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The Benefits of Geothermal Power, Evolution of the U.S. Electricity Grid, and the Need for Geothermal Research

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Keywords

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ABSTRACT

Geothermal energy systems are poised to expand significantly if technologies continue to advance. Renewable geothermal power plants provide 24/7 reliability, weather resilience, fuel security and have the lowest lifecycle environmental costs of any electric generation technology. “Always-on” but dispatchable geothermal systems can provide direct heating, decarbonize and balance the electricity grid, extract critical minerals, produce green hydrogen, desalinate water, and retrofit selected under-producing geothermal and oil & gas wells. Many unique attributes of geothermal energy exceed, as well as complement, those of solar and wind, even with batteries. To date, Enhanced Geothermal Systems (EGS) have been the showcase new technology, but emerging Closed-Loop Geothermal (CLG) systems are now being commercialized. Recent studies show large benefits for investing in RD&D to improve efficiency and reduce costs.

Many complex factors contribute to the changing mix of electricity technologies over time. These include federal and state policies and, recently, the rapid growth of solar and wind power. California is an example that can provide important lessons. Despite proven performance, ongoing research is needed to expand the accessibility and lifetimes of geothermal resources, reduce the time to permit and build, reduce drilling and exploration risks, increase scalability, develop innovative well and pipe configurations, and bring down costs. Field scale development will facilitate drilling advances. CLG retrofits will provide immediate growth at competitive costs. Both EGS and CLG can produce economic power from areas with lower temperatures and/or low permeability. This paper illustrates the benefits of geothermal energy, describes paradigm shifts that influenced power generation choices over decades, and indicates areas for research to better enable geothermal technologies to decarbonize our energy systems, while enhancing electricity grid diversity and reliability.

1. Introduction

As the global energy system decarbonizes and worldwide electricity demand grows, the complexity of satisfying our energy needs with reliable, resilient, and carbon-free resources is daunting. In May 2021, the International Energy Agency presented its roadmap for providing stable and affordable energy supplies that might produce net-zero carbon emissions by 2050. The study states: “in 2050, almost half the [emission] reductions come from technologies that are currently only at the demonstration or prototype phase. This demands that governments quickly increase and reprioritize their spending on research and development – as well as on demonstrating and deploying clean energy technologies – putting them at the core of energy and climate policy.”[1] The report indicates the need for dispatchable generation technologies to provide reliability and grid security. However, implementing the IEA roadmap by 2030 would also likely result in the global loss of 5 million jobs in the fossil fuel sector with nearly half of the losses in oil and gas and the rest in coal.[2]

The benefits of deploying renewable geothermal energy technologies are finally being recognized, because baseload geothermal power can also be dispatchable and has many essential attributes.[3] These attributes include round-the-clock reliability, fuel-security, carbon-free emissions, and low operating costs. Future plants will take advantage of recent advances in drilling and AI. Importantly, geothermal technologies have lower life-cycle environmental costs and complement non-dispatchable, intermittent solar and wind resources.[4] Resources for the Future (RFF) has projected considerable benefits from U.S. Research, Development & Demonstration (RD&D) spending to develop and implement advanced technologies, including advanced geothermal energy systems. Projected ranges of levelized costs and benefit-to-cost ratios are shown in Figures 1 and 2.[5]

