2024 TECHNICAL UPDATE

Representation of Geothermal Resources and Technologies in EPRI's US-REGEN Model

Guidelines for Enhancing Geothermal Integration in Capacity Expansion Models

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ABSTRACT

Geothermal energy is gaining attention as a reliable source of clean, firm power for the U.S. power sector, spurred by advancements in enhanced geothermal systems (EGS) and drilling techniques. To address its underrepresentation in capacity expansion models, EPRI and the National Renewable Energy Laboratory, with funding from the Department of Energy's Geothermal Technologies Office collaborate in this project to enhance the representation of geothermal technologies and resources in EPRI's US-REGEN model and to derive general guidelines for improving the representation in other capacity expansion models. To this end, hydrothermal, near-field and deep EGS resources are integrated following NREL's ReEDS model temperature-based resource supply curves and cost assumptions. Six scenarios are analyzed with the improved geothermal representation, two economy-wide net-zero pathways—differentiated by the availability of carbon capture and storage (CCS)—across three geothermal cost scenarios (conservative, moderate and advanced). In the advanced cost scenario, geothermal, particularly deep EGS, could reach 36 GW of capacity nationally by 2050 in the pathway with CCS and 59 GW in the pathway without CCS, contributing up to 8.5% of total electricity generation. However, deployment remains limited under conservative and moderate cost assumptions. These findings underscore the relevance of incorporating EGS into capacity expansion models and offer guidelines for better technology integration. These guidelines emphasize consistent resource definitions, temperature-based classifications, regional disaggregation, and addressing cost uncertainty, while tailoring the technology representation to the model's structure and complexity to ensure accurate and informed utility planning and policy development.

Keywords

Geothermal energy
Hydrothermal power generation
EGS power generation
Capacity expansion model
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EXECUTIVE SUMMARY

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Primary Audience: Electric company staff who are involved with resource planning, corporate strategy, new resource procurement, and technology assessment.

Secondary Audience: Policymakers, researchers, technology developers, and other stakeholders who want to improve the representation of geothermal resources and technologies in energy system models.

KEY RESEARCH QUESTION

The primary research question in this study is how to improve the representation of geothermal resources and technologies, particularly enhanced geothermal systems (EGS), in capacity expansion models like EPRI's US-REGEN, while maintaining model structure, spatial and temporal granularity, and complexity, and preserving key geothermal attributes for accurate characterization. The study also evaluates how enhanced geothermal representation impacts modeling outcomes and derives guidelines for integrating geothermal resources and technologies into other energy models.

RESEARCH OVERVIEW

This research focused on enhancing the representation of geothermal resources and technologies, including hydrothermal, near-field, and deep EGS, in EPRI's US-REGEN economy-wide model. Using updated datasets from NREL's ReEDS capacity expansion model, the study incorporated temperature-based classifications and updated cost assumptions for geothermal energy. Six scenarios were analyzed, including two net-zero pathways mainly differentiated by the availability of CCS and three geothermal cost scenarios (conservative, moderate, and advanced). The improved geothermal representation enabled a more accurate evaluation of geothermal capacity additions and its role in contributing to clean, firm power generation. The research results underscore the relevance of improving geothermal representation in energy models, highlight the potential capacity and energy contributions of geothermal energy under different cost assumptions, and provide guidelines for better integrating geothermal resources into other capacity expansion models.

KEY FINDINGS

- Expanding geothermal representation in US-REGEN to include near-field and deep EGS, rather than only hydrothermal resources, significantly impacts deployment of geothermal technologies in economy-wide net-zero scenarios.
- In the advanced cost scenario in a net-zero pathways without CCS, geothermal energy, particularly deep EGS, could reach up to 59 GW of capacity by 2050, contributing as much as 8.5% of total electricity generation. The enhanced geothermal representation underscores the critical role EGS can play in long-term energy strategies, which was previously underestimated.
- Geothermal deployment remains minimal in conservative and moderate cost scenarios, underscoring the need for cost reductions and technological advancements for broader adoption. However, significant cost declines for EGS have been observed between the 2023 and 2024 ATB versions. These reductions could substantially impact deployment projections, potentially increasing geothermal adoption even in conservative scenarios.
- Key guidelines for integrating geothermal into capacity expansion models include using temperature-based classifications, regional disaggregation of resources, and incorporating cost uncertainty for a more precise evaluation of the technology competitiveness.
- The level of detail in geothermal integration should be aligned with each model's structure and complexity, ensuring that models can reflect regional variations and temperature-dependent technologies effectively.

WHY THIS MATTERS

This research provides utility planners and policymakers with a clearer understanding of geothermal energy's role in future decarbonization strategies. By improving the representation of geothermal technologies in capacity expansion models, this project helps ensure more accurate assessments of the contribution of geothermal energy to clean, firm power generation, ultimately supporting more informed energy planning and policy decisions.

HOW TO APPLY RESULTS

Utilities, policymakers, researchers, and other stakeholders can implement these findings by adopting the guidelines for integrating geothermal resources and technologies into their planning models. This includes applying temperature-based classifications, regional resource disaggregation to better capture geothermal potential, and updated cost assumptions. Engaging with internal energy modeling teams and external stakeholders, such as regulatory agencies, will help ensure that geothermal resources are accurately reflected in energy planning and decarbonization strategies.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- DOE-Sponsored Virtual Workshop on Geothermal Value, Opportunities & Representation
- US-REGEN Model. EPRI Contact: David Young, dyoung@epri.com

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ACRONYMS AND ABBREVIATIONS

ATB	Annual Technology Baseline
CAPEX	capital expenditure
CCS	carbon capture and storage
CEM	capacity expansion model
CF	capacity factor
CO_2	carbon dioxide
degs	deep EGS
DOE	Department of Energy
EGS	enhanced geothermal system
GETEM	Geothermal Electricity Technology Evaluation Model
GIS	geographic information systems
GTO	Geothermal Technologies Office
hyth	hydrothermal
IRA	Inflation Reduction Act
ISO	independent system operator
LCOE	levelized cost of energy
negs	near-field EGS
NREL	National Renewable Energy Laboratory
ORC	Organic Rankine Cycle
PV	photovoltaics
ReEDS	Regional Energy Deployment System
reV	Renewable Energy Potential Model
RTO	regional transmission operator
SAM	System Advisor Model
USGS	U.S. Geological Survey
US-REGEN	U.S. Regional Economy, Greenhouse Gas, and Energy

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1 INTRODUCTION

Motivation

Interest in geothermal energy within the U.S. power sector has increased significantly, transitioning from a niche technology to a recognized source of clean, firm power. Recent studies (Blankenship, Gertler, Kamaludeen, O'Connor, & Porse, 2024) and technical advancements, particularly in drilling and reservoir stimulation (Fercho, et al., 2024) in enhanced geothermal systems (EGS), highlight the potential for geothermal energy to play a substantial role in future low-carbon electricity systems. While traditional hydrothermal resources have been heavily exploited and already contribute 0.4% to the U.S. electricity supply as of 2022 (U.S. Energy Information Administration (EIA), 2023), EGS technologies could unlock vast new geothermal potential, previously inaccessible, with estimates suggesting over 5 terawatts (TW) of power generating capacity in the U.S. alone (DOE, 2019). Although only a fraction of this resource may be economically viable, even a limited deployment could have a transformative impact on the nation's long-term electricity decarbonization goals.

As utilities seek to decarbonize the electric power sector, driven by both regulatory requirements and federal incentives for low-carbon technologies, the potential role of geothermal energy becomes increasingly important. However, utility planners often lack the expertise to evaluate the full range of geothermal technologies and their potential contribution to the grid. This is largely due to the complexity and variability of geothermal resources, which are highly site-specific and require extensive upfront exploration and investment, making them harder to model compared to more widely deployed technologies like solar and wind. Additionally, limited data on EGS resources and the relative immaturity of the technology contribute to its underrepresentation. As a result, conventional capacity expansion models (CEMs), widely used by utilities for planning purposes, typically do not include detailed representations of geothermal technologies, leaving a critical gap in understanding their future role in decarbonization.

To address this gap, EPRI and the National Renewable Energy Laboratory (NREL), with support from the Department of Energy's Geothermal Technologies Office (DOE GTO), are collaborating on a research project aimed at improving geothermal understanding among power sector stakeholders. This project aims to facilitate knowledge transfer regarding geothermal opportunities, risks, and overall value, while also enhancing the representation of geothermal technologies in resource planning models, enabling utilities and policymakers to make more informed decisions about how geothermal can contribute to the clean energy transition.

Objectives and Scope

This report focuses on the second part of the collaborative effort between EPRI and NREL, with the primary goal of improving the representation of geothermal resources and technologies in EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model by leveraging available geothermal datasets and modeling expertise from NREL's ReEDS (Regional Energy Deployment Systems) model team.

The specific objectives are:

- Understand and process available geothermal resource and technology cost datasets for their integration into the US-REGEN modeling framework.
- Identify and model a set of key scenarios to project geothermal technology capacity deployment and generation out to 2050, including hydrothermal, near-field EGS and deep EGS.
- Derive general guidelines for enhancing the representation of geothermal resources and technologies in capacity expansion models, to support broader industry adoption and utility planning.

2 BACKGROUND

Definition of Geothermal Resources and Technologies

Consistent with previous studies (Blankenship, Gertler, Kamaludeen, O'Connor, & Porse, 2024; DOE, 2019), two types of geothermal resources for power generation, namely hydrothermal and EGS, are considered in this project. Hydrothermal resources refer to naturally occurring geothermal reservoirs, which have been conventionally used to produce electricity. In contrast, EGS involves the creation of engineered reservoirs to extract heat from geothermal resources that have low permeability and/or lack natural in-situ fluids for heat extraction. EGS technologies are expected to develop and deploy in stages, initially expanding from existing hydrothermal sites to greenfield locations. For this project, the EGS resource is categorized into two groups: near-field EGS (adjacent to existing hydrothermal fields) and deep-field EGS (targeting deeper, more isolated formations).

