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The United States of America Country Update 2020 – Power Generation

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ABSTRACT

Since the early 1960s, when geothermal power was first produced in the USA in a dry steam power plant (Unit 1 at The Geysers geothermal field), additional plants were installed at The Geysers, and many more flash-steam and binary power plants have been installed in liquid-dominated geothermal fields. Liquid-dominated geothermal resources in the USA include: those found in sedimentary environments (including the hyper-saline brines of the Salton Sea field in southern California, and lower-salinity resources elsewhere in the same region); dilute, moderate-temperature geothermal fluids produced by pumped wells from volcanic and metamorphic rocks in the Basin-and-Range province; and volcanic-hosted resources in California and Hawaii. As of October 2019, the total installed geothermal power capacity in the United States was approximately 3,700 MWe. 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 (3,478 MWe) of this generation, with 2,683 and 795 MWe in California and Nevada, respectively. Since the last USA Country Update in 2015, competition from low-cost power sources (notably natural gas and solar) and the reduction in tax incentives has favored expansions of existing geothermal projects and development of shallower resources to minimize project development costs. Even so, installed geothermal power capacity in the United States has increased modestly (by 7-10%) during the last five years. In addition, some of the older geothermal power plants have been re-powered, enabling improvements in output without requiring additional geothermal fluid supply.

Federal support for R&D in Enhanced (or Engineered) Geothermal Systems (EGS) remains strong via the U.S. Department of Energy's Geothermal Technologies Office (DOE-GTO), as manifested in the EGS Collab projects (in which National Laboratories collaborate for the development of EGS technologies) and the Frontier Observatory for Research in Geothermal Energy (FORGE) project (an underground laboratory in which various EGS technologies are implemented and tested). In addition, DOE-GTO is supporting R&D related to conventional hydrothermal resources, including minerals recovery, innovative drilling techniques, expanding geothermal direct use and the application of machine learning for geothermal exploration and operations. The United States continues to participate in the International Geothermal Partnership, the Global Geothermal Alliance and other international geothermal initiatives, and to supply U.S. geothermal expertise for the exploration, development and operation of geothermal power projects in many countries around the world.

Significant additional geothermal power can be produced in the United States. DOE-GTO's recent publication of the 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 60,000 MW. Some 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 but undeveloped conventional hydrothermal resources in the United States is approximately 9,000 MWe, with another 30,000 MWe of potential from as-yet undiscovered geothermal resources, some of which may be supplied from deep sedimentary basins.

Recognizing the potential for more geothermal power in the United States, many tertiary educational institutions offer geothermal curricula that focus on a wide range of subjects, including regional favorability factors for the formation of exploitable geothermal resources, resource exploration and characterization, drilling methods, reservoir engineering, power cycles, unconventional geothermal systems and more. Collaboration on specific topics between universities, research organizations (such as DOE-GTO) and industry is creating a favorable atmosphere for technical innovations to enable the development of the remaining untapped reserves of geothermal energy in the United States and in other parts of world.

Although the past five years have been characterized by modest geothermal growth, current social, economic and political trends provide a level of optimism for the development of additional geothermal power 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 near-universal recognition of the risks associated with climate change (and the recognition of the importance of clean power); the de-stabilizing impacts on the grid from intermittent renewable power; the positive geothermal outlook provided in DOE-GTO's GeoVision study and earlier work by the USGS; and, importantly, policy engagement by the geothermal industry. The impetus 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 power in the United States, it is a significant turning point in terms of policy, which – 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.

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 is presented first, followed by the details of the currently operating geothermal assets and the potential for additional capacity. Trends in geothermal project development and the geothermal policy landscape in the United States are also discussed. R&D and other initiatives in support of the development of advanced geothermal technologies at the national level are presented, followed by estimates of the number of people working in the geothermal industry during the past five years, and a summary of geothermal offerings by tertiary educational institutions.

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 2013 (which was the basis for the 2015 USA Country Update) and 2018. These years were selected as the last full years for which the U.S. Energy Information Administration (EIA) provides annual data. 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 4.2% over the 5-year period from 2013 5o 2018, and annual output increased from 4,066 to 4,171 TWh/year (+2.6%). Table 1 also shows a shift from fossil fuel baseload capacity towards intermittent renewables.

Table 1: Present and Planned Production of Electricity (EIA, 2019)

	Geothermal		Fossil Fuels		Hydro (incl pumped)		Nuclear		Wind		Solar*		Other Renewables and Misc Sources		Total	
	Capacity MWe	Gross Prod. TWh/yr	Capacity MWe	Gross Prod. TWh/yr	Capacity MWe	Gross Prod. TWh/yr	Capacity MWe	Gross Prod. TWh/yr	Capacity MWe	Gross Prod. TWh/yr	Capacity MWe	Gross Prod. TWh/yr	Capacity MWe	Gross Prod. TWh/yr	Capacity MWe	Gross Prod. TWh/yr
In operation in December 2013	3,477	16	878,340	2,746	78,241	264	107,938	789	59,973	168	6,622	9	13,397	74	1,147,988	4,066
In operation in December 2018	3,806	16	841,288	2,653	101,783	287	104,270	807	94,971	273	32,239	64	18,132	71	1,196,489	4,171
Planned Capacity Changes 2019-2023 (net, including retirements; summer capacity)	111	-	1,302	-	309	-	-5,446	-	31,891	-	23,707	-	2,956	-	54,830	-

*Not including small-scale solar

The installed capacity of fossil fuel power plants declined by 37 GW over the five-year period. This decline is largely driven by coal plant retirements, offset to some extent by additions of natural gas combined cycle plants. Hydropower and nuclear contributions have been relatively level, as has geothermal.

Wind and solar (PV and thermal) have driven most of the growth in the overall renewable portfolio. Through 31 December 2018, renewables accounted for about 17% of total U.S. annual generation. Geothermal's overall share was modest at 2% of all renewables and 0.4% of total generation.

1.2 Potential for Additional Generation (All Sources)

The third row of Table 1 shows estimated capacity additions across all sectors from 2019-2023. Significant coal (-26,136 MW) and nuclear (-5,446 MW) retirements are expected. The main sources of added capacity are expected to be via natural gas-fueled cycles (+29,608 MW), wind (+31,891 MW) and solar (+23,707 MW). Overall, more than 54,000 MW of additional capacity is expected to be added over this period. Geothermal is expected to contribute around 111 MW of this, equating to ~20 MW per year (about the size of one modest binary unit). However, this rate of addition could easily be exceeded, driven by California's renewable power mandate and emissions cap: a significant amount of additional, large geothermal power projects planned in southern California are likely to proceed, driven by state mandates and the additional benefit of lithium recovery from some geothermal resources in that area. In addition, clean geothermal power from other states is already supplying the California market, and this is expected to continue.

2. GEOTHERMAL ELECTRICITY PRODUCTION

2.1 Total Current Installed Capacity

Table 2 presents information about installed geothermal power plants in the United States, organized alphabetically by State. Various data sources were used to develop this table, and this results in a degree of conflict in terms of reporting the installed capacity because of differences between the original nameplate capacity and the current operating gross and net output. Due to these differences, the values included in Table 2 may not be in complete alignment with each other or with the values shown in Table 1.

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 have been exploration and in a few cases small pilot projects in the states of Arizona, Washington, Wyoming, Colorado, Texas, Louisiana and Mississippi.

Total installed (generator nameplate) geothermal capacity is approximately 3.7 GW. As noted above, depending on the data source, MW ratings may differ. In addition, some plants have been re-rated due to turbine modifications or evolution of their fields or power plant equipment. Per the Energy Information Agency data in Table 1, total geothermal generation in the year ending December 2018 was 16 TWh. Table 2 indicates that 2018 total geothermal generation was 18.435 TWh.

