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Oil and Gas Technology and Geothermal Energy Development

January 31, 2023

Congressional Research Service
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SUMMARY

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January 31, 2023

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The U.S. energy industry is undergoing a decades-long transition that includes increased production of shale oil and natural gas, decreased reliance on coal-fired power plants, increased investment and deployment of renewable energy (RE) technologies, and disruptions in the international supply of traditional energy resources (for example, oil and gas). Geothermal energy—particularly enhanced geothermal systems (EGS)—though a relatively small part of the United States' current generation capacity, is expected to be one part of this transition. EGS use stimulation and hydraulic fracturing technologies, developed in the oil and gas (O&G) industry, to access geothermal resources not suitable for conventional hydrothermal energy production. EGS resources are only accessible through drilling technology, and the further development of EGS can potentially leverage some existing O&G assets, technologies, and workforce to contribute to U.S. energy needs and support the energy transition.

The O&G industry has operated for 170 years, during which various market forces and factors have resulted in idle or underutilized resources. These factors include boom and bust investment cycles contributing to and resulting from changing market conditions, the depletion or exhaustion of individual wells such that they are no longer economical to operate, and the decreasing costs of variable RE technologies.

O&G assets that are or could become idle or underutilized as a result of the ongoing energy transition and which could be used in geothermal applications include wells, power plants, drilling and support equipment, and workers. According to the U.S. Energy Information Administration (EIA), there are approximately 937,000 active wells in the United States, with about 20,000 new wells drilled each year. There were also about 3.7 million abandoned O&G wells in 2020, of which 41% were decommissioned and plugged, according to the Environmental Protection Agency. EIA notes that 67 coal and 62 natural gas plants (or parts of plants) are scheduled to retire through 2030. Though the O&G industry had around 2,000 operating drilling rigs in 2012, 768 were active as of October 2022. According to the Bureau of Labor Statistics, the industry had employment of 200,800 in October 2014, which declined to a projected 133,800 in September 2022. Some of these idle and underutilized assets, even if they are no longer viable for hydrocarbon production, could be reused or adapted for EGS energy development.

The geothermal power and O&G industries have co-developed, sharing similar technologies, knowledge bases, skill sets, and processes; thus, some of these could be directly employed in EGS development while others could be adapted with additional research, development, or retraining. EGS uses similar drilling and well completion technologies as O&G—though the equipment has to function under different operational conditions (for example, higher temperature and pressure). EGS also uses similar exploration technologies to find, estimate, test, and confirm geothermal resources. EGS stimulation technologies and processes are derived from O&G hydraulic fracturing technologies. EGS is developing tools and processes to manage reservoirs and geothermal resources over the long term, incorporating years of experience stimulating and operating O&G reservoirs. The EGS workforce uses skills and experience from O&G projects including resource exploration, drilling, well completion, and well and power plant operations, and it leverages relationships and understanding of financing and risk management related to underground resource development gained in the O&G industry.

The development of EGS faces a number of challenges. These include addressing potential environmental impacts—such as induced seismicity and the potential for environmental pollution, particularly ground water impacts—and addressing related permitting and regulatory requirements. EGS also has significant investment risks due to the costs of failed exploratory or production wells. EGS also produces relatively low-value product streams—heat and electricity—and under challenging operational conditions. These challenges result in geothermal power systems with relatively high capital costs compared to some other power technologies. A few commercial EGS plants have been built worldwide.

If expansion of EGS as an RE source is a goal, Congress could then consider a number of options that would effect the transfer and adaptation of O&G technology and assets to EGS applications. Considerations might include tax credits supporting redevelopment or reuse of O&G assets or that address the exploration and drilling challenges of EGS similarly to O&G. Congress could also examine and potentially address requirements for energy portfolio standards or carbon pricing that could incentivize expansion of EGS. Additionally, Congress could examine the approach to geothermal energy development on federal lands and the federal role in supporting state and local efforts to expand geothermal energy including the formulation of regulations and permitting processes. Given the potential to leverage some existing O&G industry resources, Congress could consider federal funding that supports the transition of idle or underutilized O&G assets to EGS applications.

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Introduction

Over the past several decades, the U.S. energy industry has been undergoing a transition. This transition includes increased production of shale oil and natural gas, decreased reliance on coal-fired power plants, increased investment and deployment of renewable energy (RE) technologies, and adjustments due to disruptions in the international supply of traditional energy resources (oil and gas) and the resulting changes in prices. Long-term considerations like decreasing technology costs or increasing environmental or security and resiliency considerations—spurred in part by climate change risks—have affected this transition. It is also affected by short-term considerations like supply chain disruptions—for example, related to the international COVID-19 pandemic or the Russian war against Ukraine.

An increase in geothermal energy production is one element of this evolving transition. Most geothermal power production comes from traditional hydrothermal technologies and provides 0.4% of current U.S. electricity capacity.[1] New technologies—including directional drilling and hydraulic fracturing—developed in the oil and gas (O&G) industry have enabled enhanced geothermal systems (EGS) with the potential for more widespread application than traditional hydrothermal technology. Though there are many challenges to greater deployment of EGS, including high capital costs, projections indicate that EGS could provide a significant portion of U.S. electricity generation in the future. This report examines what EGS technologies have been inherited from the O&G industry and where EGS could leverage existing O&G assets, technologies, and workforce as the U.S. energy industry continues its current transition.

What Is EGS?[2]

Geothermal technologies access heat resources from underground hot water and steam for either direct use or to generate electricity.[3] Conventional hydrothermal installations require sufficient naturally occurring subsurface water, gaps in the rock for fluid flow, and appropriate subsurface temperature. EGS use directional drilling and hydraulic fracturing technologies to access heat in reservoirs without sufficient water levels or rock porosity needed for conventional hydrothermal energy production. As of 2022, a few commercial EGS plants have been constructed worldwide.

Figure 1 diagrams the basic elements of a geothermal power system. Geothermal power captures heat from an underground reservoir using liquid (largely water but with other constituents), or naturally generated steam, under high pressure. The high-temperature liquid from the reservoir is converted into steam and passed through a turbine to generate electricity. Afterward, the steam is condensed back into liquid and reinjected into the ground with the goal to maintain the water level in the reservoir and capture more heat. This report will not go into the details of power plants and their operations beyond discussing where natural gas and geothermal plants have commonalities. Additionally, this report will generally focus on EGS technologies, but when geothermal is referenced it is inclusive of both conventional hydrothermal as well as EGS technologies.

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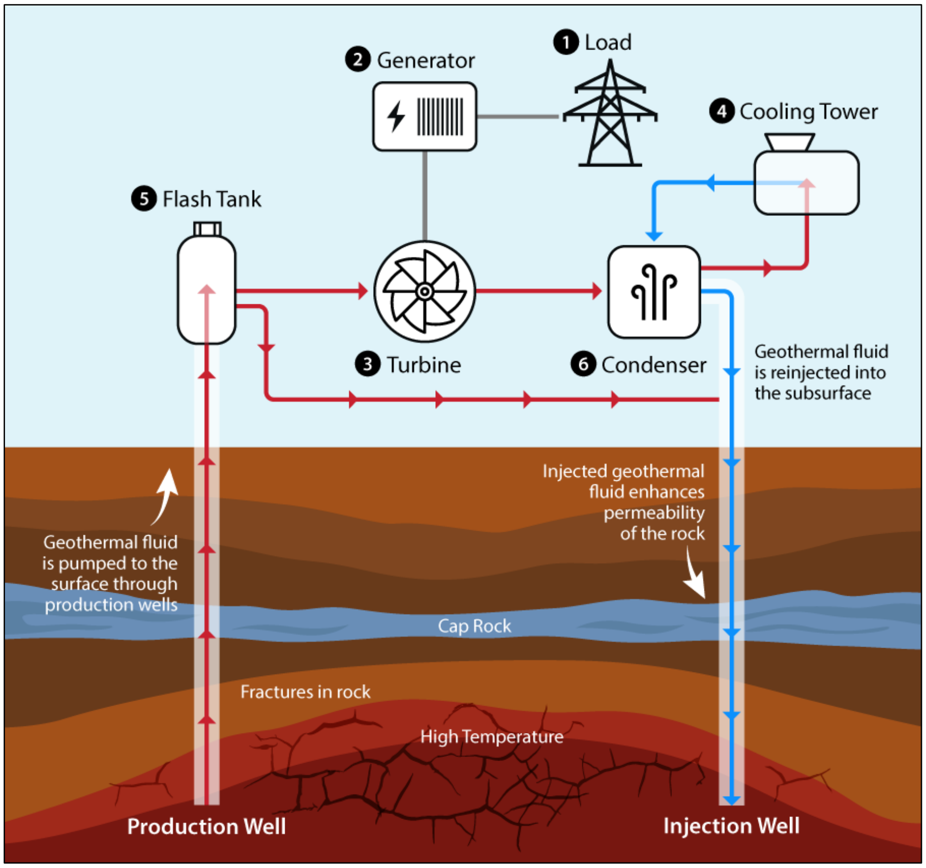
[1] U.S. Energy Information Administration, *Monthly Energy Review: May 2022*, 2022, https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

[2] For more information on EGS, see CRS Report R47256, *Enhanced Geothermal Systems: Introduction and Issues for Congress*, by Morgan Smith.

[3] Direct use generally uses resources from above ambient temperature up to about 150°C/300°F while electricity generation generally uses resources from 150°C/300°F to 375°C/700°F.

Figure 1. Diagram of the Basic Elements of a Geothermal Power System



Source: CRS publications.

