# Geothermal Representation in Power System Models

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## ABSTRACT

Power system models generally fail to capture the range of characteristics geothermal resources provide and the value they potentially contribute to decarbonization and reliability of future electricity grids as firm, dispatchable, non-combustion power resources. This study reviews the results of power system modeling efforts to investigate geothermal deployment potential in the United States, including the U.S. DOE *GeoVision* analysis and ongoing modeling and analysis efforts to support planning and development of future grids with 100% renewable energy in California. Several themes are identified that could be implemented immediately to improve the accuracy of geothermal representation in power system models: consistency of model inputs, modeling of baseload and dispatchable geothermal resources, accurate valuation of grid services, improved representation of capacity factor, use of contemporary LCOE estimates, improved understanding of the evolution of geothermal value, and use of accurate resource potential constraints. Many of the models reviewed produced significantly different amounts of geothermal resource selection—even when modeling the same region and time period. This highlights the variability of inputs and assumptions among models, so creating a consistent set of geothermal inputs is a first step toward more accurate representation of geothermal in models. Research opportunities are identified that could help improve geothermal data inputs in modeling efforts, including analyses of historical data, sensitivity to model inputs, and comparative value of geothermal generators as baseload or dispatchable resources. Outcomes of such research can inform the geothermal community about how best to guide geothermal development toward wider deployment in support of future electricity grids through improved understanding of the evolution of geothermal value over time and the characteristics that contribute to that value.

# 1. Introduction

## *1.1 Background*

U.S. electricity systems are rapidly evolving, bringing both opportunities and challenges for different power generation technologies. Increasing penetration of variable renewable energy (VRE) technologies creates new requirements for grid operation and management, including:

- Ensuring sufficient system operational flexibility to address uncertainty in short-term forecast generation
- Capability to address increased load-following needs
- Achievement of a least-cost level of renewable energy curtailment
- Need to replace conventional sources of power system inertia as well as frequency and voltage regulation.

In addition to adapting VRE operations to meet these needs (e.g., through smart inverters and integrated storage), new sources of operational flexibility and ancillary services from other technologies are needed to maintain grid reliability with sufficient capacity reserves (Ringkjob et al. 2018). Resource portfolio development is needed to find opportunities to utilize existing and potentially new, firm, renewable technologies to reduce or otherwise address these requirements, while still meeting other system constraints (e.g., emission reductions).

Geothermal power is a renewable resource that has properties to address these requirements. State-of-the-art geothermal technology can offer a host of flexibility and reliability services such as load following, frequency regulation, voltage regulation, and black-start capability in addition to its traditional role as a firm-capacity renewable resource. Delivered geothermal power is well planned by operators, resulting in high capacity factors. Even when geothermal power plants are not operating flexibly, they do not contribute to the flexibility needs created by expansion of VRE resources, particularly solar generation. Firm geothermal resources also can potentially reduce the need for additional storage as well as defer transmission infrastructure costs.

For these reasons, geothermal power is well suited to support the future grid as a dispatchable, firm-capacity, renewable resource, but it may not be accurately represented in today's power system models—most notably capacity expansion and production cost models. Power system modeling is a crucial component of power system operations and planning. Power systems have become more complex over recent decades, with greater diversity in generation technologies and increasing penetration of VRE resources. Additionally, the specific design and operational attributes that may prove most useful within higher VRE future power systems are not well understood. This uncertainty combined with the features of existing resource planning models can result in plant- and fleet-wide inefficiencies in how existing and new power and ancillary services are evaluated, procured, and compensated.

Although flexible operation capability has been demonstrated in actual geothermal operations, recent integrated resource plans (IRPs) from states where existing geothermal power plants operate and with high potential for development of new geothermal resources (e.g., California, Nevada, Oregon, Idaho, and Utah) do not yet consider these features in long-term planning (e.g., NV Energy, 2018; Idaho Power, 2019. CPUC, 2020). In addition, these IRPs are yielding a wide range of geothermal selection results in part due to changes in model assumptions in each planning iteration and the use of different tools and/or methods by different planning entities in the same region (e.g., California). This may lead to divergence between continued geothermal technology development that reduces costs and new procurement mechanisms that leverage geothermal attributes, when compared to the results from aggregated and simplified capacity expansion modeling.

To address these questions, the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) contracted the National Renewable Energy Laboratory (NREL) to review how geothermal is currently represented in power system models and identify any potential for improvement of geothermal representation in these models. More broadly, such information is valuable for GTO decision makers when considering future potential directions for grid-focused research and analysis.

### *1.2 Methodology*

NREL researchers reviewed literature on power system models and interviewed power system modeling experts, power system regulators, resource procurement and planning professionals, and geothermal operators. Fourteen subject matter experts and stakeholders were interviewed to better understand the current state of geothermal representation in power system models and to inform the content of a subsequent virtual workshop.

NREL held a virtual workshop titled "Geothermal Representation in Power System Models" on November 19, 2020. The workshop was attended by 50 people from more than 20 organizations representing grid operators, geothermal operators, load-serving entities (LSEs), regulators, and researchers. Presentations providing background and representative modeling efforts helped frame discussions focused on geothermal operations, resources, and characteristics; geothermal representation in models; model inputs and design; and future research options.

This report synthesizes findings from the literature review, subject matter expert interviews, and the stakeholder workshop to describe the current status and offer potential future directions for more accurate representation of geothermal energy within power system models. Section 2 provides an overview of power system models. Section 3 summarizes geothermal technologies and how they are currently represented in power system models. Section 4 illustrates how geothermal is modeled through several case studies, and Section 5 summarizes key takeaways from the stakeholder workshop.

## 2. Power System Models

Diverse power system models, ranging from open source to proprietary, have been developed to address the wide range of analyses necessary to support power system planning (i.e., future transmission, distribution, and resource portfolios), operations, and reliability. Ringkjob et al. (2018) provide some helpful categorizations, including the approach used, the purpose of the tool, the modeling methodology, and various spatial, temporal, and techno-economic design parameters, as shown in Figure 1.

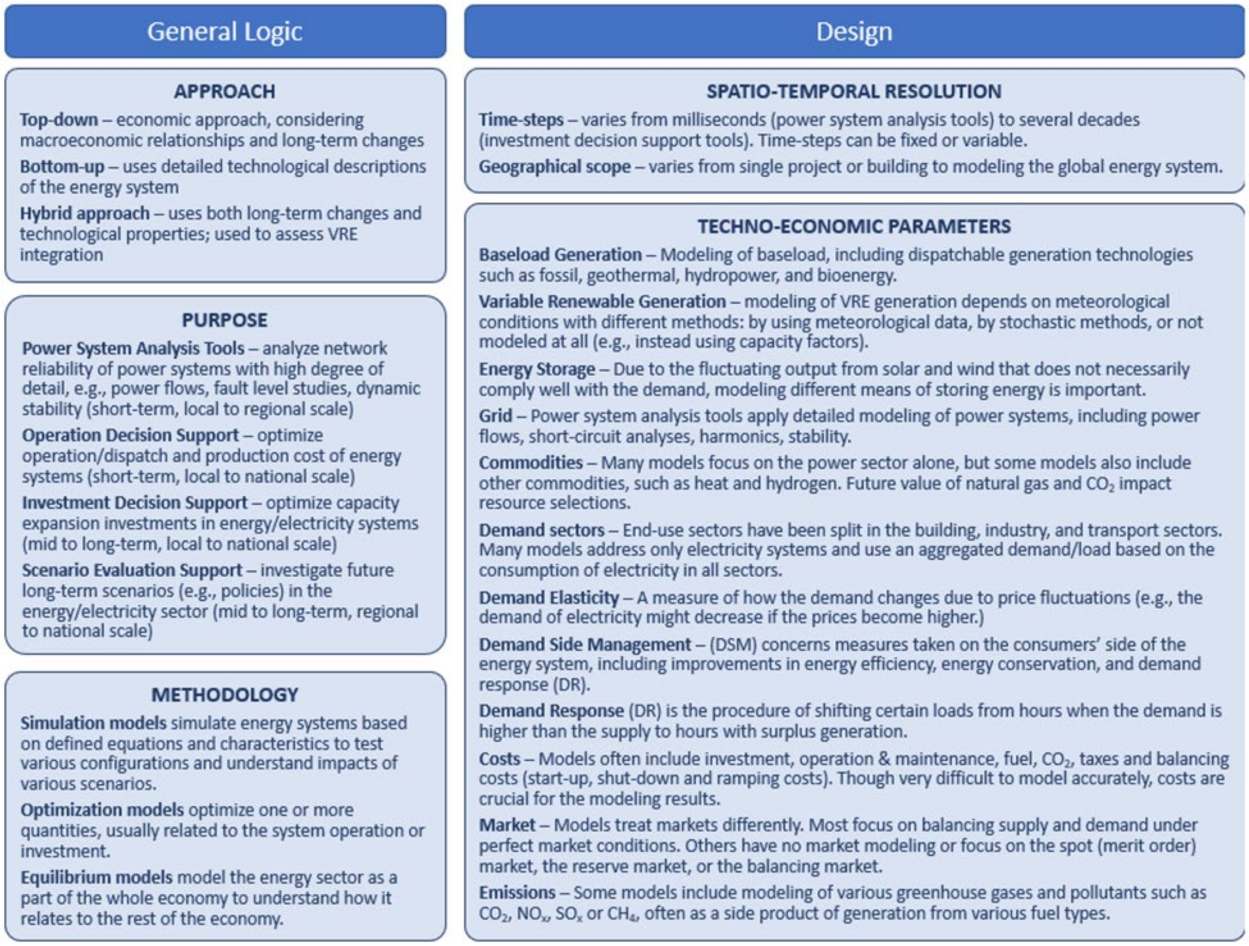


**Figure 1. Various ways to categorize power system models (adapted from Ringkjob et al. 2018)**

Geothermal generators are represented within each of these model types, either as inflexible (baseload) or flexible (dispatchable). Example model types include:

- **Power systems analysis (network reliability) models** can evaluate the reliability of delivery of geothermal power at a particular network node.
- **An operation decision support (production cost) model** might evaluate and validate the aggregate power production and dispatch of a group of generation resources (including geothermal power plants) at least cost, to meet demand subject to fuel costs and operational and reliability constraints.
- **An investment decision support (capacity expansion) model** can be used to plan future resource portfolios that include geothermal resources and perform transmission analysis to assess where new transmission is warranted to connect new generation resources to power systems.

