Geothermal Power Systems Analysis: Outcome of Industry Stakeholders Workshop

Preprint

Dayo Akindipe, Erik Witter, Matthew Prilliman, Brian Mirletz, Jonathan Ho, Whitney Trainor-Guitton, Paul Pinchuk, and Travis Williams

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Keywords

Techno-economic analysis, GETEM, Annual Technology Baseline, geothermal power, ReEDS

ABSTRACT

Geothermal cost and performance evaluation implemented via techno-economic assessment (TEA) modeling is critical for the U.S. Department of Energy (DOE) and other geothermal industry stakeholders in assessing the current state of geothermal technologies and to identify existing hurdles to commercially viable geothermal development. The Geothermal Electricity Technology Evaluation Model (GETEM) is a major TEA tool used in estimating the economic feasibility and levelized cost of energy (LCOE) of conventional hydrothermal systems and enhanced geothermal systems (EGS). Since 2021, GETEM has been transitioning from an intricate spreadsheet model to a user-friendly tool within the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL). Apart from enabling an expanded visibility of the geothermal model among other renewable resources, having GETEM in SAM has the advantage of simulation automation, better usability, updates tracking, active user inputs/feedback, and extended financial modeling. GETEM is used in developing supply curves for NREL's Annual Technology Baseline (ATB), which provides inputs to the Renewable Energy Potential (reV) and the Regional Energy Deployment System (ReEDS) models. The geothermal module in NREL's reV model assesses the geothermal energy potential in the conterminous United States by defining the geospatial intersection of geothermal resources with existing grid infrastructure within the constraint of land use characteristics. The ReEDS model is a capacity expansion model used for simulating the long-term build-out and operation of the U.S. generation and transmission system based on current energy costs and policies. To ensure enhanced representation of current industry trends in our model transitions and development, we organized a two-day virtual workshop to elicit geothermal industry stakeholder input and recommendations on our current approaches and assumptions on techno-economic, resource assessment, and deployment scenarios modeling of geothermal technologies. Participants included developers, operators, investors, regulatory agencies, system modelers, national laboratory researchers, consultants, and other stakeholders. In this workshop, we gained stakeholder insights on current geothermal plant performance (i.e., capacity factors), updated drilling costs and learning curves, and next-generation technologies such as closed-loop and superhot rock geothermal. Other outcomes from this workshop and its impact on future geothermal development feasibility, resource availability, and capacity expansion studies are compiled and discussed.

1. Introduction

The geothermal energy industry in the United States has seen a significant increase in technology advancements and public and private sector interests in recent years. Substantial investments in next-generation geothermal technologies have been reported, with an estimated \$396 million invested in next-generation companies between 2021 and 2023 (DOE, 2024a). These have translated to a record number of power purchase agreements (PPAs) since 2020 (Robins et al., 2021; DOE, 2024a). Simultaneously, technological improvements are being made in multiple phases of geothermal power development such as drilling and completion, power plant design, and optimization. These innovations are being accelerated by technology demonstration projects like FORGE and the EGS Pilot Demonstrations specifically targeted at de-risking next-generation geothermal technologies.