Notes: Hot, high-pressure geothermal fluid is extracted through production wells. Depending on the reservoir conditions, the power plant can have a variety of equipment and configurations. In this example, the fluid is passed through a flash tank [5] which allows for conversion of some of the water into steam. The steam expands to drive a turbine [3] to run a generator [2] and the resulting electricity is transmitted to the grid to supply the load [1]. After the steam expands through the turbine, it is passed through a condenser [6] where it is cooled and condensed back to liquid through the use of heat exchange via a cooling tower [4]. The cooler and denser fluid is then typically pumped underground via an injection well; ideally the fluid is returned to the reservoir to a location where it can capture heat as it flows toward the production well to repeat the cycle.

Geothermal Power and the Oil and Gas Industry

Geothermal power relies on some of the same technologies and techniques used in the O&G industry including drilling and well-completion technologies and underground resource assessment technologies, and both share power plant technologies common to thermal power generation applications.[4] Additionally, EGS were developed using the technologies that have expanded U.S. shale oil and natural gas production. These technologies include directional drilling, hydraulic fracturing (fracking), and reservoir stimulation and management tools. Geothermal power development uses similar equipment as the O&G industry, and the workforce employs similar skill sets and knowledge base. This may present opportunities to redeploy O&G

[4] Thermal power generation converts heat into electricity, often using the steam cycle, and includes energy sources such as biomass, concentrating solar-thermal, geothermal, coal, natural gas, or nuclear.

industry assets to the geothermal power industry under the right circumstances. This section of the report will examine this possibility.

Factors Affecting O&G Asset Productivity and Use

A number of factors affect the O&G industry and can result in abandoned or underutilized resources, including wells, equipment, and workers.

One factor is the exhaustion or idling of wells or reservoirs. A typical O&G well might have an operational lifetime of 15 to 30 years,[5] while a particularly productive field might be active for 50 years or more.[6] Offshore wells, due to higher costs, might only be economically viable for 10 years.[7] After these wells' productive periods end, they can be idled, decommissioned, or become inactive or minimally productive.[8]

A second factor is that over the industry's 170 years of industrial development, O&G has experienced a history of boom and bust cycles.[9] Changing market conditions result in increases and slumps in investment and activity. In addition, the development of new and better drilling technologies (e.g., improved drill bits, directional drilling, and offshore drilling platforms) allows access to new resources (or reactivation of previously idled resources) and results in a boost in development and production. Both the boom and the bust periods can result in abandoned or idled resources—a boom period, for example based on the development of new technologies like directional drilling and hydraulic fracturing, can idle equipment and wells used to access older, marginally economic resources.

A third factor is the energy sector and energy markets transitioning away from some fossil fuels such as coal and natural gas and toward lower-carbon and domestically available energy sources.[10] More market participants (investors, governments, and customers) are prioritizing environmental, social, governance, reliability, and security factors in addition to traditional cost considerations.

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[5] While O&G wells can be productive over these timeframes, their productivity can drop off significantly after the first few years, especially shale wells. Canadian Association of Petroleum Producers, "Life Cycle of a Well," 2022, https://www.capp.ca/explore/life-cycle-of-a-well.

[6] Planete Energies, "The Life Cycle of Oil and Gas Fields," Planete-energies.com, August 11, 2015, https://www.planete-energies.com/en/medias/close/life-cycle-oil-and-gas-fields; Henrik Wachtmeister, Linnea Lund, Kjell Aleklett, and Mikael Höök, "Production Decline Curves of Tight Oil Wells in Eagle Ford Shale," *Natural Resources Research*, vol. 26, January 19, 2017, https://link.springer.com/article/10.1007/s11053-016-9323-2.

[7] Planete Energies, "The Life Cycle of Oil and Gas Fields," Planete-energies.com, August 11, 2015, https://www.planete-energies.com/en/medias/close/life-cycle-oil-and-gas-fields.

[8] Congress, in the Infrastructure Investment and Jobs Act of 2021 (P.L. 117-58), defined idle and orphaned wells for federal lands and projects. Idle wells are wells that have been non-operational for fewer than four years and have no anticipated future use. Orphan wells are inactive (not used for an authorized purpose such as production, injection, or monitoring), unplugged wells that have no owner/operator on record or whose operator cannot plug and reclaim the well site. Similarly, the U.S. Environmental Protection Agency and scientific literature often use the term "abandoned" to cover many wells including idle and orphaned wells in both plugged or unplugged states. States are generally the authority for projects outside of federal lands, and they individually define and apply these terms for their programs including when using federal grants for well remediation.

[9] Colorado School of Mines, "Boom and Bust: A Cycle Familiar to the Oil and Gas Industry," 2022, https://gradprograms.mines.edu/blog/boom-and-bust-a-cycle-familiar-to-the-oil-and-gas-industry/.

[10] S&P Global, "What Is Energy Transition?" February 24, 2020, https://www.spglobal.com/en/research-insights/articles/what-is-energy-transition.

A fourth factor is the decreasing cost of variable RE technologies—particularly solar photovoltaic (PV) and wind power. From 2010 to 2021, utility-scale solar PV systems decreased in cost by more than 80%,[11] down to a levelized cost of electricity (LCOE)[12] of about $36/MWh for fixed systems and $58/MWh for single-axis tracking systems.[13] Over that same time, onshore utility-scale wind power technologies decreased in cost by approximately 55%, down to $38/MWh.[14] These decreases were the result of increased operational efficiency (larger and more efficient wind turbines and higher efficiency solar energy conversion), lower cost manufacturing (due to investments in manufacturing capacity and new manufacturing technologies), and decreased costs for support systems (e.g., power electronics like inverters).[15] Studies expect these costs to continue to decrease with both solar and wind technologies potentially reaching $25/MWh by 2050.[16] As points of comparison, the LCOE for conventional hydrothermal systems in 2021 was $40/MWh and for combined-cycle natural gas was $37/MWh.[17]

Renewable, lower-carbon electricity generation will not likely displace or replace some markets currently served by oil and natural gas without additional, supporting technology developments. These markets include some liquid transportation fuels (e.g., heavy, long-distance trucking, aviation, and maritime shipping),[18] chemicals as industrial feedstocks, and industrial process heating. Technologies that could enable replacement include developments in energy storage technologies, biologically or electrochemically derived fuels or feedstocks, and electrically supplied process heating.[19]

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[11] National Renewable Energy Laboratory, "Documenting a Decade of Cost Declines for PV Systems: NREL Marks Ongoing Cost Reductions for Installed Photovoltaic Systems, While Also Establishing Benchmark of PV-Plus-Storage Systems," February 10, 2021, https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html.

[12] Levelized costs are total costs averaged over the total electricity production (in megawatt-hours (MWh)) for the lifetime of the plant.

[13] These costs do not include tax credits. U.S. Energy Information Administration, "Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022," March 2022, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[14] U.S. Energy Information Administration, "Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022," March 2022, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[15] Prior to these changes resulting in RE technologies being economically comparable to traditional electricity sources, governmental subsidies and mandates supported and created initial market demand for these technologies.

[16] U.S. Department of Energy, Wind Energy Technologies Office, "Experts Predict 50% Lower Wind Costs Than They Did in 2015," June 2, 2021, https://www.energy.gov/eere/wind/articles/experts-predict-50-lower-wind-costs-they-did-2015-0; Mark Bolinger, Ryan Wiser, and Eric O'Shaughnessy, "Levelized Cost-Based Learning Analysis of Utility-Scale Wind and Solar in the United States," iScience, vol. 25, issue 6, June 17, 2022, https://www.sciencedirect.com/science/article/pii/S2589004222006496.

[17] Commercialized EGS LCOE values are not available as there are few operational EGS plants in the world. For more details on costs, see "Geothermal Capacity and Costs." U.S. Energy Information Administration, *Annual Energy Outlook 2022*, 2022, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

[18] Samantha Gross, "The Challenge of Decarbonizing Heavy Transport," Brookings Institution, October 2020, https://www.brookings.edu/wp-content/uploads/2020/09/FP_20201001_challenge_of_decarbonizing_heavy_transport.pdf.

[19] National Renewable Energy Laboratory, "Transforming Energy Through Sustainable Mobility: Expanding Low-Carbon Transportation R&D Solutions," October, 2022, https://www.nrel.gov/docs/fy23osti/84377.pdf; Erik Ringle, "Beyond Fossil Carbon? Green Electricity Is Opening Doors to Low-Emission Alternatives for Making Fuels and Chemicals," National Renewable Energy Laboratory, February 23, 2022, https://www.nrel.gov/news/features/2022/beyond-fossil-carbon.html; Phil De Luna et al., "What Would It Take for Renewably Powered Electrosynthesis to Displace Petrochemical Processes?" *Science*, vol. 364, no. 6438, April 26, 2019, https://doi.org/10.1126/science.aav3506; Ali Hasanbeigi et al., "Electrifying U.S. Industry-Technology and Process-Based Approach to Decarbonization," January 27, 2021, https://www.globalefficiencyintel.com/electrifying-us-industry.

Using O&G Assets and Technologies in Geothermal Applications

One proposed direct way for geothermal power to leverage existing O&G assets and knowledge is through coproduction. The U.S. Department of Energy (DOE) has partnered with O&G and geothermal companies to pilot and demonstrate coproduction technologies and demonstrate feasibility at working O&G installations. Four pilot projects were initiated in 2022 including a Geothermix project on heat recovery from O&G fluids in Austin, TX; a geothermal energy harvesting project from the Elk Hills O&G field in Bakersfield, CA; a coproduction pilot in the Blackburn Oil Field in Nevada; and a coproduction project in the Oklahoma Sedimentary Basin in Norman, OK.[20]

Geothermal fluid (mostly water with other constituents) is often present in O&G sites and is extracted along with the hydrocarbons. Normally, the hot fluid has to be cooled and/or disposed of. But if it is present at sufficient pressure and temperature, this fluid can potentially be used for simultaneous power production—coproduction.[21] Coproduction can have advantages over standalone geothermal site development including that a production well has been completed, injection wells for stimulated oil or gas production may have been completed, and there may be existing data on both subsurface conditions and the extracted fluids' properties (both hydrocarbons and hot water). Coproduction of geothermal power alongside an active O&G well can improve the economics of the O&G operations, while providing onsite electricity and mitigating other costs. Coproduction can reduce on-site power costs, water handling and disposal costs, and emissions mitigation costs. However, coproduction faces challenges which limit its implementation—O&G injection and production wells are not usually designed with geothermal power in mind (e.g., geothermal wells are generally larger diameter), O&G production might be intermittent, and the water volumes or temperatures might be insufficient for power production.