The primary attribute of geothermal resources is reservoir temperature, which directly influences the type of technology used for power generation and the efficiency of the process. For instance, while higher-temperature resources (above 200°C) traditionally favored flash technologies due to their higher efficiency, binary power plants have become the predominant choice, even for such resources, in the last decade. This shift is largely driven by water conservation priorities, as binary plants, which operate in closed-loop systems, significantly reduce water consumption compared to flash technologies. Although low-enthalpy geothermal resources can be exploited using technologies like Organic Rankine Cycle (ORC), this study sets a threshold of 175°C for power generation, as resources below this temperature are less economically viable for large-scale power production.

Capacity Expansion Modeling and Representation of Geothermal Energy

As the U.S. electricity sector undergoes transformation to meet regulatory and reliability requirements for an economy-wide net-zero energy system by 2050, power system planning models are becoming increasingly complex. Capacity expansion models (CEMs) are widely used to simulate future investments in generation and transmission capacity, incorporating assumptions about electricity demand, fuel prices, technology costs, performance, and policy constraints (Boyd, 2018). Examples of CEMs include national-level such as the power sector modules of NEMS[1], IPM[2], US-REGEN, and ReEDS, and utility-scale commercial models like RPM[3], Aurora[4], and PLEXOS[5].

Key differences among CEMs are driven by trade-offs in spatial and temporal resolution, spatial and temporal extent, as well as system complexity (EPRI, 2017; Frew & Jacobson, Temporal and spatial tradeoffs in power system modeling with assumptions about storage: An application of the POWER model, 2016). Temporal resolution is the model time step size (e.g., hourly or sub-hourly), while temporal extent defines the model time horizon (e.g., one week, one year, or one decade). Spatial resolution reflects how location-specific resources are represented, ranging from site-specific to aggregated, and spatial extent covers the geographic scope of the model (e.g., state or country). System complexity refers to the level of detail in modeling power system components such as generating technologies, electricity market, transmission and distribution, and resource adequacy. Adjusting these parameters allows CEMs to balance accuracy with computational efficiency, depending on the specific modeling objectives as shown in Figure 1.

The objectives of different CEMs vary, from the identification of regional decarbonization technology pathways to detailed unit-level capacity expansion planning. Effective low-carbon electricity transition planning requires models that address key policy, technology, and market impacts across interconnected power systems while at the same time, consider critical grid operations and reliability requirements from higher variable renewable energy integration, distributed energy resources, and storage systems (EPRI, 2024).

However, existing CEM may be inadequate to fully capture the complexity of these emerging system configurations. For example, many models inadequately represent the dynamic interplay between renewable energy variability, grid reliability, and energy storage, or they may lack the spatial granularity needed to optimize distributed energy resource deployment. Furthermore, some often fail to incorporate national and regional decarbonization technology pathways. These limitations are largely because most CEMs focus on either high-level system analyses or detailed grid operations and reliability, but rarely both.

[1] National Energy Modeling System (NEMS), developed by the U.S. Energy Information Administration (EIA). More information: https://www.eia.gov/outlooks/aeo/nems/documentation/

[2] Integrated Planning Model (IPM), developed by the U.S. Environmental Protection Agency (EPA) with technical support from ICF, Inc. More information: https://www.epa.gov/power-sector-modeling/integrated-planning-model-ipm-results-viewer

[3] Resource Planning Model (RPM), developed by NREL. More information: https://www.nrel.gov/analysis/models-rpm.html

[4] Aurora, developed by Energy Exemplar. More information: https://www.energyexemplar.com/aurora

[5] PLEXOS, developed by Energy Exemplar. More information: https://www.energyexemplar.com/plexos

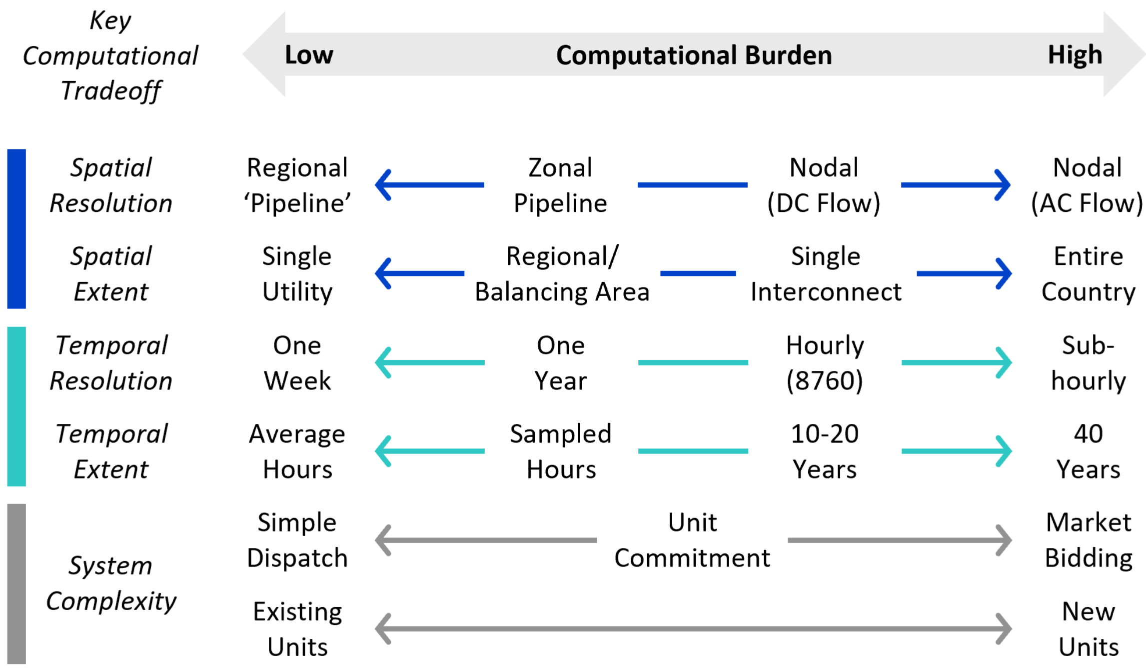

Figure 1. Key computational tradeoffs in capacity expansion models.

Understanding the trade-offs in CEM design helps modelers select the most appropriate parameters for their specific applications. When integrating new power generation technologies, such EGS, into existing models, it is crucial to maintain consistency with the representation of other technologies to accurately reflect competition. Geothermal resources, while location-dependent, are not subject to significant temporal variability like intermittent renewables such as wind and solar. Their firm, clean power attributes make them particularly valuable.

Current utilization of geothermal energy in the Western U.S. provides clear evidence of its reliability and potential, with increasing future importance as the geographic scope expands through advancements in EGS technology. Accurately capturing the value of geothermal technologies in CEMs, therefore, requires realistic representations of their resource potential, cost structures, and performance characteristics, especially as their role in providing stable, dispatchable power continues to grow.

EPRI's US-REGEN Model

US-REGEN is an economy-wide model developed and maintained by EPRI. It integrates a detailed dispatch and capacity expansion model of the U.S. electric sector with a technologically detailed consumer choice model of end-use service and energy demand as well as a fuel supply model representing alternative primary resources and conversion technologies for non-electric fuels. These models are solved iteratively to convergence, allowing comprehensive analysis of policy impacts on the electric sector, while accounting for feedback from electricity demand responses. Conversely, it also enables analysis of how end-use energy policies and technological advancements affect both electric and non-electric demands and load shapes. Additionally, US-

REGEN captures the economic incentives in the Inflation Reduction Act (IRA) and updated state-level policies (Bistline, Roney, Blanford, & Young, 2023). A detailed documentation of the US-REGEN model is available in (EPRI, 2021), and recent peer-reviewed articles and reports using US-REGEN can be found in (EPRI, 2024).

The electric sector module of US-REGEN is an intertemporal capacity expansion model that can be run either with representative hours over multiple decades or for a single year with hourly resolution and unit commitment constraints. It identifies cost-optimal electric sector pathways over time, accounting for policies, technologies, and market conditions. For each period and region, the model determines generation capacity investments, dispatch, storage charge/discharge, hydrogen production/storage, transmission and CO_2 pipeline investments, and other parameters to minimize the net present value of electric sector costs, while ensuring demand is met in every hour adhering to capacity, policy, and technology constraints. Key modeling and technology assumptions for the electric sector model can be found in the Supplementary Information of Bistline & Young (2022).

A multi-region inter-temporal optimization framework with detailed multi-sectoral technology representation requires aggregation for computational tractability. US-REGEN represents 16 distinct regions of the continental U.S., interconnected by transmission and trade (see Figure 1-1 in the US-REGEN Documentation (EPRI, 2021)). The electric model can be extended to include additional sub-state detail based on the boundaries of independent system operators (ISOs) and regional transmission operators (RTOs). It provides electricity loads and optimal technology portfolios in technology blocks for each region, while accounting for interactions and constraints across all modeled regions. Existing and new generating units with similar attributes are aggregated into technology blocks, based on the principle that units within a block would be dispatched similarly under market conditions. Prior to this project, 93 capacity blocks were used to represent existing and new generation technologies (see details in Section "Electricity Generation" in the US-REGEN Documentation (EPRI, 2021). By default, US-REGEN CEM solves in five-year time steps from 2015 through 2050, though it can be configured for different time steps and base years. The model employs a unique approach for selecting intra-annual segments, allowing for more accurate representation of the economics of variable renewables, energy storage, and dispatchable capacity (Blanford, Merrick, Bistline, & Young, 2018).

Given its aggregated spatial and temporal resolution and extent, along with the block representation of generating units, US-REGEN is a powerful tool for exploring long-run system changes. Furthermore, through scenario analysis, it supports resource planning by accounting for economy-wide interactions and associated risks. US-REGEN can provide a customized starting point for unit-level CEMs and production cost models for more detailed regional studies, informing optimal candidate generation resources, inter-regional transmission requirements, and long-term load projections (EPRI, 2024).