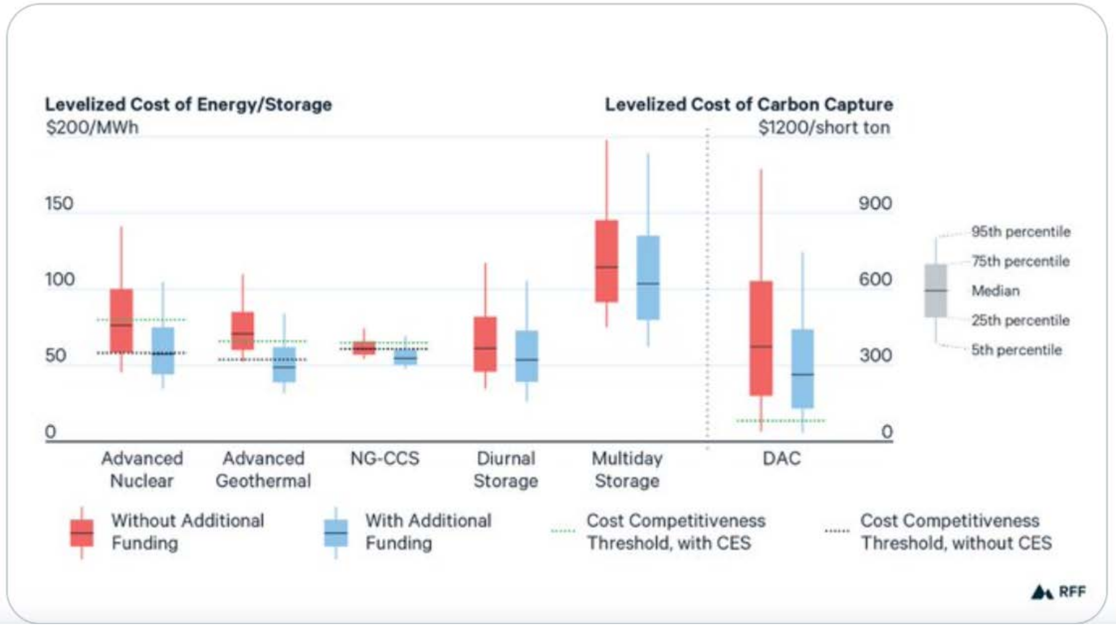

Figure 1 Levelized Cost Ranges in 2031 With and Without U.S. RD&D Funding from 2022-2031 – Resources for the Future, “The Value of Advanced Energy Funding: Projected Effects of Proposed US Funding for Advanced Energy Technologies, April 2021. (NG-CCS: Natural Gas-fired Generation with Carbon Capture & Sequestration, DAC: direct from-air capture of CO2, CES: a national clean electricity standard that requires 94 percent clean power by 2050.)

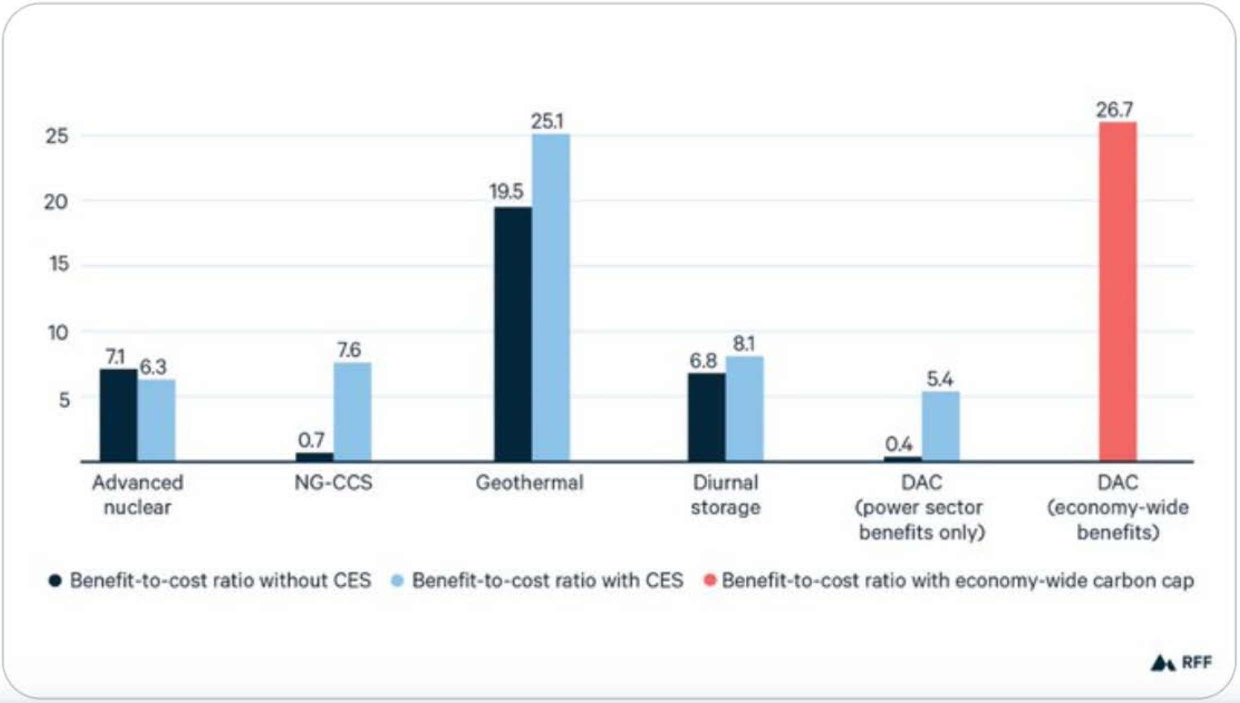

Figure 2 Estimated Benefit-to-Cost Ratios from 10 Years of U.S. RD&D Funding (2022-2031) – (NG-CCS: Natural Gas-fired Generation with Carbon Capture & Sequestration, DAC: direct-from-air capture of CO2, CES: a national clean electricity standard that requires 94 percent clean power by 2050.) RFF, April 2021.

Innovative geothermal technologies are now under development, including Enhanced Geothermal Systems (EGS) and Closed-Loop Geothermal (CLG) technologies.[6,7,8,9,10] A Princeton study points out that unless sufficient firm, dispatchable baseload power generation resources are added, the future electricity grid is likely to be riskier and less sustainable.[11] Even today, geothermal power is more cost-competitive than solar and wind combined with storage,[12] but as illustrated above, geothermal technologies would benefit significantly from focused RD&D. Because geothermal power technologies use the earth as their inexhaustible battery and have typical availabilities over 90% (while non-dispatchable solar and wind have usual availabilities below 35%), building more geothermal plants will not only help balance the grid and add resource diversity, but also provide more value per MWh delivered.[13]