A second way to leverage O&G assets is to reuse idled resources or adapt and transition currently underused resources for EGS applications. Though some O&G assets might not be economically viable for continued hydrocarbon production, they might have sufficient or greater value for geothermal energy production. These resources can include intangible assets such as leases[22] or tangible ones such as equipment or wells. Federal O&G leases can be converted into geothermal leases; the ability to convert state leases varies depending on state laws and can sometimes be challenging. A number of industry researchers as well as DOE's Geothermal Technologies Office have suggested that EGS could use resource exploration technologies, well drilling equipment including support equipment like down-well sensors, geophysical mapping tools, reservoir stimulation and management technologies, power plant systems, pipelines, idle wells, well right-of-ways, and offshore drilling platforms.[23] Reuse of these assets could provide additional value to

[20] U.S. Department of Energy, Geothermal Technologies Office, "Geothermal Energy Production with Co-produced and Geopressured Resources," July 2010, https://www1.eere.energy.gov/geothermal/pdfs/low_temp_copro_fs.pdf; Valerie King, "Oil and Gas Wells Prove Useful for Geothermal Energy Generation," TheDriller.com, October 1, 2016, https://www.thedriller.com/articles/90619-oil-and-gas-wells-prove-useful-for-geothermal-energy-generation.

[21] A related way to combine geothermal power and O&G production is through EGS combined with geopressured resources. Geopressured resources, for example methane, present within a geothermal reservoir can be extracted during operation of the geothermal plant for use as a fuel.

[22] For additional details, see "Issues for Congress."

[23] Emily Smejkal et al., "The Feasibility of Repurposing Oil and Gas Wells for Geothermal Applications," GeoConvention, June 20-22, 2022, https://geoconvention.com/wp-content/uploads/abstracts/2022/73300-the-feasibility-of-repurposing-oil-and-gas-wells-f-01.pdf; U.S. Department of Energy, Geothermal Technologies Office, "Wells of Opportunity: ReAmplify," January 12, 2022, https://www.energy.gov/eere/geothermal/wells-opportunity-reamplify; Allie Nelson, "Examining the Technological Overlap Between Oil, Gas and Geothermal," Renewable Energy World, October 5, 2016, https://www.renewableenergyworld.com/baseload/examining-the-technological-

the O&G industry during the ongoing energy transition and could support the development of geothermal power generation.

A third way to leverage O&G assets is via transitioning the workforce and support services to geothermal applications. The factors affecting the O&G industry, discussed above, sometimes result in job losses or the skilled and experienced workforce being underemployed—though many workers find other employment, those new positions might not use the full skill sets developed in the O&G work. Some advocates of geothermal energy have suggested that with some retraining or refocusing, geothermal projects could use O&G workers for their existing energy production skills and knowledge in areas such as underground resource identification, well drilling and completion, infrastructure installation, and power plant operations.[24] However, the potential for workforce transfer would be limited unless or until there is a significant scale-up of commercial EGS where the industry could then employ a large number of new workers. Regarding power plant operation, geothermal power requires similar numbers of workers as natural-gas-powered plants—unlike solar and wind generation. Additionally, the construction of geothermal power plants uses many of the same design, build, and commissioning or startup services as natural-gas-fueled plants. The power systems and power equipment are also similar, which means geothermal power can use much of the existing manufacturing and maintenance supply chains that support other thermal energy plants.[25]

O&G Assets Can Contribute to Geothermal Energy Development

The O&G industry has a variety of assets that, when idled or underutilized, could be applied to geothermal energy development. These include drilling equipment, wells, power plants, and drilling and well operation workforce.

Idle or Underutilized O&G Wells

As O&G wells require significant capital investment to develop, some have proposed reusing idle or underutilized wells (e.g., low-level operating wells) for geothermal energy development. The benefits of reusing idle or underutilized wells could include more revenue for the industry, additional low-carbon electricity for the nation, reduction of the wells' environmental impacts, and reduction of water handling and disposal costs and emissions mitigation costs at these well sites.

overlap-between-oil-gas-and-geothermal-2; George Lockett, "Geothermal Power: An Alternate Role for Redundant North Sea Platforms?" OffShore-Mag.com, March 7, 2018, https://www.offshore-mag.com/pipelines/article/16762144/geothermal-power-an-alternate-role-for-redundant-north-sea-platforms; NSEnergyBusiness.com, "Why the Oil and Gas Industry Should Expand into Geothermal Energy," August 5, 2021, https://www.nsenergybusiness.com/news/why-the-oil-and-gas-industry-should-expand-into-geothermal-energy/.

[24] Daniel Oberhaus and Caleb Watney, "Geothermal Everywhere: A New Path For American Renewable Energy Leadership," Innovation Frontier Project, November 29, 2021, https://innovationfrontier.org/geothermal-everywhere-a-new-path-for-american-renewable-energy-leadership/; Geothermal.org, "Don't Look Up, Look Down: How Oil & Gas Companies Can Survive the Energy Transition by Investing in Geothermal," June 17, 2022, https://geothermal.org/our-impact/blog/dont-look-look-down-how-oil-gas-companies-can-survive-energy-transition-investing.

[25] U.S. Department of Energy, "How a Geothermal Power Plant Works (Simple)," https://www.energy.gov/eere/geothermal/how-geothermal-power-plant-works-simple.

The feasibility of reusing O&G wells for geothermal power development is dependent on site-specific characteristics and general industry economics. The geothermal heat potential of the reservoir is a main requirement, but suitability will also likely depend on other factors such as hydrological or chemical characteristics of the reservoir, porosity and crack network conditions, and others. Additionally, O&G wells are not currently designed for geothermal applications—for example, geothermal wells tend to have larger diameters to move larger volumes of geothermal fluid—and the O&G reservoirs are not stimulated[26] and managed with the goal of sustained levels of output as EGS installations would be. Reused wells, in some instances, could be made more suitable by drilling additional injection wells or implementing stimulation procedures customized for those sites.

Despite the challenges to reuse, these O&G wells could have additional value potentially outweighing the negatives. Existing O&G sites have successful production wells already drilled and completed, injection wells for stimulation may exist, and there is likely existing data on both subsurface conditions (such as temperature profiles, rock properties like porosity, and seismic history) and fluid conditions (such as water volumes and other constituent properties)—all of which can reduce geothermal development costs and risks.

U.S. O&G producers continue to develop wells, some of which may become feasible for geothermal production. According to the U.S. Energy Information Administration (EIA), there were 936,934 active O&G wells in 2020, of which 483,326 were gas wells.[27] On average, about 20,000 new O&G wells are drilled each year in the United States (one analysis calculates 18,600 new wells expected for 2022).[28] These wells are generally operated at a low level or are decommissioned when they are exhausted or become economically non-viable.[29]

Some O&G wells may become orphan wells. The U.S. Environmental Protection Agency (EPA) estimated there were 3.7 million abandoned O&G wells in the United States in 2020, approximately 41% of which were decommissioned and plugged.[30] The Interstate Oil and Gas Compact Commission reported that out of the set of abandoned wells, there were 92,198 documented orphaned wells in the United States in 2020.[31] DOE has a grant program that supports plugging and remediating of abandoned or idle O&G wells.[32]

In general, idle or abandoned wells can be divided into two groups with different amounts of information known about them, potentially affecting their reusability. The first group, often called

[26] Stimulation is the injection of water at high pressure to break the subsurface rock to create the permeability (and sometimes pressurization) needed to access underground resources.

[27] U.S. Energy Information Administration, "The Distribution of U.S. Oil and Natural Gas Wells by Production Rate," January 2022, https://www.eia.gov/petroleum/wells/pdf/full_report.pdf; Environmental Defense Fund, "Documenting Orphan Wells Across the United States: Improperly Abandoned Wells Nationwide Are Leaking Methane, Air Toxics and Contaminate Groundwater—Now's the Time to Act," 2022, https://www.edf.org/orphanwellmap.

[28] Craig Fleming, "U.S. Drilling to Surge as Operators Prepare to Take Advantage of Higher Crude Prices," WorldOil.com, September 2022, https://www.worldoil.com/magazine/2022/september-2022/mid-year-forecast-review/u-s-drilling-to-surge-as-operators-prepare-to-take-advantage-of-higher-crude-prices/.

[29] Decommissioning involves assessing the well's condition and identifying any leaks, cleaning the wellbore, plugging the well, and then remediating the surface site.

[30] Of the 3.7 million wells, 3.0 million were oil wells and 0.7 million were gas wells. U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020," April 2022, p. 3-108, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf.

[31] Interstate Oil and Gas Compact Commission, "Idle and Orphan Oil and Gas Wells: State and Provincial Regulatory Strategies 2021," December 2021, p.2, https://iogcc.ok.gov/sites/g/files/gmc836/f/iogcc_idle_and_orphan_wells_2021_final_web.pdf.

[32] For more details, see "Issues for Congress".

"legacy" wells, includes those wells that were developed prior to state or federal requirements, and thus there may be limited information known including their exact locations and conditions. The second group includes more modern wells, idled or orphaned in the modern regulatory era, of which more information is known.[33] The availability of this data may make these wells more feasible for reuse in geothermal applications.

