Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office

Chad Augustine, Sarah Fisher, Jonathan Ho, Ian Warren, and Erik Witter

National Renewable Energy Laboratory

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Photos (clockwise) by Dennis Schroeder, NREL 36653; Alaska Center for Energy and Power, NREL 32760; Dennis Schroeder, NREL 48223 and 48223; John W. Lund, NREL 13101; Robb Williamson, NREL 13033

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List of Acronyms

ARPA-E	Advanced Research Projects Agency-Energy
ATB	Annual Technology Baseline
DAC	direct air capture
DOE	U.S. Department of Energy
EGS	enhanced geothermal systems
FORGE	Frontier Observatory for Research in Geothermal Energy
GETEM	Geothermal Electricity Technology Evaluation Model
GTO	Geothermal Technologies Office
GW_e	gigawatt-electric
kW_e	kilowatt-electric
LCOE	levelized cost of electricity
MW_e	megawatt-electric
MWh_e	megawatt hour-electric
NREL	National Renewable Energy Laboratory
OCC	overnight capital cost
RE-CT	renewable energy combustion turbine
ReEDS	Regional Energy Deployment System
TI	Technology Improvement scenario
USGS	U.S. Geological Survey

Executive Summary

In 2021, the U.S. Department of Energy (DOE) began the Energy Earthshots™ initiatives to accelerate breakthroughs of reliable clean energy solutions within the next 10 years. In 2022, the National Renewable Energy Laboratory was asked by the DOE Geothermal Technologies Office (GTO) to provide analysis for developing Energy Earthshot targets for enhanced geothermal systems (EGS), human-made underground reservoirs that extract thermal energy from the earth for electricity generation and/or heating applications.

The Enhanced Geothermal Shot analysis is based on the technology assumptions in the 2019 GTO report *GeoVision: Harnessing the Heat Beneath Our Feet*. For Earthshot, we updated some of the technology cost and performance assumptions for EGS based on recent technology advances and updated the EGS resource potential to include more detailed analysis. Drilling costs were decreased an additional 20% from the values used in *GeoVision*. Well productivity was increased from 4.6 kg/s/bar for all wells in *GeoVision* to 70 kg/s/bar for injection wells and 38.1 kg/s/bar for production wells, and the production well flow rate was increased slightly to 125 kg/s. Higher well productivity and flow rates lead to fewer wells and less parasitic pumping losses. Power plant size was also increased to 100 MW_e. Regional studies of EGS resources were used to augment the EGS resource potential in the western United States. Shallower and higher quality EGS resources found by the detailed studies were included.

We used the updated EGS supply cost curves to forecast the amount of geothermal electricity generation that could be deployed in the U.S. by 2050 using the Regional Energy Deployment System (ReEDS) capacity expansion model. In keeping with Earthshot's goals, the baseline modeling assumptions and targets use the Solar Futures Study Decarbonization scenario. This scenario targets a 95% reduction in electric sector-wide CO_2 emissions from 2005 levels by 2035, and a 100% reduction by 2050, and assumes constant existing policies as of June 2020. The ReEDS model assumes that EGS technologies become available for commercial deployment starting in 2030.

The ReEDS model results project that the total amount of installed geothermal is 38.30 GW_e in 2035 and 90.52 GW_e in 2050. Geothermal technologies account for 1.94% of national generating capacity in 2035 and 3.94% in 2050. However, geothermal technologies make 6.13% of annual generation in 2035 and 12.04% in 2050, three times larger than its percentage of installed capacity. This is due to the high capacity factor of geothermal technologies compared to other renewable energy technologies on the grid. The majority of growth in the geothermal industry comes from EGS deployments.

The capacity weighted average LCOE of all developed deep-EGS resources in 2050 is 45.9 $/MWh in 2019$. For 2035, the equivalent number is 45.6 $/MWh. The results were used to develop a cost target for EGS. On September 8th, 2022, the Enhanced Geothermal Shot was announced in Houston, Texas, by Energy Secretary Jennifer Granholm. Its target is to reduce the cost of EGS by 90%, to $45 per megawatt hour by 2035.

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1 Introduction and Background

In 2021, the U.S. Department of Energy (DOE) began the Energy Earthshots™ initiatives. The goal of the Energy Earthshots is to "accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade."[1] The Earthshots set ambitious but achievable cost targets for some of the most challenging technical problems to achieving DOE's 2050 net-zero carbon goals. The initiatives also integrate program development across the DOE technology offices, the Advanced Research Projects Agency-Energy (ARPA-E), and other offices at DOE, such as the Office of Science.

In 2022, the National Renewable Energy Laboratory (NREL) was asked by DOE's Geothermal Technologies Office (GTO) to provide analysis for developing Energy Earthshot targets for enhanced geothermal systems (EGS). EGS are human-made underground reservoirs that extract thermal energy from the Earth for electricity generation and/or heating applications. An EGS is created by drilling into a subsurface heat source and creating new and enhancing existing networks of pathways by injecting fluid. Fluid is injected from the surface to travel through these networks and collect heat before returning to the surface where the thermal energy is put to beneficial use. The result is a reliable baseload energy source that provides power regardless of weather conditions on the surface. Since temperature generally increases with depth in the Earth, EGS can theoretically be sited anywhere and have the potential to power tens of millions of homes. However, significant technical challenges and cost reductions remain before EGS can be considered a mature and commercially competitive technology.

In 2019, GTO published the report *GeoVision: Harnessing the Heat Beneath Our Feet* (DOE 2019). In the report, GTO presents the many electric and non-electric applications for geothermal energy. The report discusses EGS in detail, proposes cost and performance targets for EGS technologies, and outlines actions necessary to reach these targets. It also provides analysis of geothermal deployment potential in the United States and concludes that 60 GW_e of geothermal capacity, most of it from EGS resources, could be deployed in the United States by 2050.

The Enhanced Geothermal Shot analysis builds on the assumptions in the *GeoVision* study and updates some of the assumptions based on recent technology advances. It also updates the EGS resource potential to include more detailed analysis. Similar to the *GeoVision* study, it estimates the amount of geothermal that could be deployed by 2050 using a capacity expansion model. The results were shared and discussed with GTO and were used to develop a cost target for EGS. On September 8, 2022, the Enhanced Geothermal Shot[2] was announced. Its target is to reduce the cost of EGS by 90%, to $45 per megawatt hour by 2035.

This report summarizes the cost and resource assumptions used in the Enhanced Geothermal Shot. It also describes the assumptions used in the Regional Energy Deployment System (ReEDS) capacity expansion model to forecast geothermal deployment and discusses the results.

[1] https://www.energy.gov/policy/energy-earthshots-initiative
[2] https://www.energy.gov/eere/geothermal/enhanced-geothermal-shot

2 Earthshot Geothermal Cost Assumptions

Geothermal plant costs were modeled using the Geothermal Electricity Technology Evaluation Model (GETEM[3]). This tool models the cost and performance of electricity generation from conventional hydrothermal and EGS geothermal resources. GETEM consists of detailed subsystem models of the exploration, drilling, reservoir development, well flow, and power plant operation phases of geothermal development and considers over 300 geothermal system parameters in its techno-economic analysis.

Enhanced Geothermal Shot uses the GETEM input parameters for the Technology Improvement (TI) scenario described in the *GeoVision* study (DOE 2019) as its starting point. Key parameters were updated for Earthshot based on recent and projected technology advances. Earthshot assumes reservoirs are engineered to produce at levels more consistent with those observed at conventional hydrothermal plants. A 2017 analysis of 375 wells (196 production wells and 179 injection wells) throughout California and Nevada yielded statistical values for several well parameters including well flow rate as well as productivity and injectivity indices (Snyder et al. 2017). The injectivity and productivity indices in GETEM were increased for EGS wells to 70 kg/s/bar and 38.1 kg/s/bar, respectively, for the Earthshot analysis. These indices are within the 90th percentile of hydrothermal wells at binary power plants studied in the Snyder et al. analysis, which is aspirational but technically feasible.

Earthshot assumed a production well flow rate of 125 kg/s for EGS technologies. *GeoVision* had assumed 110 kg/s for binary plants and 80 kg/s for flash plants. A 125 kg/s flow rate is only slightly above the average of 112 kg/s for hydrothermal binary wells from the Snyder et al. analysis and is within the 90th percentile of hydrothermal flash wells studied in the 2017 analysis. We assume that flash plants, which lower the pressure or "flash" the geofluid to produce steam for electricity generation, are used for geothermal resources with temperatures of 200°C or higher. Binary plants, which transfer heat from liquid geofluid to a secondary or "working" fluid for electricity generation in a Rankine cycle, are used at lower temperatures. We did not find any reason that EGS production well flow rates would be significantly lower for flash plants than for binary plants, so we decided to recommend the same value for EGS binary and flash plants. We chose 125 kg/s since a change from 110 kg/s to the Snyder et al. study average of 112 kg/s was trivial, and we expect higher flow rates to result from the higher injectivity and productivity values that were chosen for the Enhanced Geothermal Shot.

Additionally, drilling costs were decreased to 80% of the ideal case drilling costs found in the *GeoVision* study. This decrease reflects an increase in drilling rate of penetration (ROP) seen at the Frontier Observatory for Research in Geothermal Energy (FORGE) (Bristol et al. 2021; McLennan et al. 2021), expected decreases in casing costs (Porse et al. 2022), and the expected decrease in mobilization costs due to the introduction of pad drilling (Hole 2007).

Finally, the power plant size for deep EGS plants was increased to 100 MW_e. This reflects the fact that EGS resources are not physically constrained in the same way that traditional hydrothermal resources are constrained by the size of a reservoir, but instead are extensive where

[3] https://www.energy.gov/eere/geothermal/geothermal-electricity-technology-evaluation-model

accessible throughout much of the western United States, as seen in Figure 1. The 100 MW_e capacity was chosen to maximize the marginal benefits of increasing plant size in balance with diminishing returns to scale.