Table 2: Utilization of Geothermal Energy for Electric Power Generation as of 31 October 2019

Locality	Power Plant Name	Commercial Operation Date	No. of Units	Status[1]	Type of Unit[2]	Total Installed Capacity (MW Gross)	Total Installed Capacity (MW Net)	Annual Energy Produced 2018 (GWh)	Notes
Chena Hot Springs	Chena	2006	2	O	B	0.5			
Coso	Navy I	1987	3	O	2F	102.3	92.2	1175.8	
Coso	BLM	1988	3	O	2F	99.9	90		
Coso	Navy II	1989	3	O	2F	100	90		
Honey Lake	Wineagle	1985	2	N	B	0.7			Repowering underway
Honey Lake	Amedee	1988	2	N	B	1.6			
Honey Lake	Honey Lake	1989	2	O	H	6			Hybrid biomass
Mammoth Complex	G-1 (MP-1)	1984	2	O	B	10	6	49.9	
Mammoth Complex	G-2 (MP-2)	1990	3	O	B	15	11	91.5	
Mammoth Complex	G-3 (PLES-1)	1990	3	O	B	15	12	99.9	
Ormesa Complex	OG I (Ormesa I)	2003	2	O	B	24.4	22	183.1	
Ormesa Complex	OG II (Ormesa II)	1988	2	O	B	24	23.5	195.6	
Ormesa Complex	Ormesa IE	1988	12	R	B	14.4			Shut down
Ormesa Complex	Ormesa IH	1989	12	R	B	9.6			Shut down
Ormesa Complex	GEM 2	1989	1	R	2F	18.5			Shut down
Ormesa Complex	GEM 3	1989	1	O	2F	26.5	18.5	154.0	
Ormesa Complex	GEM Bottoming Unit	2007	1	O	B	9	4.5	37.4	
Heber Complex	Heber 1	1985	1	O	2F	52	47	391.1	
Heber Complex	Heber 2	1993	12	O	B	48	45	374.5	
Heber Complex	Gould 2	2005	1	O	B	13.3	2	16.6	
Heber Complex	Gould 1	2006	2	O	B	10	8.5	70.7	
Heber Complex	Heber South	2008	1	O	B	13.3	12	99.9	
Brawley Complex	North Brawley	2011	5	O	B	80	50	416.1	
Salton Sea	Salton Sea 1	1982	1	O	1F	10.2	10	77.6	
Salton Sea	Vulcan	1986	2	O	2F	39.7	37	274.0	
Salton Sea	Salton Sea 3	1989	1	O	2F	54	49.8	332.8	
Salton Sea	Del Ranch (Hoch)	1989	1	O	2F	43.2	35.8	335.1	
Salton Sea	Elmore	1989	1	O	2F	43.2	35.8	308.7	
Salton Sea	Leathers	1990	1	O	2F	43.2	35.8	328.1	
Salton Sea	Salton Sea 2	1990	3	O	2F	19.7	19	107.4	
Salton Sea	Salton Sea 4	1996	1	O	2F	47.5	39.6	299.4	
Salton Sea	Salton Sea 5	2000	1	O	3F	58.3	49	361.2	
Salton Sea	CE Turbo	2000	1	O	1F	11.5	10	78.7	
Salton Sea	Elmore Backpressure	2019	1	O	O	9			Backpressure
Salton Sea	John L. Featherstone	2012	1	O	3F	60	49.9	456.0	
The Geysers	McCabe (5&6)	1971	2	O	D	110	106	5728.4	
The Geysers	Ridgeline (7&8)	1972	2	O	D	110	106		
The Geysers	Eagle Rock (11)	1975	1	O	D	110	106		
The Geysers	Cobb Creek (12)	1979	1	O	D	110	106		
The Geysers	Big Geysers (13)	1980	1	O	D	95	78		
The Geysers	Sulphur Springs (14)	1980	1	O	D	117.5	65		
The Geysers	Lake View (17)	1982	1	O	D	120	113		
The Geysers	Socrates (18)	1983	1	O	D	120	113		
The Geysers	Sonoma (3)	1983	1	O	D	78	72		
The Geysers	Calistoga (19)	1984	1	O	D	97	80		
The Geysers	Quicksilver (16)	1985	1	O	D	120	113		
The Geysers	Grant (20)	1985	1	O	D	120	113		
The Geysers	Aidlin (1)	1989	2	O	D	22.4	20		
The Geysers	West Ford Flat (4)	1988	2	R	D				Shut down
The Geysers	Bear Canyon (2)	1988	2	R	D				Shut down
The Geysers	NCPA I	1983	2	O	D	110	100	538.8	
The Geysers	NCPA II	1985	1	O	D	55	50	370.8	Unit 3 retired April 2010
The Geysers	Bottle Rock	2007	1	N	D	55			Shut down
Puna Complex	Puna	1993	22	O	O	35	30	249.7	Combined cycle
Puna Complex	Puna Expansion	2012	2	O	B	12	8	66.6	
Raft River	Raft River	2008	1	O	B	13.5	11	91.5	
Lightning Dock	Lightning Dock	2013	4	O	B	4	2.5	13.0	
Lightning Dock	Lightning Dock Repower	2018	1	O	B	15	11	0.5	
Beowawe	Beowawe	1985	1	O	2F	17.7	16	100.3	2018 total combined with binary
Beowawe	Beoware 2	2011	1	O	B	3.125	2		
Blue Mountain	Faulkner	2009	3	O	B	49.5	39.5	230.0	
Brady Complex	Brady	1992	3	R	2F	26.1	19	158.1	Retired 2018
Brady Complex	Desert Peak 2	2007	2	O	B	14.2	10.5	87.4	
Don A. Campbell Complex	Don A. Campbell Phase 1	2014	1	O	B	22.5	16	133.2	aka Wild Rose
Don A. Campbell Complex	Don A. Campbell Phase 2	2015	1	O	B	22.5	19	158.1	
Dixie Valley	Dixie Valley	1988	1	O	2F	64	60.5	495.0	2018 total combined with binary
Dixie Valley	Dixie Valley Bottoming	2012	1	O	B	6.2	5		
Jersey Valley	Jersey Valley	2011	2	O	B	15	10	83.2	
Florida Canyon Mine	Florida Canyon Mine	2012	1	R	B				Retired 2014
Hazen (Black Butte)	Patua	2013	3	O	B	45	30	138.0	Hybrid: 14.5 MW (DC) solar PV
Tuscarora	Tuscarora	2012	2	O	B	30	27	224.7	
McGinness Hills	McGinness Hills Phase 1	2012	3	O	B	48	45	374.5	
McGinness Hills	McGinness Hills Phase 2	2015	3	O	B	48	45	374.5	
McGinness Hills	McGinness Hills Phase 3	2018	3	O	B	74	48	399.5	
Salt Wells	Salt Wells	2009	2	O	B	18	13.4	98.3	
San Emidio	San Emidio Repower	2012	1	O	B	13	11	91.5	
Soda Lake	Soda Lake 1	1987	3	R	B	15	3.6	30.0	
Soda Lake	Soda Lake 2	1991	2	O	B	20	12	30.0	
Soda Lake	Soda Lake 3 (Repower)	2019	1	O	B	23	20		Under Construction in 2019
Steamboat Complex	Steamboat Hills	1988	1	O	1F	21.5	13	108.2	
Steamboat Complex	Steamboat 2	1992	2	O	B	18	14	116.5	Repowered 2008
Steamboat Complex	Steamboat 3	1992	2	O	B	18	14	116.5	Repowered 2008
Steamboat Complex	Galena 1 (Richard Burdette)	2005	2	O	B	30	26	216.4	
Steamboat Complex	Galena 2	2007	1	O	B	13.5	10.4	86.5	
Steamboat Complex	Galena 3	2008	1	O	B	30	26	216.4	
Stillwater	Stillwater 2	2009	4	O	B/O	48	33.1	119.8	+26 MW solar PV +2 MW solar thermal