Representation of Geothermal Energy in US-REGEN Prior to this Project

Prior to this project, geothermal energy in US-REGEN (Version 2021A) (EPRI, 2021) was limited to a single hydrothermal flash technology for power generation with no consideration of EGS technologies. New hydrothermal capacity additions were constrained based on estimates of discovered and undiscovered hydrothermal sites in the western regions by the (USGS, 2008) with a total new potential of 39 GW by 2050. The model assumed an improving capacity factor for geothermal power over time as a result of technical progress reaching 80% by 2050, with capital costs for new geothermal capacity currently around $5700/kW in 2021 USD, and gradually declining over time as observed in Section “Electricity Generation/New Generation Capacity” in the US-REGEN Documentation (EPRI, 2021).

NREL’s ReEDS Model

The ReEDS model is a mathematical programming model of the electric power sector maintained and operated by NREL. The model consists of three separate but interrelated modules: a supply module, which solves a linear program for the cost-minimizing levels of power sector investment and operation; a variable renewable energy and storage module, which calculates key parameters for assessing the value of variable renewable generators and storage; and a demand module, which solves a separate linear program for the utility-maximizing levels of end-use device investment and operation (not part of the default solve) The model can be executed iteratively to achieve supply-demand equilibrium through a simultaneous solve, or sequentially: first, solving the optimization step for power sector investments, then calculating the VRE and storage value for that period, and finally solving for the next model year. (Ho, et al., 2021).

Representation of Geothermal Energy in ReEDS

According to the model documentation (Ho, et al., 2021), geothermal resources have several subcategories in ReEDS:

- The hydrothermal resource represents potential sites with appropriate geological characteristics for the extraction of heat energy. The hydrothermal potential included in the base supply curve consists of only identified sites with a separate supply curve representing the undiscovered hydrothermal resource.
- EGS sites are geothermal resources that have sufficient temperature but lack the natural permeability, in-situ fluids, or both to be hydrothermal systems. Developing these sites with water injection wells could create engineered geothermal reservoirs appropriate for harvesting heat.
- Near-field EGS is a subset of EGS that implies proximity to existing or known hydrothermal sites.

The geothermal supply curves are based on the analysis described by Augustine et al. (2019) and are shown in Figure 11 in (Ho, et al., 2021) . The hydrothermal and near-field EGS resource potential is derived from identified sites from the 2008 U.S. Geological Survey (USGS) geothermal resource assessment (Williams, Reed, and Mariner 2008). Undiscovered hydrothermal resources as well as deep EGS resources are derived from the Renewable Energy Potential Model (reV) (Pinchuk, Thomsen, Trainor-Guitton, Buster, & Maclaurin, 2023). As with other technologies, geothermal cost and performance projections are from the ATB (NREL, 2024).

The default geothermal resource assumptions allow for new construction at identified hydrothermal sites and undiscovered geothermal sites. The development of undiscovered geothermal resources is limited by a discovery rate defined as part of the GeoVision Study (DOE, 2019). The EGS EarthShot Analysis (Augustine, Fisher, Ho, Warren, & Witter, 2023) updated the potential values for both near-field-EGS and deep EGS resources. While these resources are excluded from ReEDS default assumptions due to feasibility uncertainties, they can be incorporated into specific analyses when needed.

3 METHODOLOGY

To improve the representation of geothermal energy in US-REGEN, this project leverages a set of datasets provided by NREL, which characterize geothermal resources and technologies as currently modeled in the 2024 ReEDS[6]. In this section, we detail the process of analyzing and aggregating this information to align with US-REGEN's model architecture and modeling capabilities. The enhanced geothermal representation is then integrated into scenario analyses to conduct a preliminary assessment of the role geothermal technologies may play in achieving a net-zero U.S. energy system by 2050.

Input Data

Table 1 lists the geothermal datasets provided to EPRI's US-REGEN team by NREL's ReEDS team. In line with the definition of geothermal resources outlined in previous reports (DOE, 2019) and (Augustine, Fisher, Ho, Warren, & Witter, 2023), the datasets include information on hydrothermal, near-field EGS and deep EGS resources and their corresponding technologies.

Table 1. Datasets provided by NREL's ReEDS team for characterization of geothermal resources and technologies.

Dataset	Description
Geothermal Resource Classes	Temperature-based definition of geothermal resource classes. Same classes for hydrothermal, near-field EGS and deep EGS resources.
Resource Supply Curves	Hydrothermal and deep EGS: Geothermal site-specific information including locational (latitude and longitude, distance to grid interconnection), technical (resource potential, mean resource temperature, capacity factor) and economic (mean LCOE, spur-line costs) and other attributes. Source: reV[7] (Pinchuk, Thomsen, Trainor-Guitton, Buster, & Maclaurin, 2023; NREL, 2023). Near-field EGS: Resource potential and average capital cost by ReEDS region and temperature-based resource class. Source: GETEM model updated for (Augustine, Fisher, Ho, Warren, & Witter, 2023; Augustine, Ho, & Blair, 2019).
Discovery Rate	Hydrothermal resource discovery rate for two scenarios: conservative (1% per year) and optimistic (linear rate until full discovery by 2050) consistent with GeoVision report (DOE, 2019).
Spatial Hierarchy	Mapping of ReEDS regions to U.S. administrative divisions.
Geothermal Technology Costs	Capital and operational costs for hydrothermal, near-field EGS and deep EGS technologies by temperature-based resource class for three scenarios (conservative, moderate and advanced) from ATB 2023[8].

[6] The representation of geothermal resources and technologies in what this report refers to as the "2024 ReEDS model" differs from that described in latest available documentation (Ho, et al., 2021) as well as from the versions used for the GeoVision (DOE, 2019), EarthShot (Augustine, Fisher, Ho, Warren, & Witter, 2023), and Commercial Liftoff (Blankenship, Gertler, Kamaludeen, O'Connor, & Porse, 2024) analyses.

[7] reV Geothermal Module includes EGS improvements targeted in the EarthShot analysis (Augustine, Fisher, Ho, Warren, & Witter, 2023) with additional processing of the underlying temperature at depth data from Southern Methodist University (SMU).

[8] This report utilizes data from ATB 2023; however, ATB 2024 is already available at https://atb.nrel.gov/electricity/2024/geothermal. Note that there are significant differences in the costs for EGS between the 2023 and 2024 version of the ATB. For example, compared to the 2023 ATB, the CAPEX and LCOE for

In the 2024 ReEDS model, geothermal resources are not only classified by type, but also distinguished by temperature class, as shown in Table 2. This approach better aligns the appropriate technology with the resource conditions and applications, providing a more accurate framework for evaluating scalability and economic feasibility. Higher-temperature resources typically result in more efficient and cost-effective power generation. Consequently, the plant cycle (binary or flash), previously explicitly represented in previous versions of the model, is now embedded in the temperature-based resource classification. This method of modeling resource quality, in the form of temperature for geothermal energy, is consistent with the representation of other renewable resources such as wind and solar.

Geothermal supply curves, coming from the System Advisor Model (SAM) Geothermal Electricity Technology Evaluation Model (GETEM) Module, include three resource types (hydrothermal, near-field EGS and deep EGS), 10 temperature-based resource classes, and 134 regions, consistent with the ReEDS spatial disaggregation of the contiguous U.S. For undiscovered hydrothermal and deep EGS, the current ReEDS model uses site-specific resource potential data derived from the Renewable Energy Potential Model (reV) (Pinchuk, Thomsen, Trainor-Guitton, Buster, & Maclaurin, 2023) while still relying on GETEM (NREL, 2023) for cost structure. The provided supply curves for these resources include locational attributes (latitude and longitude, distance to grid interconnection), technical characteristics (resource potential, mean resource temperature, capacity factor) and economic metrics (mean levelized cost of energy (LCOE), spur-line costs) along with other site-specific details for identified U.S. locations. The identified hydrothermal supply curve utilizes location specific technical characteristics based upon the 2008 USGS study; spur-line costs are inferred from nearest sites in the reV hydrothermal supply curves. The provided supply curve for near-field EGS is not site-specific yet and does not include spur-line costs.

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deep EGS binary decreased by 55% and 57% respectively. These reductions could substantially impact deployment projections.

Table 2. Temperature-based classification of geothermal resource classes (including both hydrothermal and EGS), corresponding technologies for power generation, and typical applications.

Resource Class	Temperature (°C)		Technology	Application
1	> 325	High-enthalpy	Flash/Binary[9]	Power Generation
2	300 - 325			
3	275 - 300			
4	250 - 275			
5	225 - 250			
6	200 - 225			
7	175 - 200			
8	150 - 175	Medium-enthalpy	Binary	
9	125 - 150			Direct Use
10	< 125	Low-enthalpy		

Hydrothermal resources are divided into two categories: identified and undiscovered resources. Two distinct discovery rate scenarios were provided to model the availability of hydrothermal resources for development on an annual basis. In the conservative scenario, only 1% of undiscovered resources are revealed each year, gradually increasing the resource base over time. In the optimistic scenario, all undiscovered resources are fully identified by 2050, allowing for more rapid development.

Assuming a resource class threshold for power generation up to class 8[10] (150°C - 175°C), hydrothermal resources across the contiguous U.S. amount to a total potential of 340.8 GWe[11] distributed over 1,063 sites (see Figure 2(a)). In contrast, deep EGS resource provide an additional potential of 70.1 TWe, spread across 41,034 identified sites as visualized by resource class in Figure 2(b). Resources estimates exclude areas on federally protected and U.S. Department of Defense lands, where development is highly restricted. Due to the inclusion of heat flow maps in the reV-GETEM framework (Pinchuk, Thomsen, Trainor-Guitton, Buster, & Maclaurin, 2023) and a shift toward a site-specific representation of geothermal resources in the 2024 ReEDS model, the total resource potential in the provided reV-GETEM datasets differs slightly from previous studies (DOE, 2019; Augustine, Fisher, Ho, Warren, & Witter, 2023; Blankenship, Gertler, Kamaludeen, O'Connor, & Porse, 2024), , though the values remain within the same overall range.

[9] Binary cycle power plants offer greater operational flexibility compared to flash technologies, as they can efficiently utilize heat sources across a broader range of temperature conditions. This adaptability allows binary systems to operate effectively with low to moderate temperature geothermal resources, as well as higher temperature applications.

