PRINCETON UNIVERSITY

ZERO LAB

Zero-carbon Energy Systems Research and Optimization Laboratory

RESEARCH DIGEST

The Role of Flexible Geothermal Power in Decarbonized Electricity Systems

Wilson Ricks, Katharine Voller, Jack H. Norbeck and Jesse D. Jenkins
Princeton University | September 19, 2022

Enhanced geothermal systems (EGS) are an emerging energy technology with the potential to significantly expand the viable resource base for geothermal power generation. Although EGS has traditionally been envisioned as a `baseload' resource, flexible operation of EGS wellfields could allow these plants to provide load-following generation and long-duration energy storage. In this work we evaluate the impact of operational flexibility on the long-run system value and deployment potential of EGS power in the western United States. We find that load-following generation and in-reservoir energy storage enhance the role of EGS power in least-cost decarbonized electricity systems, increasing optimal geothermal penetration and significantly reducing bulk electricity supply costs compared to systems with inflexible EGS or no EGS. Flexible geothermal plants displace the most expensive competing resources by shifting their generation on diurnal and seasonal timescales, with round-trip energy storage efficiencies of 81-98%. Benefits of EGS flexibility are robust across a range of electricity market and geothermal technology development scenarios.

Firm, low-carbon resources — technologies available to generate power whenever needed, for as long as required — have been identified as critical for cost-effective decarbonization of electricity systems. Geothermal power is one such resource, with added benefits of being renewable and requiring minimal land and materials relative to other sources of electricity. Though geothermal power has historically been constrained by the need for unique geological conditions, so-called “enhanced geothermal systems” (EGS) promise to drastically expand the global geothermal resource base. In EGS, hydraulic stimulation is used to create an artificial geothermal reservoir where one did not exist previously. Relatively shallow EGS resources underlie much of the western United States, and successful development of this technology could unlock hundreds to thousands of gigawatts of geothermal resource potential nationwide.

In the past it has been assumed that EGS powerplants would adopt a ‘baseload’ operating strategy, generating at their maximum rated potential at all times. This is the preferred operating mode for conventional geothermal plants today, which derive no economic benefits from reducing output due to their near-zero fuel and variable operating costs. However, past work by our team demonstrated that EGS plants can derive much greater value in electricity systems with large amounts of wind and solar power by adopting a flexible operating strategy. By exploiting the natural properties of engineered geothermal reservoirs to alternately accumulate and discharge water from the subsurface, EGS plants can shift their energy production in time and prioritize generation during hours when demand is greatest and wind and solar output is lowest.

Princeton University’s **Zero-carbon Energy systems Research and Optimization Laboratory** conducts research to improve decision-making and accelerate rapid, affordable, and effective transitions to net-zero carbon energy systems. The ZERO Lab improves and applies optimization-based modeling tools and methods to understand complex macro-scale energy systems and uses these tools to evaluate and optimize emerging low-carbon energy technologies and generate decision-relevant insights to guide national and sub-national jurisdictions in transitioning to net-zero emissions energy systems. Prof. Jesse D. Jenkins is the Principal Investigator. For more, see http://zerolab.princeton.edu

In our new working paper, which is currently undergoing peer review, we expand on this previous research to assess the impact of flexible operations on the long-run value and deployment of EGS in the western United States. We investigate decarbonized electricity systems in the year 2045, optimizing technology operations and investments to deliver year-round reliable electricity at least cost. We explore outcomes of interest including EGS deployments and resulting electricity cost reductions across a range of possible scenarios, assessing the relative impact of EGS flexibility on these metrics. We further identify deployment trends and sources of value for both flexible and inflexible EGS.

Methods

Our study, summarized briefly in this research digest, uses numerical simulations and optimization modeling to accurately represent the operation of flexible and inflexible EGS resources in future electricity systems. We use ResFrac, a numerical reservoir simulation software, to simulate operations of engineered geothermal reservoirs over periods of up to 30 years and under a variety of subsurface conditions and operational profiles. These simulations are used to design and calibrate a novel system of linear constraints that enables optimization of EGS power plant component sizing and hourly operations while accurately representing the dynamic relationship between reservoir pressure and well flow rates. Our model formulation also captures the strong dependence of geothermal power output on local ambient air temperature, a first in macro-energy systems modeling.