## 3. Geothermal Technologies and Capabilities

### *3.1 Geothermal Resources*

In 2019, there were hydrothermal geothermal power plants in seven states, concentrated primarily in the western United States, which produced about 16 billion kilowatt-hours, equal to 0.4% of total U.S. utility-scale electricity generation (U.S. Energy Information Administration [EIA] 2019). The vast majority of geothermal power is produced in California and Nevada with 71.2% and 23.5% of U.S. geothermal generation, respectively. The state of Hawaii produces 0.7% of U.S. geothermal power and is home to the nation's sole dispatchable geothermal power plant, which provides ~30% of the Big Island's power.

### *3.2 Geothermal Technologies*

Although geothermal power plants are concentrated in the western United States, heat is located everywhere throughout the country—but often without sufficient subsurface permeability to host hydrothermal systems. At these locations, geothermal power can potentially be generated in a variety of ways. One such technology is enhanced geothermal systems (EGS), where hot rock with little or no permeability is stimulated to increase well flow rates that can support commercial power generation. GTO is supporting research and development of EGS through field testing underway at Utah FORGE, a DOE-funded laboratory dedicated to developing, testing, and accelerating EGS technologies. Undeveloped and undiscovered conventional hydrothermal resources combined with technological breakthroughs like EGS have the potential to supply significant geothermal energy to the United States.

Only hydrothermal resources are considered within many power system models used in current state or utility resource planning. However, capacity expansion modeling scenarios, such as those considered in the 2019 *GeoVision* study, include EGS technologies in future years that result in the potential for 20–120 GW[1] of geothermal generation capacity by 2050, assuming successful discovery and development of hydrothermal resources and significant breakthroughs in EGS technology (DOE 2019).

### *3.3 Geothermal Flexibility*

Flexible operation of geothermal resources has been demonstrated at dry steam, flash steam, and binary cycle geothermal power plants. Examples include Calpine's Geysers geothermal plants in Santa Rosa, California, and Ormat's Puna Geothermal Venture (PGV) in Puna, Hawaii.

The Geysers experienced large curtailments in the 1990s, which were mainly related to reduced demand and the availability of lower-cost power options. More recent curtailments have been driven by transmission constraints and by negative wholesale pricing, which resulted in requests from the California Independent System Operator (CAISO) to reduce generation (Dobson et al. 2020; Millstein et al. 2020). As with curtailment of other technologies, this led to lost revenues. Additionally, the cycling of production from geothermal wells caused thermal cycling that affected well integrity and created condensation that led to corrosion of surface equipment.

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[1] The 20–120 GW range covers multiple modeled scenarios in the *GeoVision* analysis, with the upper bounds stemming from assumed technology breakthroughs such as EGS.

Several mitigation strategies were developed to manage production-curtailment-related challenges; however, these further increased operations and maintenance (O&M) costs. Installation of turbine bypass valves enabled more stable wellfield operations during generation curtailment with maintenance of steam flows to ensure well integrity and prevention of condensation and corrosion. Therefore, flexibility is achieved but without concomitant reduction in O&M costs during periods of reduced output.

Turbine bypass valves have allowed flexible operations at PGV since 2012. Additionally, Ormat has contracted with Hawaiian Electric Light Company (HELCO) to provide automatic generator control (AGC) that allows grid operators to manage output from the plant in real-time for dispatchable power, frequency regulation, and spinning reserves (Nordquist et al. 2013). This combination of turbine bypass valves and sophisticated communication and controls between HELCO and PGV mean the plant is theoretically completely dispatchable (Nordquist et al. 2013). Specially designed contracting mechanisms allow for PGV to operate flexibly and economically through contracted minimum baseload power generation and payments for flexible capacity. However, during bypass operation the resource is essentially run at full load, meaning stable plant operation, geothermal well stability, and flexible grid operation are deemed more valuable than resource-use efficiency.

The demonstrated ability of geothermal power plants to operate flexibly means they can provide load following and ancillary services like frequency regulation and operational reserves. In addition to providing added value to grid operations, flexibly operating geothermal power plants reduces heat extraction from reservoirs, potentially extending the commercial lifetimes of these reservoirs. In addition, the ramp rate of these plants is sufficient to meet evolving operational requirements. Linvill et al. (2013) indicate that binary geothermal plants can ramp between 10% and 100% of their capacity at a rate of 15% to 30% of their nominal power per minute. At PGV, the power plant can ramp across a range of 22 MW to 38 MW at a rate of 2 MW per minute (Nordquist et al. 2013). Dobson et al. (2020) document rapid power ramp rates up to 300 MW per hour that have occurred at the Geysers in response to curtailment events.

Unless prices for flexibility services are very high—offsetting lost energy revenue—contracts that incorporate ancillary services or real-time load-following provisions must compensate geothermal operators at levels at least equivalent to energy-only contracts. Recent studies suggest that there is potential for economic benefit to geothermal operators. Edmunds and Sotorrio (2015) show how geothermal operators, given adequate pricing for ancillary services and appropriately structured contracts, can potentially increase revenues over energy-only contracts; however, sufficiently high pricing of ancillary services only occur during limited hours of the year. More recent analysis by Millstein et al. (2020) suggests the potential to add value with flexible operation of geothermal power plants in the range of \$2–\$4 per MWh, with potential to increase in value in the future with increased deployment of VRE. The possibility of these payments varies across the country as different systems and states have different power market payment structures. It must also be noted that in California and some other western states, large forthcoming deployments of battery energy storage will be competing with all other new sources of operating flexibility (e.g., the CAISO grid will have more than 2.5 GW of new batteries on-line by mid-2022). 4. Modeling Geothermal Power – Case Studies

Based on the experience of interviewees and workshop participants, geothermal in power system models is typically expected to be selected as a baseload renewable generator with selection particularly sensitive to levelized cost of electricity (LCOE). Costs and capacity factors are commonly informed by NREL's Annual Technology Baseline (ATB; NREL 2020). ATB assumptions are derived from GTO-developed cost models such as the Geothermal Electricity Techno-Economic Model (GETEM) and underscore the importance for gathering accurate technology cost assumptions. Additionally, the expectation of today's planners in the western United States is that power plants will be developed with conventional hydrothermal resources, though the *GeoVision* demonstrates much greater long-term potential with developing technologies.

### *4.1 Case Study Overviews*

Three case study overviews follow: the *GeoVision* study, California's 100% Clean Energy Act of 2018, known as Senate Bill 100 (SB100), and the Los Angeles 100% Renewable Energy Study (LA100). In addition, the workshop reviewed other geothermal modeling results, notably those under the California Public Utilities Commission's IRP process from 2017–2020. The examples reviewed for this analysis are thought to be representative of geothermal participation in capacity expansion (for *GeoVision*, SB100, and LA100), production cost (in the case of LA100), and network reliability models (also in the case of LA100) at national, regional, and municipality scales. High-level summaries of the models are outlined below, and more detailed modeling descriptions are available from DOE (2019 [*GeoVision*]), Augustine et al. (2019 [*GeoVision*]), CEC (2020a, 2020b [SB100]), and NREL (2021 [LA100]).

#### <u>4.1.1 GeoVision Study</u>

In 2019, GTO published *GeoVision: Harnessing the Heat Beneath Our Feet*—a detailed research effort to explore opportunities for increased geothermal deployment and the pathways necessary to overcome key technical and non-technical barriers (DOE 2019). The purpose of the effort was to evaluate the potential for geothermal energy to contribute to America's energy future. Supporting documentation (Augustine et al. 2019) describes many tens of scenarios that were analyzed, though only a few were selected for highlight in the *GeoVision* report to illustrate that with investment, technological breakthroughs, and modifications to the regulatory environment, geothermal can be a significant player in the future energy mix.

