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Enhanced Geothermal Systems for Reliable Decarbonization of the California Energy Grid

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ABSTRACT

In California, the progress towards net-zero carbon economy has been highly dependent on the rapid growth of solar and wind electricity, as well as electrification of transportation and heating. However, the increasing reliance on weather-dependent renewables can raise grid reliability concerns. Among the diverse array of renewables, enhanced geothermal systems (EGS) present a promising solution for clean firm energy that could alleviate such challenges. This study evaluated the techno-economic impacts of EGS integration into California's energy system by using a gas-electric capacity expansion model. This model optimizes electricity and heating investments while meeting progressively stringent emissions targets to ensure a cost-effective transition to a net-zero economy by 2045. We analyzed multiple EGS deployment scenarios, varying in drilling depth, seismic exclusion zones, and dispatch flexibility. Results indicated up to 82 GW of EGS capacity installed by 2045, reducing total system capacity needs by 40% and lowering system costs by 8.6% compared to cases without EGS. Furthermore, flexible dispatch reduced system costs by 12.3% in aggregate. EGS also significantly decreased reliance on power-to-gas systems, supporting heating electrification and reducing power-to-gas capacity needs by 50%. These findings highlight EGS as a key enabler of California's clean energy transition across both the electricity and gas sectors.

1. INTRODUCTION

The accelerated transition from traditional fossil fuels to intermittent renewable and low-carbon resources has prompted electricity grid reliability concerns. Beyond clean energy supply, demand for 24/7 clean power is growing rapidly, with projections estimating that data centers will make up to 8% of the total United States power demand by 2030 (Goldman Sachs 2023). In California, the high penetration of solar power has resulted in oversupply during the middle of the day. This formed the infamous "duck curve", a daily pattern of power demand and supply imbalance caused by high solar power generation during midday and sharp demand peaks in the evening, where the day's net load (gross electric load minus solar and wind generation) drops around noon and rapidly increases toward the evening hours. The California Independent System Operator reported that 2.4 TWh of utility-scale solar and wind were curtailed in 2022, 63% greater than total curtailments in 2021 (EIA 2023). Batteries are being installed rapidly in California and are technically effective at providing capacity for a few hours diurnally. However, batteries are not economic for longer periods because they also suffer from a diminishing effective load carrying capability, where additional investments in batteries would flatten the peak further, requiring storage for longer hours and reducing the arbitrage value of the shifted power.

Geothermal power is a key contender in the transition towards a greener and more resilient energy landscape. Recent technological advancements and successful field implementations have demonstrated commercial prospects for enhanced geothermal systems (EGS). EGS are applicable across geographies, as naturally elevated subsurface temperatures are always present at sufficient depths (Aghahosseini and Breyer 2020). Aljubran and Horne (2024a) estimated that the annual net generation potential from EGS is nearly 309 times greater than the 2023 United States power consumption of 4,014 TWh. In this study, we investigated the value of incorporating EGS into the California energy system. We achieved this through capacity expansion modeling with the objective of cost-effectively decarbonizing the California power and gas networks. Based on the most recently developed (2024) EGS resource potential estimates (Aljubran and Horne 2024b), we explored different EGS supply scenarios: baseload/flexible generation dispatch, baseline/advanced drilling costs, allowable maximum drilling depth, and land exclusion based on seismically active regions. We adopted BRIDGES (Building Resilient Integrated Decarbonized Gas-Electric Systems) (Von Wald et al. 2022), a gas-electricity sector coupled capacity expansion model developed for energy systems planning, to determine the optimal energy transition pathway for California in the presence of EGS resources.

2. METHODOLOGY

We integrated outputs from a techno-economic model of EGS into a capacity expansion model. This process is summarized in Figure 1.

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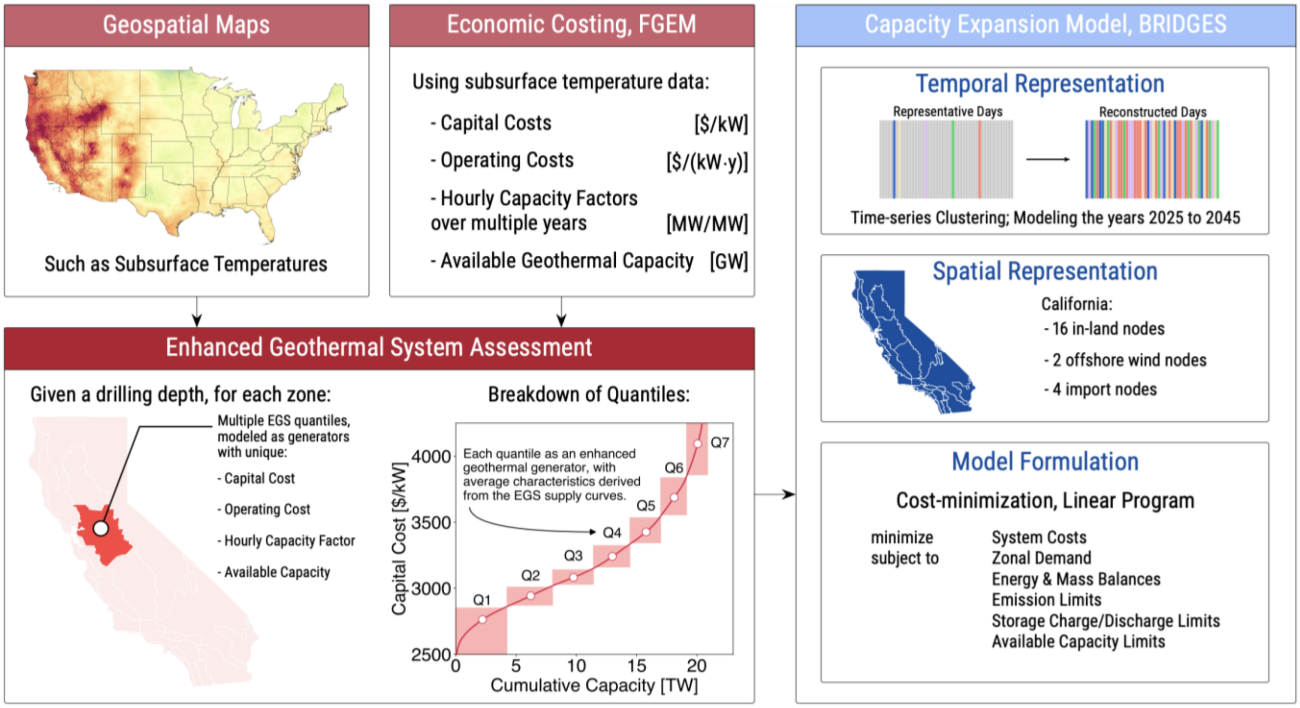