[10] The threshold refers to power generation using conventional binary and flash technologies. Binary plants, typically suited for lower-temperature resources, operate efficiently up to around 175°C (DiPippo, 2015). For higher-temperature resources, flash steam plants become more efficient. However, driven by water conservation priorities, binary power plants have become the predominant choice, even for such resources.

[11] The total hydrothermal potential, encompassing all resource classes, exceeds 3.8 TW.

The hydrothermal geothermal resource potential is primarily concentrated in the western U.S., with the majority classified as undiscovered. After accounting for current deployments, land restrictions, and other barriers, only approximately 20% of hydrothermal resources are identified (Augustine, Fisher, Ho, Warren, & Witter, 2023). While high-enthalpy EGS resources are also concentrated in the western U.S., future technological innovations are expected to expand the realizable potential of medium-enthalpy EGS to other regions of the country.

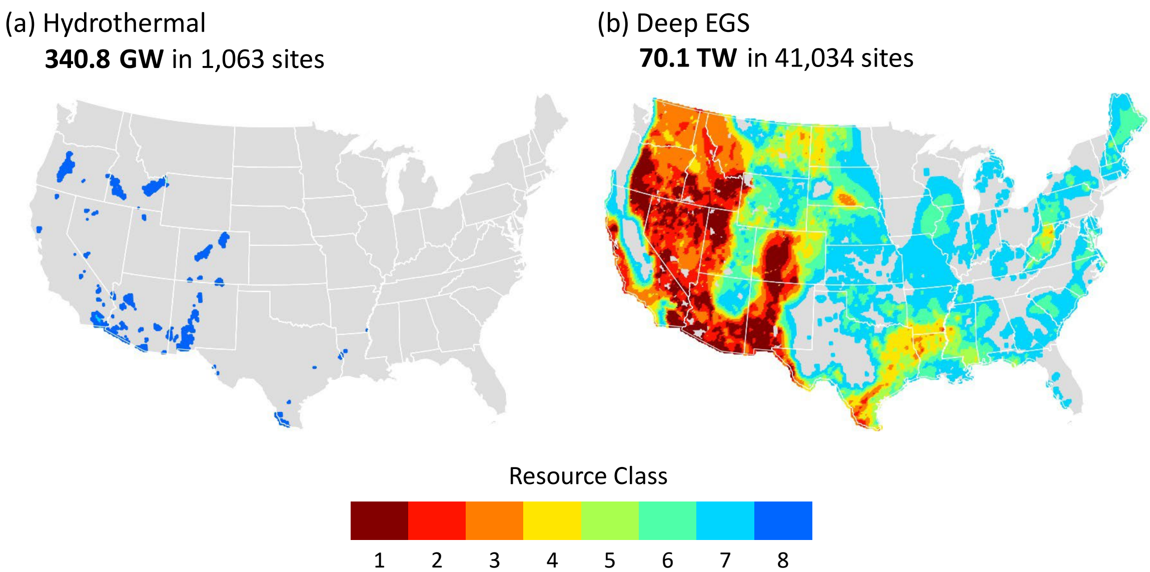

Figure 2. Spatial distribution of (a) hydrothermal and (b) deep EGS sites for power generation by resource class based on the reV-GETEM dataset.

Figure 3(a) illustrates the hydrothermal sites and Figure 3(b) the deep EGS sites in the provided reV-GETEM dataset by temperature-based resource class and mean LCOE[12]. Though available for each site, the plotted LCOE does not include the associated spur-line routing and costs. It is observed that most available hydrothermal capacity is medium-enthalpy sites with only a few high-enthalpy locations. In contrast, deep EGS resources show vast high-enthalpy potential, with resource class 1 alone accounting for more than 18 TWe. In both cases, LCOE increases as resource temperature decreases.

[12] The LCOE is site specific and accounts for regional variations in geothermal resource endowments and geologic conditions as well as regional cost multipliers that reflect differences in installation costs across the U.S. However, it does not factor in drilling depth and well productivity for individual sites. However, resource depth is semi-embedded into the cost assumptions by considering a representative technology with consistent geologic characteristics and performance for each resource class. For hydrothermal LCOE calculations, the resource is assumed to be at a depth of 1.5 km with wells producing an average of 110 kg/s of geothermal brine to a 25 MWe binary ORC power plant (NREL, 2024). For deep EGS, a depth of 3.5 km is assumed, with a productivity rate of 60 kg/s supplying a 25 MWe dual-flash power plant.

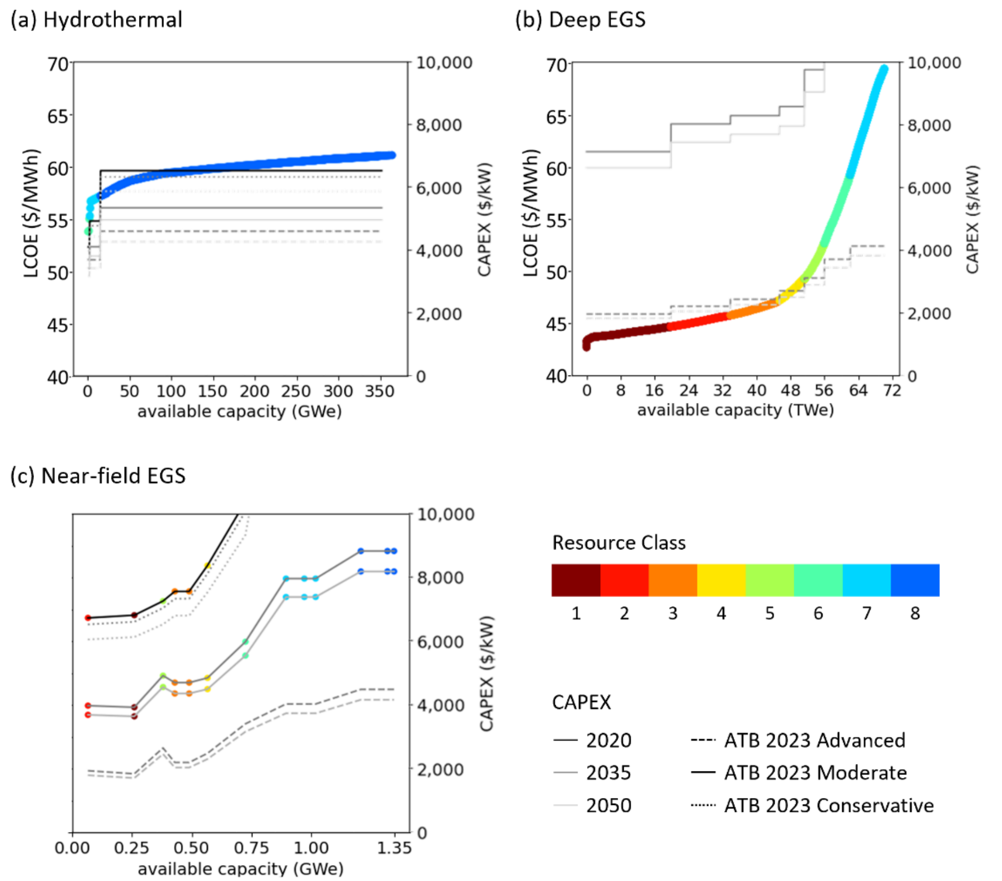

Figure 3. (a) Hydrothermal, (b) deep EGS and (c) near-field EGS supply curves by resource class. On the left y-axis, colored dots represent resource potentials by LCOE and resource class, based on the reV-GETEM model using 2030 projected costs for hydrothermal and deep EGS resources. The right y-axis shows CAPEX values for 2020, 2035 and 2050 across different ATB cost scenarios depicted by lines. Line color saturation indicates the year, while line type distinguishes ATB cost scenarios. For the near-field supply curve, colored dots also represent CAPEX values. All values are shown in 2021 USD.

The near-field EGS resource potential is not represented yet in the new site-based reV-GETEM datasets. Figure 3(c) presents the provided resource supply curve for near-field EGS, with each dot representing a ReEDS region with this resource type, color-coded by resource class. The total potential available for power generation is approximately ~1.35 GWe. LCOE information for near-field EGS is not available in this dataset.

In addition to the supply curves for the three geothermal resource types, the 2023 Annual Technology Baseline (ATB) cost data for geothermal technologies was also provided. Since the geothermal resource classification in the 2024 ReEDS model differs from previous versions, the 2023 ATB cost data used in this project is not identical to the data available in the ATB website, but remains compatible. The key change involves the shift from a binary and flash technology classification to a temperature-based classification. This transition provides greater detail, particularly for flash technologies, as projected capital expenditures (CAPEX) and fixed operation and maintenance (O&M) costs are now specified for each resource type and temperature class. Furthermore, CAPEX and FOM costs in the 2023 ATB do not reflect regional cost variations associated with labor rates, material costs, or other localized factors. Similar to the LCOE calculation in the reV-GETEM dataset, costs are calculated for a representative technology for each resource class. The provided CAPEX data is plotted on the right vertical axis in Figure 3 for the three geothermal technologies. Projected costs for 2020, 2035 and 2050 are shown in shades of gray, with different line styles representing various cost scenarios. For easier comparison across technologies, capital costs are capped at $10,000/kW, meaning not all resource class steps or cost scenarios are fully visualized.

Updated Representation of Geothermal Resources and Technologies in US-REGEN

Integrating the provided geothermal datasets into US-REGEN enhances the representation of geothermal energy by transitioning from a single hydrothermal technology to a temperature-based classification, including hydrothermal, near-field EGS, and deep EGS resources. This integration requires aligning the spatial resolution and extent to match the state-level representation of renewable resources by resource quality in US-REGEN, as well as adding and characterizing new geothermal capacity blocks.

Characterization of Geothermal Resources

Renewable potential capacity in US-REGEN is estimated using state-level datasets with different classes based on resource quality (see section “Resource and Technology Assumptions in (EPRI, 2021)). Each resource class is represented by a technology block. While increasing the number of resource classes improves model precision, it also raises the computational burden, as shown in Figure 1. Representing 8 temperature classes for 3 resource types would add 24 new technology blocks, which would substantially increase the model complexity. Therefore, to streamline their integration into US-REGEN, the number of resource classes must be reduced.

