska Corporation (OC), the Alaska Native Village Corporation for Unalaska, Alaska, formed in 1973. As described in a January 2023 press release, the joint operator (Ounalaska and Chena Power, who have formed OCCP, LLC) and Ormat have reached an EPC agreement to design and build the Makushin Geothermal Project (MGP). The project is named for the nearby Makushin Volcano, which was explored in the early 1980s by Republic Geothermal. Two wells drilled near the Makushin Volcano encountered attractive conditions for geothermal development.

Table 2.2 Details of geothermal power plants in the United States

Geothermal Field	Power Plant					Power Unit							
(1) Field Name	(7) Plant Name or number	(8) Plant operator	(9) Combined Heat and Power (CHP)?	(10) Co-prod.?	(11) Hybrid energy system?	(13) Unit Name or number (EIA, CEC or owner's)	(14) Type of unit	(15) Year of commission	(16) Status	(17) Turbine manufact.	(18) Installed Capacity (MW)	(19) GEP (GWh/a)	(20) NEP (GWh/a), 2021
AK - Chena	Chena Unit 1	Chena Hot Springs	Yes	No	No	Unit 1	B-ORC	2006	Decommissioned	Pratt & Whitney	0.3	-	-
	Chena Unit 2			No		Unit 2	B-ORC	2007	Operating	Pratt & Whitney	0.3	N/A	N/A
	Chena Unit 3			No		Unit 3	B-ORC	N/A	Operating	Kaishan	0.4	N/A	N/A
CA - Coso	Navy I	Coso Finance Partners	No	No	No	Unit 1	1F / 2F / 3F	1987	Operating	MHI	35.77	N/A	455.426
				No		Unit 2	1F / 2F / 3F	1988	Operating	Fuji	33.33	N/A	
				No		Unit 3	1F / 2F / 3F	1988	Operating	Fuji	33.33	N/A	
	Navy II	Coso Power Developers	No	No	No	Unit 4	1F / 2F / 3F	1990	Operating	Fuji	33.33	N/A	365.559
				No		Unit 5	1F / 2F / 3F	1990	Operating	Fuji	33.33	N/A	w/Navy II
				No		Unit 6	1F / 2F / 3F	1990	Operating	Fuji	33.33	N/A	w/Navy II
	BLM	Coso Energy Developers	No	No	No	Unit 7	1F / 2F / 3F	1989	Operating	Fuji	33.33	N/A	308.888
				No		Unit 8	1F / 2F / 3F	1989	Operating	Fuji	33.33	N/A	w/BLM
				No		Unit 9	1F / 2F / 3F	1989	Operating	Fuji	33.33	N/A	w/BLM
CA - Wendel	Wendel	Baseload Power US	No		No	N/A	B-ORC	N/A	Under construction (within one year of commissioning)	N/A	0.75	N/A	N/A
CA - Amedee	Amedee	Amedee Geothermal Venture	No	No	No	Units 1&2	B-ORC	1988	Decommissioned	Barber-Nichols	1.6	-	-
CA - Honey Lake	Honey Lake	HL Power	No	Yes	Yes	2	Other	1989	Operating	N/A	6	-	-
CA - Mammoth	G-1 (MP-1)	Mammoth Pacific (Ormat)	No	No	No	U100	B-ORC	1984	Operating	Ormat	5	N/A	59.191
	G-1 (MP-1)			No		U200	B-ORC	1984	Operating	Ormat	5	N/A	w/MP-1
	G-2 (MP-2)			No		T101	B-ORC	1990	Operating	Ormat	5	N/A	71.109
	G-2 (MP-2)			No		T102	B-ORC	1990	Operating	Ormat	5	N/A	w/MP-2
	G-2 (MP-2)			No		T103	B-ORC	1990	Operating	Ormat	5	N/A	w/MP-2
	G-3 (PLES-1)			No		T101	B-ORC	1990	Operating	Ormat	5	N/A	102.896
	G-3 (PLES-1)			No		T102	B-ORC	1990	Operating	Ormat	5	N/A	w/PLES
	G-3 (PLES-1)			No		T103	B-ORC	1990	Operating	Ormat	5	N/A	w/PLES
	Casa Diablo IV			No		-	B-ORC	2022	Operating	Ormat	40	-	-
CA - Ormesa	OG I (Ormesa I)	Ormat	No	No	No	26 units	B-ORC	1986	Operating	Ormat	26.4	N/A	109.889
	OG II (Ormesa II)			No		20 units	B-ORC	1987	Operating	Ormat	24	N/A	102.722
	Ormesa IE			No		12 units	B-ORC	1988	Decommissioned	Ormat	14.4	-	-
	Ormesa IH			No		12 units	B-ORC	1989	Decommissioned	Ormat	9.6	-	-
	GEM 2			No		GEM 2	B-ORC	1989	Decommissioned	Ormat	21.6	-	-
	GEM 3			No		GEM 3	B-ORC	1989	Decommissioned	Ormat	21.6	-	-
	GEM Bottoming Unit			No		GEM Btm	B-ORC	2007	Decommissioned	Ormat	8	-	-
	Ormesa III			No			B-ORC	2020	Operating	Ormat	24	N/A	74.056
CA - Heber	Heber	Ormat	No	No	No	Heber 1	1F / 2F / 3F	1985	Not operating temporarily	MHI	52	N/A	175.379
	Heber			No		Heber 1 repower	B-ORC	2023	Under construction (within one year of commissioning)	Ormat	45	-	-
	Heber			No		Gould 1	B-ORC	2006	Operating	Ormat	3.5	N/A	w/Heber
	Heber			No		Gould 2	B-ORC	2006	Operating	Ormat	7	N/A	w/Heber
	Heber			No		GEN 13	B-ORC	2006	Operating	Ormat	16	N/A	w/Heber
	Heber			No		Heber South (GEN 14)	B-ORC	2008	Operating	Ormat	16	N/A	w/Heber
	Heber			No		GEN 4	B-ORC	2018	Operating	Ormat	19	N/A	w/Heber
	Heber			No		Heber 2 (SIGC Gen 1-12)	B-ORC	1993	Decommissioned	Ormat	48	N/A	152.653
	Heber			No		Heber 2 repower	B-ORC	2022	Operating	Ormat	40	-	-
CA - North Brawley	North Brawley	Ormat	No	No	No	5 units	B-ORC	2009	Operating	Ormat	49.9	N/A	45.121
CA - Salton Sea - CalEnergy	Salton Sea 1	BHER/CalEnergy	No	Yes	No	Unit 1	1F / 2F / 3F	1982	Operating	Fuji	10.3	N/A	68.76
	Salton Sea 3			No		GEN1	1F / 2F / 3F	1989	Operating	MHI	54	N/A	248.78
	Salton Sea 2			No		GEN1	1F / 2F / 3F	1990	Operating	MHI	11.7	N/A	76.963
	Salton Sea 2			No		GEN2	1F / 2F / 3F	1990	Operating	MHI	5.2	N/A	w/SS 2
	Salton Sea 2			No		GEN3	1F / 2F / 3F	1990	Operating	GE Rotoflow	4	N/A	w/SS 2
	Salton Sea 4			No		4100	1F / 2F / 3F	1997	Operating	MHI	54	N/A	273.884
	Salton Sea 5			No		5100	1F / 2F / 3F	2000	Operating	Fuji	58	N/A	291.685
	Vulcan			No		Vulcan GEN1	1F / 2F / 3F	1985	Operating	MHI	35	N/A	218.686
	Vulcan			No		Vulcan GEN2	1F / 2F / 3F	1985	Operating	MHI	11	N/A	w/Vulcan
	Del Ranch (Hoch)			No		T0012	1F / 2F / 3F	1988	Operating	Fuji	53.5	N/A	276.906
	CE Turbo			No		T0073	1F / 2F / 3F	2000	Operating	GE Rotoflow	12.78	N/A	55.29
	Elmore			No		T0015	1F / 2F / 3F	1988	Operating	Fuji	53.5	N/A	371.101
	Elmore Backpressure			No		GEN2	Back Pressure	2019	Operating	GE	10	N/A	w/Elmore
	Leathers			No		GEN1	1F / 2F / 3F	1988	Operating	Fuji	53.5	N/A	337.637
CA - Salton Sea - Cyrq	John L. Featherstone	Cyrq Energy	No	Yes	No	1	1F / 2F / 3F	2012	Operating	Fuji	55	N/A	375.735
CA - The Geysers	McCabe (5&6)	Calpine	No	No	No	MCST5	Dry Steam	1971	Operating	Toshiba	59.4	732.63884	697.594