The power system modeling component of the *GeoVision* report presents scenarios for future growth and deployment potential of hydrothermal and EGS technologies in the electric sector that could be achieved by meeting targets for technological improvement and by easing market and regulatory barriers. The power system model utilized was NREL's Regional Energy Deployment System (ReEDS) model (Brown et al. 2020) with geothermal technology supply curve inputs generated with best estimates of resource potential combined with costs from GETEM (DOE 2016). ReEDS simulates electricity sector investment decisions based on system constraints and demands for energy and ancillary services to understand the evolution of the bulk power system from present day through 2050 or later. GETEM is a techno-economic tool used to estimate present and future LCOE for definable geothermal scenarios. Workflows for *GeoVision* modeling are schematically represented in Figure B-1.

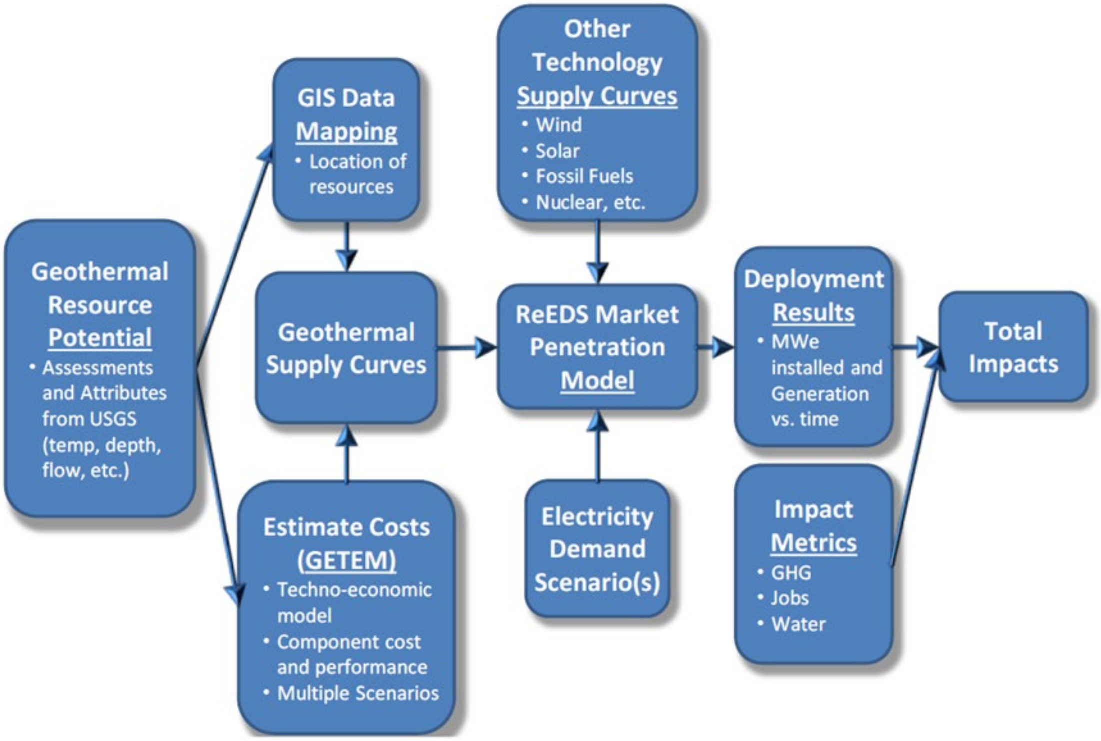


**Figure 1. Schematic of *GeoVision* workflow for modeling electricity generation (from Augustine et al. 2019)**

The *GeoVision* analysis does not consider the capacity value, dispatchability, or ancillary services that geothermal can provide as a national-scale evaluation of geothermal potential. Despite this and ignoring the potential of EGS technology and reduced impacts of non-technical barriers, geothermal deployment is modeled to more than double by 2050 in the Business-As-Usual scenario, equating to an addition of more than 3 $GW_e$ by 2050. The Improved Regulatory Timeline scenario reduces discovery and development timelines resulting in projected installed geothermal capacity additions of 13 $GW_e$ by 2050. The Technology Improvement scenario advances EGS technology to commercial status but also increases development of conventional hydrothermal resources with capacity additions of more than 17 $GW_e$ (Augustine et al. 2019).

4.1.2 Modeling for California's 100% Clean Energy Act of 2018 (SB100)

SB100 establishes a target for renewable and zero-carbon resources to supply 100% of retail sales and electricity procured to serve all state agencies by 2045. The bill also increases the state's Renewables Portfolio Standard (RPS) to 60% of retail sales by December 31, 2030 and requires all state agencies to incorporate these targets into their relevant planning. SB100 charges the California Public Utilities Commission (CPUC), California Energy Commission (CEC), and the California Air Resources Board (CARB) with planning and implementing the policy.

CPUC, CEC, and CARB contracted with Energy + Environmental Economics (E3) to use their RESOLVE capacity expansion model to inform planning of a future 100% renewable and zero-carbon electricity grid by producing least-cost resource portfolios for various electricity demand futures and resource availabilities. RESOLVE is a resource investment model that identifies optimal long-term generation and transmission investments in an electric system, subject to reliability, technical, and policy constraints (Figure 2).

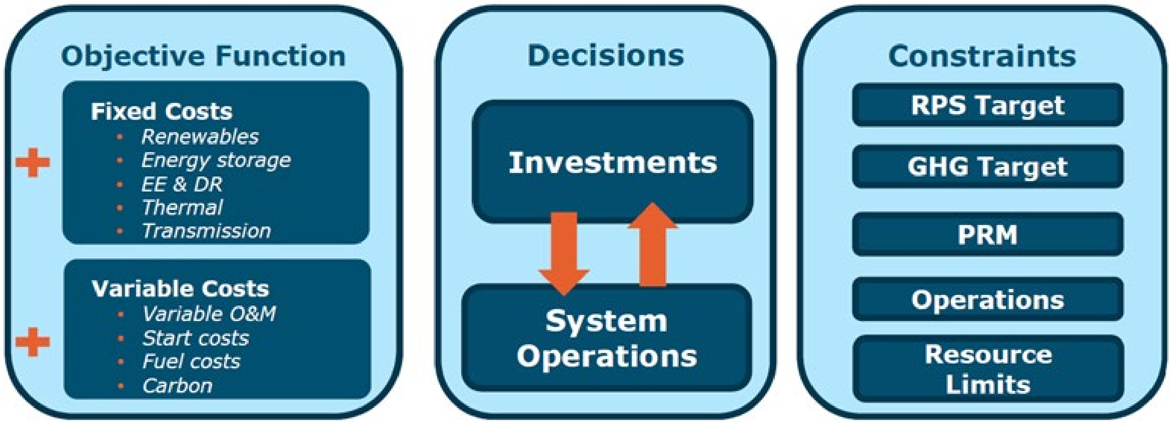


**Figure 2. Schematic representation of RESOLVE model components presented by Gill (2020)**

The core SB100 analysis is an ongoing modeling effort designed to inform resource planning for supplying 100% of retail electricity sales with renewable and zero-carbon energy by 2045 in California. Sensitivities evaluated the impact of different demand futures, the impact of availability of out-of-state and offshore wind resources, and the impact of increased demand flexibility. Notably some of the scenarios selected up to the model constraint of 2,332 MW of new geothermal. Additional study scenarios examined impacts of including generic zero-carbon firm baseload and dispatchable resources with LCOE of $60 per MWh in 2045, increasing the renewable and zero-carbon target to account for transmission, distribution (T&D), and storage losses, no combustion resources, accelerated timelines. Figure 3 compares SB100 core and generic zero-carbon firm resources at $60 per MWh, effectively equivalent to geothermal resource at this LCOE. The amounts of generic zero-carbon firm resources selected are substantial: 14,031 MW of generic dispatchable, 15,689 MW of generic baseload, and if both types are available, 13,745 MW baseload and 2,000 MW dispatchable.

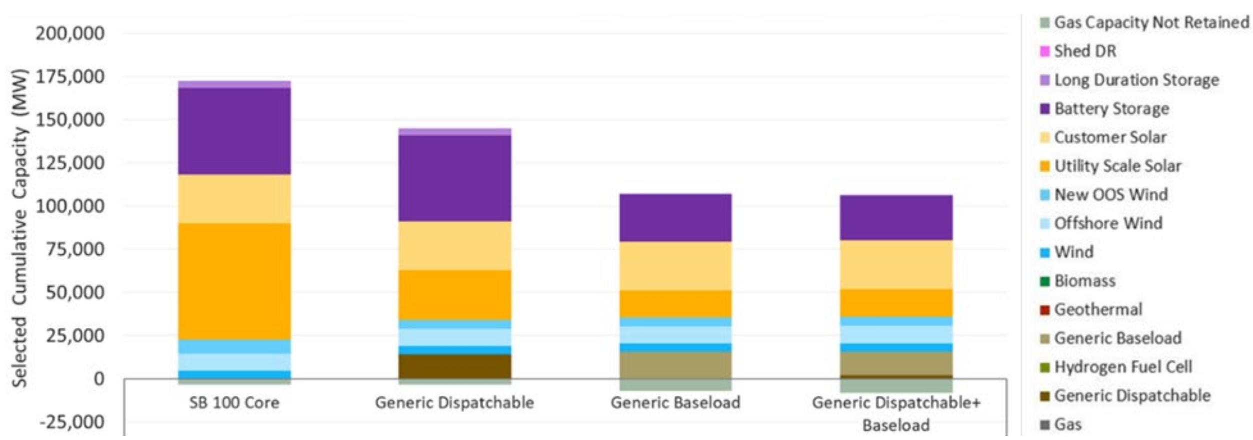


**Figure 3. Cumulative capacity additions for the SB100 Core and Generic Zero-Carbon Firm Resource Scenarios in 2045 (CEC 2020a; Gill 2020). At a LCOE of $60/MWh, up to 15 GW of geothermal resources could be selected.**

4.1.3 Modeling for the LA100 Study

After the City of Los Angeles passed a series of motions to reach 100% renewable energy by 2045, NREL was contracted to study various pathways to reach the 100% renewable targets. LA100 is the most comprehensive and detailed analysis to date of an entirely renewable-based electricity grid as complex and large as the Los Angeles Department of Water and Power (LADWP) power system, the largest municipal power and water utility in the nation, with 1.4 million power customers and record peak load of 6.5 GW. Four core scenarios modulated by two assumptions on demand growth were developed for LA100.