The National Renewable Energy Laboratory (NREL) has supported the U.S. Department of Energy's (DOE's) effort in de-risking geothermal power projects. Through its Geothermal Technologies Office (GTO), the DOE previously engaged NREL in developing the GeoVision report. The GeoVison report describes a pathways and scenarios for technology advancement (DOE, 2019). Other efforts such as the Geothermal Earthshot analysis have been used to determine the pathway to get to low-cost enhanced geothermal systems development (Augustine et al., 2023). In these studies, NREL has provided business as usual and scenario-based analyses to the DOE using a defined methodology. First, base cases for resource (e.g., hydrothermal or EGS) and technology (flash or binary) pairs are determined using the Geothermal Electricity Technology Evaluation Model (GETEM) (DOE, 2016). This bottom-up techno-economic assessment (TEA) model estimates the lifecycle performance and cost of a geothermal project based on predefined assumptions for each project development phase. The outputs from this model are used to develop supply curves (i.e., cost versus cumulative resource capacity plots) that can be used for future deployment planning. GETEM is the primary model used in the geothermal technology representation in NREL's Annual Technology Baseline (ATB) that defines the current and future costs and performance levels for multiple renewable energy technologies (NREL, 2024). Supply curves developed primarily with GETEM are used in ReEDS for capacity expansion modeling of geothermal deployments into the future relative to other electricity generation technologies, policies, decarbonization goals, and other constraints (Gagnon et al., 2024). Figure 1 illustrates the interrelationship between GETEM, the ATB, and ReEDS. Recently, GETEM has been transitioning from an Excel-based workbook to a user-friendly model within NREL's System Advisor Model (SAM) tool. This transition is at its last stage of model alignment. GETEM in SAM is available both as a module in the Graphic User Interface (GUI)-enabled SAM model and the Python code-based PySAM available on GitHub. Having GETEM in SAM will enable a wider outreach beyond traditional users, incorporation of other geothermal next-generation technologies (including closed-loop and superhot rock geothermal), comparability with other renewable energy technologies, and a robust financial modeling capability (*System Advisor Model (SAM)*, 2022).

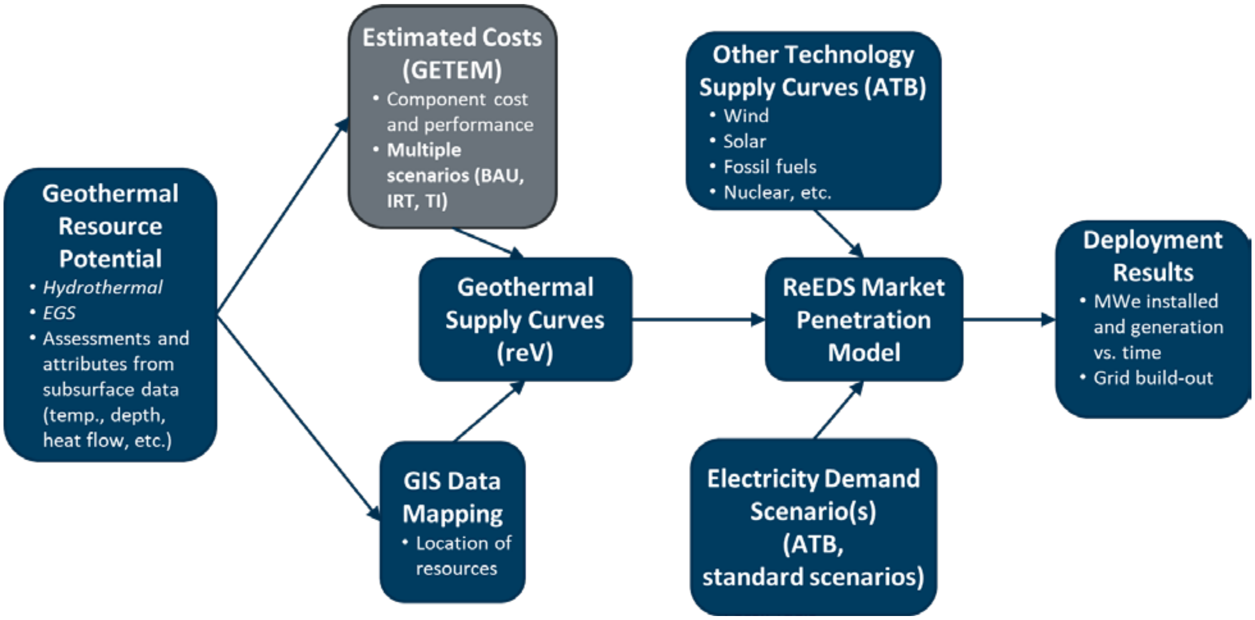

Figure 1: The interrelationship between GETEM, the ATB, reV, and ReEDS in determining future technology deployment scenarios. BAU= Business As Usual, IRT = Improve Regulatory Timeline, TI = Technology Improvement scenarios used in the GeoVision study (DOE, 2019)