	McCabe (5&6)			No		MCST6	Dry Steam	1971	Operating	Toshiba	59.4	w/5&6	w/5&6
	Ridgeline (7&8)			No		RLST7	Dry Steam	1972	Operating	Toshiba	59.4	547.32741	516.514
	Ridgeline (7&8)			No		RLST8	Dry Steam	1972	Operating	Toshiba	59.4	w/7&8	w/7&8
	Eagle Rock (11)			No		ERST11	Dry Steam	1975	Operating	Toshiba	118.8	601.10962	570.766
	Cobb Creek (12)			No		CCST12	Dry Steam	1979	Operating	Toshiba	79.05	397.39363	374.225
	Big Geysers (13)			No		BGST13	Dry Steam	1980	Operating	GE (Toshiba)	138.5	433.22076	403.275
	Sulphur Springs (14)			No		SSST14	Dry Steam	1980	Operating	Toshiba	125.5	533.99712	497.09
	Lake View (17)			No		LVST17	Dry Steam	1982	Operating	Toshiba	130.91	524.75598	471.639
	Socrates (18)			No		SCST18	Dry Steam	1983	Operating	Toshiba	120	464.47676	386.601
	Sonoma (3)			No		SOST3	Dry Steam	1983	Operating	MHI	78	469.09834	406.5
	Calistoga (19)			No		CAST1	Dry Steam	1984	Operating	Toshiba	85.991	469.11733	432.941
	Calistoga (19)			No		CAST2	Dry Steam	1984	Operating	Toshiba	w/19	w/19	w/19
	Quicksilver (16)			No		QKST1	Dry Steam	1985	Operating	Toshiba	124.65	395.37754	365.612
	Grant (20)			No		GTST20	Dry Steam	1985	Operating	Toshiba	82.65	322.611	297.09
	Aidlin (1)			No		ADST1	Dry Steam	1989	Operating	Fuji	25	106.84492	99.324
	Aidlin (1)			No		ADST2	Dry Steam	1989	Operating	Fuji	w/Aidlin	w/Aidlin	w/Aidlin
	West Ford Flat (4)			No		1&2	Dry Steam	1988	Decommissioned	MHI	2x 14.5	-	-
	Bear Canyon (2)			No		1&2	Dry Steam	1988	Decommissioned	MHI	2x 11	-	-
CA - The Geysers	NCPA I (Geothermal 1)	NCPA	No	No	No	Unit 1	Dry Steam	1983	Operating	Ansaldo	55	N/A	483.63
	NCPA I (Geothermal 1)			No		Unit 2	Dry Steam	1983	Operating	Ansaldo	55	N/A	w/Unit 1
	NCPA II (Geothermal 2)			No		Unit 3	Dry Steam	1985	Decommissioned	Fuji	55	-	-
	NCPA II (Geothermal 2)			No		Unit 4	Dry Steam	1986	Operating	Fuji	55	N/A	302.378
CA - The Geysers	Bottle Rock	Open Mountain Energy	No		No	N/A	B-ORC	N/A	Under construction (within one year of commissioning)	Kaishan?	N/A	-	-
CA - San Ardo	San Ardo	Baseload Power US	No		No	1	B-ORC	2022	Operating	Orcan	<1	-	-
HI - Puna	Puna Geothermal Venture I	Ormat	No	No	No	10 Units	Other	1993	Operating	Ormat	35	N/A	183.391
	Puna Expansion			No		2 Units	B-ORC	2012	Operating	Ormat	12	N/A	w/Puna
ID - Raft River	Raft River	Ormat	No	No	No	1	B-ORC	2008	Operating	Ormat	13.5	N/A	92.941
NM - Lightning Dock	Lightning Dock	Cyrq Energy	No	No	No	Units 1-4	B-ORC	2013	Decommissioned	Kaishan	4	-	-
	Lightning Dock Repowering			No		1	B-ORC	2018	Operating	Turboden	15	N/A	50.934
NV - Beowawe	Beowawe	Ormat	No	No	No	1	1F / 2F / 3F	1985	Operating	MHI	17.7	N/A	89.492
	Beowawe 2			No		1	B-ORC	2011	Operating	Barber-Nichols	3.125	N/A	9.043
NV - Blue Mountain	Blue Mountain I	Cyrq Energy	No	No	No	Units 1-3	B-ORC	2009	Operating	Ormat	49.5	N/A	222.915
NV - Brady	Brady	Ormat	No	No	No	Units 1-3	1F / 2F / 3F	1992	Decommissioned	GE	26.1	-	-
				No		53991	B-ORC	2018	Operating	Ormat	24	N/A	88.025
NV - Desert Peak	Desert Peak 2	Ormat	No	No	No	Units 1-2	B-ORC	2007	Operating	Ormat	14.2	N/A	92.286
NV - Don A. Campbell	Don A. Campbell	Ormat	No	No	No	Phase 1	B-ORC	2014	Operating	Ormat	22.5	N/A	128.395
				No		Phase 2	B-ORC	2015	Operating	Ormat	22.5	N/A	113.525
NV - Dixie Valley	Dixie Valley	Ormat	No	No	No	1	1F / 2F / 3F	1988	Operating	Fuji	64	N/A	467.162
				No		Bottoming	B-ORC	2012	Operating	Barber-Nichols	6.2	N/A	22.974
NV - Jersey Valley	Jersey Valley	Ormat	No	No	No	1	B-ORC	2011	Operating	Ormat	15	N/A	64.537
NV - Florida Canyon	Florida Canyon Mine	Florida Canyon	No	No	No	1	B-ORC	2012	Decommissioned	ElectraTherm	0.1	-	-
NV - North Valley	North Valley	Ormat				1	B-ORC	2023	Operating	Ormat	32	N/A	N/A
NV - Patua	Patua	Cyrq Energy	No	No	Yes	Unit 1, 3, 5	B-ORC	2013	Operating	ACMT	45	N/A	109.193
NV - Tuscarora	Tuscarora	Ormat	No	No	No	2	B-ORC	2012	Operating	Ormat	30	N/A	133.908
NV - McGinness Hills	McGinness Hills	Ormat	No	No	No	MH-1	B-ORC	2012	Operating	Ormat	36 net	N/A	1176.873
				No		MH-2	B-ORC	2015	Operating	Ormat	36 net	N/A	w/McGH
				No		MH-3	B-ORC	2018	Operating	Ormat	48 net	N/A	w/McGH
				No		Expansion	B-ORC	2021	Operating	Ormat	15 net	N/A	w/McGH
NV - Salt Wells	Salt Wells	ENEL Green Power North America	No	No	No	Units 1-2	B-ORC	2009	Operating	ACMT	18	N/A	62.175
NV - San Emidio	San Emidio Repower	Ormat	No	No	No	1	B-ORC	2012	Operating	ACMT	13	N/A	58.901
	North Valley	Ormat	No	No	No		B-ORC	2023	Operating	Ormat	25	-	-
NV - Soda Lake	Soda Lake 1	Cyrq Energy	No	No	No	Units 1-4	B-ORC	1987	Decommissioned	Ormat	15	-	-
	Soda Lake 2			No		Units 1-6	B-ORC	1991	Not operating temporarily	Ormat	20	-	-
	Soda Lake 3 (Repower)			No		3	B-ORC	2019	Operating	Ormat	23	N/A	124.524
NV - Star Peak	Star Peak	OME	No	No	No	N/A	B-ORC	2022	Operating	Kaishan	12.5 (net)	N/A	N/A
NV - Steamboat	Steamboat Hills	Ormat	No	No	No	50654	1F / 2F / 3F	1988	Decommissioned	GE	21.5	-	-
	Steamboat Hills Repower					OEC 51/52	B-ORC	2020	Operating	Ormat	35	N/A	210.572
	Steamboat II			No		54665	B-ORC	1992	Operating	Ormat	18	N/A	50.47
	Steamboat III			No		54666	B-ORC	1992	Operating	Ormat	18	N/A	54.152
	Galena 1 (Richard Burdette)			No		56321	B-ORC	2005	Operating	Ormat	30	N/A	116.318
	Galena 2			No		56540	B-ORC	2007	Operating	Ormat	13.5	N/A	35.486
	Galena 3			No		56541	B-ORC	2008	Operating	Ormat	30	N/A	100.195
NV - Stillwater	Stillwater 2	ENEL Green Power North America	No	No	Yes	50765	B-ORC	2009	Operating	ACMT	48	N/A	57.86
NV - Tungsten Mountain	Tungsten Mountain	Ormat	No	No	Yes	1	B-ORC	2017	Operating	Ormat	50	N/A	239.333