Although the technologies eligible to meet the 100% renewable target vary across scenarios, geothermal is available for selection in all scenarios. The study consists of analysis across many different models to capture all facets of the future energy system with interactions between models to develop detailed, whole-system realizations.

Results of some of the scenarios considered in LA100 are shown in Figure 4. In the core SB100 scenario (see section 4.1.2), up to 240 MW of new geothermal resource is added by 2045, while up to 1,430 MW is added under early (2035 compliance) and no biofuels scenarios. Figure 4 also shows sensitivities with respect to use of RECs (Renewable Energy Credits) to offset up to 10% of generation from natural gas and allowance for biofuel combustion turbines (RE-CT).

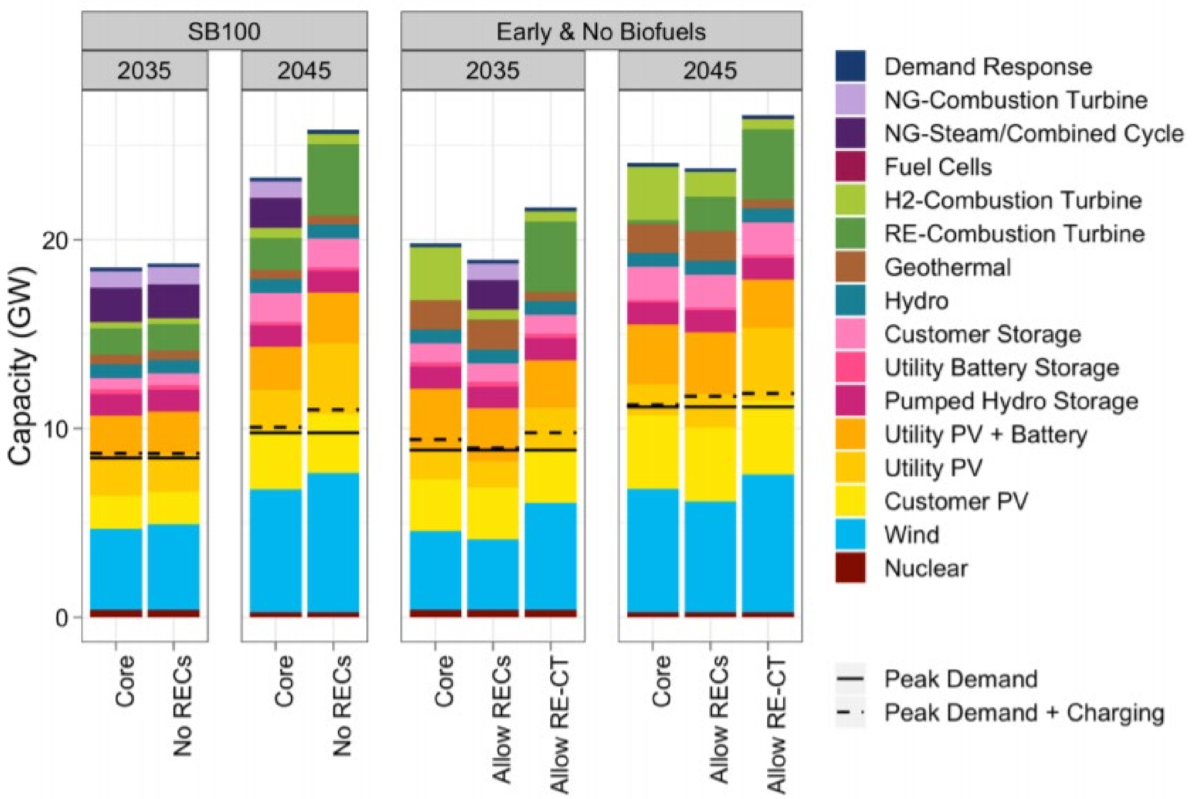


**Figure 4. LA100 resource capacity across a range of scenarios, highlighting the importance of geothermal in early 100% renewable (2035) and no biofuels scenarios (NREL, 2021).**

### 4.1.4 Case Study Model Comparison

Table 1 compares modeling approaches of *GeoVision*, SB100, and LA100 modeling studies.

**Table 1. Summary model comparison.**

| | **GeoVision** | **SB100** | **LA100** |
|---|---|---|---|
| Purpose | Investment decision support (capacity expansion modeling) | Investment decision support (capacity expansion modeling) | Investment decision support (capacity expansion modeling)<br>Operation decision support (production cost modeling)<br>Power system analysis<br>Network reliability modeling |
| Power System Models Used | ReEDs (NREL) | RESOLVE (E3) | Resource Planning Model (NREL)<br>Demand Side Grid Model (NREL)<br>Distributed Generation Market Demand Model (NREL) |
| Methodology | Optimization | Optimization | Optimization<br>Simulation |
| Timesteps | 16 4-hour time slices representing seasonality and time of day<br>A 40-hour summer super peak in each model year | Hourly dispatch for 37 representative days in each model year | Range of scales (seconds, minutes, hours, years) |
| Geographic Scope | National | CA and surrounding states: WA, OR, NV, AZ, and NM | Municipal; in-state CA; imports from WA, OR, NV, UT, and AZ |
| Select Techno-Economic Parameters | Baseload and dispatchable generation<br>VRE resources<br>Costs | Baseload and dispatchable generation<br>VRE resources<br>Energy storage<br>Costs<br>Emissions (model output, not a constraint) | Baseload and dispatchable generation<br>VRE resources<br>Energy storage<br>Demand sectors<br>Demand response<br>Costs<br>Emissions |

### 4.1.5 Other Modeling Results

The workshop reviewed other recent results from capacity expansion modeling that provide perspective on geothermal representation and selection in capacity expansion models. Thomsen (2018) reviews results from sensitivity analysis of the CPUC’s 2017–2018 IRP modeling, which utilizes a publicly available version of E3’s RESOLVE tool. Over 2017–2020, there were multiple iterations of this tool, along with inputs and assumptions (e.g., CPUC 2020) available for a stakeholder process. Among other findings, Thomsen (2018) highlights that sensitivity analysis of geothermal costs, including costs reflective of recent commercial contracts lower than the CPUC’s assumed geothermal costs, resulted in significantly higher geothermal selection. Thomsen (2018) also finds that when geothermal is selected, 1 MW of geothermal substitutes for 3–4 MW of solar photovoltaics (PV) plus 4-hour batteries in a variety of renewable energy cost scenarios. The 2019–2020 CPUC IRP modeling did not select geothermal before 2030 in its advisory portfolio; however, subsequent LSE 2020 IRPs selected more than 500 MW of geothermal by 2030. These examples highlight the sensitivity of model results to assumptions set by different entities in the same region.

### *4.2 Geothermal Model Assumptions and Constraints*

Constraints are placed on existing geothermal resources based on plant-specific information, if available, and assumed for potential new geothermal resources in model environments, and they influence how they are assumed to operate on an hourly basis or over longer periods. Workshop discussions highlighted several assumptions and constraints that may be overly inhibiting selection of geothermal in power system models.

#### 4.2.1 Geothermal Resource Potential Constraints

The U.S. Geological Survey (USGS) surveyed geothermal resources in 2008, categorizing them as "identified" or "undiscovered." Identified geothermal resources are estimated to have electrical power generation potential of 9 $GW_e$, and the electrical power generation potential of undiscovered geothermal resources is estimated to be 30 $GW_e$ (Williams et al. 2008). This estimated geothermal resource cap is an order of magnitude larger than the current output from geothermal power plants in the western United States (3.6 $GW_e$).

Models require that resource modelers include resource potential as an input. Many use the USGS 2008 resource assessment, but some lower the cap on geothermal resources available for selection based on other resource studies (e.g., Black & Veatch 2016), LSE experience and priorities (e.g., continued operation of existing generators), or for other reasons.

Transmission constraints may also limit resource potential. For example, shipping power across long distances (for example, across one or more western states) or to specific system nodes can be challenging due to limited availability of transmission, congestion limitations, importation rights, and costs of delivering power across multiple grid systems (i.e., wheeling). Modelers may, therefore, choose to limit specific resource inputs within a given distance or jurisdiction.