Figure 1: Schematic highlighting the workflow for the inputs and data processing using FGEM (Aljubran and Horne 2024c) and their connection to the BRIDGES capacity expansion model (Von Wald et al. 2022).

2.1 Enhanced geothermal systems

<u>2.1.1 Resource Potential</u>

Using the United States thermal Earth model and EGS resource supply curves developed by Aljubran and Horne (2024a), we estimated EGS potential across different scenarios for California. While previous studies estimated California's EGS supply potential at 40–700 GW (Augustine et al. 2023; Ricks et al. 2024; Chen et al. 2024), our model predicted a significantly larger potential of approximately 20,882 GW. This difference was attributed to cost reductions in drilling and stimulation, as well as more advanced commercial EGS designs (Aljubran and Horne 2024b). Figure 2 compares our adopted EGS supply curves to those from prior studies, including baseline and advanced scenarios with different cost assumptions.s

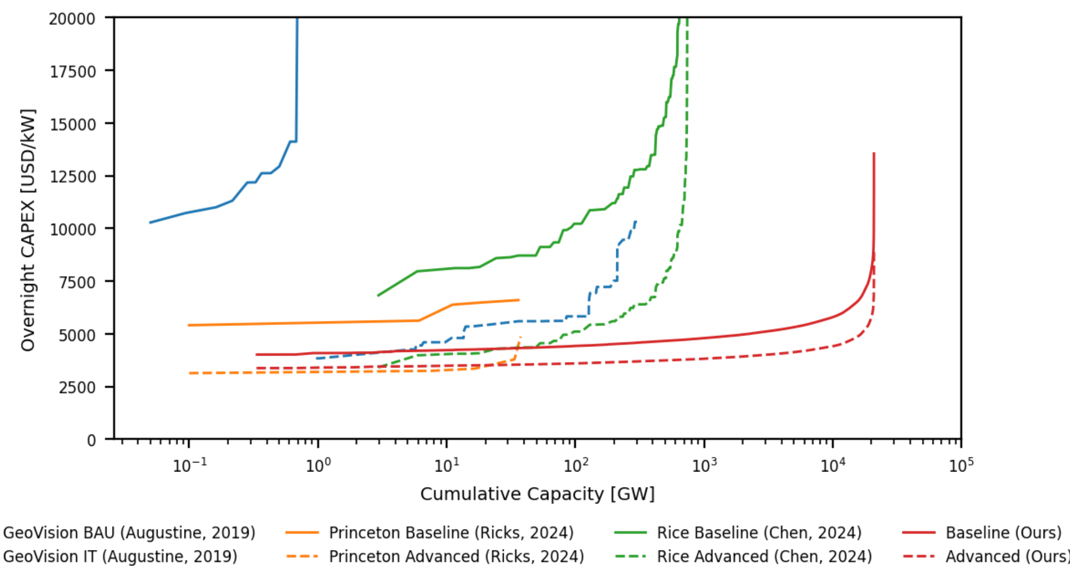

Figure 2: Comparison of different EGS supply curves for California across baseline and advanced scenarios for EGS techno-economics.

We generated our supply curves using the Flexible Geothermal Economics Model (FGEM) (Aljubran and Horne 2024c), which operates on hourly timesteps to account for variations in ambient temperature. This model simulates reservoir temperature decline over time under different operational strategies, using a transient diffusion-convection framework that allows for flexible well flow rates and injection temperatures (Aljubran and Horne 2025). Additionally, these supply curves incorporate ambient temperature forecasts with a spatial resolution of 4 km², developed through open-source generative machine learning techniques from NREL (Buster et al. 2024). The financial modeling of EGS included estimates of capital expenditure (CAPEX), operational expenditure (OPEX), and levelized cost of electricity (LCOE) with a 7% discount rate. Spatially varying transmission costs were also incorporated (Aljubran and Horne 2025). Baseline drilling costs were derived from 2022 data in GETEM (Mines 2016) using real geothermal project costs (Robins et al. 2022), while the advanced drilling scenario was based on 2024 cost reductions observed in EGS projects in Nevada and Utah, where drilling costs declined by nearly 50% (El-Sadi et al. 2024).

2.1.2 Allowable Drilling Depths

Conventional geothermal wells are typically drilled to depths shallower than 4 km to access hydrothermal resources, where naturally occurring hot water and steam can be extracted (Gutiérrez-Negrín 2024). In contrast, EGS designs rely primarily on elevated geothermal gradients, allowing access to deeper resources. However, deeper drilling presents challenges, including harder rock formations, fractured zones, and increased pressure and temperature, requiring specialized equipment such as high-strength drill pipes, real-time monitoring systems, and advanced drill bits. Additional mitigation strategies, including drillpipe insulation and mud cooling, help manage extreme temperatures exceeding 250°C. Geophysical surveys and data from previous drilling projects also aid in reducing uncertainties before deep well development.