Locality	Power Plant Name	Commercial Operation Date	No. of Units	Status[1]	Type of Unit[2]	Total Installed Capacity (MW Gross)	Total Installed Capacity (MW Net)	Annual Energy Produced 2018 (GWh)	Notes
Tungsten Mountain	Tungsten Mountain	2017	1	O	B	37	27	224.7	7 MW PV hybrid added 2019
Wabuska	Wabuska 1	1984	1	R	B				
Wabuska	Wabuska 2	1987	1	R	B				
Wabuska	Wabuska 3	2018	4	O	B	4.4	3	20.0	
Klamath Falls	OIT Unit 1	2010	1	O	B		0.3		
Klamath Falls	OIT Unit 2	2014	2	O	B		1.75		
Neal Hot Springs	Neal Hot Springs	2012	3	O	B	33	22	183.1	
Paisley	Paisley	2015	1	N	B	3.1			
Cove Fort	Cove Fort 3	2013	2	O	B	25		157.8	0.6 MW Downhole generator
Roosevelt	Blundell 1	1984	1	O	1F	30.7		223.1	Combined output
Roosevelt	Blundell 2	2007	1	O	B	14.1			
Thermo Hot Springs	Thermo 1	2008	50	R	B				Retired 2013
Thermo Hot Springs	Thermo 1 Repower	2013	1	O	B	14	11	65.0	
					Total:	3,678	Total:	18,435	

[1]**Status:** O = Operating; N = Not Operating (standby); R = Retired

[2]**Type of Unit:**
1F = Single Flash D = Dry Steam
2F = Double Flash B = Binary (Rankine Cycle)
3F = Triple Flash O = Other (please specify)

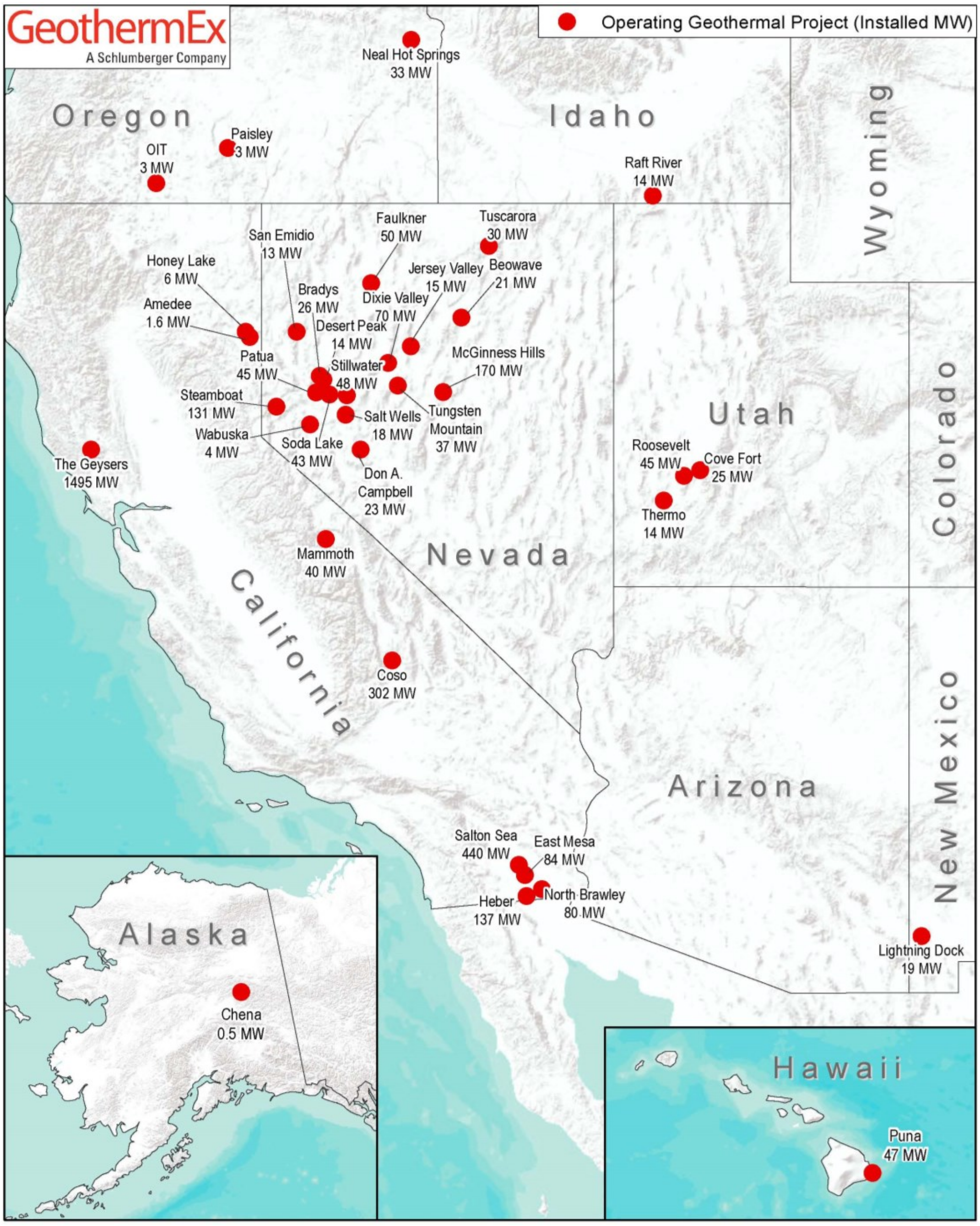

Figure 1: Locations and installed capacities at geothermal fields developed for power generation in the United States

2.2 Details of Existing Geothermal Generation Facilities

2.2.1 Alaska

One of the 2 x 200 kW PureCycle units at Chena Hot Springs continues to operate, but one was decommissioned in 2010 and replaced by a 300 kW Kaishan unit in 2013. Chena is a prime U.S. example of "micro-binary" cogeneration geothermal projects that deliver multiple benefit streams and displaces costly diesel fuel consumption in this remote area. As sub-utility scale plants, the EIA does not report the Chena generation, but its annual output would be a small percentage of Alaska's 6.2 TWh of 2018 electrical net generation.

2.2.2 California

The most recent geothermal plants added in California are the John L. Featherstone plant at Salton Sea (a flash-steam plant installed in 2012), North Brawley (a binary plant installed in 2011), and the Elmore back-pressure turbine installed at the Salton Sea in 2019.

The small 1980s vintage Barber-Nichols units at Wineagle and Amedee were retired, but re-powerings with newer small-scale binary technology are anticipated (Dr. John Lund, personal communication, 2019). With many binary units coming up on 30 years of generation, other re-powerings with larger turbines and more modern equipment (such as at the Mammoth Complex in California) have either been carried out or are anticipated. Original late-1980s designs with maximum turbine sizes around 3-6 MW can be replaced with designs now capable of generating 10-15+ MW without requiring additional resource supply, providing economies of scale in terms of both capital and operating costs.

When it was damaged in a wildfire in 2015, the West Ford Flat dry steam plant at The Geysers had an intertie pipeline project to an adjacent unit undergoing a steam path retrofit underway; however, this plant was retired shortly after the fire. Such "Super-Rotor" re-powerings (described in Maedomari and Avery, 2011) continue to sustain generation there. Its installed capacity of 1,495 MW and its field output of 6.638 TWh in 2018 keep The Geysers in position as one of the world's largest operating geothermal fields.

Planned expansions at the Salton Sea (Hudson Ranch/John Featherstone II, or multiple Black Rock units) have not yet come to pass, but additional capacity by a third operator (Controlled Thermal Resources) is anticipated in the next few years. A pilot lithium extraction system was recently implemented at the Hudson Ranch project, and Berkshire Hathaway Energy/CalEnergy (the operator of most of the existing capacity at Salton Sea) is preparing to implement a pilot lithium extraction project. Controlled Thermal Resources has made lithium extraction a centerpiece of their planned Salton Sea geothermal power project(s). With multiple operators showing renewed interest in metals extraction from geothermal brines, funding support from the California Energy Commission, and DOE-GTO's focused R&D efforts on the same subject, it will be interesting to see the extraction technologies that emerge.