The Renewable Energy Potential (reV) model is another NREL tool that has been recently adapted with capabilities to estimate and geospatially represent, with multiple levels of uncertainty, the available geothermal resources in the conterminous United States (Pinchuk et al., 2023). In developing these estimates, the reV model uses geospatial datasets, including heat flow and temperature at depth maps, grid infrastructure data, and geographical constraints (e.g., land use characteristics) to determine geothermal resource availability down to a 1-km^2 spatial resolution (Pinchuk et al., 2023). The model also takes in installation cost inputs from PySAM and in-built spur line transmission (or grid connection) cost model to develop supply curves for both hydrothermal and EGS technologies. The model methodology is shown in Figure 2.

On January 9-10, 2024, NREL gathered 66 geothermal industry stakeholders from around the country to discuss progress made in making our models more representative of the state-of-the-art and future expectations of the geothermal industry. This virtual workshop was titled the “NREL Geothermal Power Systems Analysis Workshop.” Participants represented geothermal developers, operators, state agencies, non-profit organizations, investors, power system modelers, subject matter experts, the DOE-GTO, and national laboratories. Over the two days, NREL presented ongoing work in GETEM, SAM, reV and ReEDS and their anticipated impacts on future ATB and capacity expansion and scenario modeling. Breakout sessions also gave room for participants to identify and discuss gaps in our model assumptions and methods to ensure better representation of the performance, cost, and value of geothermal power systems. In this article, we summarize the major takeaways from the workshop discussions.

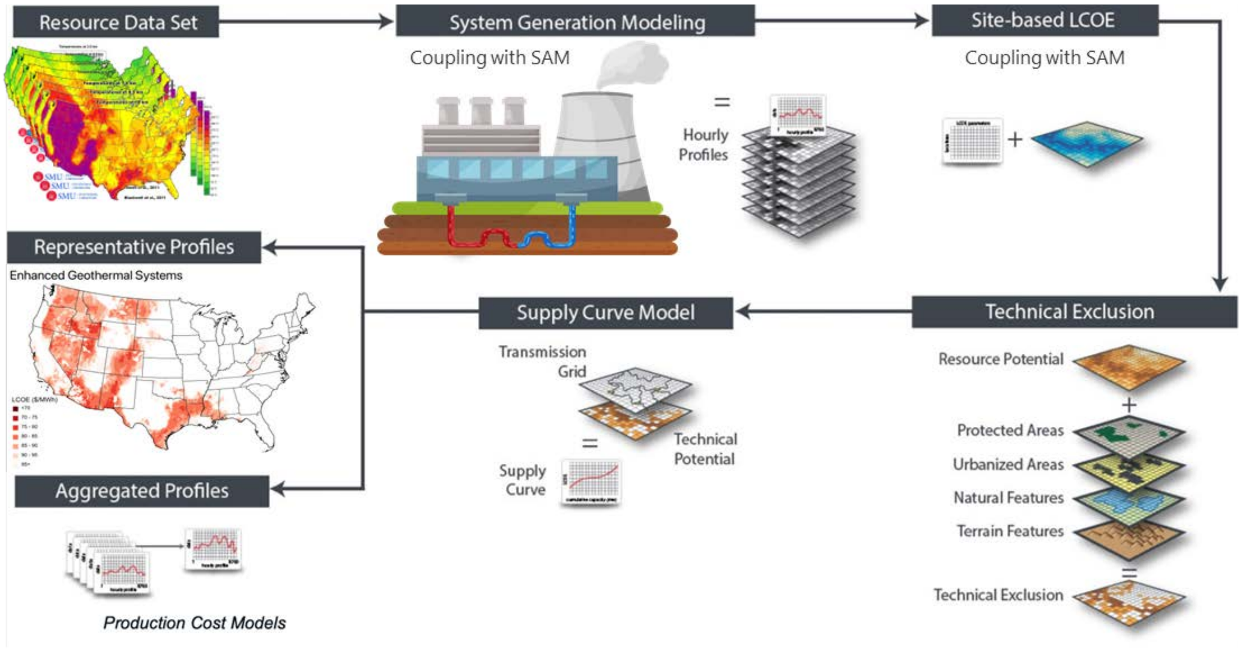

Figure 2: The reV model methodology implemented to estimate resource potential and generate geospatially-distributed cost profiles