Geothermal Field	Power Plant					Power Unit							
(1) Field Name	(7) Plant Name or number	(8) Plant operator	(9) Combined Heat and Power (CHP)?	(10) Co-prod.?	(11) Hybrid energy system?	(13) Unit Name or number (EIA, CEC or owner's)	(14) Type of unit	(15) Year of commission	(16) Status	(17) Turbine manufact.	(18) Installed Capacity (MW)	(19) GEP (GWh/a)	(20) NEP (GWh/a), 2021
NV - Wabuska	Wabuska 1	OME	No	No	No	1	B-ORC	1984	Decommissioned	Barber Nichols	0.75	-	-
	Wabuska 2			No		2	B-ORC	1987	Decommissioned	Barber Nichols	1	-	-
	Whitegrass No. 1			No		Whitegrass No. 1	B-ORC	2018	Operating	Kaishan	4.4	N/A	19.14
	Whitegrass No. 2					Whitegrass No. 2	B-ORC	2023	Under construction (within one year of commissioning)	Kaishan	6	-	-
NV - Blackburn	Pilot	Transitional Energy	No	No	No	Pilot	B-ORC	2022	Operating	Electratherm	0.075	-	-
OR - OIT	OIT Unit 1	OIT	Yes	No	No	1	B-ORC	2009	Operating	Pratt & Whitney	0.2	N/A	N/A
	OIT Unit 2			No		2	B-ORC	2014	Not operating temporarily	JCI	1.75	N/A	N/A
OR - Neal Hot Springs	Neal Hot Springs	Ormat	No	No	No	Units 1-3	B-ORC	2012	Operating	ACMT	33	N/A	182.841
OR - Paisley	Paisley	Surprise Valley Electrification Corp.	No	No	No	1	B-ORC	2015	Not operating temporarily	Barber Nichols	3.1	-	-
UT - Cove Fort	Cove Fort 3	ENEL Green Power North America	No	No	No	3	B-ORC	2013	Operating	Ormat	25	N/A	149.978
UT - Blundell	Blundell Unit 1	Pacificorp	No	No	No	1 - 299	1F / 2F / 3F	1984	Operating	GE	30.7	N/A	211.226
	Blundell Unit 2			No		2 - 299	B-ORC	2007	Operating	Ormat	14.1	N/A	w/Blundell
UT - Thermo	Thermo 1	Cyrq Energy	No	No	No	50 units	B-ORC	2008	Decommissioned	Pratt & Whitney	13	-	-
	Thermo 1 Repower			No		1	B-ORC	2013	Operating	Ormat	14	N/A	58.458