Table 1 provides a comparison of the current or business-as-usual EGS assumptions to Earthshot's cost analysis assumptions. It assumes costs are in 2019$.

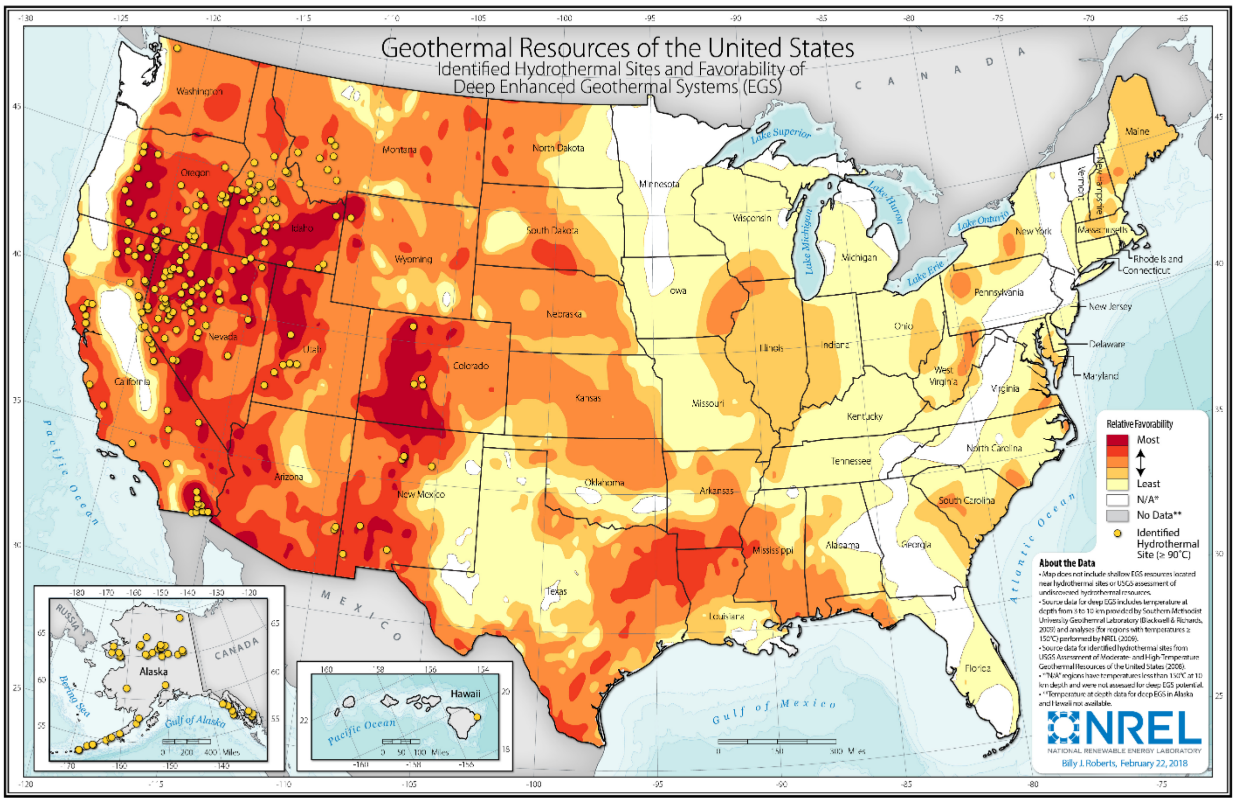

Figure 1. Deep EGS resource favorability and identified hydrothermal sites

Figure by Billy Roberts, NREL

Table 1. Enhanced Geothermal Shot Technology Assumptions Compared to Baseline Values

GETEM Input		Business as Usual	Enhanced Geothermal Shot
RESOURCE EXPLORATION	*Exploration — Pre-Drilling Costs ($/project)*	$250K	Same as BAU
	Exploration — Drilling Costs ($/project)	$1.5M–$5M	2/3 of BAU
	Full-Sized Confirmation Well Costs	Base + 50%	Ideal + 0% (no premium)
	Full-Sized Confirmation Well Success Rate	50%	75%
	Number of Full-Sized Confirmation Wells Required	9	3
DRILLING	*Drilling Success Rate*	75%	90%
	Drilling Costs	Base	80% of Ideal drilling costs from *GeoVision* study
RESERVOIR CREATION	*Well Flow Rate* (flow rate per production well)	40 kg/s	125 kg/s
	Well Productivity	0.46 kg/s/bar	Production: 38.1 kg/s/bar Injection: 70 kg/s/bar
POWER PLANT	*Plant Size*	25 MW_e	100 MW_e

To show the impact of the Enhanced Geothermal Shot assumptions, the cost of a representative EGS plant was calculated using GETEM. A 175°C, 3,000 m, binary deep EGS resource was chosen as the representative plant. Running GETEM using the business-as-usual scenario assumptions resulted in an overnight capital cost (OCC) of 32,255 $\$/kW_e$, the reference cost. Next, the cost of the plant was calculated by applying each group of Earthshot parameters in Table 1 in sequence. Figure 2 depicts the reductions in OCC associated with each additional group of Earthshot GETEM inputs. Overall, the Earthshot cost assumptions resulted in a final OCC of 3,565 $\$/kW_e$, an 89% reduction from the reference case. It should be noted that the input parameters are highly interrelated for EGS OCC calculations, and the cost reductions for each category of parameters in Figure 2 depends on the order they are applied. The cost reductions were applied in the same order as for project development—exploration, followed by drilling, reservoir creation, and finally power plant construction. If the reductions were applied in a different order, then the magnitude of OCC reductions associated with each group would differ. For example, the power plant size assumption would have a bigger impact than a $\$444/kW_e$ decrease if it were applied first instead of last.

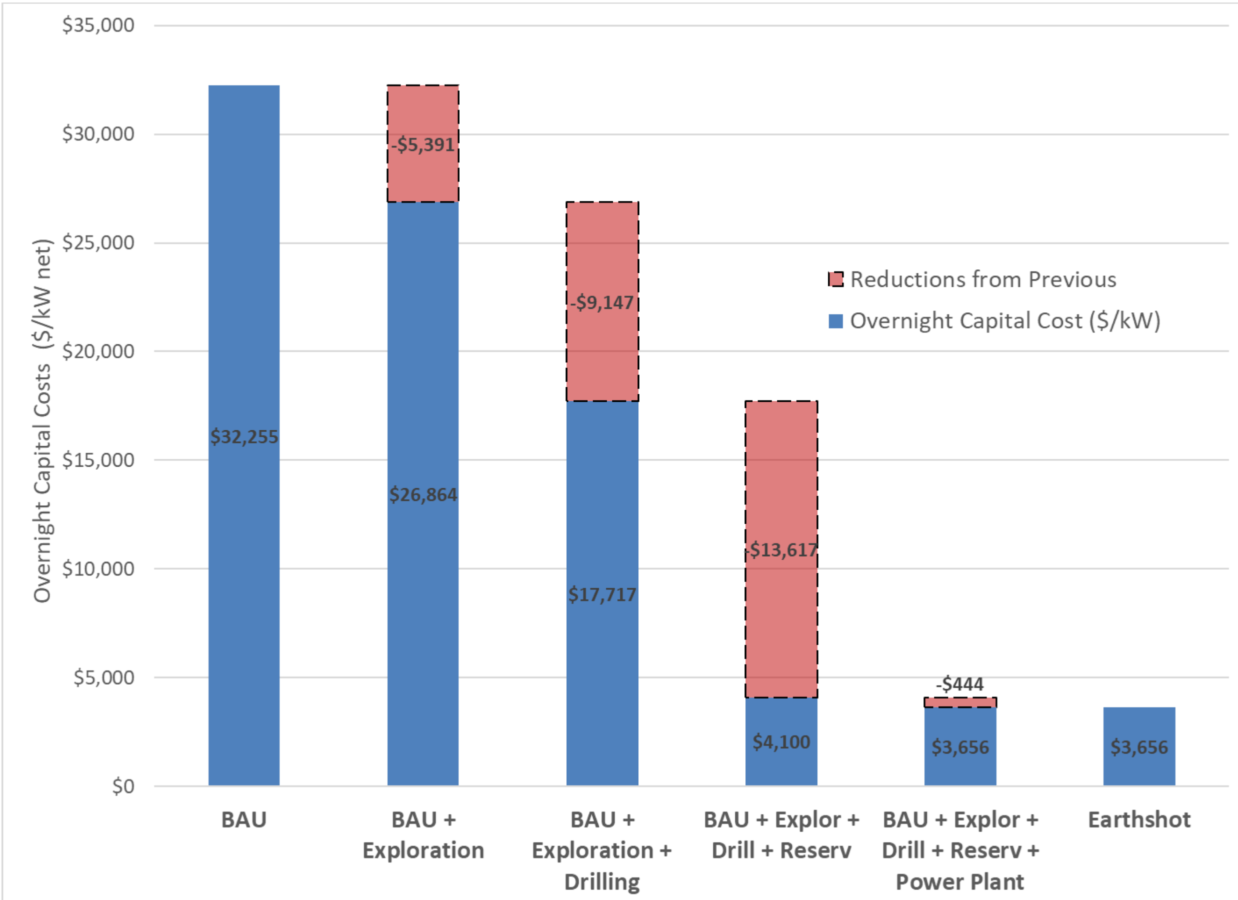

Figure 2. Cost reductions for the implementation of each parameter group seen in Table 1

BAU = business as usual

3 Geothermal Resource Updates

Like the cost assumptions for the Enhanced Geothermal Shot, the geothermal resource was based on that used in the *GeoVision* study's TI scenario (C. R. Augustine, Ho, and Blair 2019). Hydrothermal and EGS geothermal resource types were included in the Earthshot analysis. Hydrothermal resources are naturally occurring geothermal systems and are divided into identified and undiscovered hydrothermal resources for this study. EGS resources consist of underground geothermal reservoirs that have low permeability and have been engineered to allow fluids to be circulated through the rock to extract heat. EGS resources are separated into near-field EGS and deep EGS resources. The geothermal resources are discussed in detail in the *GeoVision* study (DOE 2019; C. R. Augustine, Ho, and Blair 2019).

