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Zero-carbon Energy Systems Research and Optimization Laboratory

RESEARCH DIGEST

Pathways to national-scale adoption of enhanced geothermal power through experience-driven cost reductions

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Enhanced geothermal systems (EGS) are one of a small number of emerging energy technologies with the potential to deliver firm carbon-free electricity at large scale, but are often excluded from macro-scale decarbonization studies due to uncertainties regarding their cost and resource potential. Here we combine empirically-grounded near-term EGS cost estimates with an experience curves framework, by which costs fall as a function of cumulative deployment, to model EGS deployment pathways and impacts on the United States electricity sector from the present day through 2050. We find that by initially exploiting limited high-quality geothermal resources in the western US, EGS can achieve early commercialization and experience-based cost reductions that enable it to supply up to a fifth of total US electricity generation by 2050 and substantially reduce the cost of decarbonization nationwide. Higher-than-expected initial EGS costs could inhibit early growth and constrain the technology's long-run potential, though supportive policies can counteract these effects.

Clean, firm electricity resources — technologies available to generate power whenever needed, for as long as required — have been identified as a critical component of cost-effective carbon-free electricity systems. "Enhanced geothermal systems" (EGS), which employ hydraulic stimulation to create artificial geothermal reservoirs in geographies unsuitable for conventional geothermal power generation, are one of a small handful of emerging technologies with the potential to provide clean firm power at the pace and scale needed to support a rapid transition to a net-zero carbon grid. However, EGS has generally been excluded from macro-scale decarbonization studies in the past due to deep uncertainties regarding its cost, performance, and geographic availability.

In our new working paper "Pathways to national-scale adoption of enhanced geothermal power through experience-driven cost reductions," which is currently undergoing peer review, we utilize newly available field data from the first large-scale EGS demonstration projects conducted in the United States to develop empirically grounded near-term cost projections for the technology. We then use these costs as inputs to an electricity system capacity expansion model to assess the potential role of EGS in decarbonization of the US electricity sector over the coming decades. We adopt an 'experience curves' framework to model the evolution of costs for EGS and other emerging technologies over time, assuming that – like wind, solar, and batteries before them – the cost of each of these technologies will fall with increasing deployment. Incorporation of this dynamic relationship between cost and deployment allows us to explore the conditions under which EGS (or its clean firm competitors) could achieve 'commercial liftoff' through a virtuous cycle of increasing deployment and falling costs, and the long-run implications for US electricity sector decarbonization if it is able to do so.

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

Methods

Our study, summarized briefly in this research digest, uses cost and performance parameters reported by recent public and private EGS demonstration projects in the United States to construct a near-term cost baseline for the technology. This baseline is intended to estimate the cost of early commercial EGS projects deployed after 2030, assuming approximately 500 MW of deployment before that date based on currently contracted capacity. We combine this cost baseline with temperature-at-depth datasets for the contiguous US and an assessment of 'near-field' EGS potential in areas close to known conventional geothermal reservoirs in the Western US to build national supply curves projecting EGS cost and developable capacity at over 80,000 individual candidate project areas across the country. We furthermore calculate regional electric grid interconnection costs for each candidate site, and use hourly historical weather data to represent the dependence of EGS power plant efficiency on local ambient air temperature.

We use these EGS supply curves as inputs to GenX, an open-source electricity system capacity expansion model that optimizes the deployment and operation of electricity generation, transmission, and storage technologies to minimize the cost of delivered power in a chosen future year. Because GenX reflects the same incentives faced by electricity system central planners and competitive electricity market participants, it is well-suited to assessing the potential for EGS to achieve commercial uptake under different possible scenarios. In the present study we run GenX over multiple sequential planning periods from the present day through 2050 while exploring a range possible future policy and technology development scenarios. We represent the unique operational capabilities of EGS power plants, including flexible operation and long-duration energy storage, using a flexible EGS optimization module developed for GenX in prior work.