Notes for Tables 2.1 and 2.2:

1. N/A: Data not available or not applicable.
2. Column 12 in the IGA table format is to indicate the percentage of electricity produced from geothermal for hybrid plants. As the data were not available to support those calculations, this column is not shown.
3. Column 14 Type of Unit**:** 1F/2F/3F = Single, Double or Triple Flash, B-ORC = Binary (Organic Rankine Cycle)
4. Column 19 GEP: Gross electrical production. Generally not available.
5. Column 20 NEP: Net electrical production. Generally these are 2021 year end values available from EIA.

2.2.2 California

The Casa Diablo IV project by Ormat, a 30 MW binary expansion to the Mammoth complex, started commercial operations in July 2022.

The nominal installed capacity at The Geysers (including Calpine and NCPA holdings, excluding Bottle Rock) of 1,495 MW and its field output of 6.287 TWh in 2021 keep The Geysers in position as one of the world's largest operating geothermal fields.

The California Public Utilities Commission (CPUC) developed an Integrated Resource Plan (IRP) for that state that calls for 1 GWe of new geothermal power capacity, although this may come from Nevada as well. The resource buildout is anticipated in the 2025-2030 time frame, and likely is a factor driving much of the new development mentioned herein.

Open Mountain Energy and Kaishan Group announced in late 2022 that they were taking over operations and intending to repower the idle Bottle Rock project at The Geysers (ThinkGeoenergy, 2022). Target COD for the repowering is December 2023.

In late 2022, Baseload Capital started operations of an Orcan binary plant at Chevron's San Ardo field (ThinkGeoenergy 2022). Capacity was not made public but appears to be made up of 200 kW units totaling <1 MW. This and the Transitional Energy project in Nevada (see below) are harbingers of the increasing interest in recovering heat and generating power from co-produced fluids from oil and gas wells.

Several pilot lithium extraction systems are operating at existing plants such as Hudson Ranch, which was acquired by Cyrq Energy in early 2021. Additional large developments are planned at the Salton Sea by Berkshire Hathaway Renewables (BHER), which has been developing its Lithium extraction technology for the past few years. Controlled Thermal Resources (CTR) has acquired significant lease holdings, drilled and tested its delineation wells and announced an agreement with Fuji in early 2023 for the supply of multiple units at the Hell's Kitchen combined lithium and power production project. While the buildout will depend on the available resource, the intention is for six 55 MW units, 330 MW in total (ThinkGeoenergy, 2023).

2.2.3 Hawaii

In late 2020, the Puna power plant resumed operations after an eruption and lava flow in 2018 that covered several wells and damaged a substation.

2.2.4 Idaho

The Raft River binary plant, operated by Ormat, remains the only geothermal electrical generator in Idaho.

2.2.5 Nevada

Cyrq Energy's Soda Lake repower project using Ormat equipment was commissioned in 2020 as anticipated in the last update.

Ormat continued to add capacity in 2021 at McGinness Hills with an expansion of 15 MW. With more than 135 MW (net) so far, McGinness is a successful illustration of a large, stepwise development of a binary geothermal power complex, one of several operated by Ormat. Completion of the 25 MW North Valley project at the San Emidio field was announced in April 2023.

Open Mountain Energy (OME, a subsidiary of Kaishan Group) integrated their Star Peak project to the Nevada grid in August 2022. The project had been completed in 2021 but interconnection was delayed by the utility. This plant is at the site of the previously named Rye Patch-Humboldt House project. OME is expanding operations at the Wabuska field with a planned second Whitegrass unit anticipated to start operations in mid-2023.

Transitional Energy reported the start of operations in 2022 of a pilot plant at an oilfield in rural Nevada, using an Electratherm binary unit. A gradual scale-up to about 1 MW is planned (Cestari, 2022).

2.2.6 New Mexico

The Lightning Dock 14 MW project, operated by Cyrq Energy with power plant equipment from Turboden, remains the only utility-scale geothermal electrical generator.