The flexible EGS optimization framework described above is incorporated as a new technology module into GenX, an open-source electricity systems optimization model that determines an optimal set of investment and operational decisions to minimize the cost of meeting electricity demand over the course of one or multiple planning years, subject to policy and operational constraints. We use GenX to model least-cost decarbonized electricity systems in the western United States in the year 2045, exploring a range of scenarios that vary the cost and performance of EGS and competing technologies. We use temperature-at-depth maps and geothermal project cost models to develop a set of supply curves that represent EGS cost and availability across the Western Interconnection, including estimated transmission interconnection costs. This spatially granular representation of EGS resources, combined with hourly modeling of operations at the plant and system levels and explicit representation of inter-regional transmission constraints between eleven modeled zones (see Fig. 1), allows us to accurately assess the scale and impact of EGS deployments under a given set of technology development assumptions.

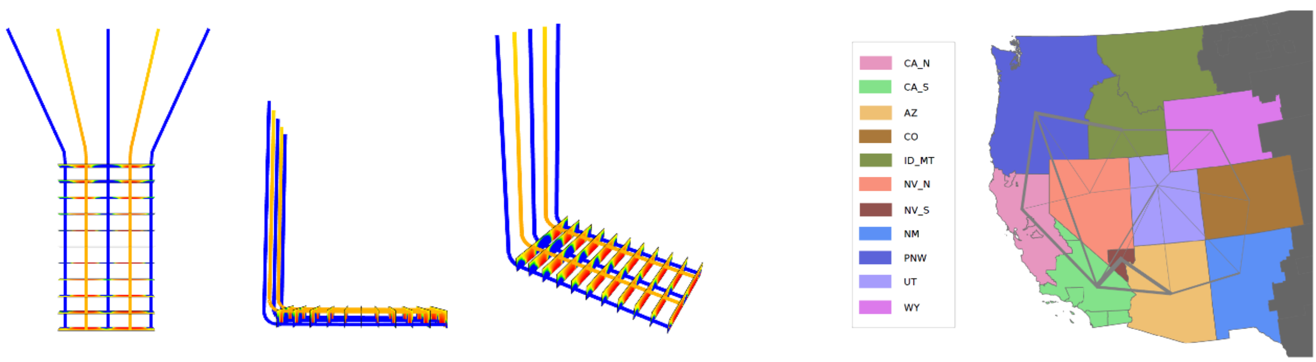

Figure 1: (left) multiple views of the at-scale EGS reservoir design simulated in this work, featuring alternating injection and production wells connected by an engineered fracture network, and (right) a map depicting the network topology used to represent the US Western Interconnection in GenX.

Findings

EGS could play a significant role in decarbonized electricity systems even without major reductions in present-day component costs. If the reservoir design simulated in this paper (or a design of similar performance) can be successfully engineered at scale, flexible EGS could see significant deployment even without reductions in wellfield or surface plant costs from the current state-of-the-art. In model scenarios featuring 'Baseline' geothermal drilling we observe 25-74 GW of flexible EGS deployed in the US Western Interconnection, with variability depending primarily on the cost of competing clean energy technologies. By contrast, current total geothermal capacity in the United States is roughly 4 GW.

Reductions in drilling costs are a pathway to much greater EGS deployment. In scenarios with 'Advanced' drilling, which unlocks high-temperature geothermal resources at depths of up to 6.5 km, EGS deployment ranges from 52-115 GW across the Western Interconnection. For comparison, the current installed capacity of the U.S. nuclear power fleet is 101 GW. In these scenarios EGS alone meets up to 45% of total annual electricity demand in the region. With advanced drilling the economically viable EGS resource base far outstrips system needs, and local resource availability is effectively removed as a constraint on EGS development in the western US. While not modeled here, these improvements in drilling cost are also likely to unlock EGS potential across other areas of the United States (and globally).