Based on the geothermal resource distribution in Figure 3, there are significant differences in resource potential and cost across the various resource classes, although the degree of variation differs by resource type. To reduce the number of capacity blocks while still capturing key differences, resources can be aggregated. One straightforward approach would be to focus solely on the highest-quality geothermal resources, as these are more likely to be deployed due to their lower costs. However, in the case of deep EGS, this would exclude medium-enthalpy resources in the midwestern and eastern U.S., limiting the scope of the analysis.

To account for both resource availability and cost, while still representing all temperature-based resource classes, we applied a k-means clustering analysis, aggregating hydrothermal resources into three classes, deep EGS into three, and near-field EGS into two. K-means is a statistical method that groups data points into clusters, minimizing the variation within each cluster, allowing for clear differentiation between groups while reducing complexity. This approach ensures that the aggregated resource classes retain their key characteristics, and the resulting classes are visualized in Figure 4.

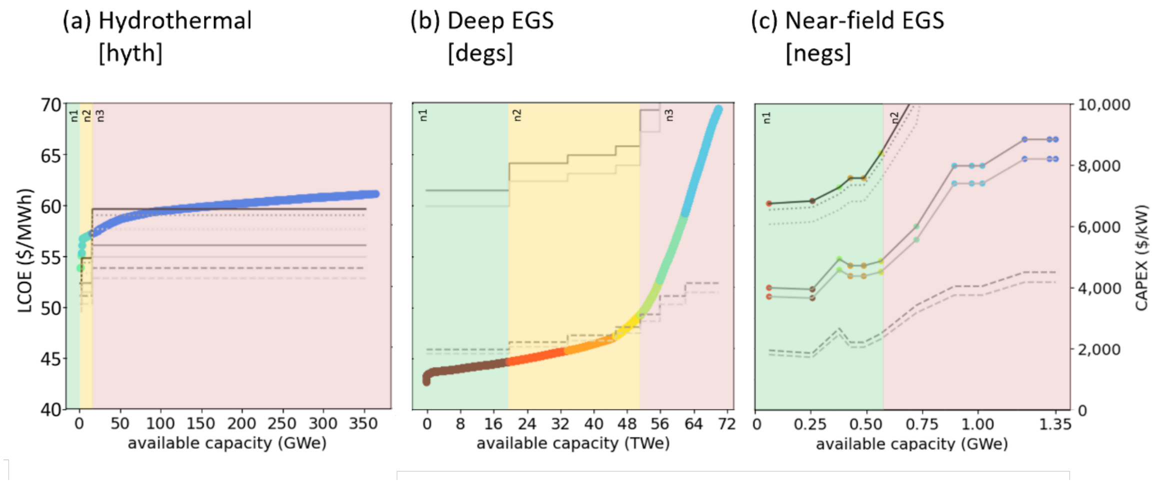

Figure 4. Aggregation of (a) hydrothermal, (b) deep EGS, and (c) near-field EGS resources into clusters for integration into US-REGEN. Technology type names in US-REGEN are indicated in brackets. The color coding for resource class is consistent with Figure 3.

In the updated representation of geothermal resources in US-REGEN, three capacity blocks are used to represent new hydrothermal technologies: hyth-n1, hyth-n2 and hyth-n3, corresponding to hydrothermal resource classes 6, 7 and 8 as shown in Figure 4(a). For deep EGS (Figure 4(b)), the capacity blocks degs-n1, degs-n2 and degs-n3 correspond to new deep-EGS technologies with resources classes 1, 2-4 and 5-7, respectively. Finally, the capacity blocks negs-n1 and negs-n2 represent new near-field EGS technologies corresponding to resource classes 1-5 and 6-8 as observed in Figure 4(c).

The map in Figure 5 illustrates the distribution of geothermal resources across states by US-REGEN resource class. These values represent the upper limits for installed capacity within each technology block. Deep EGS dominates the overall resource potential, but resource quality varies significantly by state. Nevada has the largest geothermal potential primarily in the degs-n1 and degs-n2 classes, while many states in the Mountain region also feature high-quality deep geothermal resources (degs-n1). In contrast, most geothermal potential in the Midwest and eastern states falls within the lower-quality degs-n3 class. Hydrothermal resources, though more limited compared to EGS, are present in the western U.S., particularly in the hyth-n3 class.

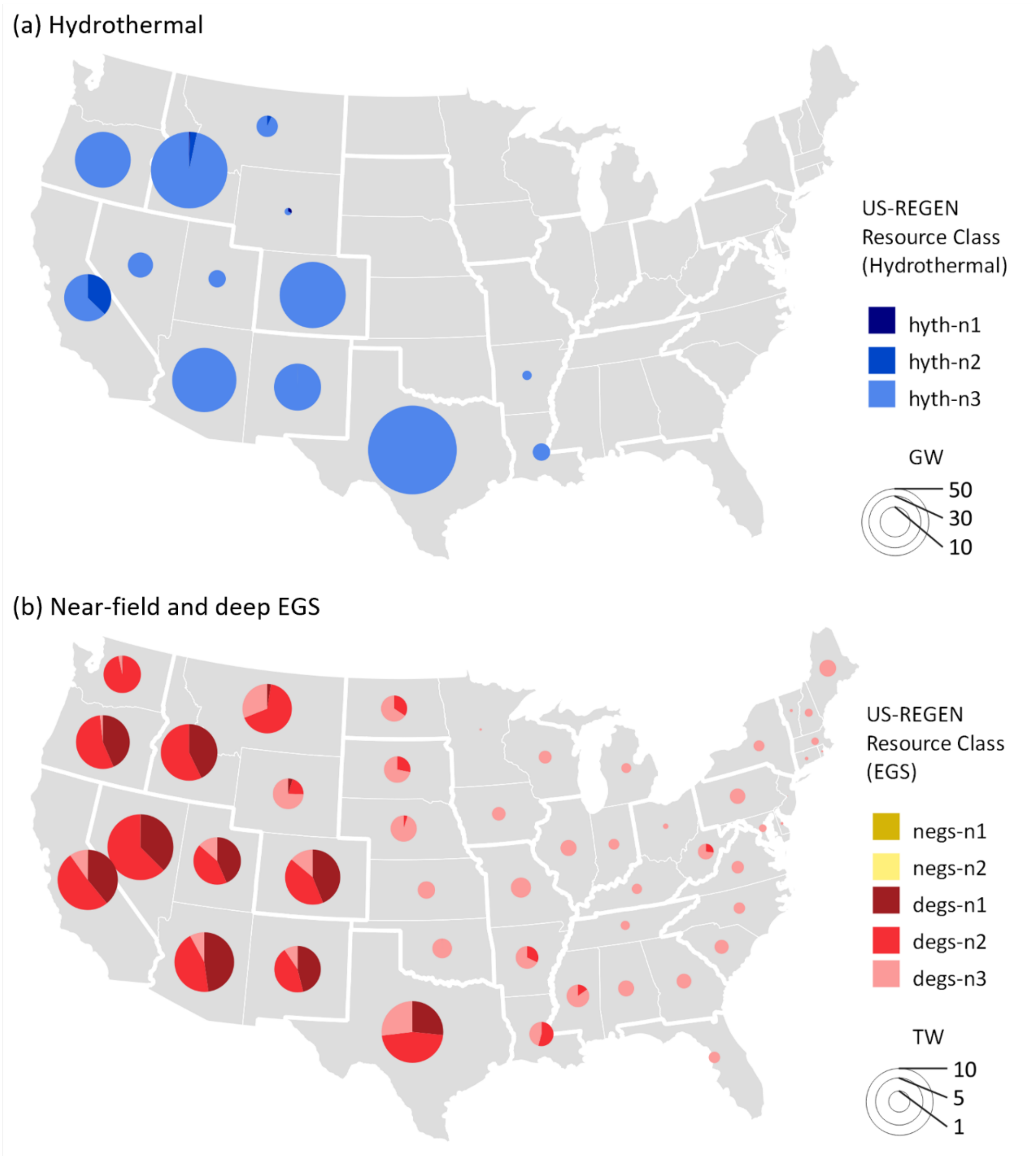

Figure 5. (a) Hydrothermal and (b) EGS (near-field and deep) resource limits by state in US-REGEN.

Characterization of Geothermal Technologies

Each aggregated resource class corresponds to a new technology block that represents a generation option for each region in the US-REGEN model. These representative technologies are characterized by various technical and economic attributes, including capital costs, fixed and variable O&M costs, lifetime, capacity factor, and water requirements, and other relevant factors.

For the updated representation of geothermal technologies, the base year capital and fixed O&M costs for the new US-REGEN capacity blocks were calculated as the 2023 ATB average cost, weighted by capacity within each technology block. The resulting capital and fixed O&M costs for the eight new technology blocks are shown in Figure 6. These costs account for regional variations reflecting differences in installation costs across the U.S. (e.g., wage, productivity).

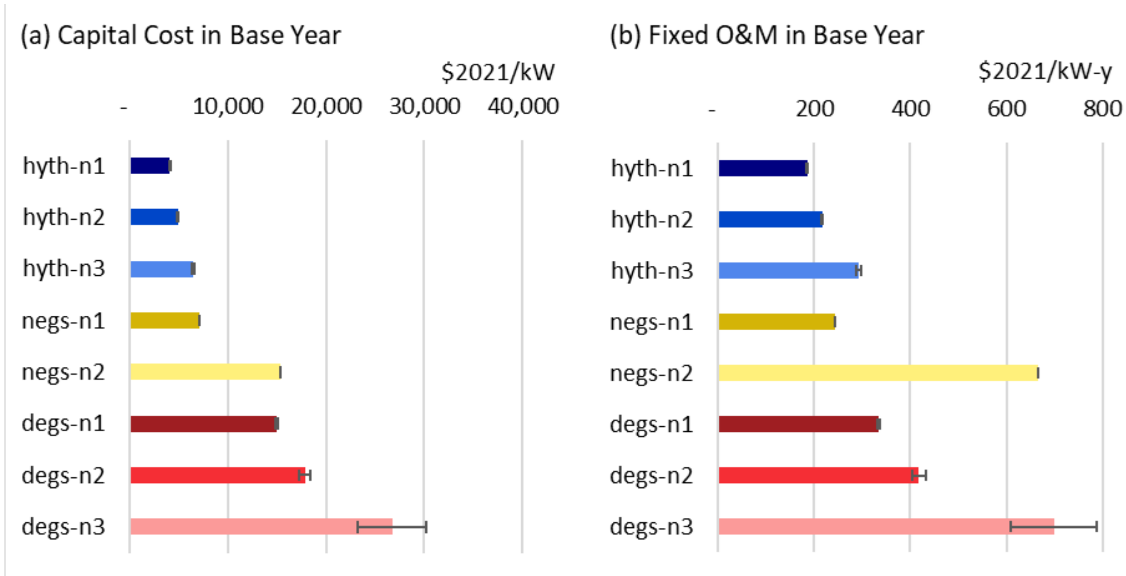

Figure 6. (a) Capital and (b) fixed operation and maintenance costs for geothermal technology blocks in base year (2015) in US-REGEN with variation across states based on 2023 ATB costs. Note that significant cost declines for EGS have been observed between the 2023 and 2024 ATB versions which are not captured in this study.