2.2.7 Oregon

The three binary units at Neal Hot Springs are now operated by Ormat, after acquiring them from U.S. Geothermal. These likely will be repowered with Ormat technology in the coming years. Small units were installed at the Oregon Institute of Technology (OIT) in 2014 and Paisley in 2015, but these have encountered technical challenges, and are yet to reach their full generation potential (Dr. John Lund, personal communication, 2019).

2.2.8 Utah

At Roosevelt Hot Springs, the single flash + binary bottoming plants at Blundell continue to operate. Cove Fort and the Thermo 1 re-powering (using Ormat equipment) are the only operating plants in Utah. The Utah FORGE project (located in Milford, close to the Blundell plant) continues to make progress, but power production and sales are not anticipated from this underground laboratory.

3. RECENT GEOTHERMAL TRENDS

3.1 Geothermal Electricity Market Trends

In the 2019 GeoVision study (US DOE 2019), DOE-GTO concludes that technology improvements – many of which are being actively investigated today – could significantly increase geothermal power generation in the United States. DOE-GTO estimates the geothermal potential of the United States at 60 GW, including capacity from Enhanced Geothermal Systems (EGS). In 2009, the United States Geological Survey (USGS) estimated that the known conventional hydrothermal resources in the United States can potentially supply another 9,000 MW of power, and that the potential of undiscovered resources is on the order of 30,000 MWe (Williams *et al.*, 2009), some of which may be provided by resources in deep sedimentary basins (see, for example, Allis *et al.*, 2011).

Though demand for geothermal power has historically lagged that of other renewables, the US has seen an unprecedented increase in demand for 24/7, carbon-free energy since the summer of 2021. In June 2021, the California Public Utilities Commission issued a monumental ruling (CPUC, 2021) requiring that all California Load Serving Entities (LSEs) procure between them 1 GW of firm, non-weather dependent, clean power by 2026, a date that was recently extended by 2 years. Driven to procure an amount of firm, clean power proportional to their share of peak demand, LSEs have entered into long-term power purchase agreements with geothermal developers at an extraordinary pace. In addition, the rising costs of battery energy storage has put geothermal energy on a much more competitive footing with other renewables on a USD/MWh basis.

Individual states are not the only entities seeking to bolster reliability, reduce costs, and meet aggressive clean energy targets. The federal government too has begun to value firm alternatives as necessary complements to intermittent energies. In December 2021, President Biden issued an Executive Order aimed at catalyzing clean energy industries and jobs through federal sustainability, mandating that the government use its scale and procurement power to achieve 100 percent carbon pollution-free electricity by 2030, including 50 percent 24/7 carbon-free electricity.

Additionally, voluntary clean energy goals have driven corporations and universities to search for ways to effectively match their hourly load and heat their campuses. Microsoft ("100/100/0" or 100% electricity 100% of the time to be matched by 0 carbon energy), Google (24/7 Carbon-Free Energy or "CFE" by 2030), and there is increasing interest in geothermal energy solutions (and more geothermal curricula) on university campuses.

Recognizing the adjacency in skills, techniques and operations, the oil and gas sector has become increasingly active in the geothermal sector. Major and minor oil and gas companies are planning geothermal developments and bringing new innovations to the sector. Previous testing such as pilot plants such as the Rocky Mountain Oilfield Testing Center (RMOTC) operating in 2011-2012 and projects in the Williston Basin have demonstrated that binary units can harvest thermal energy from hot water in deep basins, and oil and gas operators are well aware of the opportunity to produce their hot water cut. Although the differences in completions make re-purposing oil and gas wells difficult, the availability of subsurface information and production data provide a strong basis for quantifying the flow rates and temperatures of hot water that can be produced from oil and gas fields.

As examples, in 2022:

- Transitional Energy started operations of a pilot plant in May at an oil field in Nevada.
- Baseload Capital started operations of a binary plant in Chevron's San Ardo oil and gas field in July.

In addition, DOE-GTO's GEODE project was recently awarded to a broad consortium that includes deep expertise in geothermal, oil and gas, with the specific goal of cross-pollination of techniques and technologies from the geothermal and oil and gas sectors.

Learnings from these projects are being applied to more power generation and direct use applications throughout the USA at suitable sites, helping to foster collaboration across the geothermal and oil and gas industries. According to a 2023 report from the University of Texas (Austin) report (Beard *et al.*, 2023), 80 percent of oil and gas entities interviewed for the report note they have a geothermal strategy in place or under development. Installations such as these can serve as a capacity building "bridgehead" for larger projects. In addition, at the request of Energy Secretary Jennifer Granholm, a December 2022 National Petroleum Council report on net zero solutions included a section on geothermal energy.

In summary, geothermal energy in the United States is receiving significant new capital, attracting new entrants, and innovating like never before. Project development is accelerating to match increased demand, new power projects are underway across the western USA. Further east, projects are unfolding from the Williston Basin in North Dakota to the Gulf Coast in Texas and Louisiana, leveraging existing data from the many wells in deep sedimentary basins.

3.2 Power Plant Trends

Several trends seem to be continuing or are new since the 2020 update, as discussed in the section below. These include:

- A slow-down in consolidation
- Co-production
- Capacity addition through facility optimizations and upgrades

These trends are discussed briefly in the sections below.

3.2.1 Consolidation is Slowing

Consolidation allows geothermal operating costs to be spread over a larger portfolio, helping make geothermal more competitive with low-cost intermittent renewables such as wind and solar. The 2020 USA update mentioned acquisitions such as U.S. Geothermal by Ormat, and the Patua and Blue Mountain projects by Cyrq Energy. This acquisition and consolidation trend has continued for this 2023 update, as illustrated by Beowawe and Dixie Valley being acquired by Ormat in 2021. Macquarie Infrastructure and Real Assets (MIRA), an investor in renewable worldwide such as in The Philippines' Energy Development Corporation, also acquired Cyrq Energy with its previous holdings and the Hudson Ranch project that Cyrq acquired in 2021. The number of single-owner operating plants available for acquisition is diminishing, so consolidation appears to be slowing down internally within the geothermal sector. However, the re-entry of oil and gas may counter this trend.