Some modelers, however, appear to place artificially low resource constraints on geothermal selection without a stated technical justification. If all geothermal resources in the system are not selected, this may not be an issue. Some model scenarios, however, hit the maximum limit of geothermal resource available, indicating geothermal selection is constrained by the resource-availability assumption. For example, in the CPUC IRP modeling (e.g., Thomsen 2018; CPUC 2020) as well as in the SB100 study, a model constraint of approximately 2 GW of available geothermal resource capped selection, and the maximum value was selected in several long-term scenarios. Resource constraints for the three case studies examined are outlined in Table 2. As these data highlight, model results are dependent on model inputs, and modelers and planners can select a range of input values for geothermal as well as for other generators. Thomsen (2018) relaxed the geothermal resource limit constraint and found that the model selected much more geothermal, particularly at higher renewable energy scenarios. The SB100 study did not relax the geothermal resource limit but introduced a generic "zero-carbon firm resource" with no resource constraint, and the model selected more than 15 GW of this resource at an LCOE of $60 per MWh. To understand geothermal limits and modeling accuracy, it is important to have resource potential sources, constraints, and justifications clearly identified and explained in model documentation.

**Table 2. Case Study Resource Constraints, Costs, and Potential**

| | *GeoVision* | **LA100** | **SB100** |
|---|---|---|---|
| Resource Assessment | Hydrothermal: Williams et al. 2008<br>EGS: NREL | *GeoVision* Results (Williams et al. 2008, NREL) | Adapted from Williams et al. 2008 |
| Resource Potential Constraints | Reduced due to non-technical barriers (Young et al. 2019)<br>Allowed for 50 MW EGS deployment beginning 2024; increasing to 200 MW/yr by 2030 with no growth limit in subsequent years | Adapted from *GeoVision* and modified with input from LADWP | Black & Veatch (2016) |
| Resource Potential | Hydrothermal: 24 GW<br>EGS: >3,000 GW | Hydrothermal: 24 GW<br>EGS: >3,000 GW | Hydrothermal: 2.332 GW |
| Resource Costs Basis | Cost projections are from 2016 baseline with GETEM; 80% capacity factor for binary plants, 90% for flash | 2019 ATB for each of the resource and technology categorizations (hydro flash, hydro binary, near-hydrothermal field EGS [NF-EGS] flash, NF-EGS binary, deep EGS flash, and deep EGS binary); 85% capacity factor for new geothermal resources | LCOE from 2019 ATB Hydro/flash-moderate cost projections (flash steam power plant and conventional hydrothermal resource) and 80% capacity factor for new geothermal resources |
| Resource cost $/MW (start year and 2050 projected cost) | Hydro flash: $78.24<br>Hydro binary: $104.74<br>EGS flash: $130.95<br>EGS binary: $224.98<br>(ATB 2016 has fixed costs over time) | Hydro flash: $76.30-$66.80<br>Hydro binary: $111.25-$97.46<br>EGS flash: $241.19-$205<br>EGS binary: $616.74-$526.23 | Hydro flash: $76.30-$66.80<br>Hydro binary: $111.25-$97.46<br>EGS flash: $241.19-$205<br>EGS binary: $616.74-$526.23 |
| Resource Available to Select in Model (GW) | Identified hydrothermal: 5.1<br>Undiscovered hydrothermal: 18.8<br>Near-field EGS: 1.4<br>Deep EGS: 3,375<br>(Augustine et al. 2019) | Same as *GeoVision* | 2.332 |
| Comments | ATB 2020 has lower geothermal costs, which will affect geothermal selection (true for all case studies herein) | Results are only preliminary | The maximum selected in some scenarios reaches the maximum constraint set for the model. |

### 4.2.2 Assumptions About Capacity Factors

Capacity factor is defined as the ratio of actual electrical energy delivered over a given period of time to the maximum possible electrical energy delivery over that same period (EIA 2020). Since 2010, EIA has reported annual average geothermal capacity factors near 70% based on operator-reported monthly values of net generation (Form 923) and net summer capacity (Form 860; EIA

2020). Geothermal capacity factors may be site- and technology-specific, and there may be other factors that affect how much power is delivered to the grid.

The capacity factor for geothermal power plants is typically modeled on average at between 80% and 90% (e.g., NREL ATB), depending on the type of plant, downtime due to scheduled and unscheduled maintenance, and temporal and seasonal variability of plant output due to ambient temperature conditions. Due to the influence of ambient temperature on plant efficiency, geothermal generation is most efficient—and complementary to reduced solar generation—during winter months. Since 2015, NREL's ATB, commonly used by modelers for input parameters, assigns new flash plants capacity factors of 90%, while new binary plants are assigned a lower capacity factor of 80%. Binary power plants, especially those that are air-cooled, are more sensitive to variation in ambient temperatures, and this is the explanation for the ATB's lower estimated capacity value for binary technologies. The majority of new power plants to be built in the future are expected to be binary power plants that can exploit a wider range of reservoir temperatures for power generation.

Geothermal power plant operators may also compare net power production (total power output minus parasitic power used for operations) against expected performance in order to forecast power delivery, which can equate to apparent capacity factors greater than 95%, depending on how planned power plant output is calculated (e.g., uninterrupted operations delivering contract-obligated power and 2.5 weeks of planned maintenance outage in a year). Differences in performance accounting may result from geothermal operators that must meet contract power delivery obligations and report performance to stakeholders, especially finance partners, that are concerned with contracted power delivery obligations.

The assumed capacity factors will affect geothermal selection in capacity expansion models by adjusting the resulting LCOE and potentially the contribution to resource adequacy by month or season. A low capacity factor suggests a plant is not producing at design capacity, which will negatively affect the value of geothermal capacity and its contribution to grid reliability.

Parasitic power use at geothermal plants varies with plant type, operations, and reservoir characteristics. It is an operational expense that is planned in advance of contracting so that operators and LSEs can compare planned power delivery to actual power delivered. In terms of energy delivered, there is little difference between saying a plant will deliver 100 MW 70% of the time versus delivering 74 MW 95% of the time. However, representing geothermal as the former artificially increases uncertainty of geothermal availability in a model. The latter better represents how geothermal is characterized in power purchase agreements.

Capacity factors for the three models investigated are highlighted in Table 3. Other models that use the ATB for input guidance will use similar values; however, reliance on EIA-reported values would result in significantly lower values near 70%. In interviews and during the workshop, no one reported use of EIA capacity factors in modeling. The EIA is widely viewed as a definitive source of electricity data, so power system modelers and analysts would have justification for using these values, which do not accurately capture the current and future state of the technology, and thus could negatively impact geothermal representation. In recognition of the complexity of the determination of accurate capacity factors for geothermal technologies, as well as their influence on resource adequacy planning activities, recommendations are offered in Section 5.1.2. for future work that can help constrain this issue.

**Table 3. Case Study Geothermal Capacity Factors**

| | ***GeoVision*** | **SB100** | **LA100** |
|---|---|---|---|
| Capacity Factor | 90% | 90% | 80% (binary)<br>90% (flash) |
| Comments | ATB hydrothermal flash value | ATB hydrothermal flash value | ATB flash and binary values |

### 4.2.3 Operational Services

As discussed in Section 3.3, geothermal power plants can operate flexibly to provide ancillary and reliability services. However, our literature review and interviews with stakeholders suggest that most models are treating geothermal as baseload without flexible capabilities. Some models—for example, LA100—allow geothermal resources to operate flexibly as a dispatchable generator (see Table 4). With flexible operations, geothermal power plants can provide ancillary services that support network reliability (Linvill et al. 2013; NREL 2019) along with other grid-support capabilities provided by synchronous generators including:

- **Black-start capability,** with the ability to operate as a microgrid independent of external electricity
- **Inertia support,** with constants typically ranging from 1.75 seconds (20-MW turbine) to 5 seconds (10-MW turbine with flywheel)
- **Frequency support,** with governor automatic droop response, allowing the geothermal plant to support grid frequency during disturbances up to ±5% of nominal frequency
- **Voltage support**:
    - Operation in automatic voltage regulation mode to automatically adjust reactive power to provide voltage support (by producing or consuming power, for example, 15 MVAR with a 20-MW turbine)
    - Compliance with North American Electric Reliability Corporation (NERC) standard PRC-024-1, “Generator Performance during Frequency and Voltage Excursions,” providing the capability to remain online during grid disturbances to provide voltage support.

Research, interviews, and workshop discussions revealed that although it is well known that geothermal plants can potentially provide these services, these characteristics are not often incorporated into models or otherwise evaluated, resulting in potential underestimates of the value of geothermal. One reason suggested for this misrepresentation is that geothermal power plants are often small (e.g., 20–50 $MW_e$), which may not—as a single plant—be large enough to have network-wide influence. Deployed widely, and taken collectively, however, geothermal power plants can make an impact. Operational services allowed for geothermal plants in the three models investigated are highlighted in Table 4.