The economic risks are also substantial, as the costs of drilling and completing wells increase nonlinearly with depth. Nevertheless, several wells have been drilled to depths of 7 km and deeper worldwide. Tapping into deeper resources is favorable, as the power plant thermal efficiency is greater for higher geofluid temperatures, which results in favorable project CAPEX. Depending on the risk-reward portfolio of geothermal investors, there could be interest in drilling to deeper depths. Thus, we investigated the least-cost optimal grid system design for scenarios where EGS development is limited to maximum depths of 4 km, 5 km, 6 km, and 7 km.

2.1.3 Seismicity

Considering seismic events is essential to ensure the safe and sustainable EGS development. We analyzed the potential effect of seismic events limiting EGS deployment by excluding geographical regions of heightened seismic risk. Researchers at the USGS modeled natural seismicity nationwide and estimated the chance of any level of damaging earthquake shaking in 100 years (Petersen et al. 2023). Natural seismic events are more frequent and damaging in faulted zones and are indicative of increased risks of damaging induced seismicity during hydraulic stimulation and injection operations that are associated with EGS projects. We created EGS resource potential scenarios by excluding lands with relatively high risk of natural seismicity. We considered three thresholds on the chance of any level of damaging earthquake shaking in 100 years, namely 95% (Low), 85% (Moderate), and 75% (High). Figure 3 shows the extent of land exclusions in California based on these thresholds. We note that significant zones were excluded across scenarios, especially along the Pacific Coast.

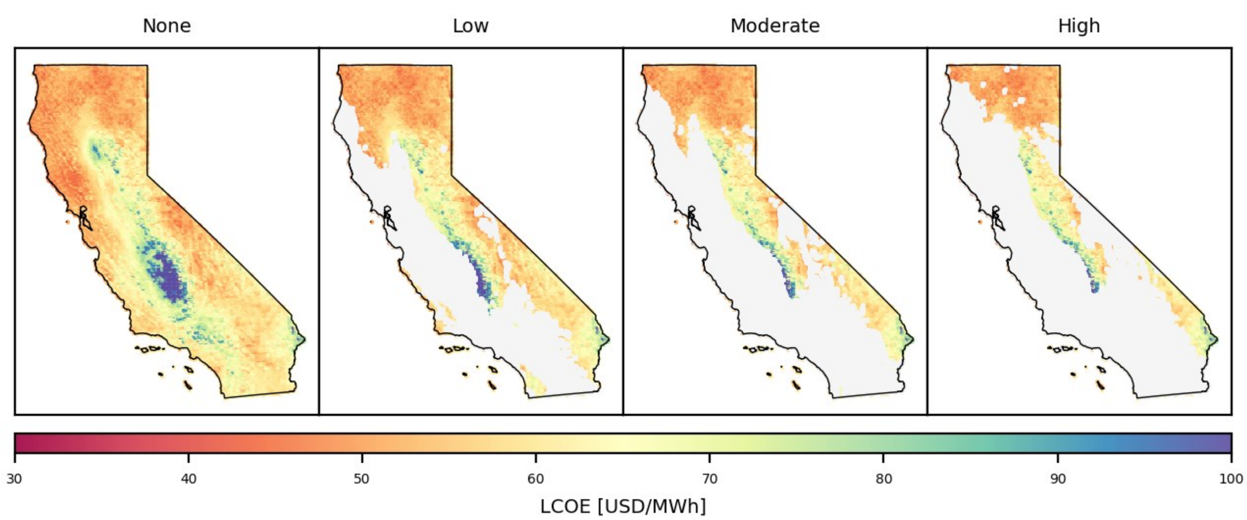

Figure 3: Land exclusion scenarios based on the chance of any level of damaging earthquake shaking in 100 years, using a range of probability thresholds. Gray pixels represent excluded land due to seismicity. The color of non-excluded pixels within California designates LCOE for an EGS project built and operated at the corresponding location.

2.1.4 Flexible Power Dispatch

We evaluated EGS deployment under flexible dispatch strategies, where power output is adjusted to maximize generation over the project lifetime. Compared to baseload operation with constant mass flow rates, flexible dispatch could reduce the levelized cost of electricity

(LCOE) by 6.4% (Aljubran and Horne 2024b). This approach lowers system costs by increasing power availability during high-demand seasons, such as summer, when power plant efficiency declines due to higher ambient temperatures. The flexible dispatch approach in consideration required minimal design modifications, relying on wellhead throttling and power plant bypass without additional operational expenditures. However, it introduced thermodynamic inefficiencies, such as changes in turbine inlet and outlet pressures, which could impact isentropic efficiency. These effects were fully modeled and captured in our supply curve modeling (Aljubran and Horne 2024b). Overall, the production mass flow rate was permitted to rise by up to 30% to sustain generation levels while maintaining a minimum flow rate of 10 kg/s to prevent power plant shutdowns. Our capacity expansion modeling in considered scenarios with both baseload and flexible dispatch for EGS. Flexible operation showed smaller seasonal reductions in capacity factors than baseload systems, making it a valuable strategy for optimizing system reliability and cost-effectiveness.

2.1.5 Supply Scenarios

We explored different scenarios for capacity expansion modeling in California based on different EGS resource potential settings. These settings were based on different factors, namely baseload/flexible dispatch, baseline/advanced drilling costs, allowable maximum drilling depth, and land exclusion based on seismically active regions. Capacity factors were modeled at hourly resolution with power plant thermal efficiencies and EGS reservoir depletion over years simulated using FGEM with ambient temperature forecasts generated based on the NREL generative machine learning model (Buster et al. 2024). The resultant installed capacity of various energy resources and system costs were compared across scenarios and with a baseline setting that did not allow EGS development (scenario “No-EGS”).