Per the Energy Information Agency, California's total geothermal generation in 2018 was 11.677 TWh, or 6% of the state's electrical generation total of 195.3 TWh. Table 2 indicates that in 2018, California's total geothermal generation was 12.953 TWh, providing an example of the discrepancies between sources discussed above.

2.2.3 Hawaii

The 8 MW expansion in 2012 at Puna Geothermal Venture (PGV) was the latest addition. In 2018, the lower Puna eruption covered several wells at the PGV site. All of the wells had been quenched and sealed in advance of the lava flow, and the plant was safely shut down. A substation was also damaged by the flow. The facilities are currently being refurbished and are expected to resume operations in the second half of 2020 (Ormat Technologies, 2020).

In 2017, the total geothermal generation in Hawaii was 0.323 TWh, or 3% of the state's electrical generation total of 9.8 TWh. Geothermal generation dropped to 0.11 TWh in 2018 due to the eruption.

2.2.4 Idaho

The Raft River binary project saw drilling and stimulation activity in 2016-2017 that was successful in improving plant output (ThinkGeoEnergy, 2017). Idaho-based U.S. Geothermal sold the Raft River project (and its other geothermal assets, which included operating geothermal projects at Neal Hot Springs, OR and San Emidio, NV plants, and the Western Geopower lease at The Geysers) to Ormat in 2018.

Total Idaho geothermal generation in 2017 was 0.083 TWh, or 0.5% of the state's electrical generation total of 18.2 TWh.

2.2.6 Nevada

Greenfield development in Nevada has largely been driven by Ormat, with projects such as Don A. Campbell Phases 1 (2014) and 2 (2015), McGinness Hills Phase 2 (2015) and 3 (2018) and Tungsten Mountain (2017). In addition, the re-powering of Cyrq's Soda Lake project is expected to be operational in 2020. Open Mountain Energy retired older 1980s vintage binary units (Wabuska 1, 2), re-powering them with Kaishan binary technology at Wabuska 3. A fourth unit at Wabuska is planned for commissioning in 2020.

With more than 100 MW of recently added generation, innovative plant designs and host of educational programs at its state institutions, Nevada is continuing to increase the use of its many geothermal resources.

Total Nevada geothermal generation in 2018 was 3.462 TWh, or 9% of the state's electrical generation total of 39.64 TWh.

2.2.5 New Mexico

At Lightning Dock, a set of small binary equipment originally installed in 2013 was replaced with a single 14 MW turbine generator unit from Turboden in 2019. This is Turboden's first geothermal power plant in the United States, although they have other biomass or waste to energy binary projects operating in North America.

Total New Mexico geothermal generation in 2018 was 0.013 TWh, or <0.1% of the state's electrical generation total of 32.7 TWh. This percentage should increase significantly with the Lightning Dock repowering.

2.2.7 Oregon

The three binary units at Neal Hot Springs are now operated by Ormat, after it acquired them from U.S. Geothermal. 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).

Total Oregon geothermal generation in 2018 was 0.176 TWh, or 0.3%% of the state's electrical generation total of 64.1 TWh.

2.2.8 Utah

At Roosevelt Hot Springs, the single flash + binary bottoming plants at Blundell continue to operate. At Thermo, the multiple small units at Thermo 1 were retired and the project re-powered with a single larger Ormat unit in 2013.

Total Utah geothermal generation in 2017 was 0.446 TWh, or 1% of the state's electrical generation total of 39.4 TWh.

2.3 Geothermal Wells Drilled, 2015-2019

The authors reached out to geothermal field developers and operators to obtain information about the total numbers of wells drilled (and their type and depth) to prepare Table 3 below. Different levels of information were provided by individual U.S. geothermal operators, perhaps because of a desire for confidentiality, or for other reasons. To augment data provided by willing operators, we reviewed public source data such as the GeoSteam database for California and a well information database hosted at the University of Nevada, Reno. The results are included in Table 3. Since some operators reported total depth drilled each year and others did not, no information is provided in Table 3 about the total km drilled.

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

Exploration	Production >150°C	Production 100-150°C	Production <100°C	Injection	Total km Drilled
13	13	11	0	31	- -

2.4 Investment in Geothermal Power Production

All US geothermal operators in the United States were requested to provide information on their investments in research, field development and plant development investments during the past five years. Because the standard WGC tables focus on development costs, operating expenses were not requested (we note that most geothermal operators prefer not to share operating costs). Table 4 presents the investment data provided by willing respondents, combined with data available in the public domain. It is very likely that the field and plant development investments are underestimated in Table 4. In addition, this table does not include government research program investments (which are discussed in detail in section 4 below) or academic resource program investments, but it does include R&D investments reported by willing operators.

Table 4: Total Investments in Geothermal Development, 2015-2019

Year	Research and Development (Million US$)	Field Development (Million US$)	Plant Development (Million US$)
2015	2	23	15
2016	5	70	71
2017	4	61	101
2018	4	23	69
2019 (est.)	4	72	91
Total:	**19**	**249**	**348**

3. RECENT GEOTHERMAL TRENDS

3.1 Resource Development Trends

In its recent GeoVision study (United States Department of Energy, 2019; see section 4.2.1 below), DOE-GTO concludes that technology improvements – many of which are being actively investigated today – could significantly increase geothermal power generation in the United States, which has the potential to reach 60,000 MW, a number that includes some contribution from EGS. Earlier, the USGS (2008; Williams *et al.*, 2009) had 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, some of which may be provided by resources in deep sedimentary basins (see, for example, Allis *et al.*, 2015).

Nevertheless, geothermal growth has been slow in the past five years, owing to the market factors discussed above. The growth that has been realized in geothermal generation in the United States during this period is due in part to expansions or re-powering at known geothermal fields, with a few new moderate-temperature fields being developed by pumped wells suppling binary power plants. Aggressive clean energy goals in many geothermal states have not been accompanied by attractive prices for geothermal power, mainly owing to lower-cost intermittent sources competing mainly on a USD/MWh basis. As discussed in section 3.4 below, work by U.S. geothermal firms – individually and through the combined efforts of the Policy Committee of the Geothermal Resources Council – is aimed at recognizing the value that geothermal brings, including grid stabilization as more intermittent renewables (particularly solar) are added to the energy mix.

3.3 Power Plant Trends

Activities in the various states over the past five years highlight several trends:

- consolidation;
- re-powering; and
- colocation/hybridization.

These trends are discussed briefly in the sections below.

3.3.1 Drive for Lower LCOE / Consolidation

As discussed above, geothermal projects in the United States face stiff competition from other renewable energy options (such as solar, wind and hydro) that have low Levelized Cost of Electricity (LCOE). As capital costs drop due to technological advancement, operating costs become a larger share of LCOE. Lowering operating costs thus becomes increasingly important when securing a reasonable Power Purchase Agreement (PPA). Operators of single or a small number of units that are unable to spread their costs over a larger fleet may be at a competitive disadvantage. This may explain the drive towards more consolidation, illustrated by acquisitions such as U.S. Geothermal by Ormat, and the Patua and Blue Mountain projects by Cyrq Energy.

3.3.2 Re-Powering

While the pace of greenfield development is modest, the fact that many geothermal projects in the United States were originally constructed in the 1980s and 1990s means these projects have now been operating for 30-40 years. As they reach their golden years, re-powering these projects is a natural opportunity to retune the designs around more modern equipment and updated reservoir conditions. The Super-Rotor projects at The Geysers (Maedomari and Avery, 2011) and the Steamboat re-powerings (Buchanan *et al.*, 2010) are examples of re-powering strategies to improve performance and availability (a few others have been discussed earlier).

Other re-powering strategies may seem either complementary or contradictory. In settings such as Ormesa, Thermo, Lightning Dock, Soda Lake and Wabuska, larger numbers of small units were upgraded to smaller number of larger turbine-generator units. While detailed information about the reasoning that led to those upgrades is not often published (and some re-powerings were simply necessary due to age), it is likely that the large units may be able to realize higher efficiencies and lower operating costs (on a per-MWh basis) due to economies of scale and – particularly for some binary plants – more efficient conversion from heat to power. Thus, there seems to be a trend toward fewer, larger units.