Hydrothermal resource potential is based on the U.S. Geological Survey's (USGS) geothermal resource assessment of identified and undiscovered resources (Williams et al. 2008; Williams, Reed, and Mariner 2008) and was not updated for Earthshot. After accounting for current deployments, land restrictions, and likely barriers to development, Earthshot assumes 5,128 MW_e of identified hydrothermal resources and 23,038 MW_e of undiscovered hydrothermal resources are available for development. Details about the location and attributes of the hydrothermal resources are available in Augustine, Ho and Blair (2019).

Both the near-field and deep EGS resource potentials were updated for the Enhanced Geothermal Shot analysis. The methodology for updating each is discussed below.

3.1 Near-Hydrothermal EGS Resource Update

Near-field EGS resources are the areas around hydrothermal sites that are elevated in temperature but lack sufficient permeability and/or in-situ fluids to be economically produced as a conventional hydrothermal resource. These resources require the application of EGS reservoir engineering techniques to become economic producers of electricity. In the *GeoVision* study, the near-field EGS potential was limited to a subset of identified hydrothermal sites that had been assessed as part of the USGS geothermal resource assessment (Williams et al. 2008) but not included in the final report. In that study, the near-field EGS resource potential for the TI scenario was assumed to be 1,443 MW_e.

Conventional hydrothermal resources are, by their nature, found in areas of elevated heat flow. It is reasonable to assume, and was shown by the USGS study, that conventional hydrothermal resources are surrounded by relatively high-temperature rock that would be good candidates for EGS development. Based on this, the near-field EGS potential was updated to be equivalent to the hydrothermal resource potential under the assumption that the accessible near-field EGS resource would be equivalent to the identified and undiscovered hydrothermal resource baseline.

The near-field EGS resources were assumed to have the same temperature, reservoir depth, and resource potential as the hydrothermal resources, resulting in 28,166 MW_e of near-field EGS potential. However, the costs for a near-field EGS resource differ from those for the identical hydrothermal resource due to differing assumptions about hydrothermal and EGS development costs and performance.

3.2 Deep EGS Resource Update

The deep EGS resource potential is made up of the heat trapped in the Earth that can be found virtually anywhere by drilling deep enough. The United States' deep EGS resource potential in the *GeoVision* study was based on national maps of temperature at depth produced by the Southern Methodist University Geothermal Laboratory (D. Blackwell et al. 2011). It consisted of the thermal energy stored in rock at depths of 3–7 km below the Earth's surface and at temperatures exceeding 150°C in the continental United States. The deep EGS resource potential based on these assumptions is huge—over 5,000 GW_e nationally (C. Augustine 2016). Even after accounting for barriers to development, the *GeoVision* TI scenario puts the deep EGS resource at 4,248,879 MW_e.

While the national-scale maps demonstrate the large overall EGS potential, they have a coarse resolution that filters out some local heat anomalies. They also ignore EGS resources shallower than 3 km entirely. Recent studies have found larger estimates of EGS resource potential for regional-scale EGS resource assessments using higher resolution temperature at depth. Higher resolution temperature-at-depth maps preserve localized, higher temperature anomalies that lead to larger estimates of available EGS resource (Figure 3).

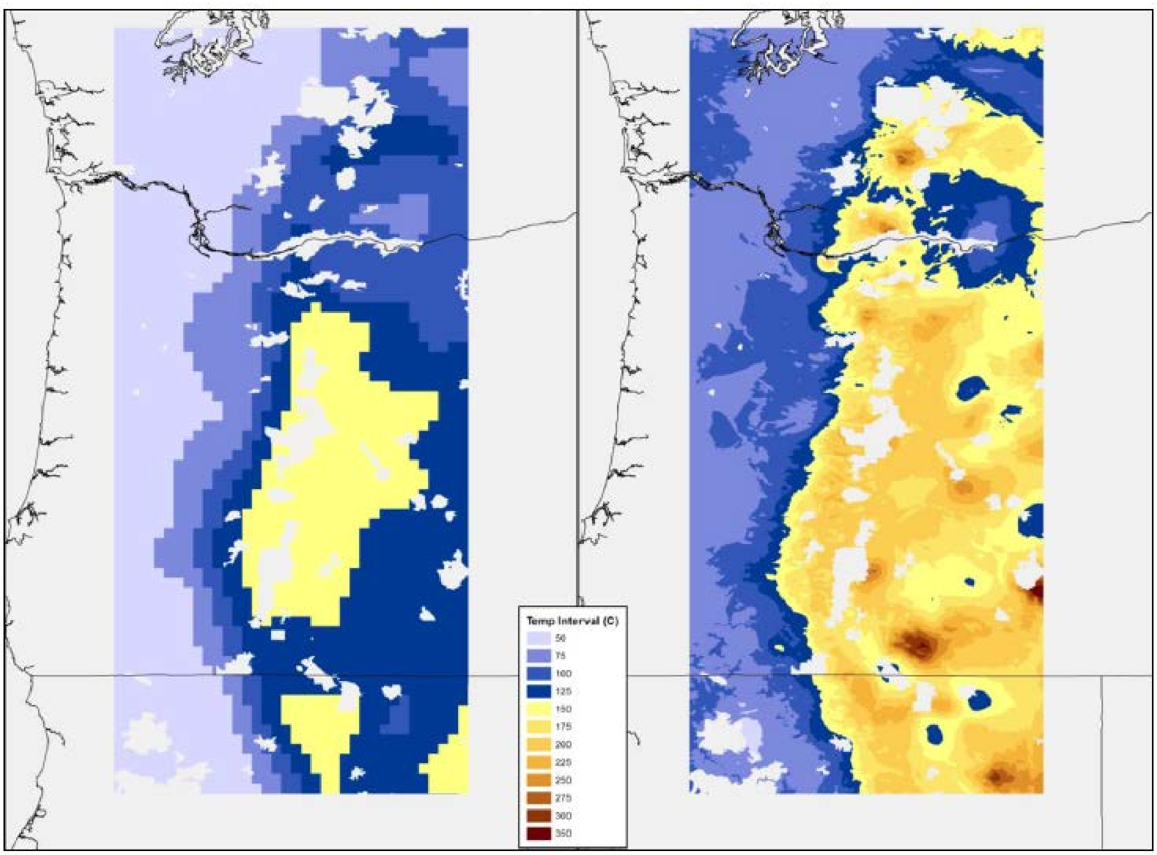

Figure 3. Comparison of Southern Methodist University's temperature estimates at a depth of 3.5 km (left) and temperature estimates at 3 km from a detailed regional study of the Cascades region by (Frone et al. 2015)

Map from Frone et al. 2015

The deep EGS resource potential for the Enhanced Geothermal Shot analysis was updated using three regional EGS resource potential studies (Figure 4). The first two regional studies focused in the Cascades (Frone et al. 2015) and Great Basin (C. R. Augustine, Ho, and Blair 2019). These resources were included in the *GeoVision* study as sensitivity studies (C. R. Augustine, Ho, and Blair 2019). The third study was completed recently and covers the Snake River Plain (Batir et al. 2020). Regional studies in the Cascades and Great Basin focused on shallower EGS opportunities (1–4 km and at 3 km depths, respectively), while the Snake River Plain study updated EGS potential estimates from shallow to deep (1–10 km) depths. Two types of updates were made. First, the regional studies were used to include resources at depths shallower than those covered by the national map. Second, the studies were used to justify increasing the resource potential at depths covered by the national maps (3–7 km).

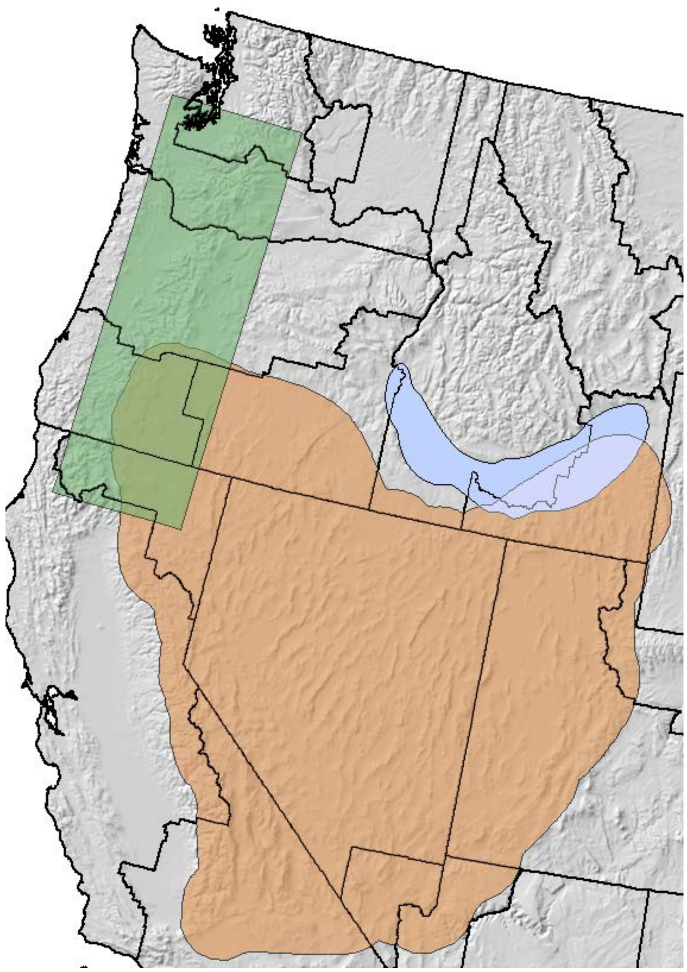

Figure 4. Maps showing the study areas for the three EGS resource potential regional studies used in the Enhanced Geothermal Shot. Map also shows boundaries for the balancing areas used in the ReEDS model.