Greenfield developers currently without operating plants (*e.g.*, CTR, Fervo, etc.) and larger established operating companies (*e.g.*, BHER, Calpine, Ormat etc.) are ramping up their development pipelines to meet the growing demands for added capacity from the CPUC and from community choice aggregators seeking clean 24/7 power.

3.2.2 Co-Production

The 2020 update mentioned hybridization (co-locating geothermal and solar or other generation technology) as an ongoing trend, as illustrated by such facilities at Stillwater, Patua, and Tungsten Mountain. Harvesting multiple value streams by leveraging existing infrastructure seems useful at any facility. A more prevalent theme in 2023 appears to be co-production, particularly with respect to strategic minerals such as lithium. Given the transformation of the energy storage industry, an acceleration towards electric vehicles, and rising lithium prices, geothermal projects that have a lithium extraction aspect have attracted major investments or interest from companies such as GM, Stellantis, SLB New Energy, Italvolt and others. Interest in strategic minerals recovery from geothermal is rising worldwide, but the strength of the resource and multiple research and development efforts in the Salton Sea geothermal field should make it one of the most promising areas to follow. Other co-production opportunities exist within deep sedimentary basins, as noted above.

3.2.3 Capacity Addition Through Facility Optimizations and Upgrades

While greenfield projects draw more media attention, the potential for capacity increases at existing facilities through optimization and retrofits should not be overlooked. Over time, field characteristics usually drift away from original design points, and equipment gradually degrades. Both effects lead to reduced output compared to what would be possible with better fitting newer eqiopment. Figure 3 shows the collective MW sizes of these aging cohorts of existing plants. Plants already decommissioned are not reflected in the figure, nor have older plants that have already been repowered been reset to a "new" commissioning decade.

Calpine's Super-rotor program with associated plant upgrades (Maedomari and Avery, 2011) is an example of a decade-plus effort to rehabilitate many units at The Geysers that were commissioned in the 1970s and 1980s. Re-powerings with upgrades in major equipment such as turbines and cooling systems are an opportunity to increase generation with best available technology and improve power delivery as the resource evolves over time. Increasing capacity and generation at existing facilities through operational tuning or retrofits have fewer hurdles related to permitting and power purchase agreement, helping to accelerate geothermal growth.

The process of plant re-optimization can be assisted with improved data collection, analysis and optimization procedures. Research programs such as GOOML (Geothermal Operational Optimization with Machine Learning) may provide more tools to help operators find improved configurations for interconnected power plants and fields (Siratovich *et al.*, 2022). If the US geothermal industry is expected to add more than a GW of new plant capacity in the next decade, a significant proportion of effort during that period needs to be steadily directed towards upgrade opportunities for the existing plants as they age.

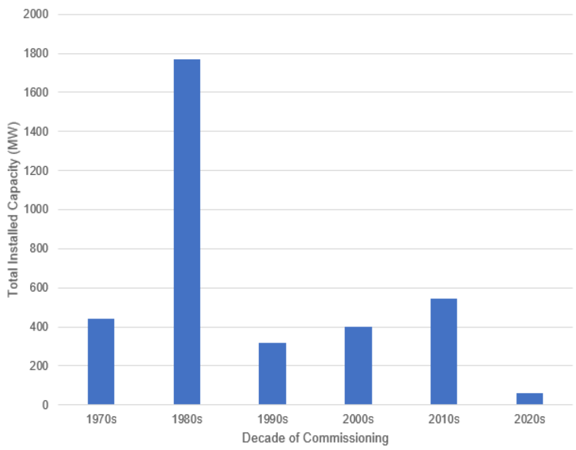

Figure 3: Total installed USA geothermal capacity as a function of decade of original plant commissioning

3.3 Geothermal Electricity Policy Support

Though the geothermal energy industry has historically been at a consistent disadvantage with lagging policy support - reflecting the widespread de-emphasis on the importance of geothermal power in the US energy mix - the tide has very recently begun to turn. Between the summer of 2021 and the end of 2022, as the market began to take notice of the premium value that 24/7 carbon-free baseload energy can provide, so too did policy makers begin to take an increased interest in what the industry might need in order to scale.

The US-based geothermal industry has experienced wins and substantial progress in both federal and state realms that have paved the way for significant forward momentum in the years ahead.

3.3.1 Federal Highlights

At the very end of 2021, President Biden signed an Executive Order directing federal facilities to achieve 100% carbon-free electricity by 2030, including 50% on a 24/7 basis, clearly delineating geothermal as an eligible source. Though the geothermal industry had hypothesized that the federal government would eventually ramp up their renewable power procurement efforts, an order of such magnitude exceeded expectations in terms of the value that Biden administration has placed on firm, clean power.

In a piece of truly historic energy and climate legislation, the federal government passed into law the Inflation Reduction Act (IRA) during the summer of 2022. The single largest investment by the US government in the history of clean energy and climate change, the IRA elevated geothermal tax incentives to an unprecedented level, finally putting the industry on a level playing field with other renewables. Under the IRA, geothermal tax incentives will have unprecedented longevity and be generally transferable, allowing companies to sell some tax credits to other entities directly. The legislation has specific provisions tied to labor requirements, environmental justice, domestic sourcing, and preferential siting for entities to earn tax credits; fortunately, geothermal projects are generally well-suited to meet these requirements.

Although the IRA legislation has a first focus on the short term (for projects that begin construction before 2025), this important legislation restores federal tax credits to the full rate for new renewable energy projects for 2025 and beyond in the Clean Energy Investment Tax Credit (CEITC) and the Clean Energy Production Tax Credit. The CEITC provides a two-tier investment tax credit equal to the eligible costs of qualified facilities (including geothermal) placed in service after December 31, 2024 at rates corresponding to the 30% ITC (6% “base”/30% maximum). For electricity produced at qualified facilities that are placed in service after December 31, 2024 and sold to unrelated taxpayers (like a utility), the CEPTC provides a two-tier, inflation-adjusted tax credit equal to the corresponding PTC amounts of 0.3 cents/kWh “base”/1.5 cents/kWh maximum, as adjusted for inflation (which for taxable year 2022 is equal to 2.6 cent/kWh). Both tax credits will phase down to 75% of the relevant credit amount for projects that begin construction in the second year following the later of (i) 2032 or (ii) the calendar year in which Treasury determines that the annual greenhouse gas emissions from the production of electricity in the United States are equal to or less than 25% of those emissions for calendar year 2022. A further reduction to 50% of the credit amount will occur in the following year and no credits will be allowed for projects that begin construction thereafter. Both credits are also subject to prevailing wage and apprenticeship requirements, and could benefit from incremental credit amounts if one or more of the domestic content, the energy community, or the low-income community rules are met.