2. Workshop Discussions

The NREL Geothermal Power Systems Analysis Workshop discussions were centered on four main topics:

- GETEM and SAM model updates
- The ATB process and geothermal representation in the ATB
- Geothermal representation in ReEDS
- Geothermal resource potential estimation with reV

The following subsections describe the major talking points around the highlighted topics.

2.1 GETEM and SAM Model Updates

2.1.1 Resource Temperature Limit on Binary Cycles

A major technical consideration that was discussed is how the GETEM model implements binary plant operations. The Excel-based GETEM model intrinsically assumes that binary plants do not operate beyond 200°C (G. L. Mines, 2016). Hence, once a system specification greater than 200°C is imputed into the model, it assumes a flash-based power cycle. According to Mines (2016), the reason for this restriction is that downhole production pump technology at the time GETEM was developed had a 200°C operational limit (G. L. Mines, 2016). GETEM assumes that flash plants have sufficient reservoir pressure and do not require production pumps. Also, the temperature-based correlations for the binary plant cost estimation in GETEM has this same 200°C limit. This temperature-based partitioning between flash and binary cycles is not an actual physical constraint. Multiple plants worldwide run on organic Rankine cycles (ORCs) that utilize geothermal energy resources above 200°C. Therefore, Excel-GETEM appears to characteristically underestimate the potential of binary cycles at high temperatures. The GETEM in SAM model accommodates simulations of binary power plants with resource temperatures above 200°C. It also accommodates flash plant operations at temperatures below this threshold. However, since it is inherently based on GETEM, there is a need to update the plant cost correlations in SAM to accommodate higher resource temperatures.

2.1.2 Exploration Drilling Success Rates

Hydrothermal resource exploration comes with its inherent resource confirmation uncertainty. In the western U.S, a vast number of convection-dominated hydrothermal plays that can be traced back to surface expressions (e.g., geysers, fumaroles, and hot springs) have been discovered. Hence, to increase the potential for resource discovery, drilling for “blind” resources is set to become the norm in future hydrothermal exploration, just as in the oil and gas industry today. This comes with an increased requirement for exploration (geological, geochemical, and geophysical) data acquisition that culminates in a test drilling phase where full-size wells are drilled to confirm resource availability (heat, permeability, and suitable reservoir fluid volume) and productivity. Generally, for hydrothermal systems, the global average historical success rate for the first full-size well has been reported as 50%, increasing to 59% for the first five wells (Allen et al., 2013). GETEM currently defaults to a 50% success rate (53% was used in the 2023 ATB). Wells are deemed unsuccessful for several reasons, including drilling dry holes, loss of mechanical integrity during drilling, inadequate pressure and temperature, low productivity, and geochemical considerations (corrosion and scaling tendencies) (Allen et al., 2013). With significant improvement in data collection before test well drilling, data-enhanced conceptual model development, and advancements in drilling technology (e.g., sidetracking), success rate estimations for hydrothermal, and by extension EGS, projects need to be revisited. Determining a representative value for exploration drilling success may require an updated study similar to Allen et al. (2013) and expert consultation on additional costs incurred to reducing well failure rates.