Idle or abandoned wells are not only unproductive, but may contribute to greenhouse gas emissions and are often costly to mitigate. Collectively, EPA estimates abandoned (and unplugged) wells emitted 276 kilotons of methane in 2020, equivalent to 6.9 million metric tons of carbon dioxide.[34] Estimates of decommissioning costs include a median cost of $20,000 to plug a well and $76,000 to plug it and remediate the surface—but costs vary based on the conditions of the well, including depth of the well and difficulty of the surface terrain.[35]

Retiring Power Plants

O&G plants can become economically non-viable to operate due to fuel price increases, the aging of plant infrastructure and equipment and related increases in maintenance costs, and changes in policy or market conditions that reduce the value of carbon-emitting power sources (including the reduced costs of alternative power sources). Nineteen coal plants (or parts of plants) with 12.6 gigawatts (GW) of generation capacity and 16 natural gas plants with 1.2 GW of generation capacity were scheduled to retire in 2022. Similarly, 67 coal and 62 natural gas plants (or parts of plants) are scheduled to retire through 2030.[36]

O&G power plant infrastructure and supporting equipment with remaining service lifetimes could be reused for geothermal energy development. This report will not cover retiring power plants and their equipment in much detail beyond noting the opportunity. These is no estimate of how many of these retiring power plants or how much of their equipment could be used for geothermal electricity production, but the potential exists.

One complicating factor is the location of these existing O&G plants. Because O&G resources, once extracted, can be transported to other locations for refining and/or combustion for electricity generation, O&G power plants can be located close to electricity demand. In contrast, geothermal plants are located at the site of the geothermal reservoir and the generated electricity is transmitted to end users. This potential mismatch between the locations of retiring O&G plants and geothermal power plants can potentially be mitigated in some cases by geothermal direct use projects and technologies supporting EGS. These technologies allow for geothermal development in wider geographic locations and thus closer to the electricity demand. This increases the potential that existing O&G installations and electricity demand might overlap with geothermal development potential.

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[33] Generally, a bond is required as a condition for the issuance of a permit to operate an oil or gas well. This bond is forfeited to the regulatory agency, if the operator does not complete the permit requirements including site reclamation. In cases where the bond value is not sufficient to complete site reclamation, the well operator often forfeits the bond, leaving the reclamation and the remainder of the reclamation costs to the agency.

[34] U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020," April 2022, p. 3-108, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf.

[35] Daniel Raimi et al., "Decommissioning Orphaned and Abandoned Oil and Gas Wells: New Estimates and Cost Drivers," *Environmental Science and Technology*, vol. 55, issue 15, July 14, 2021, https://pubs.acs.org/doi/10.1021/acs.est.1c02234.

[36] U.S. Energy Information Administration, "Coal Will Account for 85% of U.S. Electric Generating Capacity Retirements in 2022," January 11, 2022, https://www.eia.gov/todayinenergy/detail.php?id=50838.

Idle Drilling Rigs

Drilling rigs—used to drill and complete O&G wells—also experience fluctuations in use based on market conditions. Many of these idled rigs could be used to develop geothermal power projects.

In 2012, the number of rigs in operation for O&G drilling was almost 2,000. Since then, the number of active rigs decreased to around 700 in early 2020, then to a low around 200 in August 2020 in response to low oil prices and low demand due to the COVID-19 pandemic, and since then has increased to 768 as of October 2022.[37] Similar fluctuations in use have occurred in response to oil price fluctuations over the previous 15 years.

Eighty-one percent of new wells drilled in 2021 were hydraulically fractured and a majority of oil and natural gas produced comes from fractured wells.[38]

Geothermal energy development can directly reuse drilling rigs from O&G (and vice versa), but there are geothermal conditions and considerations where additional or different drilling equipment or alternative drilling and completion processes could improve the productivity of the operations.[39] The geothermal conditions include deeper well depths, harder rock conditions, higher-temperature operating conditions, and different well cementing requirements. The differences in equipment include taller rigs, harder drill bit materials, larger diameter drilling equipment, fluid cooling equipment, additional fluid pumping capacity, and materials or equipment capable of working with the elevated geothermal temperatures.

Decreasing O&G Employment

The total employment in the O&G industry has declined since 1982, and while many of these workers have found employment in other industries, geothermal energy development could benefit from experienced workers and could potentially use more of the same skill sets as O&G.

The number of employees in the O&G industries (as tracked via North American Industry Classification System (NAICS) code 211: Oil and Gas Extraction), was 267,000 in March 1982. Employment decreased to 200,800 in October 2014 (a local high in employment due to increased development of shale oil and natural gas) and to a projected 133,800 in September 2022.[40]

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[37] Jeff Della Rosa, "Most New Oil, Gas Wells Drilled Horizontally," Talk Business & Politics, April 22, 2022, https://talkbusiness.net/2022/04/most-new-oil-gas-wells-drilled-horizontally; Robert Rapier, "U.S. Oil Companies Have Increased Drilling by 60% in One Year," *Forbes*, March 27, 2022, https://www.forbes.com/sites/rrapier/2022/03/27/oil-companies-have-increased-drilling-by-60-in-one-year.

[38] Jeff Della Rosa, "Most New Oil, Gas Wells Drilled Horizontally," Talk Business & Politics, April 22, 2022, https://talkbusiness.net/2022/04/most-new-oil-gas-wells-drilled-horizontally; U.S. Energy Information Administration, "Today in Energy: Hydraulically Fractured Horizontal Wells Account for Most New Oil and Natural Gas Wells," January 30, 2018, https://www.eia.gov/todayinenergy/detail.php?id=34732; Tarika Powell, "Is Your 'Natural' Gas Actually Fracked?" Sightline Institute, October 17, 2017, https://www.sightline.org/2017/10/30/is-your-natural-gas-actually-fracked/; U.S. Energy Information Administration, "U.S. Crude Oil and Natural Gas Rotary Rigs in Operation," November 30, 2022, https://www.eia.gov/dnav/ng/hist/e_ertrr0_xr0_nus_cm.htm.

[39] P. Dumas, M. Antics, and P. Ungemach, "Report on Geothermal Drilling," European Geothermal Energy Council, GeoElec Project, March, 2013, http://www.geoelec.eu/wp-content/uploads/2011/09/D-3.3-GEOELEC-report-on-drilling.pdf; Linda Hsieh, "Geothermal Drilling Market Heats Up," DrillingContractor.org, September/October, 2008, http://www.drillingcontractor.org/dcpi/dc-septoct08/DC_Sept08_Geothermal.pdf.

[40] U.S. Bureau of Labor Statistics, "Oil and Gas Extraction: NAICS 211," October 26, 2022, https://www.bls.gov/iag/tgs/iag211.htm.

Table 1 organizes employment within O&G by occupation (based on U.S. Bureau of Labor Statistics categories)[41] into three groups—relative to skills and experience specifically applicable to the geothermal power sector. The largest group, with high-relevance, includes approximately 61% of total O&G employment. The second group of occupations, with moderate-relevance, includes Management Occupations (13%). This group includes general managers with relatively low relevance but also operations and constructions managers with direct relevance. The final group (25%) includes all other occupations with little direct geothermal power-relevant experience or skills required (though many of those jobs are still performed).

Table 1. O&G Employment by Occupation Grouped by Relevance to the Geothermal Power Sector

Occupation Group	Percent of Total Employment
High-Relevance Occupations	61%
Construction and Extraction (e.g., derrick operators, rotary driller operators, roustabouts, construction equipment operators, and construction laborers and managers)	20%
Transportation and Material Moving Occupations (e.g., truck drivers, equipment operators, but most of which are pumping station operators)	14%
Architecture and Engineering Occupations (e.g., surveyors, civil engineers, electrical engineers, environmental engineers, mechanical engineers, and petroleum engineers)	10%
Installation, Maintenance, and Repair Occupations (e.g., mechanics, technicians, and repair workers)	7%
Production Occupations (e.g., plant construction and operation)	6%
Life, Physical, and Social Science Occupations (e.g., physical, chemical, materials, environmental, hydrological, and geological scientists and technicians)	4%
Legal Occupations (e.g., lawyers, paralegals, and title examiners)	<1%
Moderate-Relevance Occupations	13%
Management Occupations (e.g., operations managers and construction managers)	13%
Low-Relevance Occupations	25%
All others including Business and Financial Operations Occupations, Office and Administrative Support Occupations, Computer and Mathematical Occupations, and Sales and Related Occupations	25%

Source: U.S. Bureau of Labor Statistics, 2021.

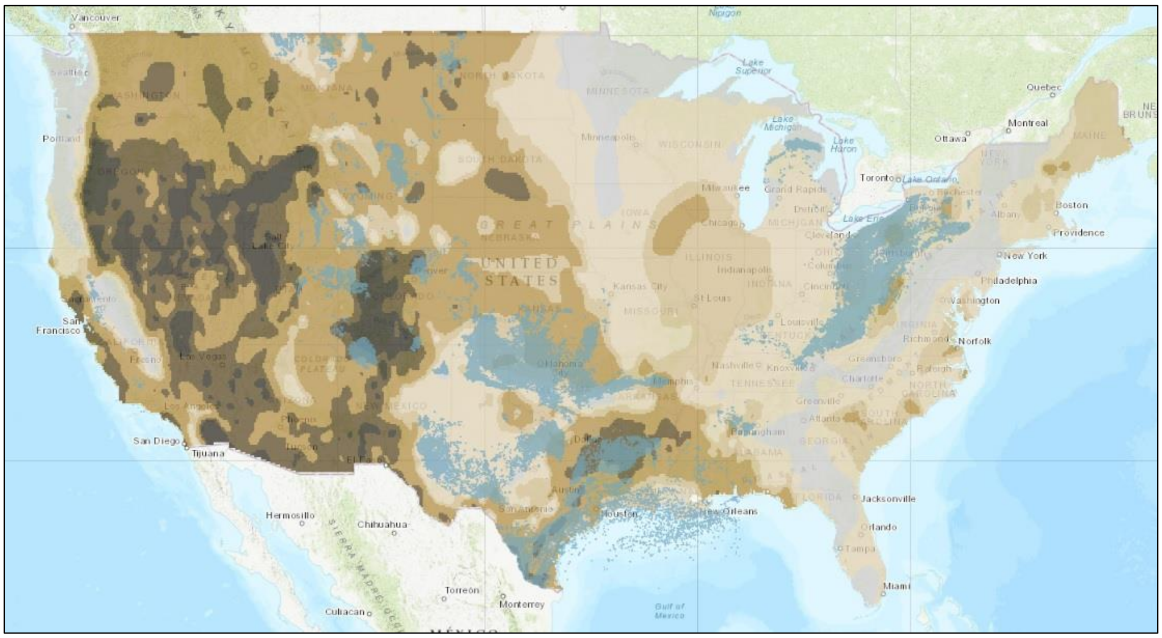
Notes: Employment in NAICS category 211 Oil and Gas Extraction by occupation, rounded to the nearest 1% of total employment, and grouped by occupational relevance of skills and experience to the geothermal power sector. Due to rounding, percentages may not total 100%.