A different trend is illustrated by the emergence of more market suppliers of small “micro-binary” <1 MW units. These may indeed be a good fit for remote areas or where power generation may be a complement to other services geothermal can provide, exemplified by the cogeneration projects at Chena Hot Springs and OIT. In such niches and especially where the overall resource extent is quite limited, standardized small modules have a role, not only for their size and convenience, but also for the resiliency that they provide. However, based on experience in the United States, it does not appear that the installation of multiple small (<1 MW) units have demonstrated a competitive advantage relative to larger 5-10+ MW units in terms of overall project LCOE competitiveness.

3.3.3 Collocation and Hybridization

Geothermal projects must be operated in a way that maximizes their potential benefits and revenue streams, especially to remain competitive in the current low-cost LCOE environment in the western United States. Collocation of other power generation facilities that leverage a geothermal project’s space, operating staff and transmission is a natural fit (Harvey and Ralph 2008).

Several geothermal power plants in Nevada have implemented collocation, such as solar PV and/or thermal at Stillwater (by Enel, with features as described in DiMarzio *et al.* 2015), Patua (Cyrq) and Tungsten Mountain (Ormat). Collocation could be extended to other power generation features such as energy storage. Although all the examples discussed here are in Nevada, it is likely that projects in other states will begin to leverage similar opportunities. In California particularly – where rooftop and utility-scale solar PV significantly reduces power demand during the day – night-time delivery from geothermal power plants could be increased by the amount of power that was generated and stored during the day. This would be a win-win situation in that it is financially attractive and off-sets the need for power from sources that are less favorable in terms of emissions.

Another strategy to boost generation is to optimize plants via a mix of wet and dry cooling, where a limited amount of fresh water can be used to boost generation in the hotter seasons or periods of the day. Such hybrid wet/dry cooling projects to boost generation have been implemented at Steamboat by Ormat (as described in Kaplan *et al.* 2011) and at Patua by Cyrq. An innovative strategy (“limited deluge cooling”) for projects in areas with limited water available for power plant cooling proposed by the National Renewable Energy Laboratory (NREL, 2013) may also be used at some geothermal power plants. Time-of-day pricing premiums can make these projects especially advantageous. As for colocation, these hybrid power generation innovations have been already implemented in Nevada, and we expect that they will become more common in the future.

3.4 Geothermal Electricity Market Conditions and Policies

As noted above, the past five years have been characterized by modest geothermal growth, owing to competition from lower-cost energy sources in a competitive market. However, the current social, economic and political trends provide a level of optimism for the development of additional geothermal power in the western United States. In combination, the following potent forces will drive a new wave of geothermal power expansion in the United States:

- the near-universal acceptance of the risks associated with climate change and the recognition of the importance of clean power;
- the de-stabilizing impacts on the power grid from intermittent renewable power generation;
- the positive geothermal outlook provided in DOE-GTO's GeoVision study and other studies noted above; and
- policy engagement by the geothermal industry.

Together, these factors will continue to enable more geothermal power projects to be developed in the western United States.

The impetus is particularly strong in California, which has a legislative mandate that is unique among the U.S. states: a renewable power requirement plus 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 (Thomsen, 2018). Although this amount may be considered modest in comparison to the potential for geothermal in the United States, it is a significant turning point in terms of policy, which – like the U.S. Senate hearings on geothermal power in 2019 – is the result of diligent efforts by the geothermal industry, supported by independent technical evaluations conducted by federal and state agencies, notably including 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.

The specific mandated requirements in the State of California can be served in part by clean sources of power generated outside the state. Among others, one example of geothermal power from another state supplying California is Ormat's Don A. Campbell project in Mineral County, Nevada (details presented here are taken from Orenstein and Delwiche, 2014). Power produced at this geothermal project is sold to the Southern California Public Power Authority (SCPPA), transmitted via a series of interconnects. A critical element of this system is the One Nevada Transmission Line (the "ON Line"), which was completed in 2013 (the same year that the Don Campbell project came on-line). The ON Line connected the northern and southern service areas (balancing authority areas) of two related Nevada utilities (Sierra Pacific Power Company in northern Nevada and Nevada Power Company in southern Nevada) for the first time. The ON Line not only improved the ability to export power from Nevada to California, it also enabled the two Nevada utilities to share renewable power and improve their ability to serve all power customers in Nevada.

There are other examples of exporting geothermal power from nearby states to California, going back to the construction of a 220-mile, 230-kV transmission line that was needed to connect the Dixie Valley geothermal project in Nevada to a substation in Bishop, California, enabling the sale of power to Southern California Edison (Benoit, 2015; Orser, 1988). This line (which was built in 1987-1988) became the largest privately owned electric transmission facility in the United States, and it continues to transmit geothermal power from Nevada to southern California. Another example is the sale of power from Cyrq Energy's Thermo geothermal power project in central Utah to the City of Anaheim, which is also located in southern California. Power from the Thermo geothermal project is delivered to Anaheim over the Northern Transmission System at the Mona interconnection tie in the Los Angeles Department of Water and Power control area (City of Anaheim, 2013).

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.

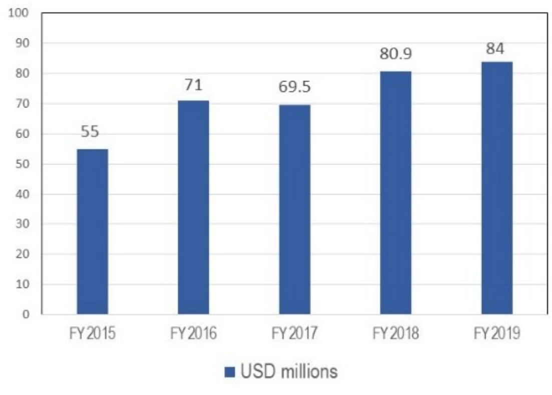

Figure 2: DOE GTO appropriations for the last 5 fiscal years

Federal involvement in early-stage research and development enables the geothermal sector to develop innovative technologies that will help harness American energy resources safely and efficiently. DOE-GTO's technology portfolio prioritizes high-risk R&D that addressed challenges that are not undertaken solely by the geothermal industry because of the early-stage nature of the work, lack of institutional knowledge, funds, or a combination of these factors. DOE-GTO-funded R&D work related to geothermal power generation is carried out across the geothermal spectrum, including: high-, moderate- and low-temperature conventional hydrothermal resources and Enhanced (or Engineered) Geothermal Systems (EGS) resources that require permeability enhancements to bring them into the commercial realm. Accordingly, DOE-GTO has set itself a suitable EGS goal: by 2050, achieving a levelized cost of electricity (LCOE) of $0.06/kWhr for newly developed EGS projects.

DOE GTO spends the bulk of its budget on extramural R&D work via National Laboratories, universities, and industry. As shown in Figure 2 above, appropriated funding for DOE GTO has increased by more than 50% since FY 2015. The FY 2019 budget of $84 million supports projects in 4 subprogram areas: EGS, Hydrothermal, Low-Temperature and Co-Produced Resources, and Systems Analysis. The programs that support R&D for the electric sector are described in the next section. The programs that support R&D for the non-electric sector are described in Lund *et al.*, 2020, a companion paper to this one that has been written for publication and presentation at WGC 2020.

4.2 DOE GTO Programs, 2017 – 2019

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

4.2.1 *GeoVision* Analysis and Report

GTO recently completed a rigorous, multi-year research effort to examine the potential role for geothermal in the Nation's affordable energy future. The result is *GeoVision: Harnessing the Heat Beneath Our Feet*.(U.S. Department of Energy, 2019). The *GeoVision* analysis included collaboration among national laboratories, industry experts, and academia to evaluate the geothermal potential and impacts in the U.S. from the present until 2050. The effort assessed opportunities to expand nationwide geothermal energy deployment by improving technologies, reducing costs, and mitigating project development barriers such as permitting. The *GeoVision* analysis also: examines economic benefits to the U.S. geothermal industry; investigates opportunities for desalination, mineral recovery, and hybridization with other energy technologies for greater efficiencies and lower costs; and quantifies potential environmental impacts of increased geothermal deployment.