The history of our electricity grid and the changing paradigms that guided its growth exemplify the difficulty of achieving the future milestones in the IEA roadmap or implementing a more practical, comprehensive and coherent strategy like that detailed in Modernizing America's Electricity Infrastructure.[14] Indeed, the formidable challenges of the “energy transition” are described in the 2021 J.P. Morgan study[15] and in articles in The Economist that describe “bottlenecks in supply chains, site approvals and finance.”[16]

The following sections of this paper summarize events that affected the evolution of the U.S. electricity grid during the last 70 years, using California as one example. We then present prior R&D funding data for energy technologies and describe specific research areas needed to develop and demonstrate advanced geothermal technologies to gain benefits beyond those of current renewables.[17]

2. The Evolution of Technology and U.S. Electricity Markets

As technologies and regulations for generating, delivering, and consuming electric power change, the evolution of the electricity grid in the United States presents an interesting story and lessons to guide future planning. Changes in the electricity grid have been driven by advanced technologies that promised to satisfy grid reliability standards and meet environmental regulations at lower costs. Performance improved, and capital costs come down significantly by research and from "learning-by-doing." While a major paradigm shift in the provision of our electric services is now underway, it is not the first. For this review, we start in the 1950s.

Following World War II, the United States became the world's premier industrial power. In doing so, it became dependent on ever-increasing amounts of electricity. The large-scale hydroelectric systems developed in the 1930s required new high voltage transmission lines to serve expanding urban and suburban loads. Large-scale coal, natural gas and oil-fired central generating facilities were built near fuel resources to minimize generating costs. These were followed by the cold war development of the Atoms for Peace Program, launched by President Eisenhower in 1953 to develop a civilian nuclear power industry. Nuclear plants tended to be exceptionally large and operate as baseload resources, generating a consistent level of power, 24/7. Dispatchable fossil-fueled plants that could more easily vary output were ramped up in the morning and down at night in response to changing demand. During the highest demand hours, inexpensive but inefficient, peaking units served peak loads. To account for regional load variations and enhance reliability, and in response to the Northeast Blackout of 1965, separate utility systems were interconnected and in 1967, integrated into a single interconnected network throughout the continental United States.[18] Problems with oscillations, intermittent exchanges, and other instabilities plagued these interconnects until the four east-west interties were permanently opened in 1975, splitting the U.S. grid into the Eastern and Western Interconnections now in operation,[19] plus the largely independent Texas grid.[20] Since 1975, HVDC links have been used to transfer energy between the East and West Interconnects.

As nuclear plant designs were modified to meet safety requirements, nuclear plants grew prohibitively expensive and took years to build. However, they became more reliable and were emission free. Coal power plants grew in size and efficiency with continued growth in coal generation from the 1970s to about 2007. Yearly coal-fired capacity additions fell after 1980, due to increasingly stringent EPA regulations requiring pollution controls. Significant growth in natural gas-fired generation started with the development of more efficient combustion turbines, leading to natural gas combined-cycle (NGCC) additions during the 1990s. A drop in natural gas prices in 2008 and the advent of fracking has led to the ongoing replacement of coal by natural gas, due primarily to lower-priced gas. By 2018, NGCC plants (264 GW) surpassed the capacity of utility coal plants (243 GW). Over the last ten years the rapid growth in solar and wind in key regions has encouraged the retirements of both coal and nuclear plants.

Along with technology advancements, market events and regulatory requirements have impacted the electricity grid. A major event was the OPEC energy embargo of 1973, which led to the

Energy Supply and Environmental Coordination Act of 1974. The ESECA included provisions prohibiting the use of oil or natural gas by electric utilities that could use coal and required that new fossil-fueled power plants be able to use coal, a domestic resource not subject to embargo. Natural gas price controls implemented in the 1970s reduced exploration and raised concerns about potentially running out of natural gas. The Natural Gas Policy Act of 1978, phased out natural gas wellhead price controls and led to the deregulation of the natural gas industry in the 1980s, paving the way for abundant, low-priced natural gas supplies to power modern combined cycle power plants that replaced coal-fired capacity.

The Public Utility Regulatory Policies Act of 1978 (PURPA) enabled independent power production projects for Qualifying Facilities (QFs). It required state regulators to develop avoided cost energy and capacity prices to compensate non-utility cogeneration and small power plants generating with renewable resources. California developed Standard Offer contracts for QFs and wind farms. Options included long-term (up to 30-year) fixed price contracts for small power plants. Prices could be based on long-term forecasts of avoided costs that projected high natural gas and oil prices like those experienced prior to natural gas deregulation in the mid-1980s. California's higher-priced contracts and wind farms of the early 1980s jump-started today's global wind industry. In addition, EPA's New Source Performance Standards were revised in 1979, necessitating Flue Gas Desulfurization for coal-fired plants. The 1990 Clean Air Amendments initiated the national SO_2 cap-and-trade (C&T) market in 1995, lowering emissions cost-effectively and significantly reducing acid rain.[21] The U.S. SO_2 market has served as the model for greenhouse gases (GHG) cap-and-trade markets now operating in over 35 countries. Increasing electricity prices and technology advances led to electricity "deregulation" in the mid-1990s. This restructuring brought about significant changes in grid operations, wholesale and retail pricing, regulatory oversight, and the ownership of assets. Today, concerns about global warming have led to the rapid growth of renewable technologies and the current "energy transition."