3.2.1 Shallow (<4 km) EGS Resources

As mentioned above, the deep EGS resource potential estimate is based on national maps of temperature at depth produced by the Southern Methodist University Geothermal Laboratory (D. Blackwell et al. 2011) and comprises the energy stored in rock at depths of 3–7 km below the

Earth's surface and at temperatures exceeding 150°C in the continental United States. The resource estimate was made by dividing the subsurface into 1-km thick sections and determining the thermal energy in each section. The estimate uses the temperature value from the maps at the midpoint of the reservoir (e.g., the temperature at 3.5 km is used to estimate the EGS resource potential of 3–4 km).

The national maps do not use data from known geothermal areas for gridding or making contours of temperature at depth, because including them causes wide variance in gradients within a small area and the high temperature gradients result in unrealistic temperatures at greater depths. The national maps limit heat flow values (which are used to derive temperature at depth) to 120 W/m^2 (D. D. Blackwell and Richards 2004). The result is that the national maps filter out many high-temperature EGS resources, especially at shallow depths. Regional studies, which focus on smaller areas, allow for more detailed analysis and can incorporate this data. Table 2 illustrates the difference between EGS potential estimates using national vs. regional maps for the Cascades region at a depth range of 3–4 km (Frone et al. 2015). The regional map not only finds a much larger EGS resource potential, but it also identifies resources at higher temperatures (higher quality) than the national maps. Using regional maps results in more overall EGS resource potential and in higher quality EGS resources that are more likely to be developed.

Table 2. Comparison of EGS Potential (MW_e) at 3–4 km Depth in the Cascades Regional Area Made Using National Maps vs. Regional Maps

Table from Frone et al. 2015

Temperature Interval	2006 National Map (MIT 2006 Report)			2014 Cascades Map (this study)		
	CA	OR	WA	CA	OR	WA
150-175	2,834	11,548		1,713	8,041	3,307
175-200				3,490	11,052	1,856
200-225				3,236	14,048	523
225-250				1,488	2,837	257
250-275				572	697	159
275-300				163	363	
300-325					284	
325-350					117	
Totals	2,834	11,548		10,662	37,438	6,102
	14,382			54,202		

For the Enhanced Geothermal Shot, data for shallow (<4 km) EGS resources from three regional studies were appended to the deep EGS supply curve. The Cascades regional study covered depths of 1–4 km and included a total of 106 GW_e of EGS potential over this depth range (Frone et al. 2015). The Snake River Plain regional study also covered depths of 1–4 km and found about 25 GW_e of EGS resource (Batir et al. 2020). The Great Basin regional study produced a map at 3 km depth and included 116 GW_e of EGS potential (C. R. Augustine, Ho, and Blair 2019). For cases where data from the maps overlapped (Figure 4), one data source was chosen to avoid double counting the EGS resource. The Cascades and Snake River Plain map data at 3 and 4 km were used in place of the national map data at 3.5 and 4.5 km, respectively. Likewise, the Great Basin map data at 3 km were used in place of the national map data at 3.5 km. The net result was an additional 230 GW_e of detailed EGS potential at depths <4 km added for the Enhanced Geothermal Shot analysis.

3.2.2 Deep (>4 km) EGS Resources

The regional study data indicate that the national map underestimates the EGS resource potential at depths less than 4 km. The EGS resources in regional study areas were compared to the data in the national map at depths where a comparison was available. EGS resource potential of the Snake River Plain at a depth of 3.5 km increased by a factor of 1.8 with new analyses using higher resolution temperature-at-depth maps (Batir et al. 2020). In the Cascades, estimated EGS potential at 3.5 km depth increased by a factor of 3.8 based on a regional study compared to a national map (Frone et al. 2015) (Table 2). In the Great Basin, estimated EGS potential at 3 km depth increased by a factor of 3.6 compared to the national map at 3.5 km (C. R. Augustine, Ho, and Blair 2019).

Based on the increase in resource potential for shallow (<4 km) EGS resources from the regional studies, the deep (>4 km) EGS resources were increased. Deep EGS resource potential was increased by a factor consistent with those seen in the regional studies. The increase was applied only in the regional study areas for EGS resources >4 km depth. A multiplier of 3.7 was assigned to the deep EGS potential of the Cascade and Great Basin study areas. Though their analyses of greater depths showed larger increases, the more conservative multiplier of 1.8 was used for estimates of deep EGS within the Snake River Plain study area. The result is an additional 3,000 GW_e of EGS resource potential added for the Enhanced Geothermal Shot analysis.

3.3 Alaska and Hawaii

The geothermal resource potential values discussed above apply to the contiguous United States and do not include resources in Alaska and Hawaii for several reasons. First, the USGS resource assessment (Williams et al. 2008) that forms part of the basis for the geothermal resource potential includes estimates for hydrothermal resources, but not for EGS. Likewise, the national maps used to develop the EGS resource (D. Blackwell et al. 2011) did not include Alaska and Hawaii due to a lack of temperature-at-depth and heat flow data.

The lack of EGS resource potential estimates in Alaska and Hawaii did not impact the Enhanced Geothermal Shot analysis because the ReEDS model is also limited to the contiguous United States. However, both states have significant geothermal resources, and efforts are underway to improve the characterization of their geothermal resources. For example, our internal identified hydrothermal resource database was updated to include 200 MW_e of additional resources at Mt. Spurr and Mt. Augustine in Alaska. Efforts are underway to improve estimates of resource potential in Alaska and Hawaii through GTO funding. Curie point depth, radiogenic heat production, and other data sets are being evaluated to assess how they can improve estimations of heat flow and geothermal potential.

3.4 Summary of Resource Potential Updates

Table 3 summarizes the resource potential values used for geothermal resource types in the Enhanced Geothermal Shot analysis compared to those used in the *GeoVision* study in 2019. The identified and undiscovered hydrothermal resource potential values are unchanged. The near-field EGS resource was updated using the assumption that the near-field EGS resources can be found around all conventional hydrothermal resources and therefore can be set equal to the hydrothermal resource. The deep EGS resource potential was increased substantially based on learnings from regional EGS studies. The increase includes the addition of about 230 GW_e of shallow (<4 km) EGS resources not identified by national maps in the *GeoVision* study, and an increase of about 3,000 GWe in deeper (>4 km) EGS resources in the study areas based on comparisons of regional vs. national study results. The increases were only applied to the regional study areas. A map showing the geothermal resource potential for the Enhanced Geothermal Shot is shown in Figure 5. The map illustrates how geothermal resources are concentrated in the western United States.

Table 3. Comparison of Geothermal Resource Potential Values Used in the *GeoVision* Study vs. in the Enhanced Geothermal Shot Analysis

Study	Identified Hydrothermal	Undiscovered Hydrothermal	Near-Field EGS	Deep EGS
GeoVision Technology Improvement (TI) Scenario	5,128	23,038	1,443	4,248,879
Enhanced Geothermal Shot	5,128	23,038	28,166	7,469,002

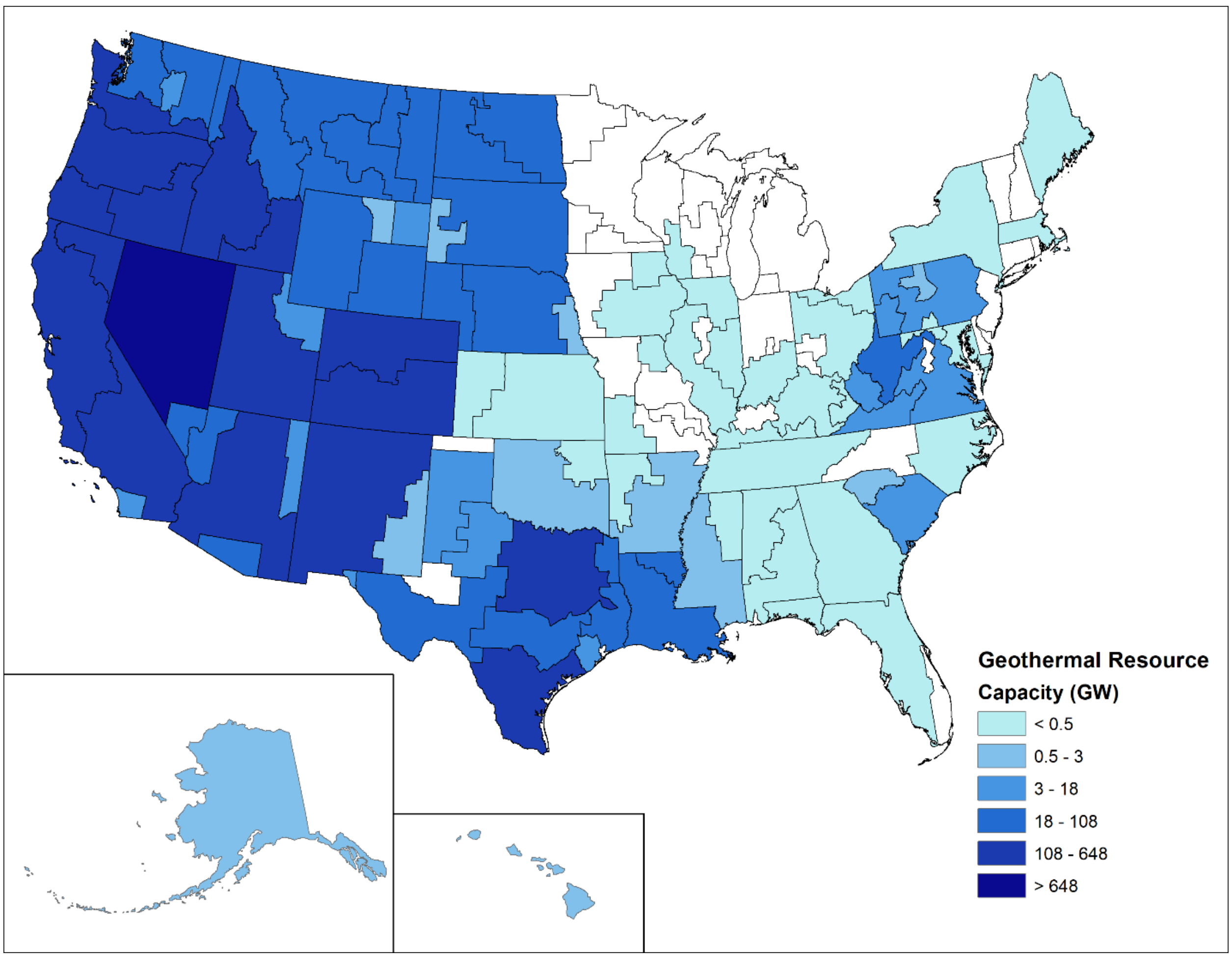

Figure 5. Total U.S. geothermal resource capacity (GWe) by ReEDS balancing authority used for the Earthshot analysis. Resource capacity map includes estimates for Hawaii and Alaska.