Data are presented for 16 California climate zones, as modeled in the capacity expansion model, showing a large spread between climate zones. Considering a scenario with baseline drilling costs, 7 km maximum allowable depth, baseload dispatch, and no land exclusions of seismically active zones, Figure 4 shows EGS resource supply across the 16 climate zones in California. Higher temperature resources naturally provided the most lucrative EGS targets, i.e., low CAPEX, high-capacity potential. We observed significant capacity potential across climate zones in the range of 4,000-8,000 USD/kW CAPEX, which was competitive and comparable to other clean firm technologies in California (Mirletz et al. 2023). EGS generation was modeled for each climate zone using grades corresponding to capacity available at different costs. This was important to capture the different qualities/grades of EGS in each climate zone. Seven CAPEX-based EGS grades were constructed with percentile thresholds of 1%, 5%, 10%, 25%, 50%, and 75%, such that each climate zone consists of variable capacity factors.

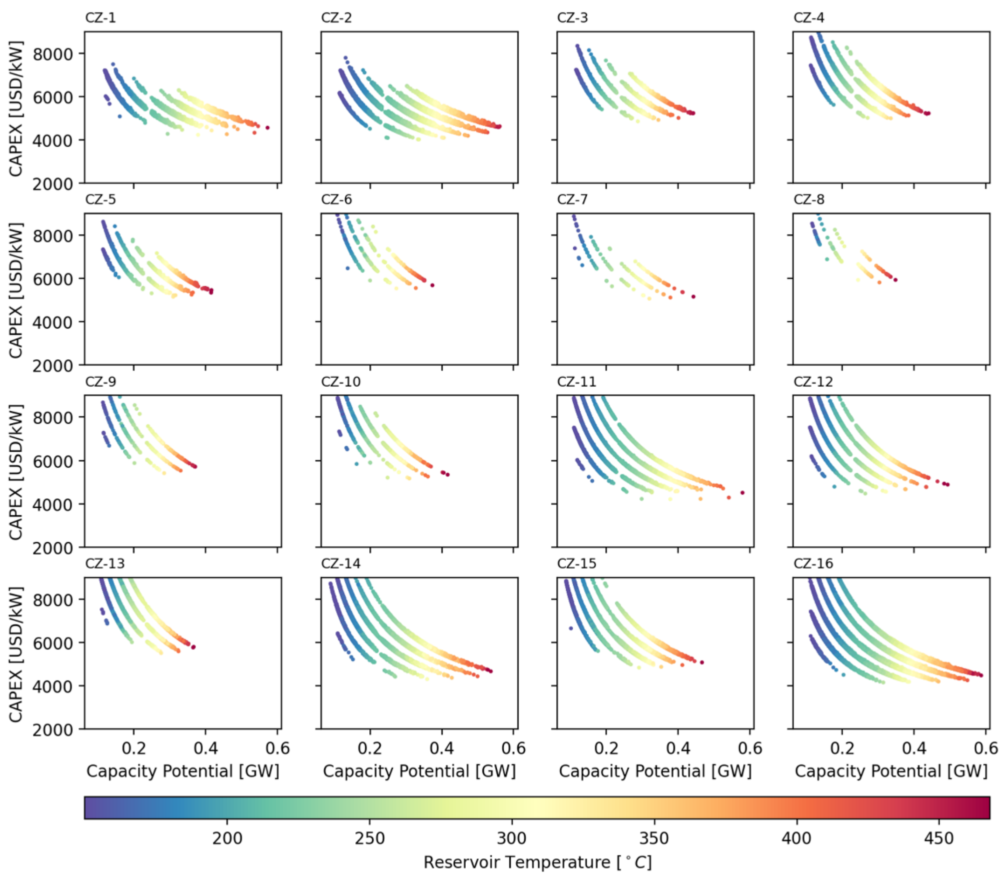

Figure 4: EGS resource supply potential across the 16 California climate zones for scenario 1-D with baseline drilling, 7 km maximum allowable depth, baseload dispatch, and no land exclusions of seismically active zones. Each panel shows a set of lines corresponding to different target depths.

2.2 Capacity Expansion Model

We used the BRIDGES capacity expansion model, developed by Von Wald et al. (2022), for energy systems planning. BRIDGES is a cost-minimization, linear optimization model that captures the interactions between gas and electricity systems. It is implemented in the JuMP framework using Julia (Dunning et al. 2017) and employs the Gurobi optimization solver. The geographic scope of this study was California, which was divided into 16 nodes based on the climate zones defined by the California Energy Commission. Additionally, two offshore and four export nodes were included to model interactions with neighboring regions, bringing the total number to 22 nodes. Meanwhile, infrastructure connectivity was derived from real-world electricity and gas transmission maps (Von Wald et al. 2022; Saad et al. 2025; Sodwatana et al. 2025).

To efficiently capture energy storage dynamics, BRIDGES employs a time-series clustering algorithm that selects representative days rather than modeling every hour of the year. Each investment year—2025, 2030, 2035, 2040, and 2045—was represented by ten characteristic days, ensuring chronological consistency in energy storage modeling (Kotzur et al. 2018). Key decision variables included investment in and retirement of generation, storage, power-to-gas systems, and end-use appliances. System constraints accounted for mass balance, energy flows, and operational limitations, such as battery discharge limits. A decarbonization constraint was imposed to achieve net-zero emissions across all sectors by 2045, leading to fossil fuel retirements and increased renewable deployment. By incorporating geospatial EGS data, this study provides a more detailed multi-sector analysis of decarbonization pathways.

Capacity expansion of renewable energy resources in California were constrained based on land-use availability and build rates. Available wind and solar capacities were based on the “Reference Access” Supply Curve by NREL (2021a; 2021b), which provides supply curve data that applies land area exclusions based on physical constraints (e.g., wetlands, building footprints) and protected lands. The supply curve data are grid-based region-specific information on available capacity and wind speed and solar irradiance for wind and solar, respectively. The total build capacity for each climate zone was constrained to half the available capacity, less any built capacity, to achieve more realistic projected builds of solar and wind systems.