3. California: A Leading Example

3.1 Technologies & Policies That Changed the Generation Resource Mix and Grid Reliability

By the mid-1990s, natural gas deregulation had decoupled natural gas prices from oil prices. Thanks to lower exploration and production costs dramatically lower gas prices resulted. However, regulated utilities, particularly in California, had made earlier procurement and construction decisions based on high price forecasts. Nuclear construction costs and QF contracts produced significantly higher rates, which impacted the competitiveness of California industry. Hence, there was pressure to "deregulate" the electricity industry to reduce costs, particularly to large energy consumers. AB 1890, the Electric Utility Industry Restructuring Act, was adopted in 1996. It established a new market structure starting in 1998 that "unbundled" electric utility rates by separating generation related costs from the costs of transmission and distribution, implemented Direct Access services for IOU customers and created the California Independent System Operator (CAISO) to operate the utility-owned transmission grid and a Power Exchange (PX) to regulate an hourly spot market for electricity supply. It froze electric rates in anticipation of wholesale power cost reductions creating sufficient headroom to pay off the stranded costs of the utilities' generation portfolios by early 2002. The PX forced transactions into the Day-Ahead market to achieve “transparency” and mitigate market power, while the California Public Utilities Commission (CPUC) required IOU divestiture of fossil power plants and eliminated long-term contracts with out-of-state suppliers.

Unfortunately, the plan was disrupted in 2000, when a combination of reduced hydro supplies from the Northwest, market design flaws and market manipulation created the 2000-2001 “energy crisis.” PG&E went into bankruptcy; the state of California went into the power procurement business, and Governor Gray Davis was recalled. This crisis sparked the development of the renewable portfolio standard in 2002 (SB 1078, Sher[22]). Further paradigm shifting legislation, AB 32, The Global Warming Solutions Act of 2006, was passed to reduce emissions of greenhouse gases and initiate the “transition to a sustainable, low-carbon future.”[23] It provided the framework for California’s successful economy-wide cap-and-trade program that started in 2015 and now extends to 2030. The annual cap is lowered each year, reducing the number of California carbon allowances (CCAs) available. CCAs are required to be “retired” based on actual emissions, thus increasing the price of CCAs.

AB 32 has affected technology choices, the capacity mix and the operations and reliability of the western electricity grid. Another paradigm changing program, The California Solar Initiative, ran from 2007-2016. By 2020 CSI incentivized the installation of over 9,600 MW of customer-sited solar generation in the state.[24] The Renewable Portfolio Standard (RPS) program currently requires renewable generation to provide 50 percent of retail electric sales in California by 2030, exclusive of customer-sited generation. According to the California Energy Commission (CEC),[25] by 2020 over 15,000 MW of utility-scale solar generation was operational in California, producing over 33,710 GWh. To meet RPS requirements, the CPUC anticipates adding another 13,000 MW of solar by 2031[26] along with over 9,000 MW of battery storage.

These events have redefined the need for more resilient, low carbon emitting resources capable of serving customer load reliably under foreseeable conditions, including “worst case risk” scenarios that have not yet been properly analyzed. In recent years the operative paradigm has shifted the peak load period, when the costliest peaking generation operates, from noon to 6 pm on summer weekdays to 4 pm to 9 pm. Early afternoon from April through June has become the “super-off-peak” period when excess solar generation that cannot be sent to recharge batteries yet to be installed, must be curtailed to avoid over-supplying the grid. After the sun sets, storage is expected to be available to discharge when the actual evening net peak period requires all available resources. However, because battery energy storage systems (BESS) are unable to generate electricity without being charged by the expected solar generation, an extended reduction in solar output due to multi-day overcast, smoke or some other events like a widespread volcanic eruption that obscures the sun for days or weeks, could wreak havoc on the electrical system. Therefore, adding reliable, resilient alternative resources that are not dependent on weather conditions is essential.

Clearly, California faces many challenges to reduce GHG, while maintaining Resource Adequacy and grid reliability, especially when 2,200 MW Diablo Canyon (the last nuclear plant in California) retires by 2025, 3,700 MW of gas-fired capacity is retired and essential hydro generation is lost due to drought.[27, 28] Many factors must be evaluated in light of growing demand. These include wholesale and retail rate design, modifications to planning reserve margins and capacity accounting, changes in resource availability, and regional grid integration throughout the west. A CPUC proceeding notes that a major cause of changes is “the increasing prominence of variable and dispatch-limited resources on the grid and the growth of behind-the-meter resources."[29] An unprecedented 11,500 MW of new resources has been proposed to be procured by 2026 to meet afternoon and early evening ramps.[30]

The CAISO "duck curve" shows net loads for a typical spring day each year from 2012 to 2020.[31] Net loads are the load remaining after wind and solar generation is operated. This is the load served by dispatchable power plants. As shown in Figure 3, the size and duration of the afternoon ramps, when the sun sets, has increased over the past eight years, demonstrating the increasing magnitude of CAISO's foreseeable problems.