4 ReEDS Modeling Results

For Earthshot, we applied the Regional Energy Deployment System (ReEDS[4]) to simulate the deployment of geothermal technologies into the electricity sector through 2050. ReEDS is a robust capacity expansion model that considers the time, cost, value, and technical characteristics and interactions of a large array of generating technologies, including fossil, nuclear, renewables, as well as transmission and energy storage. Earthshot's baseline modeling assumptions and targets align with the Solar Futures Study (Ardani et al. 2021) Decarbonization (Decarb) scenario. This scenario targets a 95% reduction in electric sector-wide CO_2 emissions from 2005 levels by 2035, and a 100% reduction by 2050, and assumes constant existing policies as of June 2020. These targets are consistent with the goals of the Energy Earthshots.

Non-geothermal technology costs are modeled to match scenarios created in the 2021 Annual Technology Baseline (ATB[5]). The ATB is a yearly initiative out of NREL that provides a consistent set of technology cost and performance data for energy analysis. Each technology in the ATB is modeled according to three scenarios: Conservative, Moderate, and Advanced. For the Earthshot analysis, all non-geothermal technologies including battery storage were modeled according to the 2021 ATB Moderate scenario assumptions. The 2021 ATB assumes costs are in 2019$.

Geothermal technologies were modeled according to the Earthshot cost modeling assumptions outlined in Section 2. The cost assumptions were applied to the geothermal resource potential outlined in Section 3 to produce supply curves for each of the geothermal resource types. The ReEDS model assumes that EGS technologies become available for commercial deployment starting in 2030. Figure 6 shows the OCC as a function of cumulative capacity for geothermal resources in 2030. It includes all cost and performance assumptions for EGS listed in Table 1. The cumulative capacity axis is truncated to show the details for hydrothermal and near-field EGS resources. Note that due to the assumed improvements in EGS technology, the highest quality EGS resources have a lower OCC than remaining[6] conventional hydrothermal resources once they are commercially available. Hydrothermal and near-field EGS resource OCC rise quickly at the end of their OCC vs. cumulative capacity curves. This rise reflects the poor quality of these resources, due to low temperatures and/or excessive depths. These resources are not likely to be developed but are included for completeness. The deep EGS supply curve would exhibit the same behavior if the cumulative capacity axis were extended to its full range for deep EGS. Figure 7 shows the same supply curve with an extended (not fully extended) capacity axis to show the full range of EGS resources that are likely to deploy.

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[4] https://www.nrel.gov/analysis/reeds/index.html

[5] https://atb.nrel.gov/

[6] Note that roughly 3 GW_e of conventional hydrothermal resources are already deployed in the United States. These deployments are mostly at high-quality resource sites with surface expressions that indicated the presence of a geothermal resource.

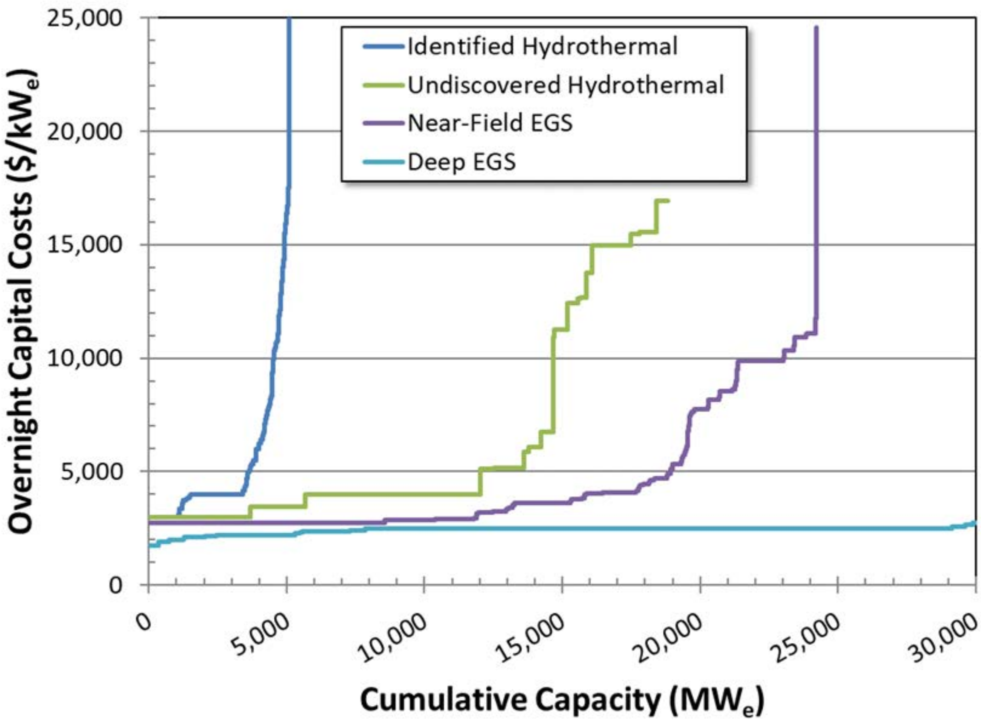

Figure 6. Available geothermal capacity (MW$_e$) at its modeled overnight capital cost ($/kW) for each geothermal technology in 2030

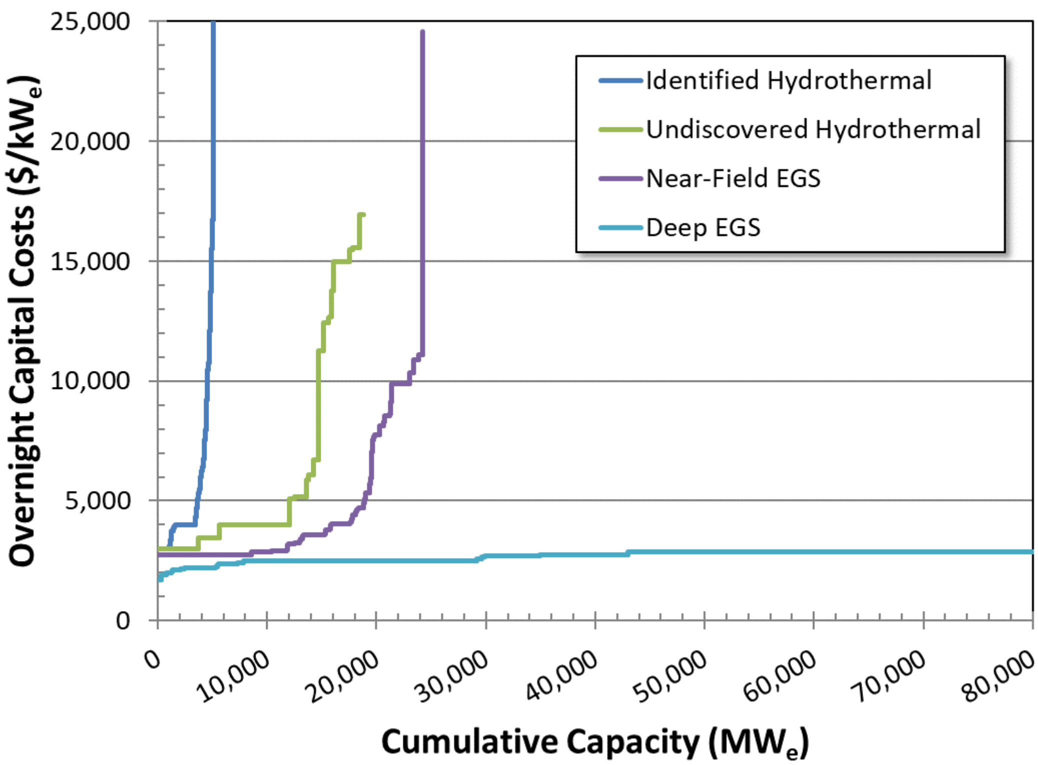

Figure 7. Extended view of available geothermal capacity (MW$_e$) at its modeled overnight capital cost ($/kW) for each geothermal technology in 2030

4.1 Geothermal Deployments

The ReEDS model was run using the supply curves developed for the Enhanced Geothermal Shot, along with the Decarb scenario from Solar Futures that assumes a 95% reduction in economy-wide CO_2 emissions from 2005 levels by 2035, and a 100% reduction by 2050. The resulting installed capacity by technology for 2020–2050 is shown in Figure 8. Geothermal installed capacity in each year is shown at the bottom of the stack. Most of the Decarb scenario decarbonization goals are met by installed solar photovoltaic (PV) and onshore wind, with support from battery storage technologies to shift periods of energy generation to supply energy demand and natural gas technologies to provide firm capacity. Geothermal technologies make 1.94% of national generating capacity in 2035 and 3.94% in 2050. However, because of geothermal's high capacity factor, its contribution to decarbonization is larger when electricity generation is considered.