Projections of future capital costs in US-REGEN are calculated by applying a learning curve to the base year cost (2015), which reflects technology learning rates over time. Learning curves from the 2023 ATB dataset were averaged for each US-REGEN resource class, weighted by capacity within each technology block, with the calculated learning curves visualized in Figure 7. Conservative, Moderate and Advanced cost scenarios are in line with (NREL, 2024):

- Conservative Scenario: Minimal improvements in drilling efficiency and EGS stimulation result in a slow 10% CAPEX reduction by 2035 and a 0.5% annual CAPEX decrease through 2050. All geothermal technologies follow the same learning rate.
- Moderate Scenario: Advances in drilling, EGS stimulation, and well productivity lead to significant cost reductions by 2035, followed by a 0.5% annual CAPEX decline thereafter, particularly benefiting high-enthalpy resources.
- Advanced Scenario: Major breakthroughs in drilling and EGS technology, along with streamlined permitting, achieve rapid cost reductions by 2035, followed by continued CAPEX improvements of 0.5% annually through 2050, with the greatest reductions seen in high-enthalpy resources.

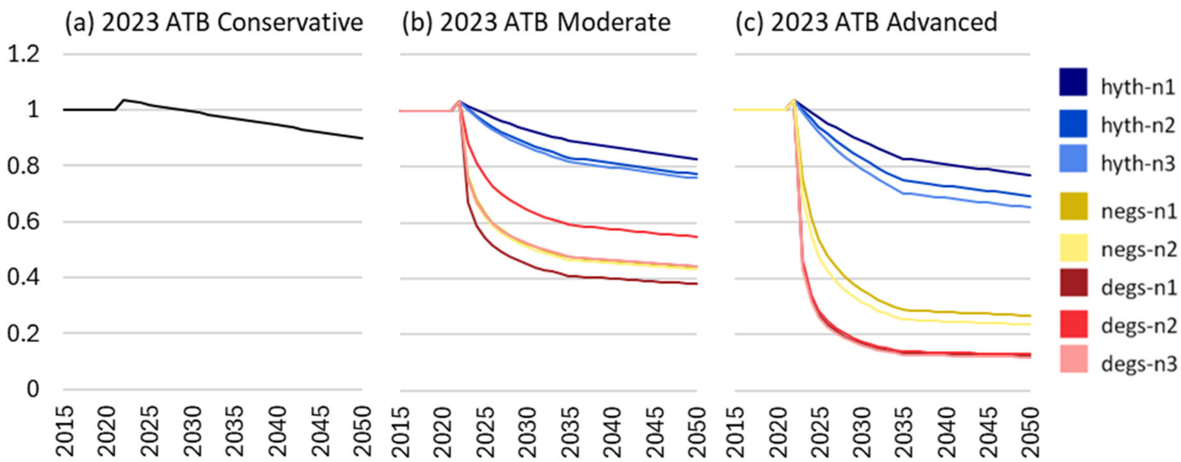

Figure 7. Learning curves for geothermal technologies in US-REGEN for three cost scenarios: (a) 2023 ATB Conservative (same learning curve for all technologies), (b) 2023 ATB Moderate, and (c) 2023 ATB Advanced.

In the previous version of US-REGEN, geothermal generation availability was calculated on a monthly basis through a de-rating process to capture average outages, based on historical data. Availability factors for existing hydrothermal technologies range from 50% during the summer months for power plants in the Pacific region to over 90% during the winter months for plants in the Mountain region. In the updated representation, the availability factor for existing hydrothermal plants is projected to improve to 90% by 2030. The capacity factor for new geothermal capacity blocks is assumed to be 90%, consistent with projections from (NREL, 2024). Additional technical attributes for the new generation blocks include an assumed investment lifetime of 30 years for all technologies, and water consumption rates of 220 gallons per MWh for hydrothermal and 1,400 gallons per MWh for near-field and deep EGS (Macknick, Newmark, Heath, & Hallett, 2011).

Scenario Design and Description

Geothermal power technology can become a key contributor to secure, domestic, decarbonized power generation for the U.S. as a source of clean firm power (Blankenship, Gertler, Kamaludeen, O'Connor, & Porse, 2024). Economy-wide deep decarbonization scenarios suggest that decarbonizing electric generation entails increased shares of intermittent renewables combined with clean firm capacity, as firm resources reduce the need to overbuild variable renewable capacity. However, the optimal mix of renewables and clean firm resources will vary by region and will depend on interactions with decarbonization options within and outside the electric sector (EPRI, 2022). This report assesses the deployment of geothermal power across two economy-wide net-zero by 2050 cases, and three geothermal learning curves for a total of six scenarios (see scenario matrix in Table 3).

The economy-wide net zero scenarios are defined around the uncertainties of three key technologies, namely the availability of geologic storage of CO_2 and bioenergy feedstock supply, as well as future natural gas costs, in line with the scenario design in the LCRI Net-Zero 2050:

U.S. Economy-Wide Deep Decarbonization Scenario Analysis (EPRI, 2022)[13]. The Net-Zero All Options case assumes the full portfolio of clean energy technologies is available, including renewables, nuclear, fossil and bioenergy with carbon capture and storage (CCS), electricity storage, hydrogen and hydrogen-derived fuels (e.g., synthetic jet fuel and synthetic natural gas), and biofuels (e.g., renewable natural gas and renewable diesel), all with reference costs. The Net-Zero Limited Options case assumes geologic storage of CO_2 is not available and bioenergy supply is limited. All other technologies are available at reference costs.

Table 3. Scenario design for assessing the role of geothermal energy in a net-zero energy system.

2050 Net-Zero Case	Geothermal Learning Curve (2023 ATB)		
	Conservative	Moderate	Advanced
All Options	NZ-A_conservative	NZ-A_moderate	NZ-A_advanced
Limited Options (no CCS and limited biofuel supply)	NZ-L_conservative	NZ-L_moderate	NZ-L_advanced

[13] The referenced report does not account for the impacts of the IRA. However, the version of US-REGEN used for this analysis incorporates these financial incentives, along with updated state-level energy policies (Bistline, Roney, Blanford, & Young, 2023).

4 RESULTS

The results presented in this section focus on the deployment of geothermal capacity and its contribution to total electricity generation in two net-zero pathways across three geothermal cost scenarios, using the enhanced representation of geothermal resources and technologies in US-REGEN. While the integration of additional geothermal technologies (near-field and deep EGS) and updated cost assumptions primarily impact the electric sector, their effects extend beyond electricity generation to the broader energy system. By influencing electricity prices and carbon intensity, geothermal deployment can shape decarbonization strategies in end-use sectors, both through direct electrification and indirectly through hydrogen production and hydrogen-derived fuels. This underscores the need for economy-wide modeling. Although US-REGEN provides an economy-wide analysis, this analysis is limited to the electric sector. Broader impacts on the economy are beyond the scope of this project.

Net-Zero All Options

In the Net-Zero All Options scenario, CCS plays a pivotal role in decarbonizing the power system as observed in Figure 8. As capacity additions are needed to meet rising electricity demand, natural gas with CCS emerges as a cost-effective clean firm capacity option, complemented by long-duration battery storage technologies to balance the growing share of intermittent renewables.

In the conservative cost scenario, hydrothermal capacity remains at current levels. In the moderate cost scenario, geothermal deployment remains minimal, with modest hydrothermal additions throughout the modeling period, reaching a total installed capacity of 4.5 GW by 2050. In the advanced cost scenario, geothermal resources begin to play a significant role in the final decade, with near-field new additions of 0.5 GW and deep EGS contributing nearly 36 GW, primarily concentrated in California and the Mountain South region. By 2050, geothermal energy accounts for approximately 5% of total generation in this scenario. Deep EGS (degs-n1) capital costs are projected to fall to around $1,800/kW by 2045, making it a cost-competitive option for clean, firm power in regions with high-quality deep EGS resources. This leads to a slight decrease in investments in intermittent renewables, reducing overall system costs. A detailed breakdown of geothermal additions by capacity block is provided in Table 4, with regional distributions illustrated in Figure 10.

Net-Zero Limited Options

In the Net-Zero Limited Options scenario, no CCS availability leads to a different strategy for achieving net-zero emissions, as it significantly restricts the potential scale of negative emissions. In this case, electricity demand is significantly higher due to greater electrification and increased hydrogen production. As a result, the role of geothermal energy as a clean firm power source becomes more evident.

Similar to the Net-Zero All Options case, the conservative cost scenario results in minimal geothermal additions, with capacity remaining just above current levels. However, in the moderate cost scenario, near-field EGS begins to see some deployment (0.5 GW). The advanced cost scenario (2023 ATB Advanced) shows the most substantial geothermal deployment, starting in 2040—five years earlier than in the more flexible Net-Zero All Options case—and reaching 58.5 GW by 2050. This capacity is concentrated in California and the Mountain South region, though the latter sees less geothermal development compared to the Net-Zero All Options case. This reduced deployment is due to the large-scale adoption of cheaper wind and solar resources in neighboring regions, which lowers the demand for geothermal energy. Nonetheless, by 2050, geothermal energy contributes 8.5% of the national electricity supply, generating 479 TWh. A detailed breakdown of geothermal additions by capacity block is provided in Table 4 in the summary section, with regional distributions detailed in Figure 10.