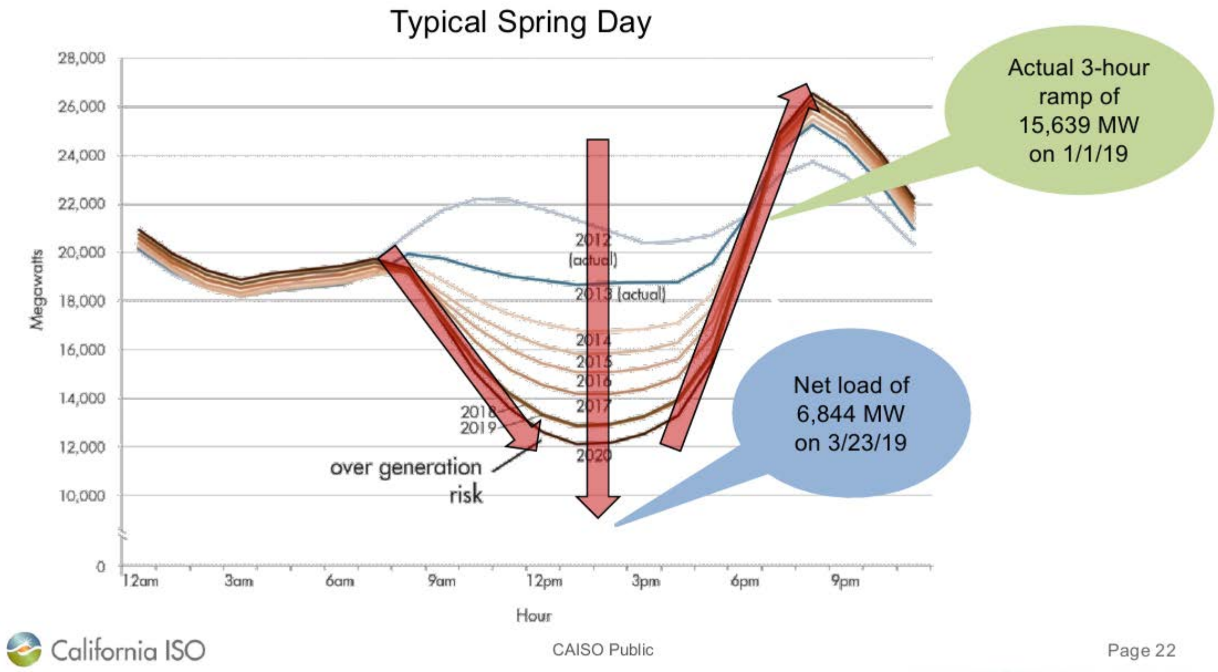

Figure 3. CAISO Hourly Net Loads After Solar and Wind Supplies (2012-2020) – April 2019

3.2. Geothermal Projects Could Have Mitigated Recent Blackouts

In August 2020, the consequences of planning without comprehensive, worst-case risk assessments and of making short-term, "least-cost" decisions were manifest by rolling outages in California. Later, in February 2021, disastrous multi-day blackouts occurred in Texas. Fortunately, the rotating outages in California lasted only several hours and were appropriately managed, but the multi-day blackouts in Texas were not. Both of these blackouts were the unintended consequences of prior policies, incomplete risk assessments and decisions.

In Texas Maria Richards of Southern Methodist University observed:

> "During the 1970s and '80s, geothermal resources along the Gulf Coast were catalogued and proven extractable. Then initiatives to put geothermal energy to work were shelved when oil prices crashed, delaying diversification… With one of the smallest surface footprints for power sources, geothermal projects are less likely to be disrupted in storms.

> Geothermal production overlaps and complements other energy supplies. For example, existing hydrocarbon wells can become "geothermal batteries" for energy storage when combined with large-scale solar. The excess heat is kept hot while stored underground in paired geothermal plants, then extracted as needed to meet peak demands for power. This means multiple benefits; local employment is maintained, and energy security is guaranteed. Before another state leads, Texas oil and gas fields are an ideal place to demonstrate proof-of-concept, improve the geothermal battery design and capitalize on the product for long-term benefit.
>
> Other opportunities exist for our energy grid to be more resilient by using geothermal heat to increase baseload capacity. Just as there are a wide range of well depths and flow rates, geothermal applications also vary.
>
> Alternative thermal energy opportunities could start from small-scale, on-site power generation from existing lower-temperature oil or gas wells. These wells, with temperatures commonly in excess of 250 degrees (F), might otherwise be shut-in or abandoned. More ambitiously, large-scale wide diameter, deep wells (10,000-plus feet) are capable of producing megawatts of geothermal electricity for our rural communities and reducing transmission loss.”[32]

Geothermal power could have served Texas quite well had it been developed to diversify its energy resource mix. Even more evidently, if California, which has 51 geothermal power plants, had increased its electric system diversity and reliability by adding more geothermal plants, it could have avoided 2020’s outages and kept the lights on.[33]

4. Expanded Research & Development Is Needed to Improve EGS and CLG Geothermal Technologies

4.1 Investment in Geothermal Energy Has Been Low

In the USA DOE support for energy technologies reveals a bias towards oil and gas, nuclear and biomass. Figure 4 shows that investment in geothermal energy remains low.