2.1.3 Beyond the Levelized Cost of Electricity (LCOE)

The LCOE is a metric that expresses the discounted cost to install and operate a geothermal plant over its generation life cycle. It is typically used to compare cost competitiveness from one geothermal project to another and between geothermal and other renewable energy technologies. It is also used to determine the contract electricity price for a PPA. Because it is strictly project-based, it does not account for the system value of the plant as a service provider to the electric grid (Mai et al., 2021; DOE, 2024a). Specifically, the ability of geothermal plants to offer both firm and dispatchable electricity (among other ancillary services) to the grid is not captured within the definition of the LCOE. The LCOE does not also account for avoided costs (e.g., additional generation and transmission costs) that could have been incurred to meet demand. Other metrics that have been proposed include the Levelized Value of Electricity (LVOE), Net Value of Electricity (NVOE), Net Value of Capacity (NVOC), Profitability-Adjusted LCOE, Levelized Avoided Cost of Electricity (LACE) and Cost of Valued Energy (COVE) (EIA, 2017; Simpson et al., 2020; Mai et al., 2021; Loth et al., 2022). Both NVOE and LACE account for only the system value leaving out the effect of cost. Others account for both system cost and value with varying degrees of complexity in their estimation. GETEM only considers LCOE and does not have the capability to estimate value-derived revenues. Although SAM calculates LCOE, it also has a robust financial model that can estimate cost- versus value-derived metrics such as return on investment

(ROI). Therefore, once a suitable metric beyond LCOE is established for geothermal, it should be implementable in SAM.

2.1.4 Other Discussion Points

We have summarized other discussion points that were raised during the GETEM in SAM session in Table 1. These relate to both performance- and cost-based parameters.

Table 1: Summary of other discussion points in the GETEM in SAM session

Discussion Point	Excel-GETEM	GETEM in SAM
Investment tax credits (ITC) and production tax credit (PTC)	Not accounted for	ITC and PTC can be included in the estimation of LCOE and in financial modeling. Other similar tax credits and incentives can be accommodated.
Reservoir modeling	No capabilities	No implicit reservoir model. However, SAM has the Gringarten model for fractured systems that can be used to determine EGS reservoir performance. Reservoir simulation results (pressure and temperature timeseries) can be imported as CSV files from other modeling software.
Ability to incorporate hybrid models e.g., solar photovoltaic (PV) /concentrating solar thermal-geothermal hybrids	No direct capabilities. Can model the geothermal part of a hybrid system	The current hybrid model just implemented in the latest SAM version is for PV-wind-battery hybrid systems. Future SAM versions could incorporate hybrid models by leveraging TEA models developed within GTO’s Hybrids Portfolio.
Imputing actual reservoir performance and plant generation data	No capabilities	SAM has an additional module for a “Generic” system. In the current Geothermal module, reservoir temperature timeseries can be uploaded into SAM.
Estimating the system value of carbon emissions reduction	Determining the cost of carbon and carbon offsets is beyond the TEA scope of the model	Determining the cost of carbon and carbon offsets is beyond the TEA scope of the model. However, SAM is sufficiently flexible to accommodate financial calculations that include cashflows from carbon credits.

2.2 Geothermal Representation in the ATB

2.2.1 Next-Generation Technologies

Next-generation geothermal technologies like EGS and closed-loop geothermal (CLG) are gaining traction in terms of technology development and a defined pathway towards commercialization. Currently, the ATB accounts for conventional hydrothermal systems and next-generation EGS (as Near-Field and Deep EGS). Near-Field EGS resources are defined as brownfields that are proximal to an existing hydrothermal resource. A case in point is Fervo’s EGS development in the Blue

Mountain Geothermal field in Nevada (Norbeck & Latimer, 2023). Deep EGS resources in the ATB are defined as greenfields that have not been previously developed and are geologically conduction-dominated plays.

CLG systems are not currently represented in the ATB. Several factors have constrained their inclusion in the ATB. The first is technology standardization. Multiple CLG system designs have been proposed and have been broadly categorized based on the loop design into coaxial/pipe-pipe/downhole heat exchanger (with or without a lateral), U-loop (single-, double-, or multi-lateral), and the Eavor Loop. Technology categorization that is strictly based on loop design may create standardization complexities as new loop designs emerge. The second factor is the definition of a representative plant size for each loop design. Can we assume similar plants sizes as in hydrothermal and EGS? A third factor is that, based on previous results from past TEA, LCOE for CLG systems could range from 2,200 $/MWh for the coaxial loop to 70 $/MWh for the Eavor Loop (Beckers et al., 2022; Beckers & Johnston, 2022). There may be a requirement to prioritize more competitive designs for representation in the ATB.