Beyond electricity generation, the BRIDGES model also addresses the decarbonization of California’s heat demand by integrating both the natural gas and electricity networks. Gas infrastructure interacts with the electricity grid in two primary ways: (1) supplying natural gas to power plants and (2) enabling electricity-driven power-to-gas processes to produce synthetic fuels such as electrolytic hydrogen (H_2) and synthetic methane. This dual integration allows for a more comprehensive assessment of cross-sector decarbonization strategies. The model considers two main heat demand sources: residential/commercial end-use appliances and industrial heat demand. For end-use appliances, BRIDGES tracks the existing mix of gas- and electric-powered units, allowing for replacements that transition toward electrification when appliances reach the end of their lifecycle. This mechanism enables demand-side decarbonization by facilitating a shift away from fossil-fueled appliances. For industrial heat, which peaks at 22 GW in California, the model assumes that up to 70% of demand can be electrified using electric boilers, as most industrial heat applications requiring temperatures below 500°C can be met with this technology (McMillan et al. 2021). The remaining 30% of high-temperature industrial heat—which is harder to electrify—is assumed to rely on gas, either from fossil fuels or synthetic alternatives produced through power-to-gas conversion. Future research using BRIDGES will further refine these assumptions, particularly in the context of industrial decarbonization.

3. RESULTS AND DISCUSSION

3.1 Sensitivity to Allowable Drilling Depths

The BRIDGES model incorporated a diverse set of energy generation and storage technologies, including solar PV, solar thermal, onshore/offshore wind, nuclear, hydropower, conventional geothermal, biopower, fossil fuel plants with and without carbon capture, and coal. Storage options included lithium-ion batteries, pumped hydro, hydrogen, and iron-air units. Figure 5 illustrates the total installed capacity in California across different scenarios, comparing a baseline case with no EGS to scenarios with varying allowable EGS drilling depths. In the absence of EGS, the total system capacity reached 272 GW by 2045, predominantly from solar, wind, and natural gas with carbon capture. The model achieved full decarbonization by 2045, with a rapid increase in installed capacity between 2040 and 2045 due to technology cost reductions and learning curves.

Introducing EGS significantly reduced the total installed system capacity to 160–180 GW by 2045, as its higher capacity factor lowered the need for intermittent renewables and battery storage. By 2045, EGS capacity ranged from 70–82 GW across depth scenarios, with deeper drilling allowing for greater deployment. Accessing higher subsurface temperatures at greater depths improved thermodynamic efficiency and power plant performance (Aljubran and Horne 2024b), hence deeper wells yielded higher capacity factors and reduced EGS capacity installation. Compared to the no-EGS case, total system costs to meet California’s 2045 decarbonization target were reduced by 8.6% in the 7 km scenario. We also found that power-to-gas conversion significantly decreased with EGS integration. Since power-to-gas conversion has a low efficiency (i.e., nearly 50%), the presence of an affordable clean firm resource like EGS made further electrification of appliances more optimal. Figure 6 presents the spatial distribution of installed EGS capacity by 2045. The largest EGS installations were concentrated in climate zones 1 and 2, as well as the northern California Pacific Coast. The 4 km scenario exhibited a broader geographic spread of EGS due to the lower available supply per climate zone, whereas deeper drilling scenarios enabled more concentrated high-capacity installations.

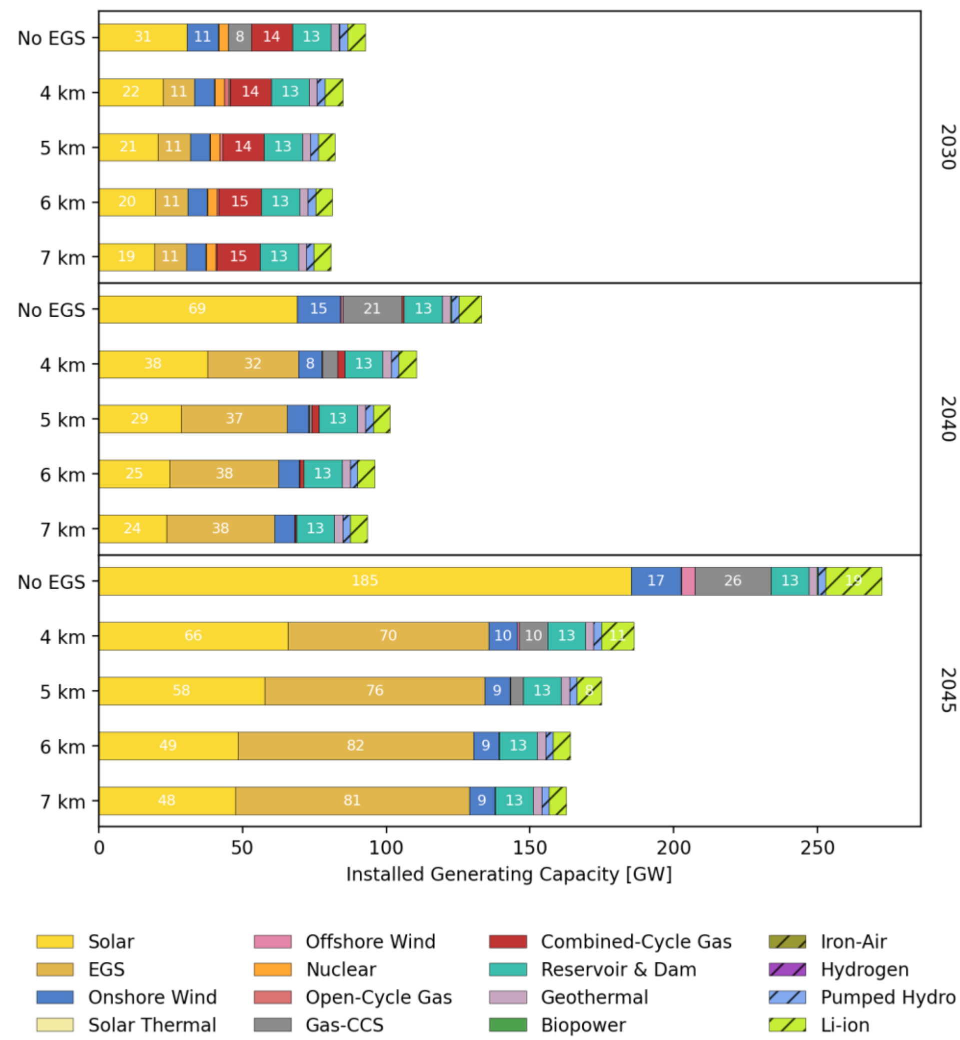

Figure 5: Comparison of total installed resource capacity in California across years for different maximum allowable EGS target depths. Both energy generators and storage units are included in the energy supply potential used by BRIDGES to solve for the optimal energy mix across scenarios.