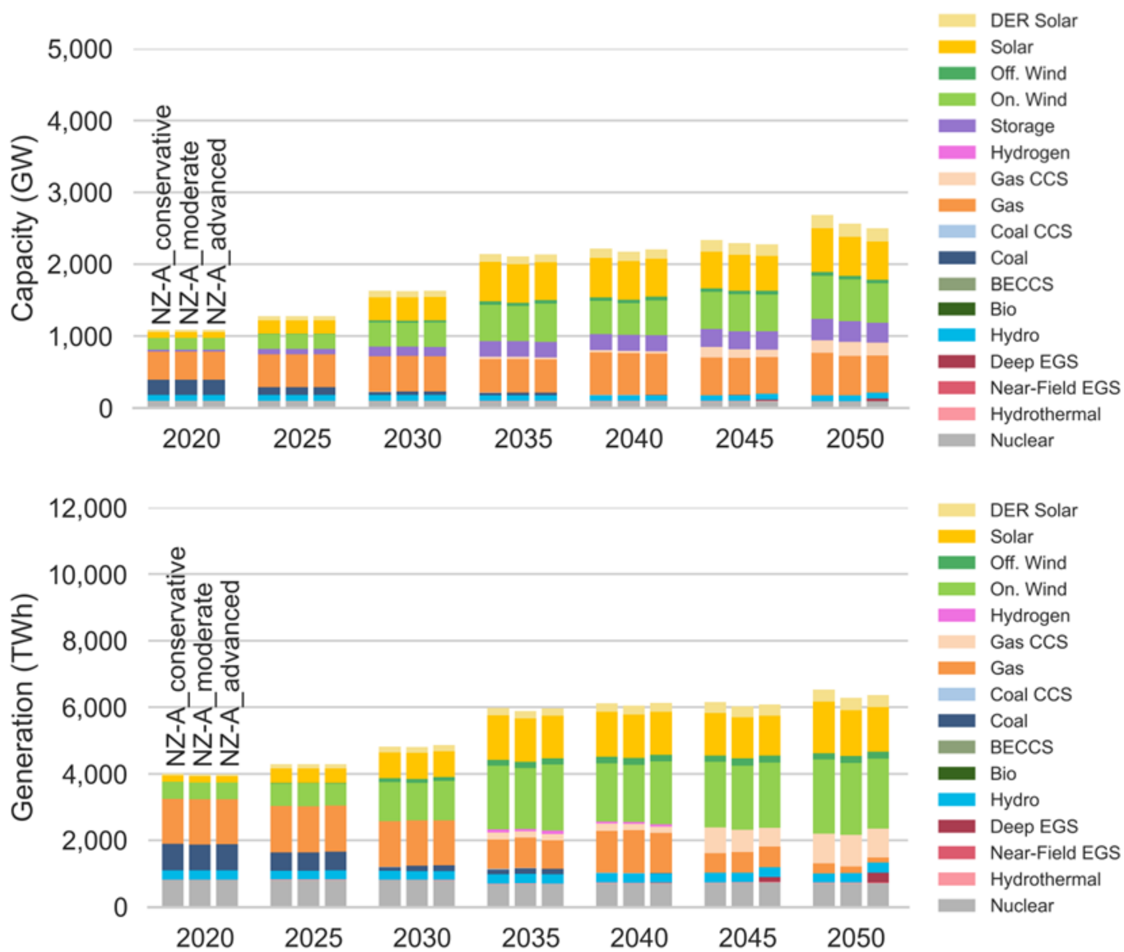

Figure 8. Evolution of power installed capacity and generation in the Net-Zero All Options case.

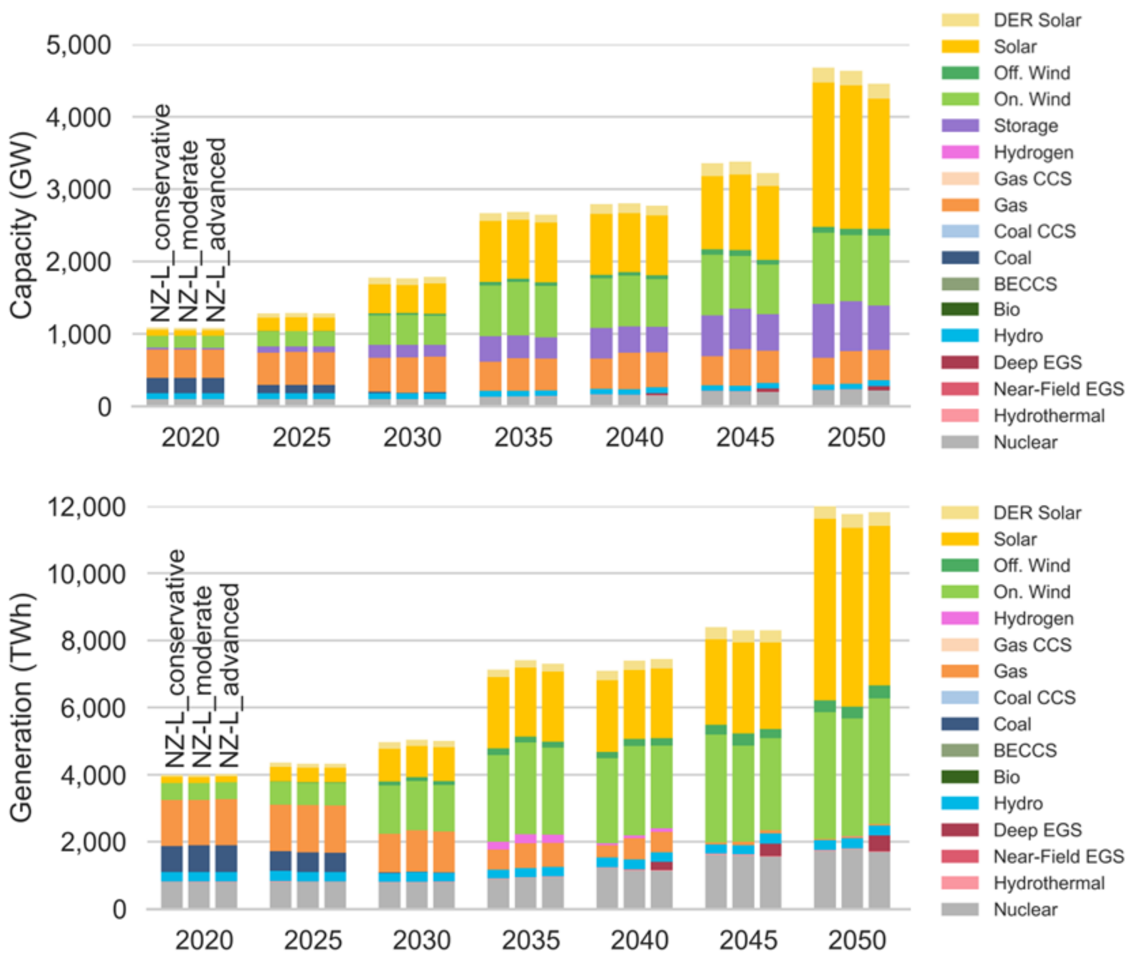

Figure 9. Evolution of power capacity and generation in the Net-Zero Limited Options case.

Summary and Discussion

The updated representation of geothermal technologies including hydrothermal, near-field and deep EGS technologies differentiated by resource quality impacts significantly the modeling results for the net-zero cases analyzed in this report, in particular when using the 2023 ATB Advanced cost scenario. Previous studies using US-REGEN, which considered only a generalized hydrothermal technology and did not account for EGS resources, indicated minimal geothermal deployment (e.g., LCRI Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis (EPRI, 2022), Figure 22). In contrast, the scenarios analyzed in this report show significant geothermal deployment.

Table 4 summarizes the installed capacity and generation in 2050 by technology type and geothermal cost scenario and Figure 10 breaks down the existing and new installed capacity by technology block and region for those scenarios with the largest geothermal additions. With conservative geothermal cost projections, hydrothermal energy grows from 3.6 GW in 2020 to 3.7 GW and 4.5 GW, for the Net-Zero All Options and Limited Options scenarios, respectively. With moderate cost projections, hydrothermal energy is further developed reaching 4.5 GW in both net-zero cases concentrated in California and the Mountain South region, but small additions are also present in Mountain North. In the Net-Zero Limited Options pathway, near-field geothermal is also deployed adding 0.5 GW of capacity. With low geothermal costs, in the 2023 Advanced cost scenario, the three geothermal technologies are deployed, with deep EGS being by far the largest capacity additions, reaching 35.9 GW and 58.5 GW, for the Net-Zero All Options and Limited Options scenarios, respectively. Similar to hydrothermal resources, deployment was concentrated in the western U.S., particularly in California.

Table 4. Total geothermal capacity and generation in 2050 by technology type and geothermal cost scenario (2023 ATB conservative, moderate, advanced).

2050 Net-Zero Case	Technology	Installed Power Capacity (GW)			Power Generation (TWh)		
		Conservative	Moderate	Advanced	Conservative	Moderate	Advanced
All Options	Hydrothermal	3.7	4.5	3.7	29.7	36.2	30.0
	Near-field EGS	-	-	0.5	-	-	4.4
	Deep EGS	-	-	35.9	-	-	291.0
Limited Options	Hydrothermal	4.5	4.5	3.7	36.2	36.2	30.0
	Near-field EGS	-	0.5	0.5	-	4.4	4.4
	Deep EGS	-	-	58.5	-	-	479.0

Clean, firm resources—gas with CCS, solar photovoltaics (PV) plus battery storage, advanced nuclear, and geothermal—exhibit varied deployment patterns across regions, driven by resource availability and cost competitiveness. Deep EGS is deployed significantly in regions with high-quality resources, particularly in the western U.S. (Figure 10), where its competitive costs displace some solar PV and battery storage for firm generation in both net-zero scenarios. In contrast, in the southern and eastern regions, gas with CCS in the All Options scenario and advanced nuclear in the Limited Options scenario see increased deployment due to the lower quality and competitiveness of deep EGS resources in these regions. These findings highlight the importance of regional resource endowments and technology competitiveness in shaping the optimal regional decarbonization pathways. Additional regional analysis to explore these trade-offs in greater detail would be valuable but is beyond the scope of this study.