[41] U.S. Bureau of Labor Statistics, "May 2021 National Industry-Specific Occupational Employment and Wage Estimates: NAICS 211000—Oil and Gas Extraction," https://www.bls.gov/oes/current/naics3_211000.htm.

Geographical Overlap of O&G Development and Geothermal Potential

Many states with O&G development also have potential for EGS development. Counties that have had some of the highest relative concentrations of employment in O&G extraction are located in states including Texas, Louisiana, Oklahoma, Kansas, Colorado, Wyoming, Pennsylvania, and West Virginia, many of which are locations of potential EGS resources.[42] **Figure 2** shows a map of areas of geothermal energy potential (brown fields) in the continental United States overlaid with the locations of natural gas wells (blue dots).[43] In addition to much of the western United States, areas in the upper Midwest, Oklahoma/Texas/Louisiana, Iowa/Wisconsin/Illinois, and West Virginia/Pennsylvania have significant potential for EGS and many of these areas overlap with gas wells.

Figure 2. Geothermal Potential and Gas Wells in the Continental United States



Source: U.S. Energy Information Administration, U.S. Energy Atlas, 2022.

Notes: Blue dots show gas well locations. Brown fields indicate areas of geothermal potential with darker fields having greater potential. Geothermal potential data was not available in the EIA mapping system for Alaska, Hawaii, or other territories, though Alaska does have both gas and oil wells.

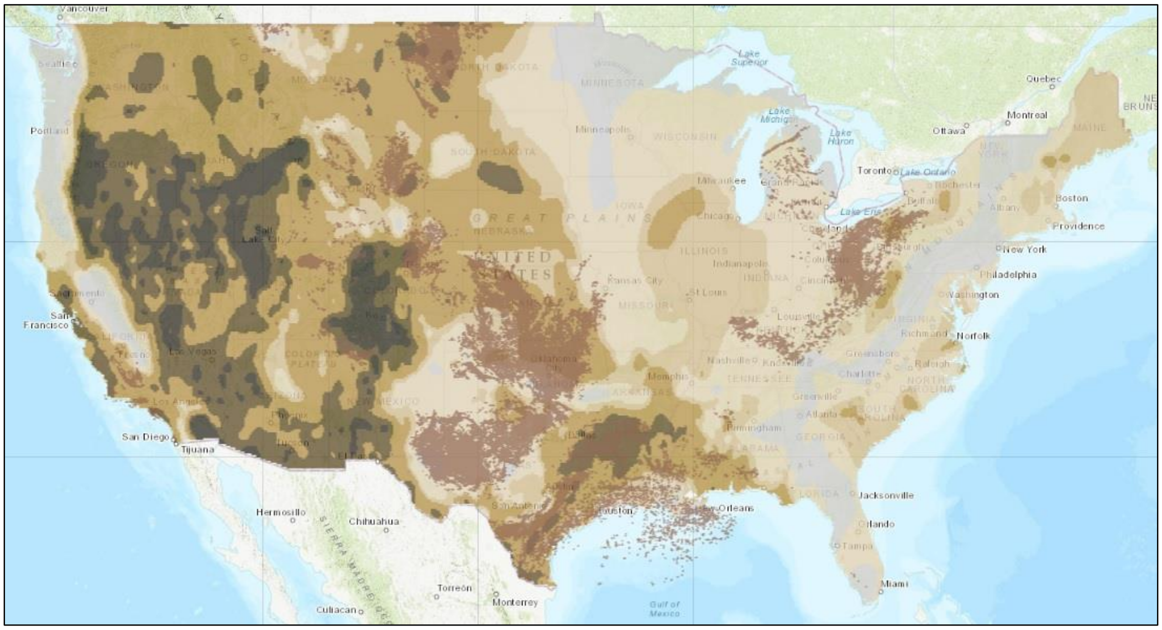
Figure 3 shows a similar map with geothermal energy potential and oil wells.[44]

[42] U.S. Bureau of Labor Statistics, "Counties with Highest Concentration of Employment in Oil and Gas Extraction, June 2014," January 9, 2015, https://www.bls.gov/opub/ted/2015/counties-with-highest-concentration-of-employment-in-oil-and-gas-extraction-june-2014.htm.

[43] U.S. Energy Information Administration, "U.S. Energy Atlas," 2022, https://www.eia.gov/state/maps.php.

[44] U.S. Energy Information Administration, "U.S. Energy Atlas," 2022, https://www.eia.gov/state/maps.php.

Figure 3. Geothermal Potential and Oil Wells in the Continental United States



Source: U.S. Energy Information Administration, U.S. Energy Atlas, 2022.

Notes: Red dots show oil well locations. Brown fields indicate areas of geothermal potential with darker fields having greater potential. Geothermal potential data was not available in the EIA mapping system for Alaska, Hawaii, or other territories, though Alaska does have both gas and oil wells.

Geothermal Capacity and Costs

While geothermal energy currently produces 0.4% of U.S. electricity,[45] the United States produces the largest amount of geothermal electricity worldwide[46] and DOE projects that EGS could provide 60 gigawatts (GW) of electricity capacity by 2050 (8.5% of U.S. generation capacity).[47]

Table 2 summarizes LCOE and levelized capital costs for select electricity generation technologies including conventional hydrothermal. It shows conventional hydrothermal costs are on par with other generation technologies in terms of the cost to produce electricity from a successfully developed geothermal site. Expected ranges of current and potential EGS LCOE values are difficult to determine because few plants are currently operating.

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[45] Energy Information Administration, *Monthly Energy Review: May 2022*, 2022, https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

[46] Alexander Richter, "ThinkGeoEnergy's Top 10 Geothermal Countries 2021—Installed Power Generation Capacity (MWe)," ThinkGeoEnergy.com, January 10, 22021, https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2021-installed-power-generation-capacity-mwe/; Gerald Huttrer, "Geothermal Power Generation in the World 2015-2020 Update Report," Proceedings World Geothermal Congress 2020+1, April-October 2021, https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01017.pdf.

[47] For more details, see U.S. Department of Energy, Geothermal Technologies Office, *GeoVision: Harnessing the Heat Beneath Our Feet*, May 2019, https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf.

Table 2. Levelized Costs for Select Electricity Generation Technologies

	Capacity Factor	Levelized Capital Costs ($/MWh)	Total LCOE ($/MWh)	LCOE Including Tax Credits ($/MWh)
Combined-Cycle Plants (e.g., natural gas-fired)	87%	8.56	37.05	37.05
Geothermal (conventional hydrothermal)	90%	21.80	39.61	37.43
Wind (onshore)	43%	27.45	37.80	37.80
Solar (photovoltaic)	29%	26.35	36.09	33.46

Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022.*

Notes: Costs are capacity weighted by new capacity expected to come online in 2025 to 2027. Presented in dollars per megawatt-hour ($/MWh). Tax credit values are those prior to the passage of the Inflation Reduction Act (P.L. 117-169). Levelized cost of electricity (LCOE) are total costs averaged over the total electricity production (in megawatt-hours (MWh)) for the lifetime of the plant. Estimates of current and potential EGS LCOE values range widely because few plants are currently operating.

EGS are potentially viable in more locations geographically than conventional hydrothermal installations, but their LCOE costs are potentially higher and their development costs are generally higher—because of additional exploration costs including the costs for failed wells. Outside of demonstration sites, two EGS plants are operating commercially worldwide: a 1.7 megawatt (MW) plant in Soultz-sous-Forêts, France, and a 5 MW plant in Insheim, Germany.[48] Estimates of potential EGS LCOE values vary widely and include $54 per megawatt-hour (MWh),[49] $70/MWh,[50] $150/MWh,[51] or as high as $100,000–$300,000/MWh for some modeled installations.[52] The costs vary depending on the site geology, difficulty in drilling and confirming the geothermal resources, and technology and operational costs. Drilling and well completion costs can account for 50% or more of the total capital costs for a geothermal power project.[53] Like other energy technology developments, these costs may trend downward as the technologies are more widely implemented.

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[48] Justine Mouchot et al., "First Year of Operation from EGS Geothermal Plants in Alsace, France: Scaling Issues," Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, February 12-14, 2018, https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2018/Mouchot.pdf; Britta Ganz et al., "Geothermal Energy Use in Germany," European Geothermal Congress 2013, June 3-7, 2013, http://www.geothermal-energy.org/pdf/IGAstandard/EGC/2013/EGC2013_CUR-13.pdf.

[49] Subir K. Sanyal et al., "Cost of Electricity from Enhanced Geothermal Systems," *Proceedings, Thirty-Second Workshop on Geothermal Reservoir Engineering*, January 22-24, 2007, https://geo.stanford.edu/ERE/pdf/IGAstandard/SGW/2007/sanyal1.pdf.