The ability to operate flexibly greatly enhances the value and deployment potential of EGS power in all cases. For scenarios with identical technology performance and costs, EGS sees significantly greater deployment when it is allowed to operate flexibly. At baseline drilling costs inflexible EGS achieves 0-28 GW of deployment by 2045, a significant reduction from the 25-74 GW observed for flexible EGS. Reductions in overall electricity system cost due to EGS deployment are also much larger when flexibility is enabled, with improvements of up to 10 percentage points. While flexibility does nothing to reduce the levelized cost of geothermal energy, it significantly improves the *value* of this energy by shifting it in time to high value periods.

Flexible EGS can reduce or eliminate the need for other firm generation and storage resources. When EGS operates as an inflexible baseload generator, flexible firm resources and energy storage are often still required to balance variable wind and solar generation. These resources tend to be expensive but are needed to provide power temporarily during periods of unusually high demand and/or low wind and solar generation. Flexibility significantly enhances the value of EGS power by enabling it to fill the roles of these resources, shifting its generation to times of increased system need when storage and other firm generators would typically be called upon. Flexible EGS is thus able to displace installed capacity of the most expensive competing resources, reducing system costs more effectively than its inflexible counterpart.

Flexible EGS shifts energy over periods of days to months at high efficiency. Through in-reservoir energy storage, which is accomplished by accumulating and discharging water from a confined geothermal reservoir, flexible EGS can rapidly shift its generation on hourly to weekly timescales. Seasonal energy shifting can also be accomplished by reducing or increasing average well flow rates over much longer periods, so long as the total annual flow is kept constant. We find that this energy shifting, effectively a form of long-duration energy storage, can achieve round-trip efficiencies of 81-98%. This efficiency is comparable to that of lithium-ion batteries and greater than all competing long-duration electricity storage technologies.

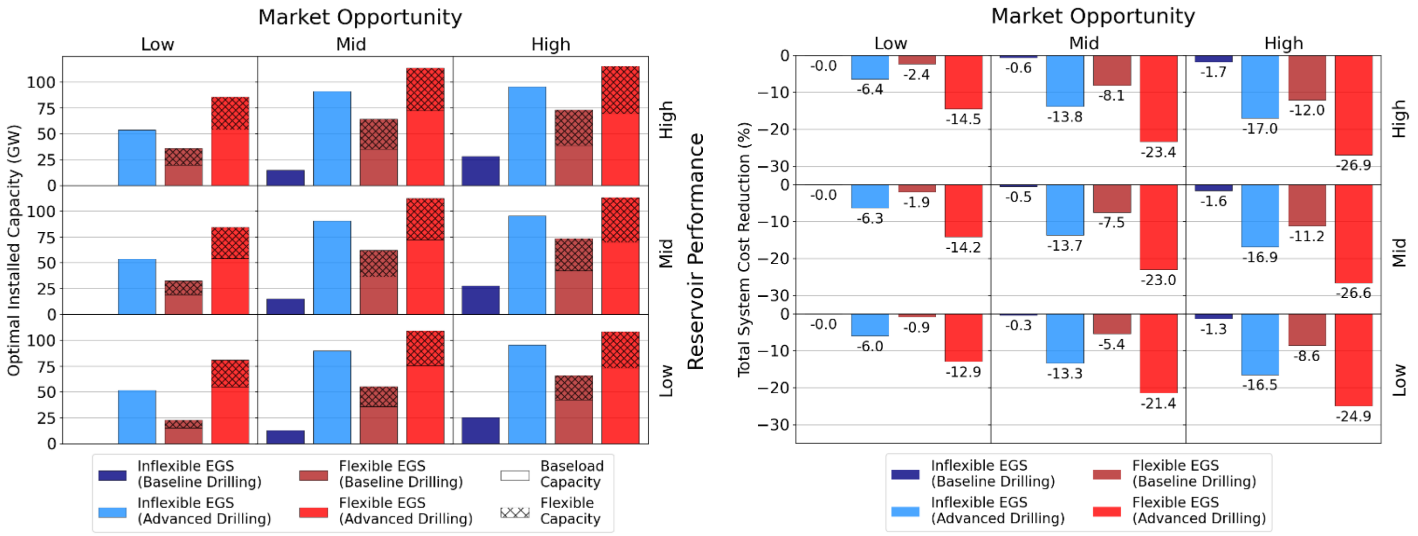

Figure 2: optimal EGS deployments (left) and reductions in total system cost as a result of EGS deployment (right) under a range of cost, performance, and flexibility scenarios. EGS 'Market Opportunity' cases vary the cost of competing energy technologies to create market conditions that are more or less favorable to EGS development, and 'Reservoir Performance' cases vary the properties of the engineered reservoir.