Together with eight supporting National Laboratory Task Force Report, the *GeoVision* report was published in May 2019 and can be accessed at DOE-GTO's website via the link in the references section. Key findings from the *GeoVision* study for the electric power generation sector are compelling and indicate that geothermal can play a substantial and unique role in the U.S. energy mix in the future. The major takeaways include:

- Technology improvements could reduce costs and increase geothermal electric power deployment 26-fold by 2050, to more than 60 gigawatts-electric (GWe). In 2050, this capacity represents 3.7% of total U.S. installed capacity and 8.5% of all U.S. electricity generation.
- Optimized permitting timelines could triple resource discovery rates, thus reducing costs and facilitating geothermal project development. Optimizing permitting alone could increase installed geothermal capacity to 13 GWe of electricity generation by 2050—more than double the 6 GWe projected in GeoVision's baseline case.
- Increased geothermal deployment could improve U.S. air quality and reduce CO_2 emissions. The GeoVision analysis indicates opportunities for reductions in sulfur dioxide (SO_2), nitrogen oxides (NOx), and fine particulate matter (PM2.5) emissions. For the electric sector, this could cumulatively result in up to 516 million metric tons (MMT) of avoided carbon dioxide equivalent (CO_2e) emissions through 2050—the equivalent of removing 6.4 million cars from the road.
- The geothermal deployment levels calculated in the GeoVision analysis could be achieved without significant impacts on the nation's water resources. Compared to the baseline, the high levels of deployment evaluated in the GeoVision analysis result in a slight increase (~4%) in the amount of water consumed by the power sector in 2050. This increase in consumption can be mitigated through the use of non-freshwater resources such as municipal wastewater and brackish groundwater.

4.2.2 Advanced Energy Storage Initiative

In support of the U.S. DOE Grid Modernization Initiative, DOE-GTO is investing close to $10 million in reservoir thermal energy storage (RTES), cements, and geothermal heat pump RD&D at DOE's national laboratories. As a result, national laboratory researchers are partnering with industry and geothermal stakeholders to develop energy storage (as an alternative to battery storage) and "behind-the meter" generation, storage and electric load shaping technologies.

An example of an alternative storage technology that could be used to increase flexibility on the generation side are geothermal reservoirs designed specifically to store excess heat from large, inflexible thermal power stations. These RTES systems would allow power stations to reduce electrical power output while remaining connected to the grid during periods of high variable renewable availability. While a pre-existing hydrothermal resource is not necessary to obtain the benefits of a RTES system, co-locating one with a low-temperature geothermal resource would improve the efficiency of the power cycle and the economic viability of low-temperature resources while increasing low-temperature geothermal resource development in the U.S.

A technology that increases the ability of geothermal generation to provide flexibility or grid services at the bulk or distribution level is thermal insulating lightweight and shock-resistant cements, currently under development at Brookhaven National Laboratory and Sandia National Laboratory.

In addition, U.S. small business and university researchers are teaming up to develop new thermal energy storage technology that could increase the degree to which geothermal power can be dispatched. As a process improvement to geothermal plants that can currently ramp up and down by using the current state-of-the art "bypass method," phase-change thermal energy storage units are under investigation that if successful could protect a plant against temperature fluctuations allowing it to meet various ramp rate requirements while allowing the geothermal resource to drawn down at the duty-cycle-averaged extraction rate rather than the full rated-output extraction rate.

Enabling flexible geothermal power is important because other renewable energy sources such as solar and wind are not dispatchable.

4.2.3 Beyond Levelized Cost of Electricity

Levelized Cost of Electricity (LCOE) is a commonly used metric in the energy community and is also used to track progress on DOE-GTO funded R&D activities. While easy to understand and a useful means of assessing and comparing the cost for one type of technology over time, the metric does not consider broader values and costs that are necessary for the operation of a reliable and resilient power system. These values include the provision of grid services other than energy supply (*e.g.*, spinning reserves, voltage support, capacity, dispatchability, etc.) and when and where they are provided in the power system. Because it involves more than just geothermal energy, this initiative is led from a level above that of DOE-GTO: U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE).

The objective of this project (which has been ongoing since FY 2018) is to develop a methodology to incorporate the broader equitable set of costs and values for electricity generating and storage technologies into a metric or series of metrics to aid in comparison between generation technologies. Specifically, BLCOE is analyzing and evaluating:

- Power Plant Costs. These are all the capital, operational, fuel, and other expenditures necessary to build and operate the plant. Although most of these are already included within typical LCOE calculations, it is within the scope of Beyond LCOE to ensure that the cost boundaries are the same across facilities (*e.g.*, decommissioning costs, spur line costs), thus enabling a more informed comparison between generation technologies.
- System Costs & Values. Beyond LCOE is focusing on any system cost or value arising from the operation of a technology in a specific system. The values are related to the grid services needed for the reliable and resilient operation of the power system, which are distinct from market value of a service within a specific set of market rules.

Total funding to date (November 2019) for Beyond LCOE is $4.4 million total from various DOE Offices; of this, $0.5 million is from DOE-GTO.

4.2.4 EGS Collab

Beginning in FY 2017 and ongoing today, DOE-GTO is funding a large collaborative team led by Lawrence Berkeley National Laboratory and Sandia National Laboratories to develop a small-scale field site at the Sanford Underground Research Facility in Lead, South Dakota (at the former Homestake Gold Mine). This field site allows the subsurface modeling and research community to establish validations against controlled, small-scale, *in-situ* experiments focused on rock fracture behavior and permeability enhancement. The EGS Collab initiative was designed to address critical and fundamental barriers to EGS advancement by facilitating direct collaboration between the geothermal reservoir modeling community, experimentalists, and geophysicists in developing and implementing methods for reservoir characterization, development, stimulation and monitoring. The EGS Collab project consists of three major experiments, as described below.

Experiment 1. The goal was to establish a fracture network that connects an injection well and a production well via hydraulic fracturing. The team selected a site on the 4,850-foot (1,478-m) level of the facility for this experiment. All eight holes drilled for the experiment are approximately 60 meters long and drilled sub-horizontally. The experimental set-up included six monitoring wells (yellow) and injection (green) and production (red) wells drilled in approximately the direction of the minimum principal stress. The Collab effort, although focused on rock fracture behavior and validation of numerical simulators, extensive and innovative characterization methods are employed to characterize the boreholes including optical and acoustic televiewers, full waveform seismic, electrical resistance tomography, cross-borehole compressional and shear wave seismic characterization, distributed acoustic and strain, and water temperature/conductivity (Kneafsey *et al.* 2019). In the last year the team has performed a controlled stimulation, hydraulic characterization of the created fracture system, tracer testing, and long-term flow testing (still underway). Modeling played an integral role in all aspects of the first experiment, focused on conceptual design and scenario testing, predictive modeling, and for evaluation of the created system. Evidence of stimulation defined by flow through the created hydraulic fracture as well as significant flow through natural fractures was evident in the electrical resistance tomography survey data and Continuous Active Source Seismic Monitoring (CASSM) data, and corroborated by microseismic and Distributed Temperature Survey (DTS) data and tracer analysis to generate a baseline model for the created fracture network (see Kneafsey *et al.,* 2019).

Experiment 2. Planned for FY 2020, Experiment 2 will occur at the 4,100-foot (1,250 m) level, and will be designed with the intent of primarily creating shear stimulation along existing discontinuities. The surrounding rock at this level is a different formation than that targeted in Experiment 1; it is a less foliated rock, which the team is currently logging and testing.

Experiment 3. This experiment will focus on alternative stimulation procedures, such as different fluid properties, different pressure applications, use of proppants, and other methods that can be evaluated in a scaled environment. Experiment 3 will use one of the testbeds developed in Experiment 1 and 2.

Total funding for the EGS Collab project to date (November 2019) is $27 million.