Figure 4. Cumulative investments by DOE in geothermal and various energy technologies. Olsen (2020).

Recent studies indicate that energy and power companies have shied away from geothermal exploration and development, because of perceived exploration and appraisal risks, combined with the initial cost of geothermal projects and long lead times for permitting.[34] Lack of geothermal development and investment has led geothermal energy to be called "the forgotten renewable.[35]" If the last 10 years are examined, geothermal has received only a tiny fraction of research dollars compared to onshore and offshore wind and solar PV. In 2020, the global renewable energy industry received investments representing about $303.5 billion. The following industries received the lion's share of the investments: solar, $148.6 billion, wind $142.7 billion; biomass and waste-to-energy capacity attracted $10 billion, storage technologies attracted $3.6 billion, green hydrogen $1.5 billion and CCUS $3 billion.[36] To put this into perspective, from 2010 to 2020, a total of only $40 billion was invested globally in new geothermal energy projects,[37] several orders of magnitude lower than invested in wind and solar technologies.

What does RD&D investment accomplish? Studies reveal that wind and solar have achieved significant benefits in cost, performance, and efficiency as a result of aggressive policies supporting these technologies. The rate of learning has been significant. Historically biomass, natural gas, wind and solar have all shown large improvements in their power generating costs and efficiencies brought about by R&D and learning-by-doing.[38] Indeed, major advancements in electric power technologies have contributed to changes in the capacity mix and to the evolving nature of the electricity grid, as discussed above. Yet not all energy technologies will achieve similar rates of learning, and rates of improvement eventually diminish.

Over the last 10 years, geothermal R&D investments supported by DOE have focused on conventional geothermal and EGS research and development. The FORGE project is a Department of Energy (DOE) program to conduct EGS tests at a site run by the University of Utah in Milford, Utah.[39] Historically EGS has received much more research funding than CLG, which has only emerged as a technological advancement since 2019, after successful tests by GreenFire Energy, a California company, and Eavor Technologies, headquartered in Alberta, Canada.[40] Thus far, CLG has received very limited public research dollars.[41]

Both EGS and CLG have great potential to expand the accessible geothermal resource base, since each has fewer physical requirements than conventional geothermal. Both have smaller land footprints and lower environmental impacts than wind and solar. Specifically, conventional geothermal technologies require the co-location of permeability, heat and water/flowing geofluids. However, EGS applies geothermal fracking methods (different from oil & gas techniques) to create and/or maintain geofluid flow. Unlike EGS, CLG circulates a project-specific working fluid in sealed pipes, doesn't require fracking, won't induce seismicity, doesn't remove geofluids, reduces corrosion, enables earlier surface equipment design, and consumes less water. Major advances are anticipated in the next 5-10 years for geothermal applications, if sufficient funding is provided, and if siting and permitting requirements are accelerated.[42]

4.2 Areas for RD&D Funding

Sustained RD&D in several areas could significantly reduce geothermal energy's capital and operating costs. Research can expand the accessibility and lifetimes of geothermal resources, reduce the time to permit and build, reduce drilling and exploration risks, increase scalability, develop innovative well and pipe configurations, and bring down costs. FORGE field scale development will facilitate drilling advances. CLG retrofits will provide immediate growth at competitive costs. Both EGS and CLG can produce economic power from areas with lower temperatures and/or low permeability.

Professor Eric van Oort of the University of Texas recommends research to improve “key well drilling and design parameters that will ultimately affect DCLGS [Deep Closed-Loop Geothermal Systems] operating efficiency, including strategic deployment of managed pressure drilling / operation (MPD/MPO) technology, the use of vacuum-insulated tubing (VIT), and the selection of the completion in the high-temperature rock formations. Results show that optimum design and execution can boost initial geothermal power generation [per borehole] to 25 MWthermal and beyond… A main conclusion is that DCLGS is a realistic and viable alternative to EGS, with effective mitigation of many of the (potentially show-stopping) downsides of EGS.”[43]

Advances can be made in many areas including:

- resource exploration and characterization,
- refinement of geothermal workflows and data integration,
- well drilling, monitoring and operation,
- heat transfer and thermodynamic modeling,
- downhole heat exchangers and electricity production,
- topside conversion of hot water/steam/brine/refrigerants into power.

The designers, manufacturers and service companies providing downhole components need RD&D funding to enable high-reliability functions to be performed throughout the geothermal well drilling process. Companies are working to develop better downhole tools, equipment and methods for drilling and completions. However, the geothermal market is quite small, so that large investments in time and dollars needed to improve drilling processes are difficult to fund without governmental or other large funding sources.