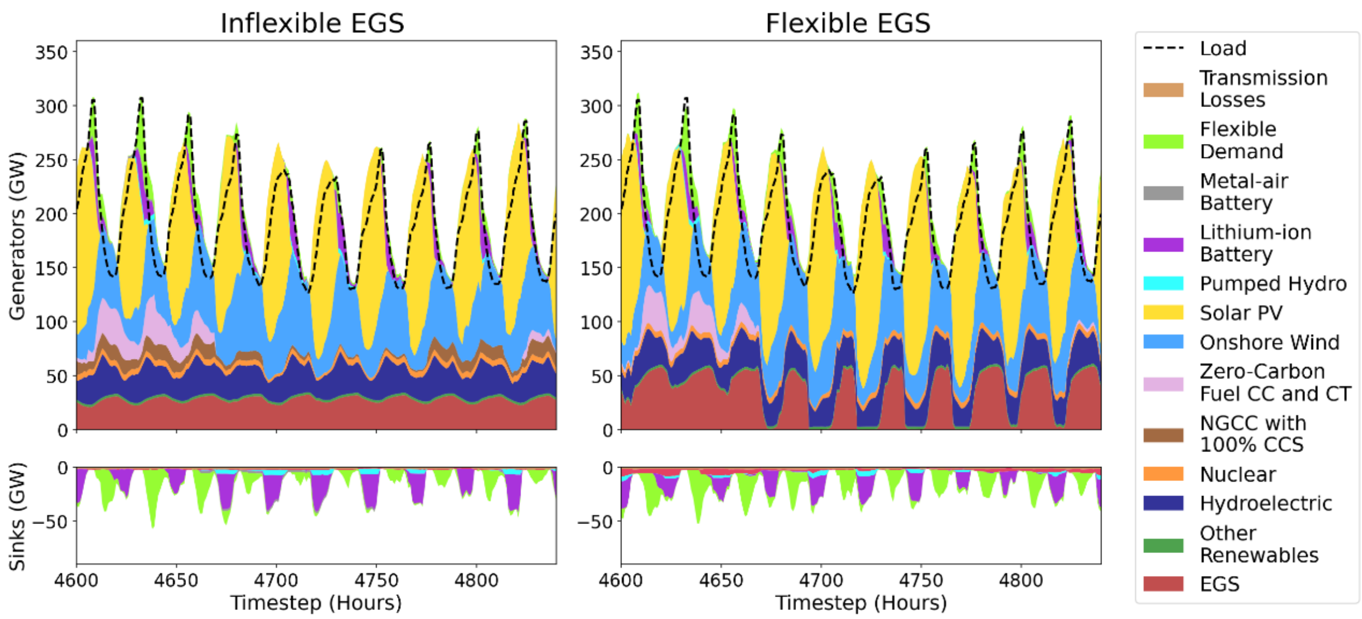

Figure 3: operational snapshots of otherwise identical systems in which EGS is restricted to operating inflexibly (left) or allowed to operate flexibly (right). Flexible EGS complements solar power by shifting generation primarily to nighttime periods.