**Table 4. Geothermal Operational Services in Case Studies**

| | *GeoVision* | SB100 | LA100 |
|---|---|---|---|
| Operational Constraints | *GeoVision* analysis does not consider geothermal flexible capacity, dispatchability, or ancillary services | Geothermal is treated as a baseload, must-run resource. Some scenarios include a generic zero-carbon firm resource comparable to geothermal. | Geothermal is modeled as a dispatchable generator parameterized by a ramp rate, outage rates, and maximum capacity |
| Comments | National-scale study of technical and economic potential | Capabilities and values to be updated as new information becomes available | Preference toward minimizing curtailment of wind and solar PV before ramping up dispatchable geothermal assumes a slightly higher marginal cost for geothermal than for VRE resources. |

#### 4.2.4 Development and Contracting Considerations

Geothermal project development timelines impact when a power plant is ready to deliver power. Project development on federal lands can potentially span 7–10 years from exploration through to power generation (Young et al. 2014). Development timelines are typically shorter for experienced developers or on state and private lands; however, they are invariably multi-year projects, and timelines impact how quickly a geothermal developer can become an operator ready to contract with an LSE.

The vast majority of geothermal power contracts stipulate payment to operators for a contracted amount of energy—few include payment for both energy and capacity, though procured geothermal energy contributes to resource adequacy capacity requirements. The use of alternative contract structures will support flexible operations of geothermal power plants to jointly provide energy, flexible capacity, and ancillary services. The only current geothermal flexible operations contract in the United States is between HELCO and Ormat on Hawaii (Nordquist et al. 2013).

Contracting for ancillary services is a regular part of energy markets, since they are produced and consumed in real-time, or near-real-time, to maintain reliability and support electricity grid operations. Minimum amounts of contracted ancillary services are prescribed by NERC and regional entities (FERC 2020). The market determines the value of ancillary services, and as previously mentioned, ancillary services are rarely priced greater than the energy price in geothermal contracts (Edmunds and Sotorrio 2015). It remains challenging for geothermal operators to pursue contracts for flexible operations without ancillary services being compensated at or above displaced MWh energy sales.

These development considerations are currently largely external to modeling efforts. For example, in California IRPs, the timing of geothermal selection is entirely determined by the least-cost resource portfolio in each modeled time period. However, if large amounts of geothermal power were desired in the near future or over a short time period in the future, such modeling would need to be adapted to the timelines of geothermal development. Currently, some modelers constrain the amount of geothermal resource available for deployment over time to account for development timelines (e.g., *GeoVision* [DOE 2019]).

## 5. Workshop Outcomes

### *5.1 Potential Improvements to Geothermal Representation in Power Systems Modeling*

Several potential improvements to geothermal representation in power systems modeling were identified during the virtual stakeholder workshop.

#### 5.1.1 Modeling Geothermal Flexibility

Though there is broad awareness that geothermal power plants can operate flexibly to provide dispatchable energy and ancillary services, geothermal is contracted to provide only firm energy (except at Puna, Hawaii) and is typically treated as inflexible capacity for meeting LSEs' capacity obligations in the United States. Based on the case studies examined herein and interviews with stakeholders, it is not clear whether LSEs require more baseload or dispatchable power from geothermal resources. The roles played by traditional combustion resources will likely need to be filled by alternative technologies to meet the objectives set forth in future grid studies such as LA100 and SB100. The generic zero-carbon firm resource modeled for SB100 is a good indicator of this need. Furthermore, the capacity values of VRE resources are expected to decline with increasing deployment, thus creating greater need for firm-capacity resources. Geothermal resources have these attributes and future grids could have diverse, valuable roles for geothermal resources.

Baseload versus dispatchable geothermal resources are investigated with the generic zero-carbon firm resource scenarios modeled in SB100 studies. The modeled zero-carbon generic resources at $60/MWh, whether baseload or dispatchable and equivalent to a similarly priced geothermal resource, out-competed the $72/MWh geothermal for selection along with all the other generator resources in the model. When only a generic zero-carbon baseload resource was modeled, 15.7 GW was selected, and when modeled as a dispatchable resource, 14 GW was selected. When both baseload and dispatchable generic zero-carbon resources were modeled together, 13.8 GW of baseload and 2 GW of dispatchable generic zero-carbon resources were selected by the RESOLVE model. Additional sensitivity studies such as these are important for understanding geothermal's role in future electricity grids and whether it will be more valuable as a baseload or dispatchable resource. Related to this, a better understanding of flexible generation generally and the future value of ancillary services (e.g., number of yearly hours of high-priced regulation up and down) are important for addressing the value proposition for new baseload versus dispatchable geothermal resources.

From the perspective of resource cost, an evaluation of fixed and variable cost differences for geothermal plants operating as inflexible (baseload) and flexible (dispatchable) power plants will be needed to support representation in capacity expansion models. Additionally, flexible operations mean geothermal resources may not be operated at their full capacity, comparable to being curtailed. Costs of curtailment for dispatchable geothermal power plants need to be evaluated and compared to those of VRE resources in order to more completely understand the value of geothermal for future electricity grids.

Flexible operation of geothermal power plants needs to be evaluated against other resources that can operate flexibly (e.g., battery storage) to understand what improvements (e.g., increased ramp rate) might be necessary, and achievable, in the future to make geothermal resources viable options for providing load following and ancillary services (Linvill et al. 2013).

#### 5.1.2 Accurate Capacity Factors

As explained in Section 4.2.2, different values for geothermal capacity factors exist and the reasons for this are nuanced. A full quantification and exploration of this topic is outside of the scope of this report, however potential improvements to geothermal representation in power systems modeling could be achieved through rigorous documentation of the current and projected future state of these values for geothermal power generation technologies.

Capacity factors in the case study models are lower than those used internally by some geothermal operators. These are based on resource and operational limits, seasonal ambient temperature variations, and planned energy delivery. Model outcomes could improve for geothermal selection if new geothermal resources are modeled with these operator-defined capacity factors. Further analysis, confirmation, and documentation of higher and more accurate values will benefit the resource adequacy planning process. However, doing so will require comparing net generation to planned power delivery in order to understand the performance of geothermal power plants. Furthermore, these data are often not reported, presenting additional challenges. Detailed hourly data from air-cooled and water-cooled power plants could be examined at hourly scales to better understand geothermal performance. Engaging geothermal operators to better understand their internal performance metrics versus operational reports that are used by EIA for capacity factor calculations also can help inform a more realistic strategy for capacity factor calculation. These studies would allow comparison, and potential integration, with estimates of geothermal capacity factors in the NREL ATB, providing power systems modelers with a more rigorously determined, accurate, and citable justification for the use of higher capacity values.

#### 5.1.3 Contribution to Grid Reliability

With increasing penetration of VRE resources, electricity grids require greater flexibility to meet demand while maintaining grid reliability. Geothermal generators can contribute to low- and zero-carbon grids by providing baseload power (see Section 5.1.1); however, future scenarios could place higher value on geothermal's ability to operate flexibly and provide ancillary services, including system inertia and black start capabilities. These characteristics are particularly important in scenarios without combustion resources (e.g., the LA100 no-emissions scenario; NREL [2021]). In contrast, SB100 scenarios suggest, based primarily on LCOE, that geothermal is valued for providing baseload power in future electricity grids (CEC, 2020a).

Production cost models validate capacity expansion resource selections, and along with network reliability models, are used to assess reliability of future grids. These model environments will help inform geothermal energy's contribution to future grid reliability, with the potential that significantly more geothermal resources will be indicated compared to present day. Specific grid reliability services that could be provided by geothermal resources (e.g., black start and inertia) need to be evaluated with respect to geothermal resource locations relative to load centers and within transmission networks. The same services also can be evaluated with limited geographic constraint on geothermal resources, assuming technological advancements make EGS economic in the future leading to wide deployment.

5.1.4 Lower Levelized Cost of Electricity

As part of the *GeoVision* analyses, cost estimates for geothermal were updated to more accurately reflect lower values represented by recent geothermal developments, as indicated in Table 5. If this lower LCOE is modeled in no-combustion scenarios, geothermal selection could increase substantially. Some scenarios studied (e.g., SB100 scenarios with generic zero-carbon firm resources with LCOE of $60/MWh [CEC, 2020a]) suggest increased geothermal selections could result when using 2020 ATB LCOE values for new geothermal resources. A re-formulation of financing costs such that they spread across a geothermal power plant's lifetime in the 2020 ATB reduced LCOE of geothermal by 33% (EGS) to 23% (hydrothermal) compared to the 2019 ATB (Table 5). Other renewable resources saw cost reductions in the ATB between 2019 and 2020, but none greater than those of geothermal resources.