[50] Sandia National Laboratory, "Cost and Performance Analysis of Enhanced Geothermal Systems (EGS)," June 1, 2103, https://www.osti.gov/servlets/purl/1661353.

[51] Philipp Heidinger, "Integral Modeling and Financial Impact of the Geothermal Situation and Power Plant at Soultz-sous-Forêts," *Comptes Rendus Geoscience*, vol. 342, no. 7-8, July-August 2010, https://www.sciencedirect.com/science/article/pii/S163107130900248X?via%3Dihub.

[52] Nikolay Belyakov, "Chapter Twenty—Geothermal Energy," in *Sustainable Power Generation: Current Status, Future Challenges, and Perspectives* (Academic Press, 2019), https://www.sciencedirect.com/science/article/pii/B9780128170120000347.

[53] Sandia National Laboratory, "GeoVision Analysis: Reservoir Maintenance and Development Task Force Report," August 1, 2017, https://www.osti.gov/servlets/purl/1394062.

Geothermal Technologies

While the O&G industry has seen greater commercial development and more R&D investment than the geothermal industry, the industries are similar in that they both access and engineer underground resources to produce energy.[54] The following sections provide an overview of the technologies inherited or adapted from the O&G industry and involved in, or compatible with, geothermal power.

Exploration Technologies

Exploration is an area where geothermal resources share similarities with the O&G sector. The technologies to identify, estimate, confirm, map, and characterize subsurface resources are being refined to get better performance for geothermal resources and to support commercial EGS development.

A primary exploration technology is the exploratory well. Test wells identify or confirm the existence of geothermal resources and allow for monitoring of the resources in the longer term. These wells are supported by other technologies including chemical, temperature, and pressure characterization technologies using standard detection technologies, and often rely on the downhole sensor technologies used in drilling. Additionally, reservoir (geophysical) modeling tools support these wells. Reservoir modeling combines available geological, geophysical, and geochemical data into models and seeks to capture and model the core physics and chemistry of the reservoir. This enables resource estimation, supports the installation of the injection and production wells, and supports well operation and long-term management of the reservoir once the geothermal power plant is in operation.

Some of the technologies used and developed to support exploration include tracers[55] and seismic sensors[56] or other distributed acoustic sensing[57] to aid in siting wells and eventually managing reservoirs.

The O&G industry uses subsurface data from multiple sources to model and predict underground conditions. The geothermal industry needs and is developing detailed subsurface data such as porosity, permeability, heat flow, and other thermal parameters to make accurate predictions for economical resource development and plant operations.[58]

[54] U.S. Department of Energy, "Geothermal Energy from Oil and Gas Demonstrated Engineering (GEODE): Funding Opportunity Announcement (FOA) Number: DE-FOA-0002776," August 10, 2022, p. 6, https://eere-exchange.energy.gov/FileContent.aspx?FileID=b06b366e-cc6c-409b-a4fe-7cc0ad5b0b26.

[55] Natural tracers are chemicals naturally present in a reservoir that can be injected to trace the connectivity and flow of the reservoir. Artificial tracers are developed and used for their characteristics like easy detectability or stability at high-temperatures. PetroWiki, "Tracer Testing in Geothermal Reservoirs," accessed May 25, 2022, https://petrowiki.spe.org/Tracer_testing_in_geothermal_reservoirs.

[56] Trevor M. Letcher, *Future Energy: Improved, Sustainable and Clean Options for Our Planet* (Elsevier, 2020), https://www.sciencedirect.com/book/9780081028865/future-energy.

[57] Takeshi Tsuji, Tatsunori Ikeda, Ryosuke Matsuura, Kota Mukumoto, Fernando Lawrens Hutapea, Tsunehisa Kimura, Koshun Yamaoka, and Masanao Shinohara, "Continuous Monitoring System for Safe Managements of CO2 Storage and Geothermal Reservoirs," *Scientific Reports*, vol. 11, September 27, 2021, https://www.nature.com/articles/s41598-021-97881-5.

[58] Alexander Richter, "ThinkGeoEnergy's Top 10 Geothermal Countries 2021—Installed Power Generation Capacity (MWe)," ThinkGeoEnergy.com, January 10, 2021, https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2021-installed-power-generation-capacity-mwe/.

Other exploration technologies and techniques developed in the O&G industry are underutilized or still being developed or adapted for geothermal applications.[59] These include data and technology to improve drilling performance, reservoir stimulation and management, and well design.

Drilling and Well Completion Technologies

Much of the drilling and completion[60] technologies (and related considerations) for geothermal power are similar to those of O&G. O&G technology developments (like stimulation and directional drilling) were adapted and applied to geothermal power and have enabled the development of EGS. This includes developments in below ground technologies like drilling motors, drill bits,[61] drilling fluids, lubricants, and related technologies, downhole sensors and controls, and casing materials.

In addition to these technologies, there are supporting processes and best practices that have been developed for EGS either as adaptations of O&G practices or in response to wholly new considerations for geothermal applications.[62] Some of these processes and technology include the management of fluids and well pressure during drilling, techniques for installing the well casing, and systems for maintaining drill speed and well development rates.

There are important differences with geothermal applications that pose challenges to the technologies and processes as developed and implemented for O&G drilling. To be economically viable for commercial-scale power production, geothermal wells generally have to move a higher volume of fluid than the extraction of hydrocarbons in O&G, resulting in larger diameter wells. Larger diameter wells are more expensive to drill and more difficult to maintain than smaller O&G wells. Geothermal wells also operate differently than O&G wells, because they work for a maximized sustainable electricity generation over the lifetime of the plant.[63] However, the major differences that affect most of the drilling technologies are the higher temperatures and harsher environments of geothermal wells.

[59] U.S. Department of Energy, Geothermal Technologies Office, "Geothermal Technologies Office: Fiscal Years 2022-2026 Multi-year Project Plan," February 2022, https://www.energy.gov/sites/default/files/2022-02/GTO%20Multi-Year%20Program%20Plan%20FY%202022-2026.pdf.

[60] Completion is the process where wells are finished and ready for use, potentially including preparing the conditions at bottom of the well for production (or injection), installing any tools or monitors, performing any well stimulation, and extracting the drilling fluids and installing a casing to prevent well collapse.

[61] The U.S. Department of Energy (DOE) supported development of polycrystalline diamond compact (PDC) bits in the 1970s and 1980s, which enable modern drilling for shale gas. U.S. Department of Energy, "Retrospective Benefit-Cost Evaluation of U.S. DOE Geothermal Technologies R&D Program Investments: Impacts of a Cluster of Energy Technologies," August 2010, https://www.energy.gov/sites/prod/files/2014/02/f7/gtp_benefit-cost_eval_aug2010.pdf.

[62] For example, DOE's National Energy Technology Laboratory (NETL) in Morgantown, WV, and Pittsburgh, PA (which includes work on coal, natural gas, and oil technologies) is adapting O&G technology for EGS. National Energy Technology Laboratory, "NETL Project Partner to Advance New Enhanced Geothermal Systems Technologies," December 28, 2021, https://netl.doe.gov/node/11465; National Energy Technology Laboratory, "Subsurface Modeling Explores New Geothermal Hot Spots for Renewable Energy," September 11, 2017, https://www.netl.doe.gov/node/2300.

[63] O&G wells can be productive over similar timeframes, but their productivity can drop off significantly after the first few years. Planete Energies, "The Life Cycle of Oil and Gas Fields," Planete-energies.com, August 11, 2015, https://www.planete-energies.com/en/medias/close/life-cycle-oil-and-gas-fields; Henrik Wachtmeister, Linnea Lund, Kjell Aleklett, and Mikael Höök, "Production Decline Curves of Tight Oil Wells in Eagle Ford Shale," *Natural Resources Research*, vol. 26, January 19, 2017, https://link.springer.com/article/10.1007/s11053-016-9323-2.

Higher temperatures affect the materials suitable for use in many of these technologies. Low-temperature materials, for example rubber or low-temperature plastics, work in an O&G well, but not in a geothermal well. Drill bits for a typical geothermal application are designed to prevent excess wear and maintain performance in high-temperature operations and to handle the typically harder rock that is found with geothermal wells.[64]

Additionally, the well casing material needs to operate for long durations at high temperatures and in often highly saline environments.[65] Typical well casings are cement or metal, but other technologies are being developed for geothermal applications including polymer/oxide composites and coatings, special alloying or heat treatments for metals, or chemical additives for cement.

Finally, downhole data collection and controls contribute to successful well exploration and development and are important to long-term operation of the wells. Sensors and other data acquisition electronics need to be able to operate in the harsh environment (heat and corrosion) of the geothermal well. Improvements to downhole data collection and controls for geothermal drilling and completion would likely shorten drilling time and reduce costs for geothermal development. As an example of the benefits already seen in O&G applications, DOE estimates that downhole data collection in the O&G sector has "decreased drilling time and cost and increased penetration rates by 35%–55%."[66]

Stimulation Technologies

Directional drilling and stimulation technologies (as well as binary power plant technologies) are being developed to enhance the technical viability of EGS. The main component of stimulation technology is the injection of fluids (largely water with some additional constituents) into a reservoir to break the subsurface rock to create additional permeability and access the geothermal resources. This permeability allows the fluid to flow through the rock and absorb heat. Additionally, reinjection of the produced geothermal fluid (along with some additional chemicals or additives) back into the underground reservoir after the electricity generation steps, helps maintain reservoir pressure, maintain permeability, prevent dry gaps in the reservoir, prevent chemical precipitation and lost circulation, and maintain fluid flow for energy production.