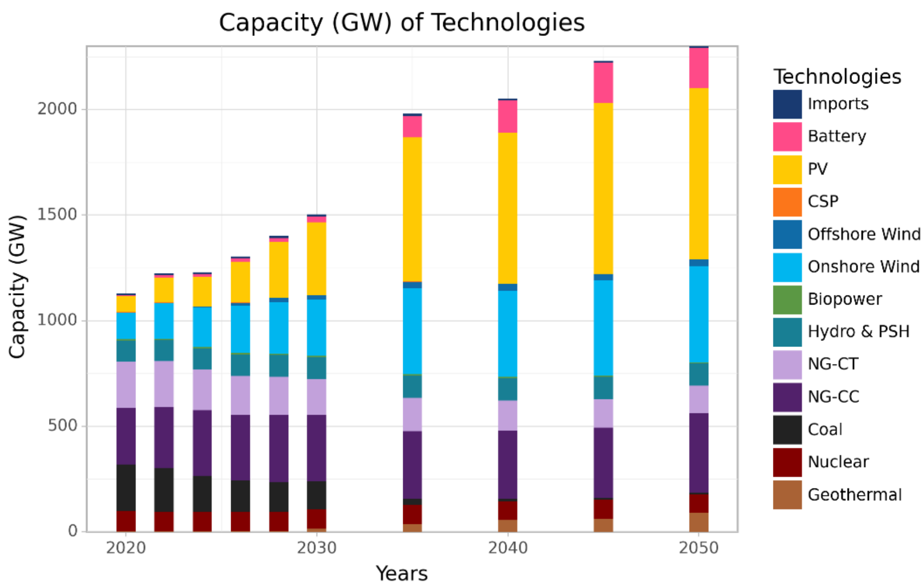

Figure 8. ReEDS model results for installed capacity by technology for the Enhanced Geothermal Shot analysis

CSP = concentrating solar power; PSH = pumped storage hydropower; NG = natural gas; CT = combustion turbine; CC = combined cycle

The total annual electricity generation by technology for 2020–2050 is shown in Figure 9. Geothermal annual electricity generation in each year is again shown at the bottom of the stack. Geothermal technologies make 6.13% of annual generation in 2035 and 12.04% in 2050, three times larger than its percentage of installed capacity. This is again due to the high capacity factor of geothermal technologies compared to other renewable energy technologies on the grid. Conversely, natural gas technologies' contribution to generation is much smaller compared to its generating capacity. This illustrates how natural gas technologies are used to firm capacity and are only called on to generate when necessary. Battery technologies are not included in Figure 9 because they do not generate electricity, only store it.

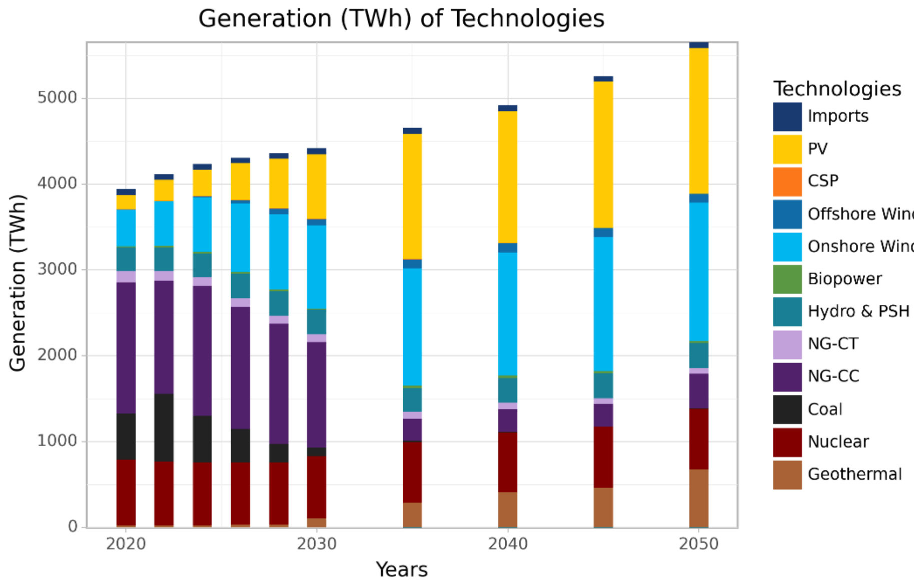

Figure 9. ReEDS model results for annual electricity generation by technology for the Enhanced Geothermal Shot analysis

Figure 10 and Table 4 provide a more detailed view of the geothermal technologies comprising the installed geothermal capacity under the Enhanced Geothermal Shot. The total amount of installed geothermal is 38.30 GW_e in 2035 and 90.52 GW_e in 2050. The majority of growth in the geothermal industry comes from EGS deployments once it is available for deployment starting in 2030. Most new installed capacity is specifically from the deep EGS resource. This is consistent with the geothermal supply curves in Figure 7, which show a large amount of deep EGS resources at a low OCC compared to other geothermal resource types.

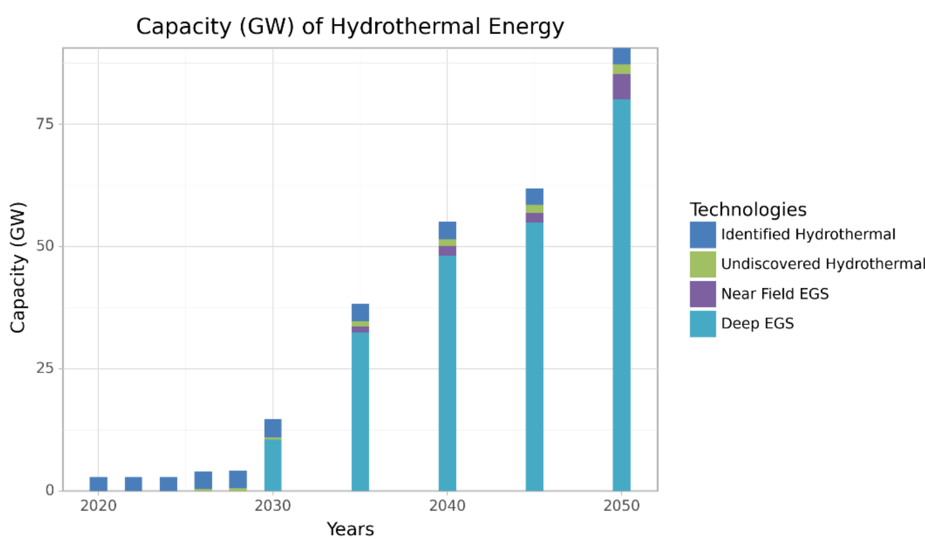

Figure 10. ReEDS model results for installed geothermal capacity by technology type for the Enhanced Geothermal Shot analysis

Table 4. ReEDS Model Results for Installed Capacity by Technology Type for the Enhanced Geothermal Shot Analysis

	2035	2050
Identified Hydrothermal	3.61	3.24
Undiscovered Hydrothermal	1.01	2.03
Near Field EGS	1.30	5.13
Deep EGS	32.38	80.13
Total	**38.30 GW_e**	**90.52 GW_e**

The results of the ReEDS model for the Enhanced Geothermal Shot can be used to characterize future potential growth trends in the geothermal industry by observing geothermal deployments over time. Table 5 shows the average annual deployments of geothermal resource types by decade from the ReEDS results. Conventional hydrothermal resources make up all deployments in the 2020s but only make up a minority of deployments in later years. Deep EGS deployments dominate once they become available in 2030. Geothermal deployments reach their maximum in the 2030s but remain strong through 2050. Table 5 shows annual financed capital expenditures for geothermal by decade. The results show that geothermal project construction in the U.S. becomes a $10+ billion dollar per year industry starting in 2030.

Table 5. Average Annual Geothermal Capacity Deployments by Resource Type and Total Average Annual Expenditures on Geothermal Installations by Decade for the Enhanced Geothermal Shot

Time Period	Annual Average Additions (MW_e/yr)				Annual Averaged Financed Capex (2020 $/yr Billions)
	Hydrothermal	Undiscovered	Near Field EGS	Deep EGS	
2020–2029	149	92	0	0	0.91
2030–2039	0	68	170	4183	15.32
2040–2050	0	68	286	3192	12.19

Figure 11 and Figure 12 show EGS deployments by state for 2035 and 2050, respectively. The majority of deployments are in the west, with most in California. However, we do see some deployments projected in the east and in the southwest in later years. West Virginia has a relatively good EGS resource that results in significant EGS deployment. In later years, Texas and Louisiana both see a large amount of EGS deployment.

Additional scenarios using the Enhanced Geothermal Shot assumptions were run to study the sensitivity of geothermal deployments to scenario assumptions. Those scenarios, along with further discussion of the primary Decarb scenario, are included in Appendix A.