Superhot rock/supercritical geothermal, which targets resources above 375°C, is also not currently represented in the ATB. The technology is still emerging with the first-of-a-kind (FOAK) demonstration to be implemented in Newberry, Oregon as part of GTO's EGS Pilot Demonstrations portfolio (DOE, 2024b). There is presently no comprehensive TEA model for superhot systems due to the uncertainty in assessing costs for major project phases including drilling and completion, stimulation, and power plant construction. Future iterations of the ATB will accommodate superhot rock geothermal as data from the Newberry project and other pilot projects become available.

2.2.2 Effect of Plant Size

Plant size is an important factor in the estimation of lifecycle costs of a geothermal project. Generally, larger power plants tend to enjoy the benefits of economies of scale. Allowing for less intensive costs (on a per-kW basis) for leasing and permitting, project infrastructure, project financing, and operation and maintenance. From a thermodynamic perspective, larger plants could also benefit from higher energy conversion efficiency (at higher resource temperatures) and better overall plant efficiency. The economics of next-generation technologies like EGS can be improved at larger plant size deployments. The 2023 ATB assumes the following plant sizes for EGS technologies: Deep EGS = 25 MW (Binary) and 30 MW (Flash); Near-Field EGS = 30 MW (Binary) and 40 MW (Flash) based on the classification by Mines (2013). EGS developers are targeting 100-MW commercial plant build outs. Although a 100-MW plant size is used in the EGS Advanced Scenario ATB for a 2035 deployment year, it is currently too aggressive for a mid-case (Moderate) scenario. However, it may be considered in a future ATB once a FOAK 100-MW EGS plant is operational. In the 2024 ATB, we will revise the EGS plant sizes to 40 MW for both Deep and Near-Field EGS to keep pace with technology trends.

2.2.3 Capacity Factor

The capacity factor is a major plant performance indicator in the ATB and a direct input to the calculation of project capital expenditure (CAPEX). In the ATB, geothermal capacity factor is assumed to be constant throughout the project lifecycle but differs by plant technology (80% for binary for 90% for flash) (NREL, 2024). These capacity factor estimations are based on historical plant data and may be heavily affected by the performance of legacy hydrothermal developments that are currently producing way below their designed plant output capacities. A revision of capacity factor estimation that takes account of improvement in air-cooled binary cycle technology and plant availability would require extensive input from geothermal plant operators. Further discussion on this topic is planned for a follow-on workshop this summer.

2.2.4 Technology Maturation

The ATB categorizes technologies as either “mature” or “nascent”. Mature technologies are defined as those with a representative plant in operation or under construction in the United States in the base year (i.e., 2021 for the 2023 ATB) (NREL, 2023). Technologies outside the maturity definition are classified as nascent. Over time, hydrothermal technologies have been classified as mature while EGS are nascent. From an ATB perspective, the FOAK commercial EGS project developed in 2023 does not precisely fit the definition of mature technology in the ATB because it did not lead to the build out of a new power plant. Two horizontal wells were drilled, completed, and stimulated, and the resulting flow was tied back to an existing geothermal plant (Norbeck & Latimer, 2023). Future ATB iterations may need to account for this case by defining a mid-case technology definition as this may be the technology commercialization pathway for Near-Field EGS projects.