Geothermal stimulation is similar to hydraulic fracturing used in O&G, but takes place at lower pressures, seeks to generate greater long-term permeability,[67] and has relatively low risk of induced seismicity.[68] Additionally, geothermal power systems reinject almost all of the geothermal fluid extracted from the subsurface for continual operation limiting loss from the subsurface. As a result, there is little-to-no seismic activity caused or enabled by these stimulation activities. Subsurface activities with higher volumes of fluid injected or extracted—for example

[64] U.S. Department of Energy, Geothermal Technologies Office, *GeoVision: Harnessing the Heat Beneath Our Feet*, May 2019, https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf.

[65] National Renewable Energy Laboratory, "Advanced Wells," https://www.nrel.gov/geothermal/advanced-wells.html.

[66] National Renewable Energy Laboratory, "Advanced Wells," https://www.nrel.gov/geothermal/advanced-wells.html.

[67] Ning Li, Heping Xie, Jianjun Hu, and Cunbao Li, "A Critical Review of the Experimental and Theoretical Research on Cyclic Hydraulic Fracturing for Geothermal Reservoir Stimulation," *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, vol. 8, November 27, 2021, https://link.springer.com/article/10.1007/s40948-021-00309-7.

[68] U.S. Department of Energy, Geothermal Technologies Office, "What Is an Enhanced Geothermal System (EGS)?" September 2012, https://www1.eere.energy.gov/geothermal/pdfs/egs_basics.pdf; National Research Council, "Induced Seismicity Potential in Energy Technologies," The National Academies Press, 2013, p. 107, https://doi.org/10.17226/13355.

wastewater disposal and O&G extraction, respectively—are associated with more induced seismicity.[69]

DOE EGS in-field and near-field demonstration projects have successfully used low-pressure stimulation.[70] Other examples of attempted EGS projects have failed to control the fracture zone, resulting in uneconomical wells. More effective geothermal fluids compositions and injection processes are being developed,[71] with some exploring cyclical injection schemes,[72] additional constituents like proppants,[73] or additives like polymers[74] to reduce the volume of water needed or increase the performance of the fluid and the system. Injection schemes including the volume of water and types of added constituents have been a source of contention for the O&G industry, and will likely continue to be with further development of EGS.

Due to the high costs of drilling and completing geothermal wells, use of trial and error to develop and advance stimulation technologies—as was used in the O&G industry—is not likely to be a realistic option.[75] Development that leverages existing knowledge from the O&G sector and dedicated R&D efforts including pilot projects will likely be needed to support successful development of stimulation technologies and commercial EGS projects.

Power Plant Technologies

Geothermal power plants use a lot of the same equipment, processes, and control systems as gas-fired power plants. The steam cycle equipment—including pipelines, turbines, and cooling systems—are common to many thermal power plants.[76] Additionally, geothermal and O&G plants make use of similar workforces including construction workers, plant operators, and support services, and the two industries can use similar supply lines, manufacturing capabilities, and construction and maintenance services.

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[69] For more information on induced seismicity, see CRS Report R47386, *Earthquakes Induced by Underground Fluid Injection and the Federal Role in Mitigation*, by Linda R. Rowan and Angela C. Jones.

[70] U.S. Department of Energy, Geothermal Technologies Office, *GeoVision: Harnessing the Heat Beneath Our Feet*, May 2019, https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf.

[71] Mark McClure, "Why Multistage Stimulation Is the Most Exciting Idea in Geothermal," ResFrac.com, May 16, 2021, https://www.resfrac.com/blog/why-multistage-stimulation-most-exciting-idea-geothermal.

[72] Ning Li, Heping Xie, Jianjun Hu, and Cunbao Li, "A Critical Review of the Experimental and Theoretical Research on Cyclic Hydraulic Fracturing for Geothermal Reservoir Stimulation," *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, vol. 8, November 27, 2021, https://link.springer.com/article/10.1007/s40948-021-00309-7.

[73] Proppants are additives, like sand or aluminum oxide, included in stimulation fluids to help maintain subsurface permeability. Rafał Moska, Krzysztof Labus, and Piotr Kasza, "Hydraulic Fracturing in Enhanced Geothermal Systems—Field, Tectonic and Rock Mechanics Conditions—A Review," *Energies*, vol. 14, no. 5725 (September 2021), https://www.mdpi.com/1996-1073/14/18/5725/pdf; Clay G. Jones, Stuart F. Simmons, and Joseph N. Moore, "Proppant Behavior Under Simulated Geothermal Reservoir Conditions," *Proceedings, Thirty-Ninth Workshop on Geothermal Reservoir Engineering*, February 24-26, 2014, https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2014/Jones1.pdf.

[74] Pacific Northwest National Laboratory, "Packing Heat: New Fluid Makes Untapped Geothermal Energy Cleaner," April 15, 2015, https://www.pnnl.gov/news/release.aspx?id=4195.

[75] U.S. Department of Energy, Geothermal Technologies Office, "Geothermal Technologies Office: Fiscal Years 2022-2026 Multi-year Project Plan," February 2022, https://www.energy.gov/sites/default/files/2022-02/GTO%20Multi-Year%20Program%20Plan%20FY%202022-2026.pdf.

[76] U.S. Department of Energy, "How a Geothermal Power Plant Works (Simple)," https://www.energy.gov/eere/geothermal/how-geothermal-power-plant-works-simple.

Compared to the 2,020 natural gas power plants and the 1,104 plants that primarily use petroleum,[77] there are relatively few geothermal power plants in the United States. Of the 96 total operating geothermal units in 2021, 17 were dry steam, 28 were flash, and 51 were binary—the three primary types of geothermal power systems.[78] There are no operational EGS units in the United States, though there are some demonstration projects.[79] For more information on geothermal power plant technologies, see CRS Report R47256, *Enhanced Geothermal Systems: Introduction and Issues for Congress*, by Morgan Smith.

As of 2020, the United States had 58 conventional geothermal projects in development, 54 of which were on undeveloped geothermal resources; the remaining 4 were expansions on existing resources.[80] While commercial coproduction and EGS projects have been in development as recently as 2015, none were in development as of 2020.

Transferable Workforce Skills and Experience

The geothermal workforce includes personnel with experience and skills developed in or derived from the O&G sector. If the conditions of the current energy transition continue, the developing geothermal sector may see a need for additional personnel transfer or skills and knowledge transfer from the O&G sector.

The geothermal energy industry requires many of the same knowledge and skill sets used in the O&G industry. These include knowledge of underground conditions to identify the best locations for resource exploration and support drilling operations;[81] skills and best practices for managing hydraulic fracturing and wastewater injection; mitigating or dealing with potential induced seismicity;[82] and skills and experience for completion and operation of wells. Additionally, many of the developers creating and adapting technologies for geothermal applications include senior executives from the O&G industry who apply their knowledge and experience of the challenges and solutions from O&G to geothermal.[83]

Outside of technical skills and knowledge, the O&G workforce has experience in financing and risk management for subsurface resource development. The challenges related to these types of

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[77] U.S. Energy Information Administration, "Table 4.1. Count of Electric Power Industry Power Plants, by Sector, by Predominant Energy Sources within Plant, 2011 through 2021," Electric Power Annual, November 7, 2022, https://www.eia.gov/electricity/annual/html/epa_04_01.html

[78] A power plant can consist of one or more power units. Energy Information Administration, "Electricity Data Browser," accessed May 25, 2022, https://www.eia.gov/electricity/data/browser/#/topic/1?agg=1,2,0&fuel=001&geo=g00000000004&sec=g&freq=A&datecode=2021&rtype=s&start=200101&end=201911&ctype=map&ltype=pin&rse=0&maptype=0&pin=; National Renewable Energy Laboratory, "2021 U.S. Geothermal Power Production and District Heating Market Report," July 2021, https://www.nrel.gov/docs/fy21osti/78291.pdf.

[79] For example, the U.S. Department of Energy-supported Utah FORGE project: https://utahforge.com/.

[80] National Renewable Energy Laboratory, "2021 U.S. Geothermal Power Production and District Heating Market Report," July 2021, https://www.nrel.gov/docs/fy21osti/78291.pdf.

[81] James Pethokoukis, "Can Geothermal Energy Replace Oil and Gas? My Long-Read Q&A with Jamie Beard," American Enterprise Institute, October 21, 2021, https://www.aei.org/economics/can-geothermal-energy-replace-oil-and-gas-my-long-read-qa-with-jamie-beard/.

[82] James Pethokoukis, "Can Geothermal Energy Replace Oil and Gas? My Long-Read Q&A with Jamie Beard," American Enterprise Institute, October 21, 2021, https://www.aei.org/economics/can-geothermal-energy-replace-oil-and-gas-my-long-read-qa-with-jamie-beard/.

[83] Geothermal.org, "Don't Look Up, Look Down: How Oil & Gas Companies Can Survive the Energy Transition by Investing in Geothermal," June 17, 2022, https://geothermal.org/our-impact/blog/dont-look-look-down-how-oil-gas-companies-can-survive-energy-transition-investing.

exploration and development—geological risk—are familiar to the O&G industry. Prior knowledge and relationships with investors, who are already familiar with the conditions of subsurface O&G development, including the related risks and benefits, could facilitate additional private sector investment in EGS projects.[84]

Overall, geothermal energy development requires similar types and numbers of workers to those same operations in the O&G sector—including drillers, geoscientists, and drilling services for well development and manufacturers, construction contractors, and operations and maintenance staff for power plant operation.[85]

Challenges

Supporters and critics of geothermal energy note the industry will likely need additional public support, if it is to address its challenges. A selection of challenges related to geothermal power applications are discussed below.[86]

Geothermal power can face permitting challenges due to the potential for environmental impacts including ground water impacts and the potential for induced seismicity—though seismicity risks are relatively low.[87] These challenges include the federal permitting process and permitting times as well as the challenge of meeting a variety of different state and local regulations.[88]

Compared to tax provisions relating to the O&G industry (for example, 26 U.S.C. §617), the geothermal industry does not have risk-mitigating deductions for failures in well exploration and drilling activities.[89] Thus, exploration and well development are relatively more risky and expensive for geothermal projects.