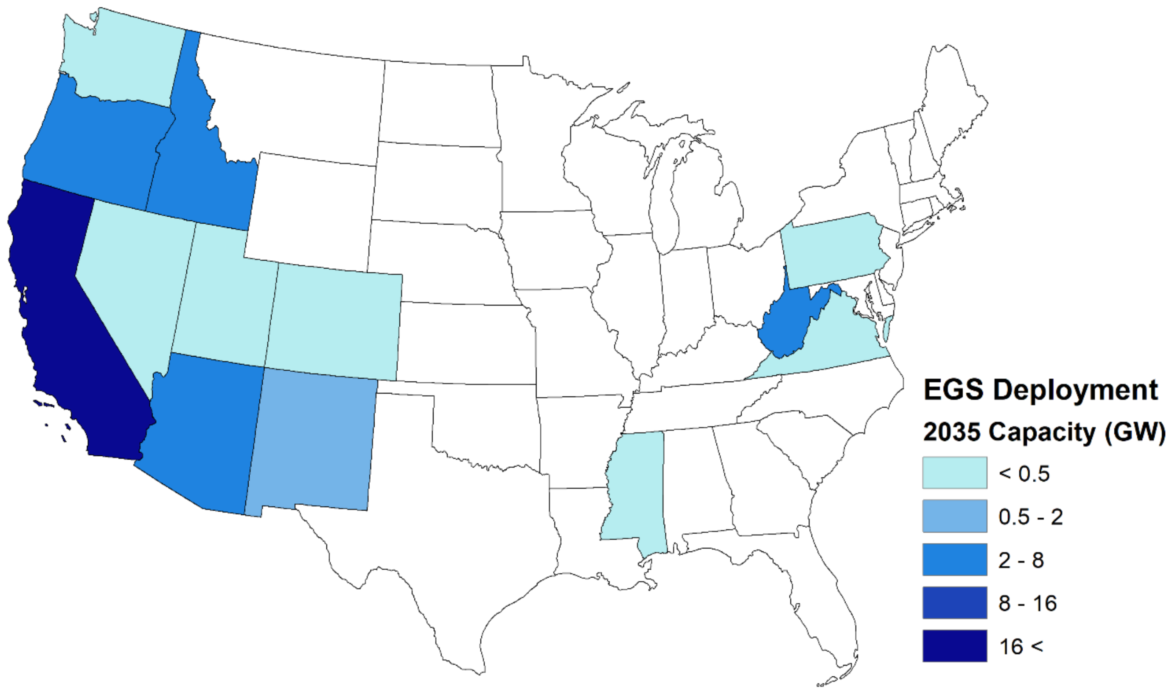

Figure 11. EGS cumulative installed capacity in 2035 using Enhanced Geothermal Shot assumptions and Decarb scenario in ReEDS

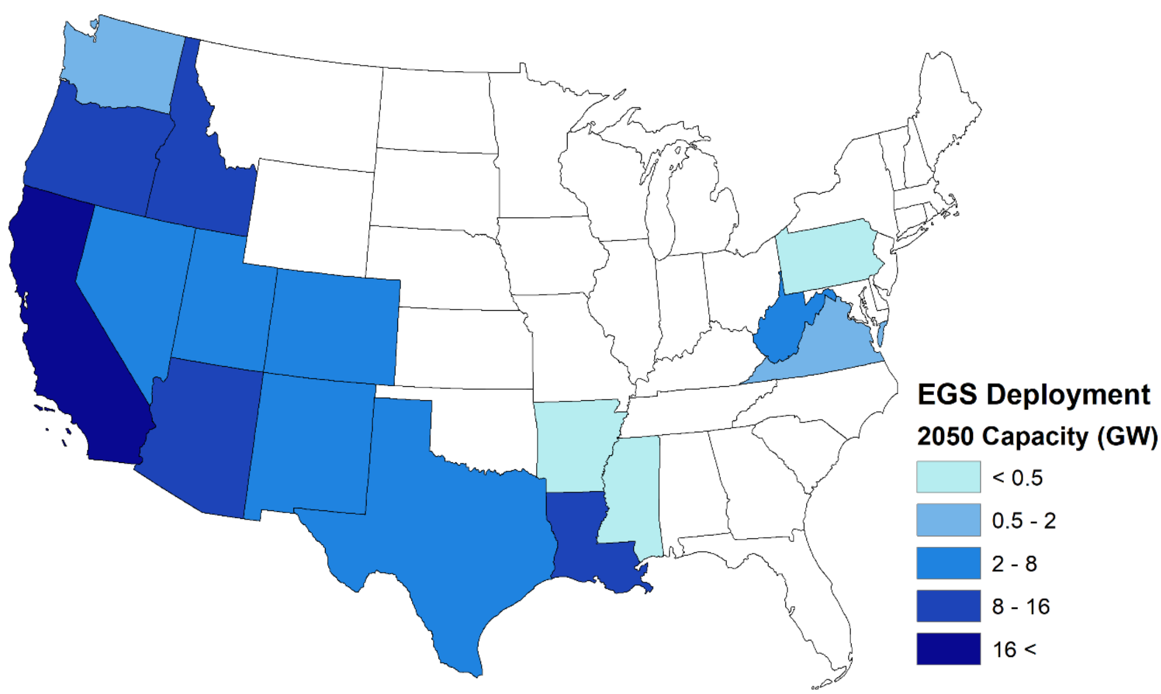

Figure 12. EGS cumulative installed capacity in 2050 using Enhanced Geothermal Shot assumptions and Decarb scenario in ReEDS

4.2 Geothermal Costs

In addition to deployment capacity and location, the cost of deployed geothermal is also of interest. The cost of deployed geothermal is a function of the market it is deployed in and varies with time and location due to variations in the cost, availability, and demand for competing generation technologies. Figure 13 and Figure 14 show the range of levelized cost of electricity (LCOE) for deployed EGS resources by state from the analysis for 2035 and 2050, respectively. The share of EGS deployment by state in 2035 and 2050 is detailed in Table 6. The figures show that deployed EGS costs vary from around \$30–\$60/MWh in 2035 and \$30–\$70/MWh in 2050. Note that EGS resources in western states, where the EGS resource is better, deploy at lower costs than those in eastern states like West Virginia. Also, states with low-cost EGS resources, like California and Oregon, have a wider variability in deployed costs since the lowest-cost resources are deployed first and then more expensive resources are deployed. In the western United States, EGS deployments are limited to resources that cost about \$50/MWh_e or less in 2035 and about \$45/MWh_e in 2050. The reason that EGS deploys at higher costs in the Eastern U.S. is that it has fewer and lower-quality renewable energy resources than the west, so geothermal can compete to meet the decarbonization requirements.

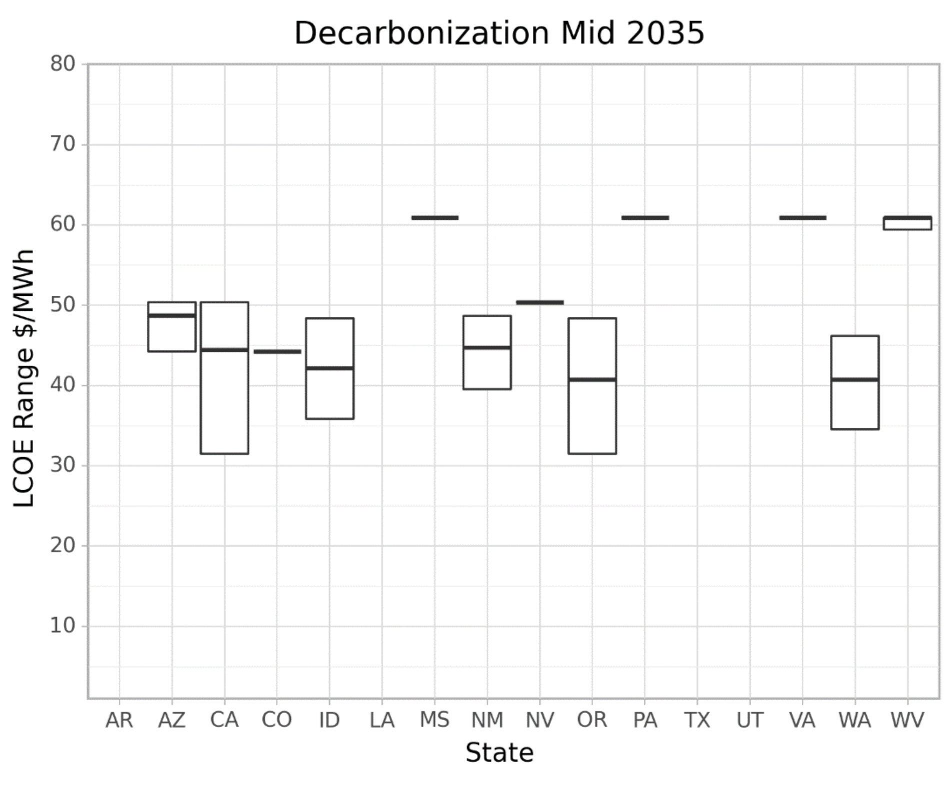

Figure 13. Range of costs for deployed EGS resources by state in 2035 using Enhanced Geothermal Shot assumptions and Decarb scenario in ReEDS

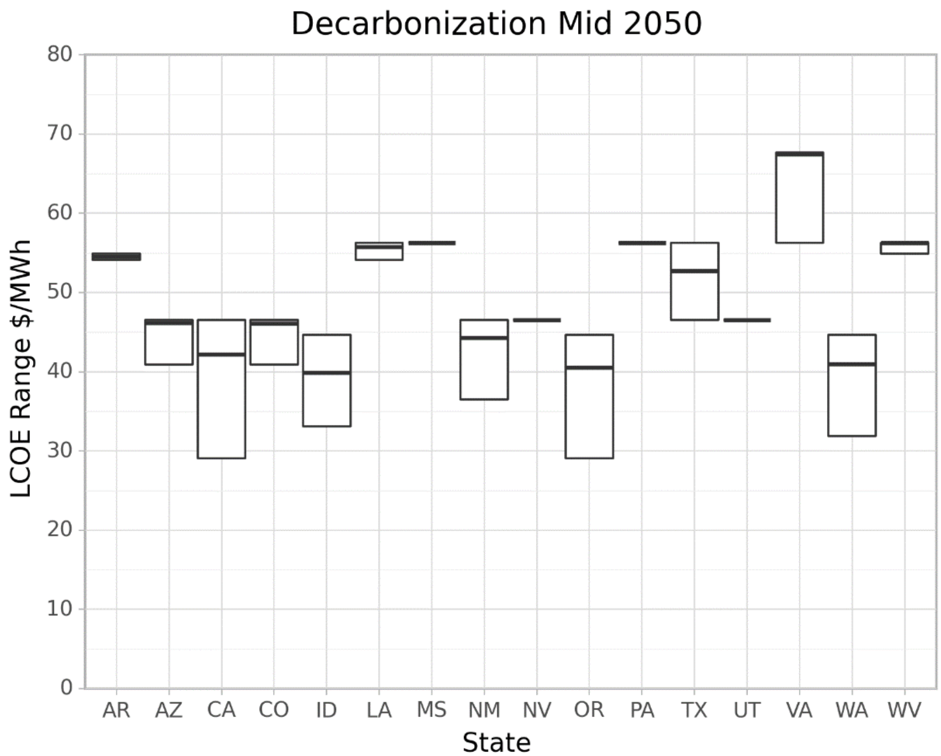

Figure 14. Range of costs for deployed EGS resources by state in 2050 using Enhanced Geothermal Shot assumptions and Decarb scenario in ReEDS

Table 6. Total Enhanced Geothermal Installed Capacity by State for 2035 and 2050 for the Enhanced Geothermal Shot.