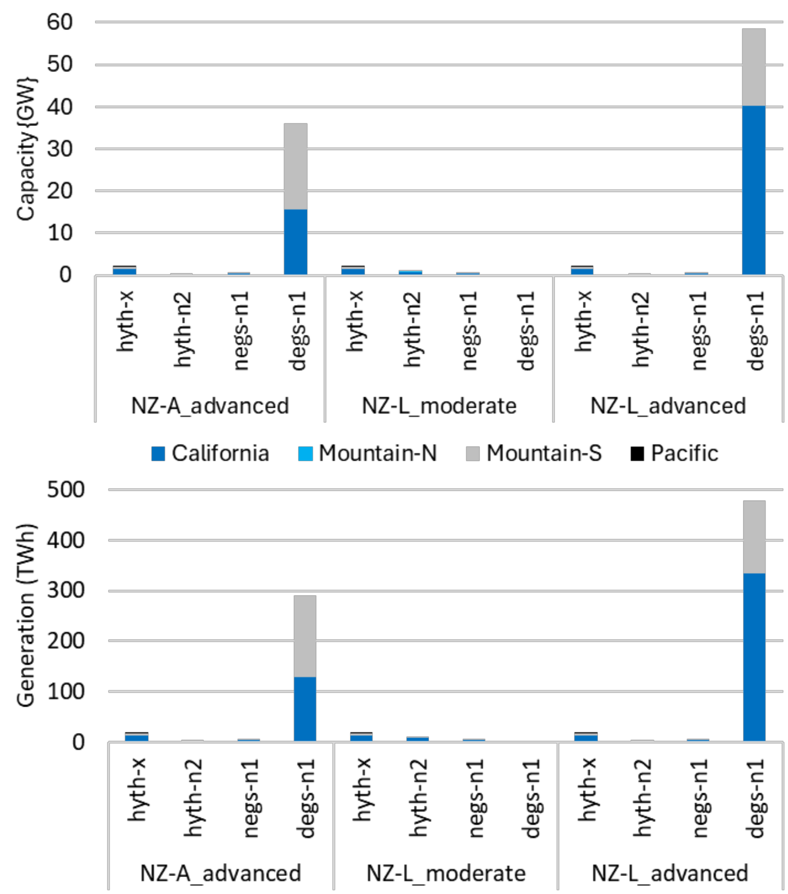

Figure 10. Breakdown of existing (hyth-x) and newly installed geothermal capacity and generation by technology block and region in 2050 for relevant scenarios.

Although geothermal additions in the scenarios analyzed in US-REGEN are significant, they remain considerably lower than in previous studies. For example, in the *Pathways to Commercial Liftoff: Next Generation Geothermal Power* report (Blankenship, Gertler, Kamaludeen, O'Connor, & Porse, 2024), projected geothermal installed capacity by 2050 to range from 90 GW to 327 GW, depending on the scenario. Several factors contributed to this difference, including assumptions of 95% decarbonization by 2035 and full decarbonization by 2050, with an overnight capital cost of $3,565/kW, which accelerated geothermal deployment. Additionally, restrictions on nascent technologies and land use significantly impacted capacity additions. In the scenario with the highest deployment, hydrogen and direct air capture were restricted, and solar and wind generation was capped at 1.1 TW. Furthermore, the ReEDS and GenX models used in the analysis focus on the power sector and do not model economy-wide decarbonization, leaving out cross-sectoral tradeoffs that are represented in US-REGEN.

Moreover, significant cost declines for EGS have been observed between the 2023 and 2024 ATB versions. For instance, the CAPEX and LCOE for deep EGS binary technologies decreased by 55% and 57%, respectively (NREL, 2024). These reductions could substantially impact deployment projections, potentially increasing geothermal adoption even in conservative scenarios.

Given the significant uncertainty surrounding geothermal costs and the wide range of energy mixes observed in both this study and others, it is essential to further evaluate additional scenarios using economy-wide models. This will not only help to understand the specific conditions under which geothermal energy is deployed but also assess the broader impacts of this deployment across the entire energy system, beyond the power sector alone. A regional analysis is also crucial, as differences in resource endowments, including geothermal potential, existing infrastructure, and available decarbonization options, lead to varying decarbonization pathways and associated risks.

A first high-level assessment, e.g., long-run system change, can already provide valuable insights into the role of geothermal technologies at the national and regional levels. However, to achieve a more detailed understanding, site-specific data—including resource depth—should be incorporated into nodal, unit-level capacity expansion models, resource adequacy assessments, and production cost analyses. These more granular approaches will provide a clearer picture of geothermal's competitiveness and integration within specific regions and energy markets.

Furthermore, geothermal energy holds significant potential for direct-use applications, particularly in end-use sectors like heating and industrial processes. This could further enhance its contribution to decarbonization efforts, expanding its role beyond electricity generation. Understanding these broader system interactions is essential for designing effective policy incentives and shaping decarbonization strategies across the energy system. By addressing these dynamics, policymakers can ensure that geothermal energy is leveraged to its fullest potential in the transition to a low-carbon economy.

5 GUIDELINES FOR ENHANCING GEOTHERMAL INTEGRATION IN CEM

Based on the experience of this project improving the representation of geothermal and technologies in EPRI's US-REGEN using up to date NREL's ReEDS data, the following key guidelines were identified for effectively incorporating geothermal technologies CEMs:

- **Consistent Resource Definitions**: Maintaining consistency in defining geothermal resources across datasets and models is essential. Clear distinctions between hydrothermal, near-field EGS, and deep EGS technologies allow for comparability and accurate assessment of resource potential.
- **Temperature-Based Resource Classification**: Given the temperature dependence of geothermal resources, a temperature-based classification system is recommended. This approach aligns the appropriate technology—whether binary or flash—with specific resource conditions, enabling a more accurate evaluation of scalability and economic feasibility, much like the modeling of wind and solar energy based on resource quality.
- **Regional and Technological Disaggregation**: Geothermal supply curves should be disaggregated by region, resource class, and technology type to capture local variations in resource potential, cost, and performance. This improves model accuracy while managing computational complexity, as broad aggregation risks missing key regional and technological distinctions.
- **Inclusion of Cost Scenarios**: Incorporating a range of cost and performance scenarios provides a more robust understanding of geothermal technologies under different development pathways. This ensures the model reflects realistic uncertainties in future technological advancements, drilling costs, and policy impacts.
- **Model Structure and Complexity**: The representation of geothermal technologies should be tailored to the structure and complexity of the specific CEM. Models with high regional resolution may incorporate site-specific geothermal data, while models with coarser resolution might aggregate geothermal resources into broader categories. However, it is crucial to account for the different types of geothermal resources and their associated temperature-dependent costs. Ultimately, the questions the model aims to answer—whether focused on technology deployment, regional resource planning, or long-term decarbonization—will dictate the level of detail needed for geothermal integration.

With these guidelines, CEMs can more effectively capture the spatial distribution of geothermal resources and the temperature-dependent technological variations, ensuring a robust representation for evaluating their contribution to clean, firm power generation. This supports more accurate decision-making in utility resource planning and the development of energy policies, allowing geothermal deployment strategies to be integrated into broader decarbonization frameworks. Scenario-based analyses are critical for identifying the specific conditions under which geothermal technologies are most viable, at both national and regional scales. Furthermore, evaluating geothermal's interaction with the wider energy system is necessary to fully quantify its potential impacts on long-term decarbonization pathways.

6 CONCLUSIONS

Geothermal resources, particularly enhanced geothermal systems (EGS), have been underrepresented in capacity expansion models (CEMs) due to their site-specific nature and the technical and economic uncertainties surrounding their deployment. As the energy sector shifts toward economy-wide decarbonization, a more detailed and accurate representation of geothermal technologies is necessary to evaluate their role in future energy systems.

This project aims to improve the representation of geothermal resources and technologies in EPRI's US-REGEN model. Using updated datasets from NREL's ReEDS model, this study incorporates temperature-based classifications of hydrothermal, near-field EGS, and deep EGS resources. The integration involves modifying US-REGEN's resource supply curves to reflect geothermal resource quality, regional variability, and temperature-dependent cost structures, providing a more precise framework for assessing geothermal scalability and economic viability.

The enhanced geothermal representation is tested in a scenario design with two net-zero pathways mainly differentiated by the availability or absence of CCS and across three geothermal cost scenarios (conservative, moderate, and advanced). In contrast with earlier US-REGEN model runs that did not include deep EGS, this study shows that geothermal deployment, particularly deep EGS, could play a substantial role in the U.S. energy system, contributing up to 58.5 GW of capacity by 2050 in the advanced cost scenario. In contrast, geothermal additions remain minimal in conservative and moderate cost scenarios, highlighting the importance of cost reductions and technological advancements. However, significant cost declines for EGS have been observed between the 2023 and 2024 ATB versions. These reductions could substantially impact deployment projections, potentially increasing geothermal adoption even in conservative scenarios.

While this study focuses on the electric sector, geothermal energy's impact extends beyond electricity generation to broader energy system interactions, such as electrification and hydrogen production. Future assessments should include cross-sectoral analysis to fully understand the role of geothermal technologies in an economy-wide decarbonized energy system. Additionally, regional variations in geothermal resource availability and existing infrastructure necessitate further regional analyses to tailor decarbonization strategies.

Guidelines for improving geothermal integration in CEMs were also derived from the project, emphasizing the importance of consistent resource definitions, temperature-based classifications, regional disaggregation, cost uncertainty while tailoring the technology representation to the model structure, complexity, and research questions. These guidelines can help model developers and users to better reflect the nuances of geothermal resources and provide more accurate insights for utility planning and policy development.

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