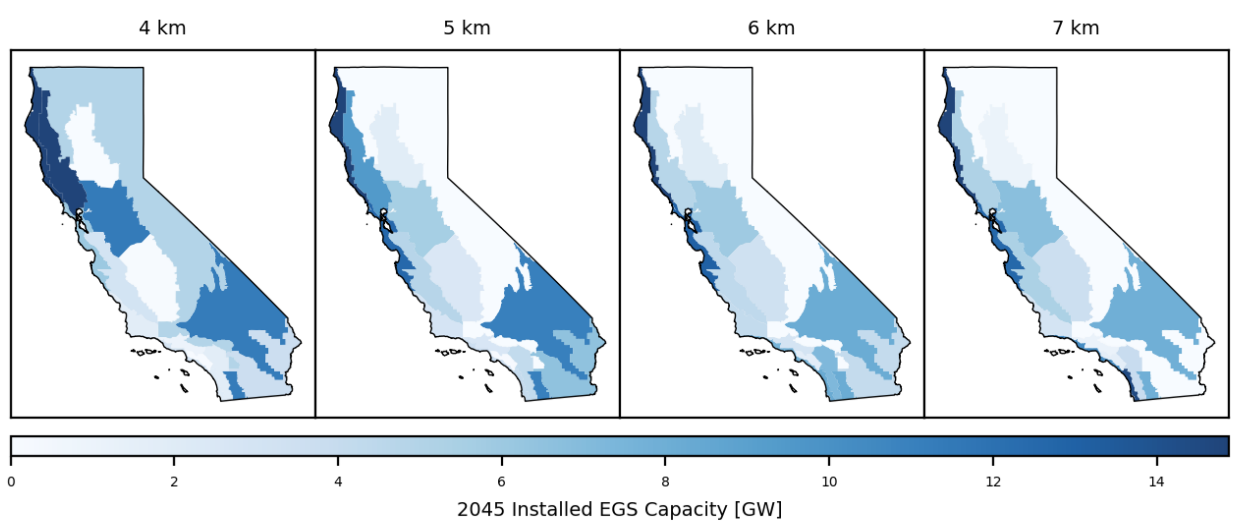

Figure 6: Spatial distribution of the installed EGS capacity by 2045 for different maximum allowable EGS target depths.

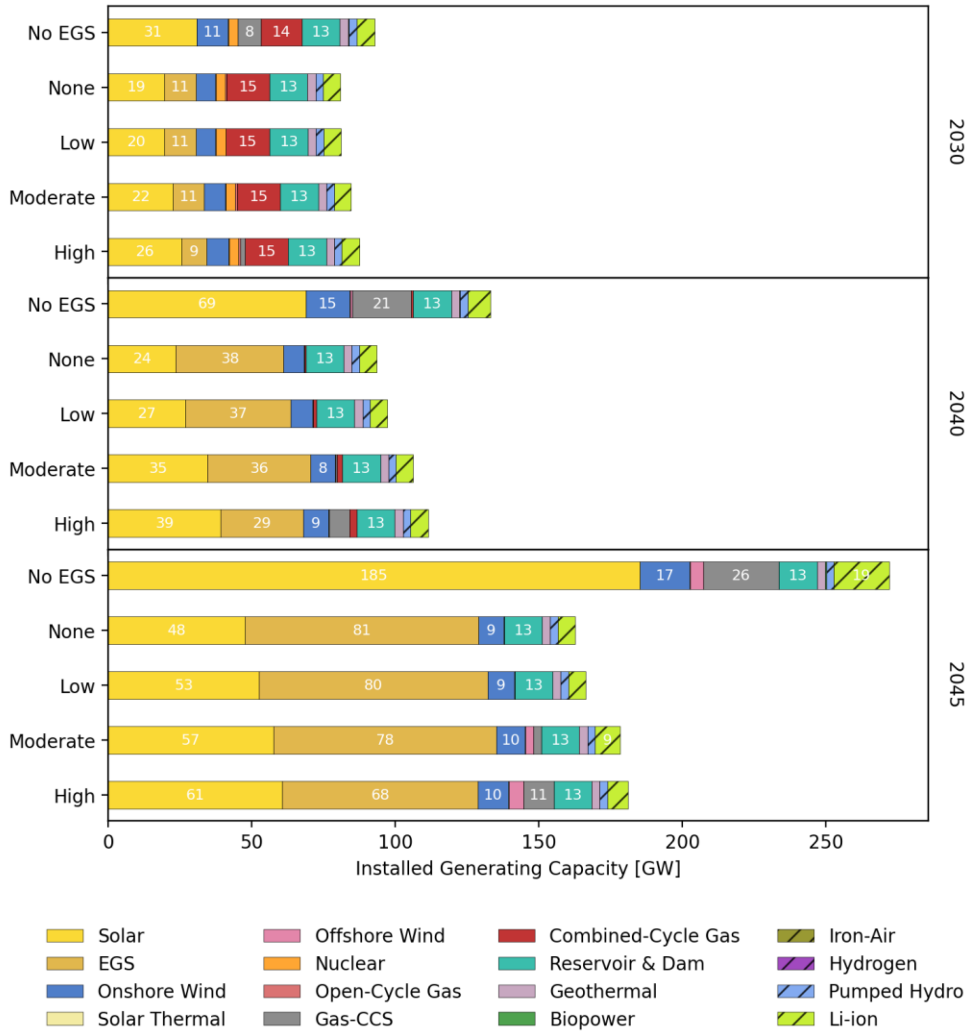

Figure 7: Comparison of total installed resource capacity in California across years for different seismic land exclusion criteria.