2.2.5 Geothermal Learning Rates

Since the 2023 ATB, we have adopted a learning curve approach to determining future costs of geothermal technology development scenarios. An explanation of this approach can be found in the ATB documentation (NREL, 2024). Essentially, a single factor learning curve that expresses the power-law relationship between cumulative capacity and cost was used to determined future capital costs beyond the base year to the full deployment year of the Moderate and Advanced scenarios (i.e., 2035). The learning rate, which determines the slope of the curve, expresses the rate at which technologies adopt learning by doing practices to increase capacity and reduce cost. The assumptions for geothermal learning rates are shown in Table 2. The 13% learning rate for the hydrothermal Moderate scenario was derived from historical drilling and completion learning rates in the unconventional oil and gas industry (Fukui et al., 2017). The EGS Moderate learning rate was derived from the low-end approximation for learning rates found in the study by Latimer & Meier (2017) that compiled at historical learning rates in both geothermal and oil and gas projects. The 30% rates for the Advanced EGS and hydrothermal are based on the high-end estimation of learning rates found in the same study (Latimer & Meier, 2017). In a recent paper by El-Sadi et al. (2024), a 35% in-project learning rate has been achieved so far in the Cape Station, Milford, Utah drilling campaign (El-Sadi et al., 2024). This in-project improvement can form a basis for reevaluating the inter-project learning rate assumptions in future ATB efforts.

Table 2: Learning rate assumptions used in the 2023 ATB

Scenario	**Base Year–2035**	**2035–2050**
Moderate Scenario	13% (hydrothermal), 18% (EGS)	0.5% annual cost reduction
Advanced Scenario	30%	0.5% annual cost reduction

2.3 Geothermal Representation in ReEDS

2.3.1 Classification of Geothermal Resources

The ATB classifies geothermal resources as hydrothermal, Near-Field EGS, and Deep EGS with a resource temperature dependent tie back to a binary or flash cycle. In capacity expansion modeling in ReEDS using defined standard scenarios (Gagnon et al., 2024), this classification obscures the high-value and low-cost sites on the supply curve that are competitive with other renewable technologies. Hence, a new temperature-based resource classification for geothermal in ReEDS that could elucidate these high-value sites was discussed at the workshop. Table 3 below shows the 10 resource classes. This applies to each resource type – hydrothermal, Near-Field EGS, and Deep EGS. A comment was made at the workshop on the skewness of the temperature bins towards higher temperature resources with lower site counts. Hence, it was recommended that the bin size should be proportional to the site counts or available resource count within each class.

Table 3: Temperature-based resource classes for geothermal in ReEDS

Resource Class	Bin Lower Bound (Resource Temp, °C)	Bin Upper Bound (Resource Temp, °C)
1	>325	None
2	>300	325
3	>275	300
4	>250	275
5	>225	250
6	>200	225
7	>175	200
8	>150	175
9	>125	150
10	0	125

2.5 Geothermal Resource Potential Estimation with reV

Discussions during the workshop on the reV model were limited to questions about understanding how the model works and how to improve data collection on estimating resource potential at higher geospatial resolution for both hydrothermal and EGS. For example, the reV model uses the temperature at depth and thermal conductivity data layers for both hydrothermal and EGS resources. Since hydrothermal units are more convection-dominated than EGS, this increases the uncertainty of estimating hydrothermal resource potential with reV since it is solely based on conductive heat flow. There is a need for more high-resolution convective heat flow data to characterize hydrothermal resource potential at national scale.

3. Outcomes and Future Plans

The NREL Geothermal Power Systems Analysis Workshop exposed areas for improvement in both modeling capabilities and scope. Discussions covered TEA modeling with GETEM and SAM, geothermal representation in the ATB, scenarios analysis modeling with ReEDS, and resource potential estimation and geospatial representation in the reV model. Participants at the workshop were fully engaged and provided suggestions on model improvement, especially in the representation of next-generation geothermal systems, including closed-loop and superhot rock geothermal. As these next-generation technologies become mainstream, opening a new frontier in dispatchable and flexible geothermal operations, geothermal power analysis models will be required to represent crosscutting performance, cost, and value of geothermal to the electric grid. A follow-on workshop is planned for this summer with a focus on improving and updating assumptions on various phases of a geothermal project lifecycle in the GETEM in SAM model.

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