A few brief examples, including some to be presented at the upcoming Offshore Technology Conference 2021 in Houston, follow.[44]

4.2.1 Drilling Geothermal Wells

Drilling conventional geothermal wells requires significant pre-drill planning, design, thermal analyses, operational applications expertise, broad understanding and cooperation between the resource owner, geologist, drilling and completion engineers, metallurgical engineers, drilling contractor, cement/grout provider, and applicable service companies. Geothermal wells are complex and critical; their purpose is to capture as much subsurface reservoir heat as possible and deliver that thermal product to the surface wellhead outlet or downbore heat exchanger with limited heat loss. Certain drilling & completion techniques in high-temperature high-pressure (HTHP) oil & gas practice are now applied in geothermal drilling operations yet require significant modifications. RD&D employing new technologies will advance geothermal drilling and well completion and construction methods, develop better equipment and optimized work flows, along with resultant cost reductions.

Key areas of research should focus on the very high temperatures and hard rock encountered when drilling different geothermal formations. These include utilization of preferred large borehole sizes to deeper total depths. For reference comparisons, oil & gas wells have been drilled, completed, and produced with bottom hole temperatures up to 450 deg F (282 deg C) at vertical depths beyond 30,000 ft. (9,150 m), but borehole sizes under those conditions are typically 7-inch (18 cm) diameter or smaller. Where deep geothermal wells may have bottom hole temperatures over 600 deg F (315 deg C) or double that, depending upon the thermal resource at 17,000 ft. (5,200) m vertical depth, borehole sizes would preferably be 10-inch (25 cm) diameter or larger. Drill bit and drilling bottom hole assembly designs that can withstand high geothermal heat and avoid vibrations in hard rock need further development. Bottom hole drilling assemblies include downhole motors that use the energy of circulated drilling mud to turn the drill bit, as well as to transmit mud pulse telemetry of downhole measurements to the surface. Today's sensors, electronic components, and hardware in the bottom hole assemblies are not robust enough to provide longevity under severe high temperature geothermal conditions greater than about 220 deg C.

As previously stated, oilfield drilling techniques, such as MPD/MPO are necessary, yet with modifications that utilize high-temperature equipment and rotating control devices (RCDs), newly developed high-temperature mud return measurement systems, influx management envelopes (IMEs) and matrices for geothermal well efficiencies that can mitigate non-productive drilling time. Completion techniques that maximize thermal heat transfer from the reservoir rock into the downhole wellbore, such as formation stimulation and cement/grout formulation and placement, are analogous to, yet not the same as, oil & gas methods. Drilling analytics that analyze real time data are pivotal to estimate well performance. Funding these critical developments is essential to make deeper and hotter geothermal resources widely available.

4.2.2 Resource Exploration

Geological and geophysical (G&G) exploration of subsurface resources have focused on finding basins, rock types, and traps that are sources and reservoirs for oil & gas. Tremendous advancements have been made in 2D and 3D subsurface imaging, including imaging in offshore deep waters under thick salt formations. As G&G data gathering and interpretation capabilities improved rapidly during the past 20 years, legacy oil & gas fields that were previously considered depleted beyond their economic life have been revived by finding new reservoirs below what earlier G&G technologies could see. To date the geothermal industry has not expanded by developing similarly situated new, larger geothermal resources. This is partially because G&G technologies that explore and describe undiscovered deep subsurface formations that contain extensive reservoirs of extractable heat are not yet available to the geothermal industry.

Earlier well and drilling reports often did not record what the bottom hole temperatures were. Now, there are good records for recent HTHP oil & gas wells in the U.S., especially in the north, coastal and south Texas regions, along the Gulf Coast of Louisiana, and in Mississippi. In U.S. western states, such as California, Nevada, Utah, and certain hot spots in Alaska and Washington, known geothermal field resources have been identified. However, even in these states, geothermal exploration has not been routine nor have new G&G techniques been employed. The U.S. Geological Society (USGS) and academic institutions, such as the Southern Methodist University Geothermal Laboratory (SMU), the University of Texas Bureau of Economic Geology (UT), and Cornell University have compiled subsurface 'heat maps' across the country at various depths. Yet, these maps do not accurately extend to the deep subsurface depths that drilling can achieve today. Additional U.S. G&G research into seismic interpretation will help increase our understanding of deeper basins and provide impetus to drill more exploratory geothermal wells that are needed to ascertain bottom hole temperatures at much deeper depths and at the same time to examine the rock properties that determine the thermal transitivity in future geothermal fields.

Globally, existing and new geothermal development sites focus on known subsurface thermal hot spots. These include Pacific "ring of fire" countries, including Indonesia, The Philippines, New Zealand, Japan and China. Tectonic plate rift zones and areas of volcanic activity, such as Iceland, Italy, Mexico, Colombia, Nevis & Caribbean countries, eastern Europe, south Asia, east & southern Africa, Argentina, Chile, and other locales are now being investigated. Similar to the U.S., known oil & gas high temperature fields are being considered for geothermal re-development and expansion using closed-loop and other advanced technologies. Targeted RD&D in G&G techniques will advance the industry by reducing geologic exploration and production risks, especially when coupled with the exploratory drilling of new geothermal wells.