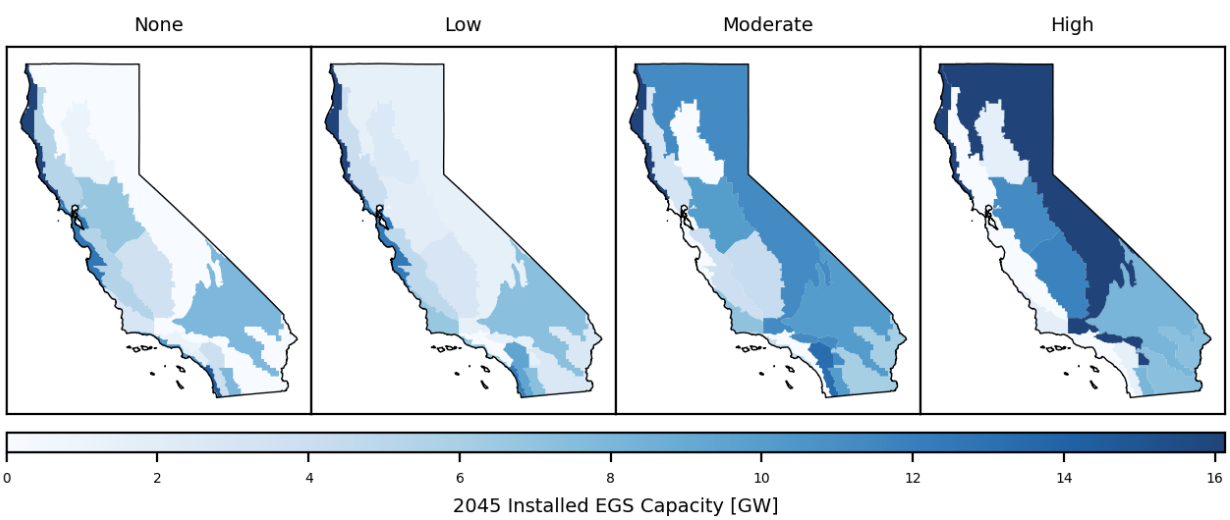

Figure 8: Spatial distribution of ins of the installed EGS capacity by 2045 for different seismic land exclusion scenario.

3.2 Sensitivity to Seismicity

Figure 7 illustrates the impact of seismic land exclusion on total system capacity. Under the High seismic exclusion scenario, a greater total system capacity was required due to reduced EGS deployment, which led to increased reliance on solar PV and storage. While offshore wind and natural gas with carbon capture were generally suboptimal in the presence of EGS, they became more viable alternatives in scenarios with Moderate and High seismic exclusions. Figure 8 shows the spatial distribution of installed EGS capacity by 2045 under different seismic land exclusion scenarios. Multiple climate zones along the Pacific Coast were entirely restricted from EGS development under Moderate and High exclusion cases. Consequently, BRIDGES optimized the system by shifting EGS deployment toward Sierra Nevada and the western flank of the Great Basin. In a conservative scenario that combined High seismic land exclusions with a 4 km drilling depth limit, only 47 GW of EGS capacity was deployed, 40% less than the 81 GW installed in the 7 km scenario with no exclusions.

Integrating seismic hazard models into early EGS planning can help identify geologically stable areas while maximizing deployment potential. Future capacity expansion modeling should incorporate drilling safety constraints and induced seismicity risks to improve site selection. Risk mitigation strategies, such as controlling injection pressures, fluid volumes, and implementing onsite seismic monitoring with observation wells and fiber optics, can further reduce seismic risks while maintaining productivity. The seismicity challenges identified in California also highlight the need for regional assessments on a national and global scale. The coupled energy system modeling approach demonstrated in this study provides a replicable framework for evaluating the feasibility of EGS in different geographies.