In addition to historic tax legislation, the geothermal industry saw a record increase in federal appropriations and attention focused on facilitating the permitting process for geothermal projects. The Bipartisan Infrastructure Law (BIL) dedicated $84 million to funding geothermal demonstration projects, and the Geothermal Technologies Office saw an eight percent increase in topline funding, expanding the annual budget to $118 million.

There has been additional emphasis placed on leasing and permitting reform for geothermal projects. With much of the nation’s quality geothermal resources existing under federal lands, the leasing and permitting processes can be key gating factors to the success of geothermal developments. This year, a much greater emphasis was placed on solving the challenges associated with leasing and permitting geothermal energy projects on federal lands, and geothermal leasing and permitting was mentioned in the Enhancing Geothermal Production on Federal Lands Act, the Public Land Renewable Energy Development Act, the Transparency and Production of American Energy Act, and the Committing Leases for Energy Access Now Act. All of this legislation represents positive progress from a permitting perspective, and the industry is optimistic about near-term resolution on this issue.

3.3.2 State Highlights

In the summer of 2022, Western Governors Association (WGA) Chair Jared Polis launched the Heat Beneath Our Feet (HBOF) as the leading annual initiative for the Association. Through the initiative, the WGA will examine opportunities for and barriers to the increased deployment of geothermal energy technologies for both electricity generation and heating and cooling systems in the Western US. With the launch of this initiative, the leaders of those states with some of the highest geothermal potential on the globe indicated the priority focus on geothermal energy for both electricity generation and building heating and cooling.

Another important initiative at the state level is the aforementioned California CPUC ruling that mandated that all California LSEs (as a group) must procure 1 GW of firm, non-weather dependent, clean power by 2028. Geothermal power is perfectly suited to provide what the CPUC requires, and US geothermal developers (particularly in California and Nevada) are actively responding.

4. FEDERAL GEOTHERMAL RESEARCH & DEVELOPMENT INITIATIVES

4.1 Introduction

The primary federal agency responsible for geothermal R&D initiatives is the U.S. Department of Energy’s Geothermal Technologies Office (DOE-GTO), whose mission is to drive research and development (R&D) and manufacturing solutions to address technical challenges and support widespread development and deployment of innovative, clean, geothermal energy technologies. Technological innovation will help reduce the costs and risks in converting geothermal resources into useful energy services.

4.2 Recent DOE-GTO Programs

DOE GTO supports projects across the geothermal spectrum; major programs during the last few years are presented below.

4.2.1 Frontier Observatory for Research in Geothermal Energy (FORGE)

DOE-GTO's flagship FORGE initiative is a dedicated site where scientists and engineers will be able to develop, test, and accelerate breakthroughs in EGS technologies and techniques. FORGE is a critical step toward creating a commercial pathway to EGS because it will promote transformative and high-risk science and engineering through the development and testing of cutting-edge technologies, which the private sector is not financially equipped to undertake. FORGE will bridge lessons learned from past DOE-funded and international EGS field demonstrations, and R&D portfolios, and with broad collaboration among academia, industry, and DOE National labs, facilitate optimization and validation of EGS technologies. Initiated in FY 2015, the FORGE initiative has been rolled out in three phases:

1) Planning
2) Site Characterization and Selection (the site in Milford, Utah was selected)
3) Technology and Evaluation

Since 2020, the Utah FORGE Team has undertaken a series of activities that have included extensive community outreach, conceptual resource modeling, installation of a seismic monitoring network, drilling several seismic monitoring wells, and drilling full-diameter wells, including the doublet that that has been subjected to well testing and stimulation, and extensive numerical reservoir modeling.

In February 2021, DOE awarded $49 million to 17 research and development (R&D) projects. In addition, Utah FORGE has made several technology solicitations, as shown in Figure 3. In April 2022, the first hydraulic stimulation of the first full-diameter well was successfully conducted, and the second full-diameter well of the doublet was completed in mid-2023. Both wells are deviated, achieving angles of up to 60° from vertical. The doublet is a testing ground for various EGS tools and technologies. Progress made at Utah FORGE to date can be found at the Utah FORGE website (https://utahforge.com/laboratory/), which also has extensive links to information in the Geothermal Data Repository (GDR).