4.2.5 Efficient Drilling for Geothermal Energy (EDGE)

Early-stage R&D in drilling technologies presents an opportunity for innovation that can have a significant impact on improving the economics of geothermal development. Drilling operations can account for up to half of the cost to develop a geothermal project. Given that much of the drilling occurs in the early stages of a project, complications from drilling failures can lead to cascading consequences resulting in overall project failure. Enabling the geothermal industry to drill more efficiently will reduce both the risk and cost and can help spur industry to expand capacity in the near-term.

In the EDGE initiative (started in FY 2018 and currently underway), DOE-GTO solicited projects to enable the geothermal industry to double the average penetration rate for a geothermal well and improve the industry standard drilling vs. depth to 250 feet per day by 2025. A total of 10 projects were selected for award in three research areas: 1) reducing non-drilling time; 2) advanced drilling technologies; and 3) innovative partnership models. The Funding Opportunity Announcement (FOA) is available here. $15.4 million has been awarded to date (November 2019).

4.2.6 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:

Phase 1 – Planning. Teams proposing five sites (Snake River Plain, ID; Newberry, OR; Coso, CA; Fallon, NV and Milford, UT) developed comprehensive geologic models based on existing data as well as a series of operational plans and logistical tasks to demonstrate their site's viability and their team's full capability to implement the entirety of the FORGE project.

Phase 2 – Site Characterization. In summer 2016, DOE-GTO down-selected two teams for Phase 2 (Fallon, NV and Milford, UT), and the respective teams further characterized their sites through surface and subsurface means, including well drilling. In addition, the teams undertook administrative and logistical activities focused on permitting, site preparation, team organization, etc. to prepare for Phase 3 work. Upon completion of this phase, the final site (Milford, UT) was selected by DOE-GTO in June 2018. At time of writing (November 2019), the University of Utah-led FORGE team is completing Phase 2C, where they established a seismic monitoring network, performed additional reservoir testing in an open and cased hole section of their initial well, established a data portal for access to FORGE data, as well as a number of other critical administrative tasks to bring the site and effort to full readiness for Phase 3.

Phase 3 – Technology Testing and Evaluation. During the five-year Phase 3 (slated to start in Q4 2019), all technical, administrative, and logistical tasks necessary for management and oversight of FORGE operations and tasks specific to the solicitation, selection, testing, and evaluation of new and innovative EGS tools, techniques, and supporting science will be conducted.

In 2020, the Utah FORGE Team will complete additional numerical modeling and analysis to inform their initial well location to be drilled late in the calendar year. In parallel, they will release the first of the Annual FORGE solicitations open to the community for the opportunity to develop technologies and methodologies to be tested at the Utah site. The FORGE project is anticipated to be ongoing through FY 2024 with competitive solicitations released on at least an annual basis and at least two full-scale wells available for testing.

Total funding for the FORGE initiative to date (November 2019) is $156 million.

4.2.6 Machine Learning for Geothermal Energy

The rapidly advancing field of machine learning offers substantial opportunities for technology advancement and cost reduction throughout the geothermal project lifecycle, from resource exploration to power plant operations. DOE-GTO is funding ten projects to support new analytical tools for finding and developing geothermal resources, to establish the practice of machine learning in the geothermal industry, and maximize the value of the rich datasets utilized in the geosciences.

Under Topic 1 (Machine Learning for Geothermal Exploration), DOE-GTO is funding seven projects that advance geothermal exploration through the application of machine learning techniques to geological, geophysical, geochemical, borehole, and other relevant datasets. Of particular interest are projects that will identify drilling targets for future work. Under Topic 2 (Advanced Analytics for Efficiency and Automation in Geothermal Operations), DOE-GTO is funding three projects that apply advanced analytics to power plant and other operator datasets, with the goal of improving operations and resource management.

The FY 2018 FOA is available here, and a DOE progress alert announcing the awards is available here. Initiated in FY 2018 and currently ongoing, the total budget to date (November 2019) is $5.5 million.

4.2.7 Play Fairway Analysis

A major barrier to the development of the large geothermal resources in the United States is the difficulty in locating blind hydrothermal systems, because their discovery requires costly exploratory drilling. DOE-GTO has made a priority of advancing the state of the art in exploring for blind hydrothermal systems, and key among these technologies is the concept of play fairway analysis. Already successfully used in the oil and gas sector, play fairway analysis can be a key tool for decision making in any exploration project. DOE-GTO's efforts to adapt play fairway methods for use in geothermal exploration, with the ultimate goal of quantifying and reducing risk in geothermal exploration, have been very successful to date.

DOE-GTO began its Play Fairway Analysis (PFA) initiative in FY 2014 with a goal to use combinations of data sets to pinpoint high-grade potential drilling areas. The initiative, which will wrap up in early 2020, was comprised of three phases. Phase 1 (a desktop analysis phase) supported 11 projects that: 1) focused at the basin or regional scale; 2) addressed a wide range of possible geothermal resources; 3) developed methodologies to couple multiple data types; and 4) applied innovative analysis methods to extract new value from existing data. DOE-GTO then down-selected to six projects for Phase 2 and invested funds for teams to obtain new geophysical and other data to better constrain the areas where geothermal resources were predicted to be found.

The final phase (Phase 3), which started in 2018 and will end this fiscal year, funds a final drilling phase to validate the predictions of the first two phases for five of the projects. At the time of this writing, the first two drilling campaigns are complete. The first consisted of twelve shallow temperature gradient holes at sites near Gabbs Valley, NV and Granite Springs Valley, NV. Both of those sites yielded new discoveries in areas that had not seen significant previous exploration (Faulds, 2018).

The other completed PFA project drilled a single slim hole near Camas Prairie in the Snake River Plain region of Idaho. That well successfully intersected both heat and permeability at depth; results of the subsequent flow testing are being analyzed. Drilling operations are finishing at sites in Hawaii and near Mt Baker in Washington State, with results expected by the end of 2019.

The Play-Fairway Analysis projects will conclude in FY 2020. The total budget to date (November 2019) is $15.2 million.

4.2.8 Waterless Stimulation

The most commonly applied wellbore stimulation technology, hydraulic fracturing, relies heavily on water-based fracturing fluids due to the general availability and low cost of water as well as its capability for proppant transport. DOE-GTO has been interested in developing stimulation methods that require little to no water – reducing the usage needed for geothermal progress and easing constraints on water consumption. In addition, there are crosscutting applications with oil and gas, where there is growing concern with the amount of water disposed after similar operations have been completed. Starting in FY 2018, DOE-GTO began funding three National Laboratory projects in waterless stimulation investigating anhydrous energetic stimulation, a novel stimulation fluid requiring less water, and pulsed injection of a foam-based stimulant.

The Waterless Stimulation project is ongoing; the total budget to date (November 2019) is $4.3 million.

4.2.9 Zonal Isolation for Manmade Geothermal Reservoirs

Zonal isolation technologies can radically improve the performance and economics of EGS or manmade geothermal reservoirs. These technologies provide the ability to target specific zones for stimulation activities, which can enable the command and control of fracture location and the economy of resources. In turn, this reduces development costs and operational risks associated with EGS development and facilitates more power from fewer wellbores. Effective and reliable zonal isolation remains one of the most critical technology needs to enable widespread EGS development. Initiated in FY 2018 and currently ongoing, the total budget to date (November 2019) is $4.5 million.

DOE-GTO is funding four R&D efforts that focus on the creation of new zonal isolation technologies and the modification of existing zonal isolation technologies for use in EGS stimulations that can operate in high temperature, caustic environments. The R&D efforts will result in prototypes of zonal isolation technologies, and these technologies should be ready for testing in a geothermal reservoir such as FORGE immediately following conclusion of the project. The FY 2018 FOA is available here, and a DOE-GTO progress alert announcing the awards is available here.

Initiated in FY 2018 and currently ongoing, the total budget to date (November 2019) is $4.5 million.

4.2.10 Other Initiatives

DOE-GTO is engaged with several other initiatives directly and indirectly related to the electric sector. Among these are R&D in mineral recovery, hybrid operations, co-production, and systems analysis.