4.2.3 Expanded Power Generation from Steam Dominated Resources, 2-Phase Reservoirs, and Hot Dry Rock Systems

Steam dominated resources and 2-phase reservoirs are found in the major legacy geothermal production fields producing today. These include geothermal fields where subsurface natural water sources flow into or are partially or directly converted to steam by formation heat. Natural water sources may also be supplemented by wastewater pumped down into these geothermal reservoirs. However, many legacy steam dominated geothermal wells are shut-in and not producing largely due to water depletion. In addition, production from steam dominated and 2-phase wells in resources using conventional geothermal systems typically degrades production from other wells in the resource and decreases the resource as a whole by removing vast quantities of water, thereby reducing resource pressure.[45] Closed-loop geothermal energy systems designed using advanced thermodynamic analyses can be applied to individual legacy geothermal wells and to the portions of those fields with depleted steam resources in order to restore production and reduce resource degradation.[46] Other applications of CLG retrofit technology include idle wells working at a lower pressure than the existing surface expander conditions, slugging flow regimen wells, wells that partially condense in the casing section, wells with casing failures or damage, and wells that have feedzone competition.

For steam-dominated and 2-phase reservoirs, downbore heat extraction uses the latent heat of vaporization mechanism directly at the feedzone level. By controlling and injecting the optimal CLG working flow rate, the feedzone temperature and pressure are reduced. This increases power production because the downbore pressure is inversely proportional to the feedzone productivity index and flow rate. The thermal heat recovered by downbore closed-loop systems can be converted to electrical power by using different surface systems: e.g., conventional steam expansion at the existing turbine conditions or binary Organic Rankine Cycles (ORC).

Additional RD&D funding could analyze the geothermal base resource size with new G&G technology for hot, dry rock systems, perform advanced thermal analyses for extracting the heat in downbore heat exchangers, or other methods to transfer heat to the surface. Field expansions could apply newly developed geothermal drilling and completion methods, advanced equipment, and updated operational methods to produce power economically without resource degradation.

Invariably, a techno-economical analysis of closed-loop geothermal systems is required for each case (retrofit or new purpose-drilled well). Some of the techno-economic choices for an optimal downbore CLG system are: the appropriate downbore working fluid, the proper size of equipment to remove heat but not water mass from the resource, the optimal materials of the equipment, and the correct approach for the heat transfer mechanism. Future goals in CLG design are to optimize a system that can achieve a comparable transfer of subsurface heat without depleting the geothermal resource, to retrofit idle conventional geothermal wells, and to produce power from hot, dry rock systems, as well as providing the other practical benefits of conventional geothermal energy.

CONCLUSIONS

Long-lived electricity technologies have advanced across the decades via innovations spurred by research and by learning-by-doing. Technology advances have been encouraged by market design, just and reasonable rates, energy and environmental policies and appropriate regulations. In each era, decisions governing electricity system capacity additions have generally selected the most cost-effective technologies to satisfy grid power needs while ensuring a diverse, robust, reliable, and weather-resilient capacity mix under likely future conditions.

In contrast, the rapid pace of change forced by climate imperatives, differences in user requirements, and more potential technology options complicates decisions about future energy portfolios. The global energy transition necessitates large changes in the mix of technologies for electric power generation and delivery, which will reduce GHG emissions and other pollutants by retiring many fossil-fired plants. Consequently, renewable but intermittent, non-dispatchable solar and wind power plants with availabilities under 35% are rapidly replacing coal and natural gas.

However, this transition is simultaneously decreasing reliability in the power grid. Unless substantial capacity additions include corresponding efforts to properly analyze and adjust the capacity mix, there will be more outages and blackout situations like those in California in August 2020, and in Texas in February 2021. These failures underscore the critical importance of balancing energy portfolios to ensure reliable and resilient grid operations despite adverse weather conditions and other foreseeable risks.

Considerable investment has been focused on improving batteries and other energy storage systems. However, despite impressive advances in performance and cost, batteries still fall well short of providing a cost-effective grid-balancing function. Adding unproven energy storage technologies with limited duration and unknown lifecycle impacts to provide essential reliability may be palliative in the short run but more costly in the long run.

There is no need to risk grid instability by relying on unproven technologies. Instead, there is a fuel secure, 24/7 reliable, carbon-free renewable resource that has a proven history and operates with availabilities over 85%: geothermal energy. Geothermal energy systems provide clean, resilient, cost-competitive, and stable energy resources that complement other renewable power resources.[47,48] However, to fully utilize their enormous potential, sufficient RD&D efforts must be funded and carried out to enable deeper and hotter resources to be used.[49] For example, improvements in drilling technologies and heat-to-power conversion will make emerging geothermal technologies like Closed-Loop Geothermal (CLG) cost-effective for heat or power utilization in wells in a variety of resources, for retrofit of idle conventional geothermal wells and for applications in deep wells drilled in hot, dry rock. Similarly, more research is required for Enhanced Geothermal Systems (EGS) technology to become more capable across a broader range of global geothermal resources.

The USA remains the world's top geothermal producer.[50] To date, however, U.S. and worldwide geothermal energy investment has been significantly lower than for other energy technologies, despite geothermal technologies having more favorable lifecycle impacts. Now that the global energy transition is underway, making geothermal energy one of the cornerstones of our future energy supplies is not only wise, but imperative.

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