Year	Installed Enhanced Geothermal Capacity (GW)															
	AR	AZ	CA	CO	ID	LA	MS	NM	NV	OR	PA	TX	UT	VA	WA	WV
2035		2.1	18.2	0.3	5.1		0.0	1.1	0.1	3.4	0.0			0.0	0.3	3.1
2050	0.0	9.7	27.9	4.1	8.6	10.5	0.0	2.5	2.4	8.4	0.0	3.1	3.4	1.0	0.5	3.1

One of the goals of this analysis was to help the Earthshot initiative choose a cost target for EGS. The capacity weighted average LCOE of all developed deep-EGS resources in 2050 is $45.9\ \$/\text{MWh}_e$. For 2035, the equivalent number is $45.6\ \$/\text{MWh}_e$. Based on these results, a value of $\$45/\text{MWh}_e$ was chosen as a target for the Enhanced Geothermal Shot.

5 Conclusions

NREL provided analysis to GTO to help develop targets for EGS as part of the Enhanced Geothermal Shot. NREL researchers started with the *GeoVision* study TI scenario and made adjustments to cost and resource assumptions based on recent work and technology advancements. Cost reductions included a 20% decrease in average drilling costs and increased well productivity, which reduces the number of wells needed, for EGS projects. Resource potential adjustments included adding shallow, hot EGS resources based on regional studies, and increasing the total amount of deep EGS resources in those same areas. The net effect of the Enhanced Geothermal Shot cost reductions, compared to current or business-as-usual EGS costs, is a 90% reduction in overnight installed EGS costs.

The ReEDS model was used to project geothermal deployments using the Enhanced Geothermal Shot assumptions. The analysis and modeling used the Decarb scenario from the Solar Futures Study (Ardani et al. 2021). This scenario sets a 95% reduction in economy-wide CO_2 emissions from 2005 levels by 2035, and a 100% reduction by 2050, and assumes constant existing policies as of June 2020. The results of the simulations were that geothermal technologies make 1.94% of national generating capacity in 2035 and 3.94% in 2050. When annual electricity generation is considered instead, percentages increase to 6.13% of annual generation in 2035 and 12.04% in 2050, due to the high capacity factor of geothermal technologies compared to other renewable energy technologies.

The costs of the deployed EGS resources vary by location and time, due to variations in geothermal resource quality with geography, and also by variations in demand and the cost and availability of competing technologies able to help meet the Decarb targets. EGS installed LCOE varied from a little over \$30/MWh_e to just under \$70/MWh_e in the ReEDS results. EGS resources in the eastern United States were found to be the most expensive that still deploy. The capacity-weighted average LCOE of all developed deep-EGS resources in 2050 is 45.9 \$/MWh_e. For 2035, the equivalent number is 45.6 \$/MWh_e. These formed the basis target chosen for the Enhanced Geothermal Shot. Combined with the EGS cost reduction targets, the ReEDS results helped DOE choose their Enhanced Geothermal Shot—to reduce the cost of EGS by 90%, to \$45 per megawatt hour by 2035.

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Appendix A. Sensitivity Scenarios

This appendix discusses the Enhanced Geothermal Shot ReEDS results in more detail and presents the results of some sensitivity studies as well. We used ReEDS to simulate the deployment of geothermal technologies into the electricity sector through 2050. For our primary scenario, we used the Solar Futures Study (Ardani et al. 2021) Decarbonization (Decarb) scenario to describe technology costs and performance, electricity demand, policy requirements, and other model assumptions. This scenario requires a 95% reduction in economy-wide CO_2 emissions from 2005 levels by 2035, and a 100% reduction by 2050, and assumes constant existing policies as of June 2020. To meet these reductions, the Decarb scenario includes batteries, renewable energy combustion turbines (RE-CT) and direct air capture (DAC) as technology options. RE-CTs are modeled with a fuel cost of $20/MMBTU, encompassing multiple fuel types such as biofuels, hydrogen, synthetic methane, and others (Ardani et al. 2021). DAC technologies extract carbon dioxide from the air and convert it to a stable form that removes it from the atmosphere. ReEDS can use DAC to offset emissions from CO_2 emitting technologies that remain part of the capacity and generation mix in this scenario. DAC performance and cost estimates are based on the conservative estimates in the journal article "Techno-economic assessment of CO_2 direct air capture plants" (Fasihi, Efimova, and Breyer 2019). For DAC systems, we assume a capture conversion efficiency of 2.79 MWh/metric ton of CO_2 with capital costs starting at 820 $/Tonne-year but declining to 323 $/Tonne-year and 224 $/Tonne-year in 2035 and 2050, respectively.

Batteries play a significant role in the Enhanced Geothermal Shot Decarb scenario. They have more installed capacity than geothermal in 2035 and 2050. However, they do not contribute anything to electricity generation, where geothermal plays a much larger role. Batteries store generated electricity until it is needed and return it to the grid.

RE-CTs do not deploy in the results at all. Instead, natural gas technologies are kept online, and DAC are used to offset their emissions. Like batteries, DAC does not contribute electricity generation to the grid, but instead increases electricity demand. As such, DAC does not provide any electricity generation capacity either and does not appear in Figure 8. Figure A-1 shows installed capacity by technology but includes DAC (using its electric power rated capacity) for comparison.

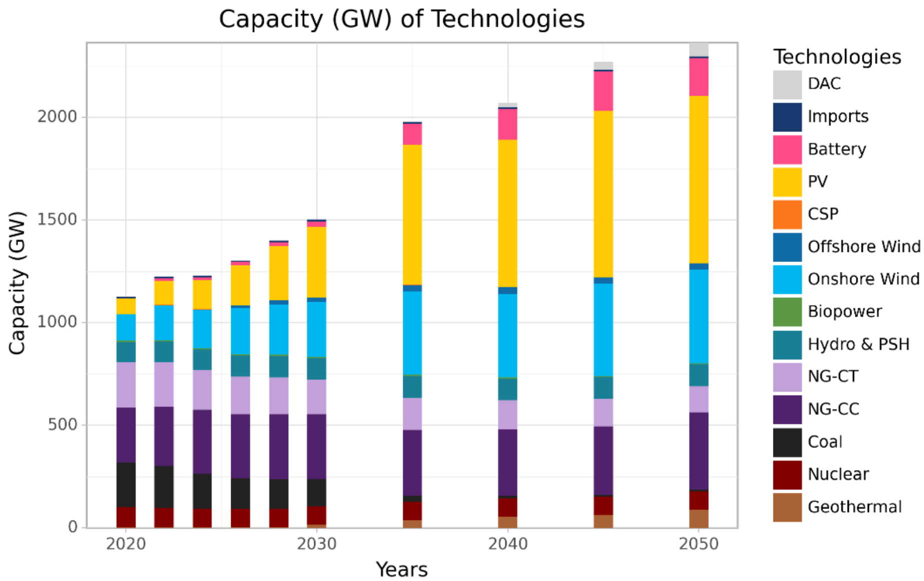

Figure A-1. ReEDS model results for installed capacity by technology for the Enhanced Geothermal Shot analysis

DAC= direct air capture; CSP = concentrating solar power; PSH = pumped storage hydropower; NG = natural gas; CT = combustion turbine; CC = combined cycle

Sensitivity cases were run in addition to the primary analysis scenario. Sensitivity runs for four groupings were run to identify potential deployment ranges under the Enhanced Geothermal Shot resource cost projections. The first sensitivity removes the power system decarbonization pathway. The second grouping of sensitivities use high and low price scenarios based on alternate EIA AEO 2022 natural gas price trajectories. The non-geothermal RE cost sensitivities uses ATB 2021 advanced and conservative costs, in the low and high cost scenarios, respectively, for wind, PV, concentrating solar power, and batteries. The reduced access sensitivity represents barriers to siting non-geothermal grid resources. The first of these cases is a low transmission expansion scenario where transmission development costs are increased and transmission expansion is planned regionally. The latter case reduced wind and solar resource by applying more restrictive land access exclusions and siting setbacks (Mai et al. 2021).

Table A-1. Installed Geothermal Capacity by Type in 2050 for the Enhanced Geothermal Shot and Modeled Sensitivities

Scenario		Geothermal Capacity 2050 (GW)			
		Identified Hydro-thermal	Undiscovered Hydrothermal	Near Field EGS	Deep EGS
Enhanced Geothermal Shot Scenario		3.24	2.03	5.13	80.13
No CO_2 Policy Sensitivity		3.24	1.69	0.33	36.46
Natural Gas Sensitivity	High Price	3.83	2.23	5.55	96.81
	Low Price	3.24	2.03	5.15	59.44
Non-Geothermal RE Costs Sensitivity	High Costs	5.24	3.04	8.31	135.77
	Low Costs	3.20	0.34	0.00	30.56
Reduced Access Sensitivity	Low Transmission Expansion	4.52	2.38	3.44	115.04
	Reduced Wind/Solar Resource	3.83	2.38	6.30	106.63