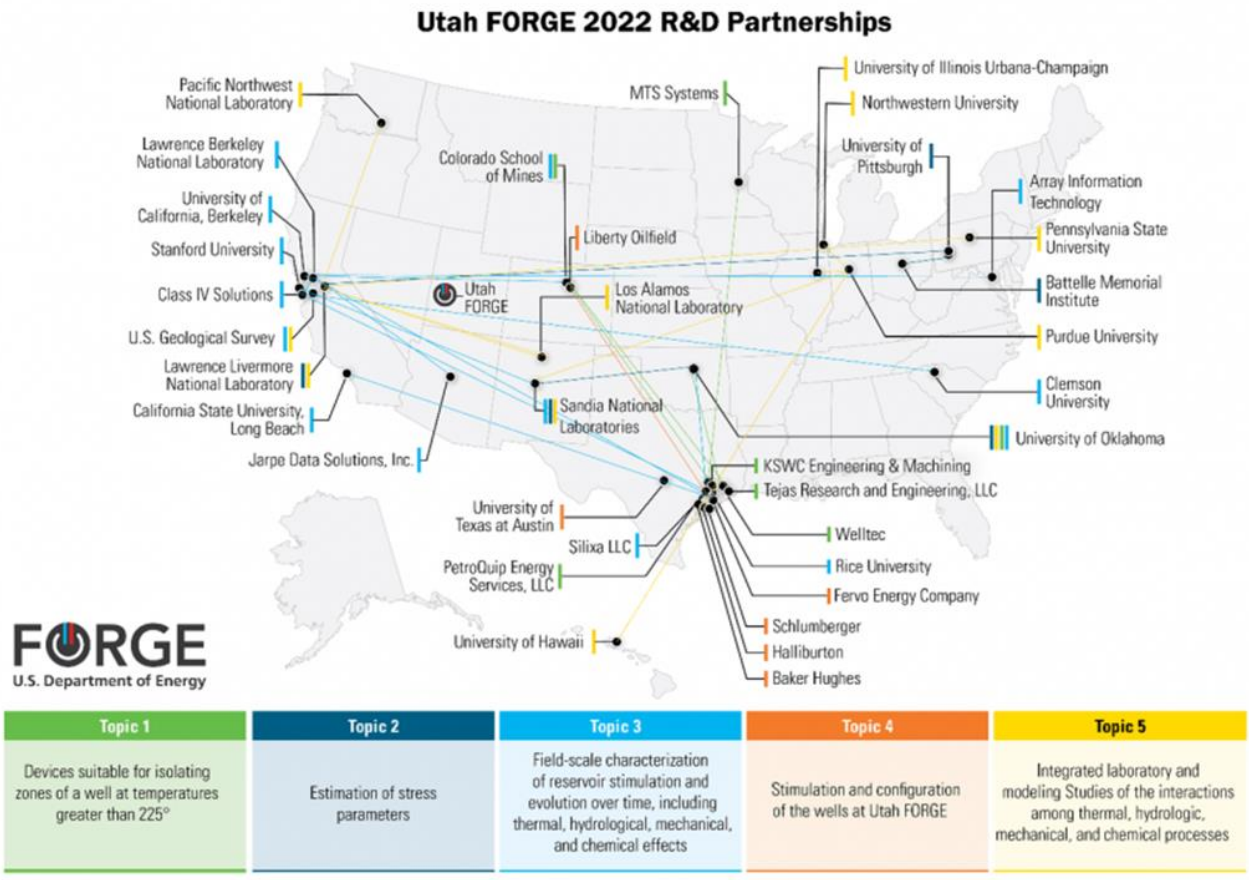

Figure 3: 2022 R&D topics and partnerships at Utah FORGE (https://utahforge.com)

4.2.2 Geothermal Energy from Oil and Gas Demonstrated Engineering (GEODE)

DOE-GTO has taken an important step with the GEODE project, which will facilitate the natural synergies between two closely adjacent sectors: oil and gas and geothermal. In May 2023, this project was awarded to a consortium that includes Project InnerSpace, the Society of Petroleum Engineering International (SPE) and Geothermal Rising (GR), and many partner entities. The first phase of GEODE provides $10 million to identify barriers and develop a roadmap to advance geothermal using expertise from the oil and gas sector. The second phase (5 years) will provide up to $155 million more to address technical, workforce and public engagement challenges, with the goal of reducing development costs and expanding geothermal power projects at a rapid pace.

4.2.3 American-Made Geothermal Prize

The United States Department of Energy's American-Made Challenges prize program (https://americanmadechallenges.org/) was launched in 2018 to support US entrepreneurship and innovation in clean energy. To date, DOE has awarded about $100 million in cash and incentives to competitors in more than 30 prizes spanning solar, water, geothermal, buildings, hydrogen, energy storage, transportation, technology transitions, manufacturing, and more. In April 2022, a new Geothermal Geophone Prize was announced, offering $3.65 million in incentives to develop high-temperature seismic sensors (geophones) that collect real-time data on subsurface changes during EGS stimulations.

4.2.4 Community-Scale Geothermal Heating and Cooling Systems

Although this paper focuses on geothermal power projects, DOE-GTO has a recent focus on geothermal heating and cooling. In May 2022, DOE-GTO announced a new Funding Opportunity Announcement (FOA) that speaks directly to using geothermal energy for decarbonizing heating and cooling, noting that more than half of US home energy use is for heating. The goal: reducing CO2 emissions by eliminating fossil fuels for heating and cooling by replacing it with geothermal energy at the community scale, using coalitions that include community, workforce, design/analysis, and deployment expertise to implement clean and renewable heating and cooling systems.

4.2.5 Geothermal Collegiate Competition

This US DOE program is promoted to university students to learn more about geothermal energy, consider new career opportunities, learn geothermal skills, and connect to communities. As part of the competition, students assumed the role of project developers, working with communities across the U.S. to identify local energy challenges and explore geothermal energy solutions. In addition to technical research, teams conducted an economic feasibility analysis, crafted a strategy for local stakeholder engagement, and created geothermal education modules in partnership with local schools. Students from the University of Oklahoma team won first place and $10,000 in prize funding. The university students designed a system for repurposing six abandoned oil and gas wells in Oklahoma that would provide clean, renewable geothermal energy for more than 730,000 square feet of educational and municipal buildings, including sites in the jurisdictions of the Shawnee Tribe and Potawatomi Nation.

5. SUMMARY

During the previous three years, the installed geothermal power capacity increase by approximately 100 MW. The pace is increasing now in response to the CPUC mandate, and the United States will experience an uptick in the pace of geothermal installations through 2028. The combination of state initiatives, increasing focus on the strategic value of mineral recovery and interest in leveraging geothermal power from deep basins that host existing oil and gas fields should drive the rate of capacity addition to several hundred MW per year. The US geothermal industry - in combination with the oil and gas industry - has an unprecedented opportunity to use their combined capabilities to increase geothermal deployment across a spectrum of resource types. It will be critical to capitalize on these advantages now to solidify geothermal's reputation in the United States as a preferred baseload source of clean electricity, and an important source of co-produced strategic minerals.

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