Relative to some other energy generation technologies, geothermal tends to have higher capital costs. This is due to a number of operational and plant design factors. Compared to O&G, geothermal power projects tend to move higher volumes of fluid through larger diameter wells.

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[84] Alexander Richter, "ThinkGeoEnergy's Top 10 Geothermal Countries 2021—Installed Power Generation Capacity (MWe)," ThinkGeoEnergy.com, January 10, 2021, https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2021-installed-power-generation-capacity-mwe/.

[85] Neel Dhanesha, "Clean Energy Is Buried at the Bottom of Abandoned Oil Wells," Vox.com, April 19, 2022, https://www.vox.com/recode/23024204/geothermal-energy-heat-oil-gas-wells; James Pethokoukis, "Can Geothermal Energy Replace Oil and Gas? My Long-Read Q&A with Jamie Beard," American Enterprise Institute, October 21, 2021, https://www.aei.org/economics/can-geothermal-energy-replace-oil-and-gas-my-long-read-qa-with-jamie-beard/; Dev Millstein et al., "GeoVision Analysis Supporting Task Force Report: Impacts—The Employment Opportunities, Water Impacts, Emission Reductions, and Air Quality Improvements of Achieving High Penetrations of Geothermal Power in the United States," Lawrence Berkeley National Laboratory and National Renewable Energy Laboratory, May 2019, https://www.nrel.gov/docs/fy19osti/71933.pdf.

[86] For a fuller exploration of the benefits and challenges of EGS, see CRS Report R47256, *Enhanced Geothermal Systems: Introduction and Issues for Congress*, by Morgan Smith.

[87] For more details, see "Stimulation Technologies."

[88] Some states have regulations specifically addressing geothermal projects. Those states are Alaska, California, Colorado, Hawaii, Idaho, Montana, Oregon, Nevada, New Mexico, Texas, Utah, Washington, and West Virginia. Brent Chicken and Joseph Negaard, "Renewable Energy Webcast Series: Legal Considerations of Geothermal Projects," January 5, 2022, https://www.steptoe-johnson.com/sites/default/files/Renewable%20Webcast%20-%20Geothermal.pdf; Carlo Cariaga, "West Virginia State Regulatory Program Signed into Law," ThinkGeoEnergy.com, April 1, 2022, https://www.thinkgeoenergy.com/west-virginia-state-regulatory-program-signed-into-law/.

[89] Alex Brown, "Geothermal Bubbles Up as Another Way to Fight Climate Change," PewTrusts.org, September 9, 2022, https://www.pewtrusts.org/en/research-and-analysis/blogs/stateline/2022/09/09/geothermal-bubbles-up-as-another-way-to-fight-climate-change.

The high fluid volumes and operational challenges of the reservoirs—including the high temperatures and reactive chemistry—means geothermal projects often need customized system designs with binary fluid loops, high-cost specialty metals, and maximized operational efficiency, which contribute to higher capital costs.[90]

Issues for Congress

If the conditions of the current energy transition continue, the results could be idled or underutilized assets and workforce from the O&G sector. Congress may be interested in how some of these assets could be transferred, adapted, and retrained for use in EGS applications.

Congress has already considered and passed laws that have supported redevelopment as part of the current energy transition. For example, the Inflation Reduction Act of 2022 (IRA, P.L. 117-169) includes an extension of the Renewable Electricity Production Tax Credit (Section 45) and adds a 10% bonus for RE facilities (including geothermal) in "energy communities"—brownfield sites or fossil fuel communities—to support development in communities that have lost jobs or revenue in coal, oil, or gas sectors.[91] The IRA also created a new loan guarantee authority to re-power fossil fuel power generation facilities.

In the current energy transition, RE sources like geothermal energy are incentivized and valued by some federal and state policies and other market factors. Additionally, some elements of the O&G sector are disincentivized or see additional costs. Congress could consider approaches—such as carbon pricing[92] or price premiums for baseload renewable electricity—that would contribute to the energy transition or others that might support the transfer of assets from the O&G industry. Congress could consider the development of standards and frameworks where electricity valuations could be included as part of RE portfolio standards[93] or other power pricing regulations, which are often the domain of state regulations.

Current incentives supporting clean electricity (including geothermal energy) include recent expansions and extensions of the production tax credit (PTC) and the investment tax credit (ITC) in the Inflation Reduction Act of 2022 (P.L. 117-169).[94] Geothermal development also qualifies for DOE's Title XVII loan guarantee program (both Sections 1703 and 1706) created via the Energy Policy Act of 2005 (P.L. 109-58) and expanded and funded by the IRA. Further incentives could include loan guarantees or tax deductions for exploration or drilling operations—the O&G

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[90] Sertaç Akar et al., "Global Value Chain and Manufacturing Analysis on Geothermal Power Plant Turbines," National Renewable Energy Laboratory, September 2018, https://www.nrel.gov/docs/fy18osti/71128.pdf.

[91] The Inflation Reduction Act defines fossil-fuel-related energy communities as census tracts where a coal-fired power plant has closed since 2010, or a coal mine has closed since 2000, or where sufficient direct employment or local tax revenues come from coal, oil, or natural gas extraction, processing, transport, or storage.

[92] For more information on carbon pricing, see CRS Report R45625, *Attaching a Price to Greenhouse Gas Emissions with a Carbon Tax or Emissions Fee: Considerations and Potential Impacts*, by Jonathan L. Ramseur and Jane A. Leggett.

[93] For more information on portfolio standards, see CRS Report R45913, *Electricity Portfolio Standards: Background, Design Elements, and Policy Considerations*, by Ashley J. Lawson.

[94] Before the IRA was enacted, there was a permanent 10% investment tax credit for taxpayers investing in geothermal property, defined as "equipment used to produce, distribute, or use energy derived from a geothermal deposit." Geothermal energy technologies also qualify for the renewable electricity PTC, a per-kWh tax credit for electricity generated using qualified energy resources, so long as the facility had begun construction by the end of 2021. For additional information, see CRS In Focus IF10479, *The Energy Credit or Energy Investment Tax Credit (ITC)*, by Molly F. Sherlock; and CRS Report R43453, *The Renewable Electricity Production Tax Credit: In Brief*, by Molly F. Sherlock.

industry has such tax benefits for intangible drilling costs and other exploration and development costs.[95]

The federal role in regulating geothermal development outside of federal lands is rather limited—applications of the Safe Drinking Water Act (P.L. 93-523) being one example. This regulation is largely up to states and localities, and many of those do not have geothermal-specific policies. Congress could examine the federal role in supporting state and local efforts to develop policies related to geothermal energy development. Congress could consider whether to provide additional support to states relating to the development of or change to regulations and permitting; DOE has noted permitting challenges in some states make it difficult to transition existing O&G leases to geothermal leases.[96]

Congress could consider changes to permitting conditions or bond levels related to federal O&G permitting to account for high site-remediation costs or to support the transition of relevant wells to geothermal development. The Infrastructure Investment and Jobs Act (IIJA) of 2021 (P.L. 117-58) Section 40601 provides funding for plugging and remediation of abandoned or idle O&G wells where there is "no anticipated beneficial future use"; a revised approach could support the assessment and transition of idle or orphaned wells suitable for geothermal energy production.

Congress could consider reviewing current investment in federal research, development, and deployment (RD&D), including the types and effectiveness of the research programs that support geothermal development. Congress might determine if these are sufficient to meet current U.S. energy, environmental, and security goals and if there are any gaps in support for deployment of geothermal energy as a resource, for the development of EGS technology, or for the application of O&G technologies and assets to EGS projects. In addition to general RD&D programs developing relevant technologies in the Geothermal Technologies Office, DOE supports the Geothermal Energy from Oil and Gas Demonstrated Engineering (GEODE) initiative, which seeks to transition O&G technologies, assets, and workforce to geothermal power applications.[97] DOE has also supported a funding program called Wells of Opportunity (WOO), which targets projects that advance the commercial viability of using existing O&G wells for geothermal power.[98] Further, DOE has supported RD&D into advanced manufacturing technologies that support developing and adapting technologies from O&G to the operating environment of geothermal power.[99] DOE is also developing technologies for underground thermal energy storage that could reuse O&G wells, including some that might not be suitable for geothermal electricity production but that would still require geothermal technologies and data.[100]

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[95] Intangible drilling costs: 26 U.S.C. § 263(c). Other exploration and development costs: 26 U.S.C. § 617. See CRS In Focus IF11528, *Oil and Gas Tax Preferences*, by Molly F. Sherlock.

[96] Neel Dhanesha, "Clean Energy Is Buried at the Bottom of Abandoned Oil Wells," Vox.com, April 19, 2022, https://www.vox.com/recode/23024204/geothermal-energy-heat-oil-gas-wells.

[97] U.S. Department of Energy, Geothermal Technologies Office, "Geothermal Energy from Oil and Gas Demonstrated Engineering," https://www.energy.gov/eere/geothermal/geothermal-energy-oil-and-gas-demonstrated-engineering.

[98] U.S. Department of Energy, "Going Back to the Well (Again): Harnessing Geothermal Energy's Potential," April 13, 2022, https://www.energy.gov/eere/articles/going-back-well-again-harnessing-geothermal-energys-potential.

[99] U.S. Department of Energy, "DOE Announces Geothermal Manufacturing Prize Winners," August 29, 2022, https://www.energy.gov/eere/articles/doe-announces-geothermal-manufacturing-prize-winners.

[100] U.S. Department of Energy, Geothermal Technologies Office, "Geothermal Technologies Office: Fiscal Years 2022-2026 Multi-year Project Plan," February 2022, p. 32, https://www.energy.gov/sites/default/files/2022-02/GTO%20Multi-Year%20Program%20Plan%20FY%202022-2026.pdf.

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