**Tables 5. Historic Values of NREL ATB Geothermal LCOE and Projections to 2050**

| LCOE-mid case | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|
| GEO-Hydro Flash | $ 99.52 | $ 78.24 | $ 64.25 | $ 73.46 | $ 76.30 | $ 58.40 |
| GEO-Hydro Binary | $ 116.73 | $ 104.74 | $ 85.90 | $ 107.10 | $ 111.25 | $ 85.73 |
| GEO-NF EGS Flash | $ 113.70 | $ 130.95 | $ 106.14 | $ 228.20 | $ 241.19 | $ 160.98 |
| GEO-NF EGS Binary | $ 187.36 | $ 224.98 | $ 183.00 | $ 583.82 | $ 616.74 | $ 424.40 |
| GEO-Deep EGS Flash | $ 113.70 | $ 130.95 | $ 106.14 | $ 228.20 | $ 241.19 | $ 160.98 |
| GEO-Deep EGS Binary | $ 187.36 | $ 224.98 | $ 183.00 | $ 583.82 | $ 616.74 | $ 424.40 |
| | | | | | | |
| LCOE-mid case (2050) | Each ATB year's projected 2050 LCOE | | | | | |
| GEO-Hydro Flash | $ 99.52 | $ 78.24 | $ 60.21 | $ 76.74 | $ 66.80 | $ 46.56 |
| GEO-Hydro Binary | $ 116.73 | $ 104.74 | $ 80.47 | $ 102.71 | $ 97.46 | $ 72.19 |
| GEO-NF EGS Flash | $ 113.70 | $ 130.95 | $ 98.98 | $ 128.19 | $ 205.00 | $ 102.39 |
| GEO-NF EGS Binary | $ 187.36 | $ 224.98 | $ 170.90 | $ 220.35 | $ 526.23 | $ 300.79 |
| GEO-Deep EGS Flash | $ 113.70 | $ 130.95 | $ 105.93 | $ 137.52 | $ 205.00 | $ 102.39 |
| GEO-Deep EGS Binary | $ 187.36 | $ 224.98 | $ 170.90 | $ 220.35 | $ 526.23 | $ 300.79 |

5.1.5 Remove Artificial Resource Limits

The *GeoVision* report describes a range of future resource potential, but even the conservative Business-As-Usual case, with no technological breakthroughs or regulatory improvements, models a deployment potential of 5.92 GW of conventional hydrothermal resources. Of that amount, as much as 4.8 GW are within California, with the potential to import another 0.5 GW from Nevada and 0.2 GW from Oregon. Collectively, these resource estimates are much larger than the 2.3-GW resource constraint used in SB100, suggesting caps might need to be better aligned with *GeoVision* and supporting resource assessments (e.g., Williams et al. 2008; Augustine et al. 2019). Further adjustments could be made in light of LSE requirements or other case-specific constraints (e.g., cases where no resources are allowed outside the balancing authority area or where resource location must be proximal to existing and planned transmission infrastructure).

5.1.6 Update Resource Assessments

Updated assessments of geothermal resource potential will support exploration and discovery, and the USGS is authorized to do this work through H.R. 133, Section 3002. Regulatory environments will also need updating, as documented in *GeoVision*, to support timely development of geothermal resources. The most likely to be developed geothermal resources (e.g., USGS identified hydrothermal resources) would benefit from better understanding of size and location, if capacity expansion models begin to select larger amounts of new geothermal resources, as suggested may occur with the SB100 studies that include allowance for generic zero-carbon firm and dispatchable resources (CEC, 2020a).

5.1.7 Demonstrate Rapid Deployment Capabilities

Confidence in the geothermal sector's ability to meet future needs will be enhanced if the geothermal industry can demonstrate to LSEs that sufficient resources can be brought online in a timely fashion when capacity expansion modeling and planning decisions point toward a substantial increase in firm-capacity requirements for future grids.

### *5.2 Modeling Analysis Improvements*

Opportunities to improve geothermal modeling analysis include increasing understanding of inter-model variations, better quantification of the financial benefits of grid services, and expanded testing of model sensitivities to input assumptions.

5.2.1 Comparative Model Assessment

The example of LA100 shows how detailed and comprehensive modeling efforts can be directed toward 100% renewable planning efforts. Similar studies could use other modeling tools and produce different results. Though the focus of this report is geothermal representation, all technologies need similar levels of veracity in their cost and performance inputs. Financing assumptions greatly affect technology costs, and the level of maturity and perceived risk associated with different technologies may warrant differing financial assumptions. Model constraints need to be similarly well-informed and appropriate for modeling goals. Capacity expansion model scenarios discussed herein demonstrate how resource selections are very sensitive to input parameters. Better understanding of such sensitivities can be efficiently investigated with parametric models to inform scenarios for more computationally intense optimization models. There are many model environments (Ringkjob et al. 2018), and it would be beneficial for regulators, industry, and researchers to clearly articulate, and when possible, find common understandings of their respective modeling assumptions. Comparison of different model outputs can increase understanding of how and why outputs vary across modeling platforms to improve design of future model platforms and modeling studies. Approaches such as modeling-code-comparison working groups that includes specific focus on geothermal representation and analysis of geothermal's participation in future grids can address code variations and also allow the modeling community to better align cost inputs, performance metrics, and strategies for modeling various components of power systems.

5.2.2 Quantifying Financial Benefits of Grid Services

Production cost and network reliability models are important to demonstrate and validate how resources contribute to the security and reliability of future grids as either baseload or dispatchable resources. Gaining a better understanding of the performance and cost impacts of geothermal generators providing grid services can improve the economic competitiveness of geothermal in these scenarios. Sensitivity analyses that vary the amounts of geothermal resources in future scenarios and how they participate (i.e., baseload versus dispatchable) can help elucidate optimized participation of geothermal resources in future grid scenarios, including comparison to other planned resources that can contribute toward grid flexibility (e.g., battery storage). Parametric models can efficiently test multiple scenarios to investigate sensitivities and direct more computationally intensive optimization models toward promising resource portfolios to simulate.

High-penetration VRE resource scenarios, across the United States or limited to western states with hydrothermal resource potential, could determine sensitivities that affect geothermal selection for provision of baseload or dispatchable power. The SB100 studies (CEC, 2020a) have begun that effort and currently favor low-cost geothermal selection (represented as a firm, zero-carbon generic resource) as a baseload resource rather than a dispatchable resource (if the LCOE is $60/MWh). In the generic-baseload-only scenario, approximately 15 GW of baseload generic zero-carbon resources and approximately 25 GW of battery storage are selected. Here, however, battery storage selection is only half that compared to its selection when generic dispatchable resources are modeled (~50 GW; CEC, 2020a), with or without baseload generic resources. At least in the SB100 scenarios, battery storage and other resources seem capable of providing sufficient system flexibility. Similar comparisons of flexibility in future grids need to be examined with respect to geothermal resources' roles to determine if flexible geothermal operations are economically valuable and necessary to support future grid reliability.

5.2.3 Understanding Model Sensitivities

Variation of model input assumptions will help identify how geothermal is valued in electricity grids and the input parameters to which the models are most sensitive. Examples include:

- Using parametric models to investigate sensitivity related to LCOE values, geothermal selection thresholds, ancillary services pricing, and value of geothermal resources providing ancillary services versus energy only.
- Investigating dispatchable versus baseload geothermal with reliability of capacity expansion model resource portfolios (e.g., SB100 studies with generic zero-carbon resources) examined with production cost modeling.
- Evaluating the impact of "must-take" geothermal resources (e.g., 100 MW of new geothermal per year) and scenarios that remove or limit other resources to understand how "optimal" resource mixes are selected can show predicted outcomes for targeted development of geothermal resources (e.g., 3675 MW, P95 for USGS identified resources [Williams et al. 2008]).
- Testing of greenhouse gas (GHG) reduction scenarios versus RPS scenarios where emissions-generating resources are maintained with renewable energy credits.
- Exploring impacts of extensive geothermal resources in production cost and network reliability models to validate resource portfolios with abundant geothermal resources, to

quantify geothermal value, and to further understand how geothermal resources contribute to the operations and reliability of future grids. This includes assessing future value of ancillary and reliability services, and whether or not geothermal is valued as a baseload or dispatchable resource and the conditions that favor one or the other.

To assess potential real-world implications, utilities might be engaged to run scenarios with modifications to their "base case" scenarios:

- Examining, for example, 100 MW/yr for 10 years of baseload geothermal at zero cost to determine levelized avoided cost of electricity (LACE).
- Testing capacity factor assumptions with higher values (e.g., 95%) and $/MWh sensitivities (e.g., 2020 ATB values for hydrothermal flash and binary plants and, if different, the most recent, lowest cost contract price that is reported).
- Eliminating, if present, category 3 unbundled renewable energy credits that are sold separately from energy delivered and enable carbon-emitting generation to be offset by renewable generation.
- Eliminating RPS and optimizing the resource portfolio to minimize total grid GHG emissions at relevant $CO_2$ prices, for example, $50/ton and $60/ton.

Such sensitivity analyses would also contribute to understanding variation in outputs between different capacity expansion tools and inform utilities and other stakeholders about the future value of geothermal resources in their resource portfolios.

### *5.3 Additional Future Research Opportunities*

Several identified research themes extend beyond power system modeling but may also be important in helping boost modelers' confidence in geothermal.

#### 5.3.1 Analysis of Historical Data

Historical data analysis can guide improvement of model inputs and design of scenarios to evaluate sensitivity to model inputs. Potentially valuable analyses and activities might include:

- Evaluate hourly production data from air-cooled and water-cooled power plants to understand variability of geothermal output to improve estimates of capacity factors.
- Examine operator-submitted data used by EIA to calculate capacity factors to capture the range of values for individual power plants and interview operators as needed to better understand methodology, especially for low and high values.
- Query operators regarding what, if any, instructions have been given by grid operators (e.g., curtailment requests at the Geysers).
- Examine high-load hours in multiple grid marketplaces (CAISO, ERCOT, others) to better understand and help quantify the value of capacity and ancillary services.