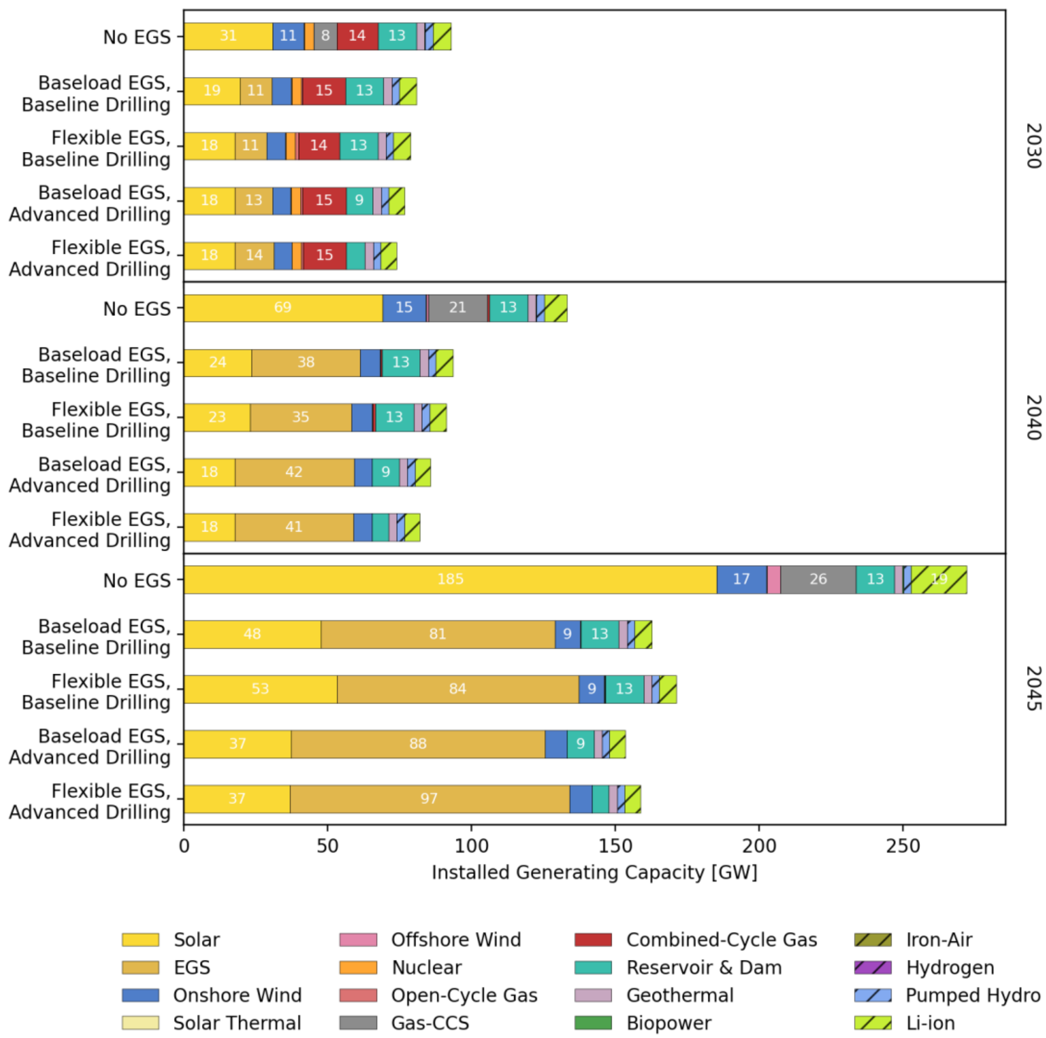

Figure 9: Comparison of total installed resource capacity in California across years for baseline/advanced drilling rates and baseload/flexible dispatch strategies.

3.3 Sensitivity to Drilling Rates and Dispatch

The sensitivity analysis on drilling rates and dispatch strategies underscores the balance between technological advancements, operational flexibility, and system-wide decarbonization goals. Variations in drilling rates and the adoption of flexible dispatch significantly influence EGS's ability to reduce dependence on intermittent renewables and large-scale storage. Figure 9 compares total installed capacities under baseline/advanced drilling rates and baseload/flexible dispatch scenarios. Flexible dispatch resulted in lower system capacity requirements initially, as it provided higher capacity factors. However, the more rapid reservoir depletion associated with flexible dispatch necessitated greater system capacity by 2045, compared to baseload operations. Overall, the flexible/advanced scenario led to 97 GW of EGS deployment, achieving a 12.3% reduction in total system cost compared to the no-EGS scenario.

The flexible dispatch approach, which utilized wellhead throttling and power plant bypass, aimed to maximize power generation during peak demand periods (e.g., daytime and summer), rather than altering EGS's role as a clean firm resource. This strategy reduced the need for large-scale battery storage and reliance on natural gas peaker plants. However, it introduced trade-offs in terms of reservoir longevity and system capacity expansion. Higher initial capacity factors led to faster reservoir decline, necessitating additional capacity in later years. Strategies such as allowing reduced output periods for thermal recovery could extend reservoir life while still providing dispatchable power. The adoption of flexible dispatch strategies is contingent on economic incentives. While flexible dispatch offers immediate benefits by reducing system costs and storage needs, the risk of accelerated reservoir depletion may deter developers focused on long-term sustainability. To support adoption, policy mechanisms like production tax credits or subsidies for flexible operations could offset associated risks. Advances in monitoring technologies (e.g., real-time wellhead sensors) and predictive modeling can also help optimize production and mitigate reservoir depletion risks.

We compared our findings to other studies focused on EGS deployment. The Enhanced Geothermal Shot Analysis by Augustine et al. (2023) estimated 27.9 GW of EGS capacity in California by 2050 using the ReEDS model, while Ricks et al. (2024) projected 25-35 GW with the GenX model under advanced drilling rates and flexible generation scenarios. Both studies indicated EGS capacity accounting for 20-35% of total system power capacity in California. In contrast, our study projected that EGS could constitute 25-60% of total capacity by 2045. This higher estimate is attributed to our more optimistic EGS resource supply curves, the simultaneous optimization of electricity and gas markets in the BRIDGES model, and the aggregation of power transmission capacity across California's climate zones, which favored EGS deployment in optimal areas.

4. CONCLUSIONS

This study examined the role of EGS in decarbonizing the California electricity and gas sectors using the BRIDGES capacity expansion model. We found that EGS can effectively complement intermittent renewables, reduce storage needs, and provide firm, low-carbon power, enhancing grid reliability and stability. The analysis revealed that allowing deeper drilling (up to 7 km) enables EGS deployment of up to 82 GW by 2045, leading to a 40% reduction in total installed system capacity compared to scenarios without EGS. Access to higher-temperature resources at greater depths increased the capacity factor of geothermal plants, reducing reliance on solar PV and battery storage and lowering system costs by 8.6%. Additionally, excluding high-risk seismic areas increased the total system capacity requirement by 10–15%, as lower EGS availability required additional solar and storage capacity to compensate for the loss of firm generation. Flexible EGS dispatch strategies were found to be effective in enhancing the value of geothermal energy in a system increasingly reliant on variable renewables. This approach reduced the need for large-scale battery storage and gas-fired peaker plants, resulting in a 12.3% reduction in total system costs compared to scenarios without EGS. The BRIDGES model further showed that integrating EGS allowed for a nearly 50% reduction in deployed power-to-gas capacity, as geothermal energy provided firm, continuous power, reducing reliance on synthetic fuels. The results indicate that integrating EGS into California's energy system accelerates decarbonization across both the electricity and gas sectors, leading to a more efficient and cost-effective energy transition.

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