4.3 International Geothermal Projects

4.3.1 Statement of Principles for Cooperation with New Zealand

In 2018, GTO and New Zealand's Ministry of Business, Innovation and Employment (MBIE) announced an agreement to collaborate on the advancement of geothermal technologies. The overarching goal of the Statement of Principles for Cooperation agreement is to establish a framework for cooperation in the development of advanced, cost-effective geothermal energy technologies; accelerate the availability of geothermal technologies worldwide; and identify and address wider issues relating to geothermal energy, such as induced seismicity and mineral recovery. The proposed areas for collaboration include the joint development and improvement of modeling tools, mineral recovery, direct use applications, and supercritical geothermal systems.

4.3.2 The GEOTHERMICA Consortium

The United States has recently joined the GEOTHERMICA Consortium. GEOTHERMICA's objective is to combine the financial resources and know-how of 18 geothermal energy research and innovation program owners and managers from 14 countries and their regions. GEOTHERMICA will launch joint projects that demonstrate and validate novel concepts of geothermal energy deployment within the energy system, and that identify paths to commercial large-scale implementation. Membership in this Consortium will allow the U.S. researchers to leverage massive investment from Europe in geothermal research on EGS and low temperature applications, and facilitate access to world-class researchers and their facilities, demonstration sites, and data. With each research call, each member country funds only applicants from their nation. A GEOTHERMICA research call was released in May 2019, with full proposals due in January 2020.

4.3.3 Participation in International Geothermal Groups

The U.S. geothermal industry can learn from international work across the geothermal spectrum. The U.S government takes the lead in engaging in international collaborations; investing in international participation can propel the industry forward across all geothermal energy sectors and technology applications. The U.S. is active in several international geothermal groups, as described below.

- International Energy Association (IEA) Geothermal. IEA Geothermal, with a mission to foster and promote sustainable use of geothermal energy worldwide and communicating geothermal energy's benefits, currently comprises 16 members, including 13 Country Members: Australia, France, Germany, Iceland, Italy, Japan, Mexico, New Zealand, Norway, Republic of Korea, Switzerland, United Kingdom and the United States; the European Commission; and two Sponsors (Ormat Technologies and the Spanish Geothermal Technology Platform Geoplat). DOE-GTO is a member of the Executive Committee of IEA Geothermal.

- International Partnership for Geothermal Technologies (IPGT). The purpose of the IPGT is to accelerate the development of geothermal technology through international cooperation. Five countries make up the IPGT: Australia, Iceland, Switzerland, New Zealand, and the United States. DOE-GTO is a member of the Steering Committee and is therefore a voting member of IPGT.
- Global Geothermal Alliance (GGA). Developed under the auspices of the International Renewable Energy Agency (IRENA), the GGA is a coalition for action to increase the use of geothermal energy, both in power generation and direct use of heat. It calls on governments, business and other stakeholders to support the deployment of realizable geothermal potential. The Alliance has an aspirational goal to achieve a five-fold growth in the installed capacity for geothermal power generation and more than two-fold growth in geothermal heating by 2030. The Alliance has 46 member countries and 36 Partners: Argentina, Bolivia, Burundi, Chile, Colombia, Comoros, Costa Rica, Djibouti, Ecuador, Egypt, El Salvador, Ethiopia, Fiji, France, Germany, Guatemala, Honduras, Iceland, India, Indonesia, Italy, Japan, Kenya, Kingdom of the Netherlands, Malaysia, Mexico, Nicaragua, New Zealand, Pakistan, Papua New Guinea, Peru, Philippines, Poland, Portugal, Romania, Saint Vincent & the Grenadines, Switzerland, Solomon Islands, United Republic of Tanzania, United States of America, Tonga, Turkey, Uganda, Vanuatu, Zambia, and Zimbabwe.

5. HUMAN CAPITAL

The United States is fortunate to have a significant and experienced geothermal work force. This is a result of the development of a wide variety of resource types in the United States, the involvement by U.S. geothermal personnel in many other geothermal projects around the world, and the presence of many universities and colleges that offer geothermal curricula.

5.1 Professional Geothermal Personnel

The total number of personnel engaged in geothermal projects is difficult to assess, requiring the authors to use a variety of techniques. As a first step, we first reached out to U.S. geothermal operators to assess the total number of full-time employee equivalents (FTEs) engaged in geothermal work. Allocations of FTEs from other U.S. firms involved in the geothermal sector were made in some cases based on specific knowledge by authors Robertson-Tait and Harvey. In the absence of such specific knowledge, estimates were made using records of U.S. participants at the Geothermal Resources Council Annual Meetings during the past few years. Table 5 below provides a summary of the responses and estimates. The values in Table 5 are considered to under-estimate the number of professional geothermal personnel in the United States by a significant margin.

Table 5: Allocation of Professional Personnel to Geothermal Activities (Estimated)

Year	FTEs
2015	1,549
2016	1,613
2017	1,673
2018	1,726
2019	1,725

The estimates do not distinguish between FTEs for government staff engaged in geothermal (*e.g.*, the Bureau of Land Management, Federal and State permitting agencies, DOE-GTO, etc.), academics, geothermal developers and operators, plant and wellfield service providers (*e.g.*, chemical suppliers, equipment and material suppliers, repair technicians, construction labor, drilling companies, etc.) and foreign firms working in the USA, all of which were difficult to survey directly in the context of preparing this paper.

Hance (2005) estimated that the geothermal industry accounted for 1.7 jobs per MW of power production capacity, with 44% of those directly related to power plant operation and maintenance and 56% related to other activities such as research, consulting and supply services, environmental, legal and government issues, etc. Using this ratio, the 3,700 MW of US installed capacity might translate to around 6,290 FTEs. The 2019 U.S. Energy and Employment Report, developed by the Energy Futures Initiative (EFI, 2019) and the National Association of State Energy Officials (NASEO), estimates that employment related to geothermal totaled 8,526 in 2018 (up from 7,927 in 2017), values which are comparable to those assessed using the ratio provided by Hance (2005). In sum, it would appear the geothermal-focused workforce has grown steadily over the past five years and may reach 10,000 in a few more years.

5.2 Geothermal Education

Future geothermal experts are being educated at many American institutions of higher education that offer geothermal curricula. At the undergraduate level, in addition to the subjects that are fundamental to geothermal (civil and environmental engineering, chemical engineering, geology, geological engineering, geophysics, hydrology, mechanical engineering, petroleum engineering, physics, etc.), GEA (2010) notes that a few institutions, such as Southern Methodist University (SMU), have a geothermal focus within a major. Others, including the Oregon Institute of Technology (OIT), Massachusetts Institute of Technology (MIT), Cornell University, and University of Nevada, Reno (UNR) offer undergraduate renewable-energy-related minors that highlight geothermal energy. OIT also offers an undergraduate renewable energy major, and Truckee Meadows Community College (in Reno, Nevada) offers a 2-year Associate Degree in Applied Science – Energy Technologies with a geothermal energy emphasis.

GEA (2010) also reports on the opportunities to learn geothermal specifics at the graduate level. Specific geothermal programs and coursework are available at Boise State University, Brown University, Colorado School of Mines, Cornell University, University of Kansas, MIT, New Mexico Institute of Mining and Technology, Oklahoma State University, OIT, Rice University, Stanford University, Texas A&M University, University of California (Berkeley, Davis and Riverside), UNR (including the National

Geothermal Academy and the Great Basin Center for Geothermal Energy), University of North Dakota, University of Utah, Virginia Polytechnic Institute and Washington State University. These institutions focus on a wide range of subjects, including regional favorability factors for the formation of exploitable geothermal resources, resource exploration and characterization, drilling methods, reservoir engineering, power cycles, unconventional geothermal systems and more.

Based on the current trends in geothermal resource development, power plant technologies, significant geothermal R&D (including the promise of EGS), policy initiatives, and interactions with cohorts of recent graduates of institutions that focus on geothermal energy, the authors conclude that the United States has a bright geothermal future.

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