#### 5.3.2 Reducing Upfront Risk

Geothermal developers face high risk during the early phases of exploration and development. Greater confidence that discovered resources can be contracted to provide energy, capacity, and ancillary services would reduce the risk associated with these early project development costs. Expanded resource assessments and more representative modeling efforts like those described above can improve understanding of geothermal's value in power systems, when outcomes of such efforts are communicated across the broader power system planning, operations, and regulatory communities.

5.3.3 Improved Contract and Policy Design

Collaboration among geothermal operators and LSEs can support development of contract mechanisms that include compensation for grid services that can provide financial as well as grid resilience and reliability benefits for both parties. One example exists between HELCO and Ormat for the Puna Geothermal Venture on the Big Island of Hawaii. Better understanding of the cost sensitivities and benefits accrued through this flexible-operations contract, even if a unique geographic and political setting, can help inform evaluation of flexible geothermal contracts on the mainland. This may extend beyond contract design to include policy development that supports the valuation and purchase of operational services to support grid reliability. A current example is ongoing rulemaking in California with regard to resource adequacy requirements. Future grids with high VRE penetration could be more reliant on—and, accordingly, would more highly value—firm geothermal resources based on evolving resource adequacy requirements. Also, the dramatic growth in corporate renewable power purchase agreements could evolve to tie renewable generation more directly to the power used by their operations, which could increase the need for firm renewable resources like geothermal. Corporations purchased a record 23.7 GW of clean energy in 2020, up from 20.1 GW in 2019 and 13.6 GW in 2018 (BloombergNEF 2021).

5.3.4 Fostering Greater Communication

Workshop participants emphasized the importance of fostering greater communication among industry, academia, and government to ensure model inputs are up-to-date, appropriate, and clearly explained with referenced sources. Across the modeling community, a Multi Model Workshop could inform technical aspects of geothermal representation in power system models, while model scenario results inform the broader community of stakeholders. Geothermal industry participation in these discussions about the future grid are critical to vetting geothermal input parameters and maintaining geothermal interests. For example, the LA100 advisory group included both solar and wind industry organizations, but no geothermal representation was present. Securing geothermal representation in large planning efforts like LA100 can occur through collaboration among a number of geothermal stakeholders.

## 6. Summary

As technology and electricity grids evolve to include ever-greater percentages of VRE resources, the need will increase for technologies that can supply the mix of grid services required for reliability while meeting cost targets and constraints on emissions. Geothermal resources are well qualified to support the complete needs of an affordable, reliable, and sustainable power grid given that they are low-carbon, firm, dispatchable resources that can support integration of VRE resources. The models discussed in this report predict a wide range of geothermal deployment in future grid scenarios. While competitive LCOE is a key factor, investigation of the differences in model-input assumptions and constraints as well as their effects on geothermal selection in capacity expansion models can support improved geothermal representation, provide increased confidence in resource selections, and support planning for future, reliable, 100%

renewable electricity grids. Validation of diverse resource portfolios with production cost and network reliability models that include increasing amounts of geothermal resources can further quantify the value geothermal resources contribute to grid operations and reliability.

Major themes for focusing future research identified through stakeholder interviews and the virtual workshop address geothermal value with respect to flexible operations, model inputs, and resource potential. Analysis of sensitivities associated with model assumptions can better inform an understanding of geothermal representation and value in power system models. Outcomes of ongoing and future research can inform the geothermal community about how best to guide geothermal development toward wider deployment in support of future electricity grids.

## REFERENCES

Augustine, C., Ho, J., and Blair, N. 2019. GeoVision Analysis: Electric Sector Potential to Penetration Task Force Report. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71833, 93p.

Black & Veatch. 2016. RPS Calculator, V.6.3. https://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Energy_Programs/Electric_Power_Procurement_and_Generation/LTPP/RPSCalc_CostPotentialUpdate_2016.pdf.

BloombergNEF. 2021 "Corporate Clean Energy Buying Grew 18% in 2020, Despite Mountain of Adversity." https://about.bnef.com/blog/corporate-clean-energy-buying-grew-18-in-2020-despite-mountain-of-adversity/

Brown, M., Cole, W., Eurek, K., Becker, J., Bielen, D., Chernyakhovskiy, I., Cohen, S. 2020. Regional Energy Deployment System (ReEDS) Model Documentation: Version 2019. Golden, CO: National Renewable Energy Laboratory, NREL/TP-6A20-74111, 140p.

CEC. 2020a. Draft 2021 SB 100 Joint Agency Report. https://efiling.energy.ca.gov/GetDocument.aspx?tn=235848&DocumentContentId=68803

CEC. 2020b. Inputs & Assumptions: CEC SB100 Joint Agency Report. https://efiling.energy.ca.gov/GetDocument.aspx?tn=234525&DocumentContentId=67350

Cole, W., Mai, T., Logan, J., Steinberg, D., McCall, J., Richards, J., Sigrin, B., and Porro, G., 2016. Standard Scenarios Report: A USA Electricity Sector Outlook. Technical Report NREL/TP-6A20-66939, 60p.

CPUC. 2020. LSE's 2020 Integrated Resource Plans. https://www.cpuc.ca.gov/General.aspx?id=6442467489

Dobson, P., Dwivedi, D., Millstein, D., Krishnaswamy, N., Garcia, J., and Kiran, M. 2020. "Analysis of curtailment at The Geysers geothermal Field, California." Geothermics 87, 14p.

DOE. 2016. Geothermal Electricity Technology Evaluation Model: https://www.energy.gov/eere/geothermal/geothermal-electricity-technology-evaluation-model

DOE. 2019. *GeoVision: Harnessing the Heat Beneath Our Feet*. DOE/EE1306. U.S. Department of Energy, Washington, D.C. https://www.energy.gov/sites/prod/files/2019/06/f63/GeoVision-full-report-opt.pdf.

Edmunds, T. and Sotorrio, P. 2015. Ancillary Service Revenue Potential for Geothermal Generators in California FY15 Final Report: LLNL-TR-669828, 20p.

EIA. 2019. "Geothermal Explained." https://www.eia.gov/energyexplained/geothermal/use-of-geothermal-energy.php.

EIA. 2020. Electric Power Monthly, October 2020. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b.

FERC. 2020. "Energy Primer: A Handbook for Energy Market Basics." 150p. https://www.ferc.gov/sites/default/files/2020-06/energy-primer-2020_Final.pdf.

Gill, L. 2020. "Implications of Geothermal Modeling on the SB100 Portfolio." November 19, 2020, Geothermal Representation in Power System Models, NREL Virtual Workshop.

Idaho Power. 2019. Integrated Resource Plan – Second Amended. https://docs.idahopower.com/pdfs/AboutUs/PlanningForFuture/irp/2019/SecondAmended2019IRP.pdf

Linvill, C., Candelaria, J., and Elder, C. 2013. "The Value of Geothermal Energy Generation Attributes." Aspen Report to Ormat Technologies, Aspen Environmental Group. Unpublished manuscript, 42p.

Millstein, D., Dobson, P., and Jeong, S. 2020. "The Potential to Improve the Value of USA Geothermal Electricity Generation Through Flexible Operations." Journal of Energy Resources Technology, v. 143, 9p.

NREL. "LA100: The Los Angeles 100% Renewable Energy Study." (2021) Access online at: https://maps.nrel.gov/la100/report

NREL. 2019. GeoVision: Harnessing the Heat Beneath Our Feet—Analysis Inputs and Results. Data set. Retrieved from https://dx.doi.org/10.15121/1572361.

NREL. 2020. "Annual Technology Baseline." Accessed December 30, 2020. https://atb.nrel.gov/.

Nordquist, J., Buchanan, T., and Kaleikini, M. 2013. "Automatic Generation Control and Ancillary Services." GRC Transactions, v. 37, p. 761–766.

NV Energy. 2018. Integrated Resource Plan – Summary. https://www.nvenergy.com/publish/content/dam/nvenergy/brochures_arch/about-nvenergy/rates-regulatory/recent-regulatory-filings/nve/irp/NVE-18-06003-IRP-VOL4.pdf

Ringkjob, H-K, Haugan, P.M., and Solbrekke, I.M. 2018. "A review of modelling tools for energy and electricity systems with large shares of variable renewables." Renewable and Sustainable Energy Reviews, v. 96, p. 440–459.

Thomsen, P. 2018. "Geothermal selection in California resource planning: Preliminary results from the CPUC's IRP tools and recommendations for future development and analysis." GRC Transactions 42, 20p.

Williams, C.F., Reed, M.J., and Mariner, R.H. 2008. "A review of methods applied by the U.S. Geological Survey in the assessment of identified geothermal resources." U.S. Geological Survey Open-File Report 2008-1296. http://pubs.usgs.gov/of/2008/1296/.

Young, K. R., Witherbee, K., Levine, A., Keller, A., Balu, J., and Bennett, M. 2014. "Geothermal Permitting and NEPA Timelines." GRC Transactions 38, 12p.

Young, K., Levine, A., Cook, J., Heimiller, D., and Ho, J. 2019. GeoVision Analysis Supporting Task Force Report: Barriers—An Analysis of Non-Technical Barriers to Geothermal Deployment and Potential Improvement Scenarios. National Renewable Energy Laboratory. NREL/PR-6A20-71641, 126p.