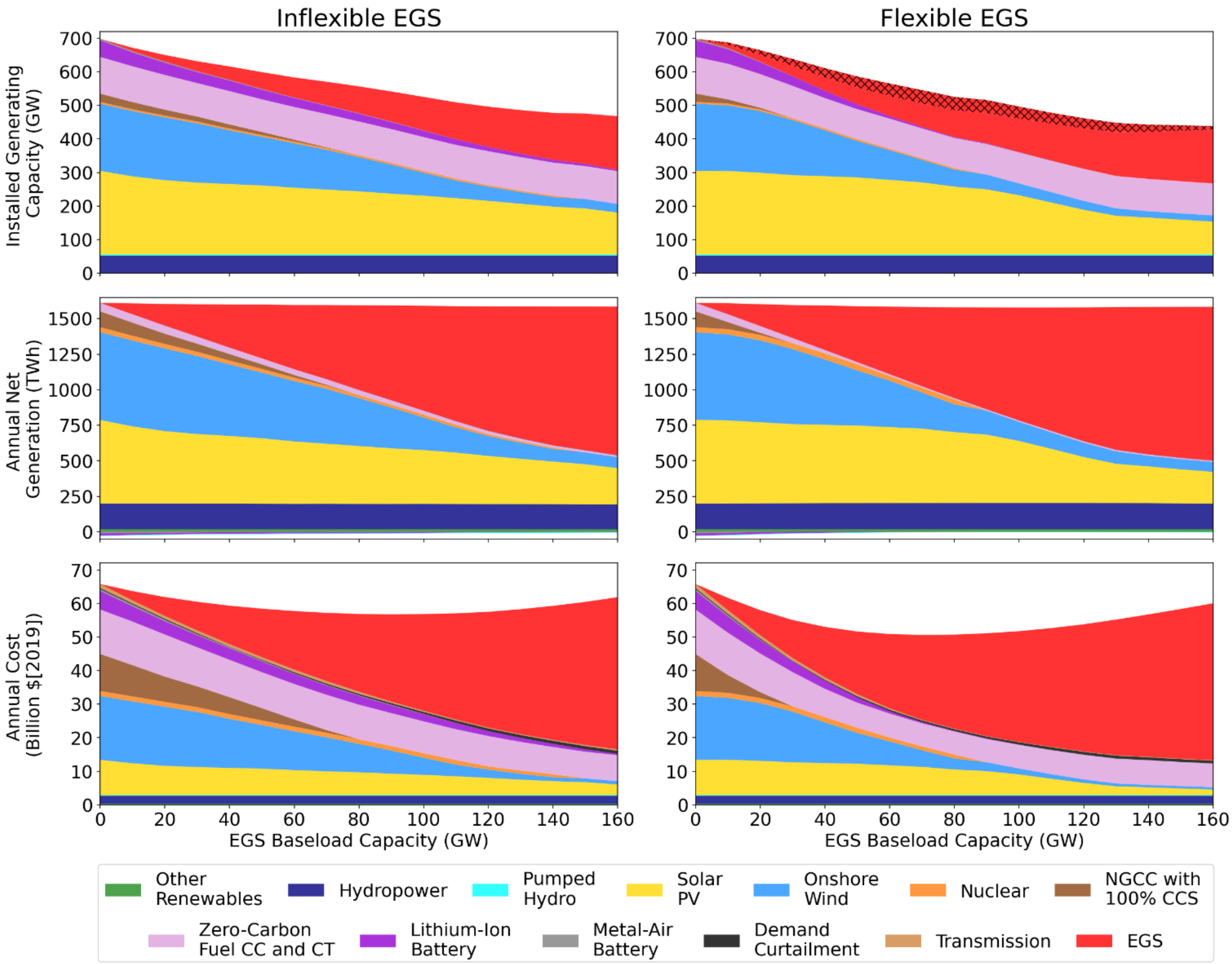

Figure 4: optimal system configurations and costs as functions of installed EGS capacity, for both inflexible (left) and flexible (right) operating strategies. Flexible EGS displaces competing firm generation and storage resources much more rapidly.

About the authors

Wilson Ricks is a PhD candidate in the Department of Mechanical and Aerospace Engineering at Princeton University. @wilson_ricks

Katharine Voller is a Geothermal Reservoir Engineer at Fervo Energy. @vollerkate

Jack H. Norbeck is the co-founder and Chief Technology Officer at Fervo Energy. @jacknorbeck

Jesse D. Jenkins is an assistant professor at Princeton University with joint appointments in the Department of Mechanical and Aerospace Engineering and Andlinger Center for Energy and the Environment. @jessejenkins

Funding: This work was supported by the US Department of Energy Office of Science SBIR program under Award No. DE-SC0020823, and by Princeton University’s Low-Carbon Technology Consortium, which is funded by gifts from Google, GE, and ClearPath.