Unlike most similar studies, which generally use fixed input cost assumptions for all technologies, we model the cost of nascent clean firm technologies dynamically. For EGS and two similarly early-stage clean firm competitors – nuclear small modular reactors (SMRs) and Allam cycle gas plants with 100% carbon capture and storage (CCS) – we calculate costs in each GenX planning period as a function of initial costs *and* cumulative deployment up to that point. This 'experience curves' framework reflects the well-documented phenomenon that the cost of emerging technologies tends to fall predictably with increasing deployment as a result of 'learning-by-doing,' as manufacturing processes benefit from economies of scale, increased worker experience and expertise, and iteratively improved designs. Representing emerging technologies in this way means that their modeled costs can fall substantially if they can be deployed at scale, but also that these costs will remain high indefinitely if initial commercial deployments cannot be achieved. We furthermore represent limits on the pace at which supply chains and labor forces for these technologies can be scaled up by imposing a 50% cap on year-over-year growth in new capacity additions.

Findings

Near-term EGS costs are likely high in most of the United States, but high-quality resources in the Western US could support commercially competitive development. Within reasonable uncertainty bounds, we find that near-term EGS costs will likely be too high to support commercial competition with established electricity resources in most areas of the country (see Figure 1). Baseline unsubsidized costs in Texas and the Eastern US are significantly higher than current wholesale electricity prices, and are comparable to those of the recent Vogtle nuclear project. However, costs are significantly lower in the Western US, and particularly at 'near-field' sites where the presence of nearby natural geothermal reservoirs leads to abnormally high temperatures at shallow depths. Though these resources are limited in their total developable capacity, they offer a path to much lower-cost near-term EGS development. Outside of these near-field sites, near-term post-subsidy cost estimates for EGS are generally higher than those for competing clean firm nuclear SMR and Allam cycle gas technologies.

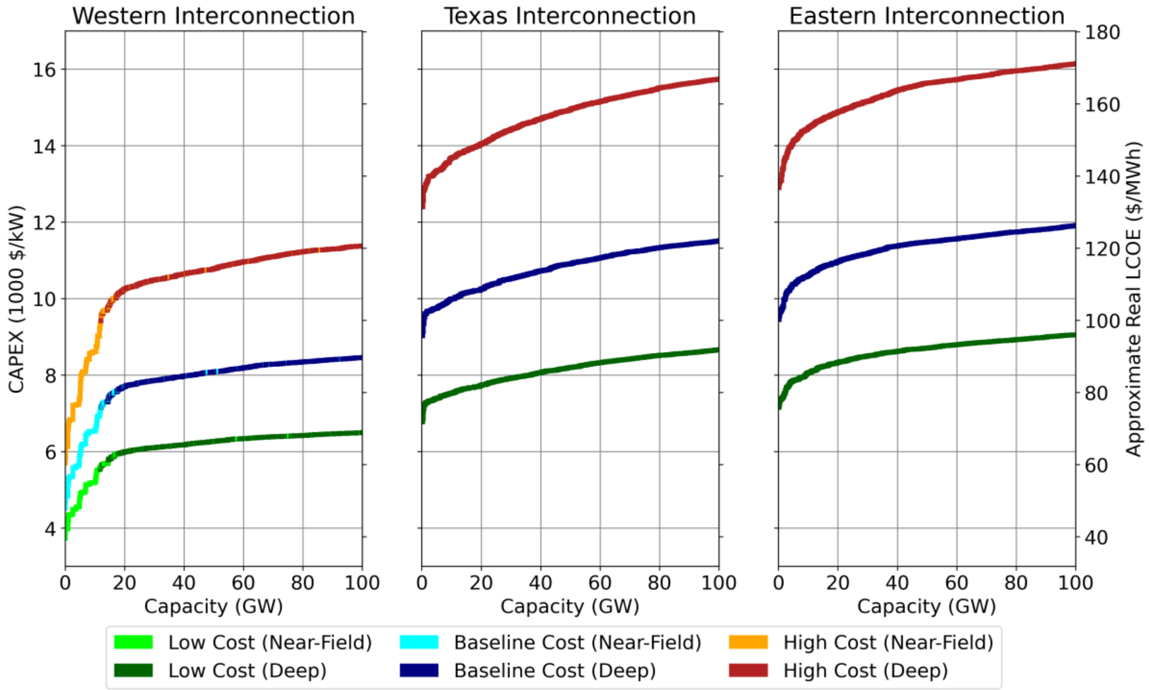

Figure 1: Near-term EGS supply curves showing unsubsidized CAPEX (total capital cost per kW-electric, left axis) and LCOE (levelized cost of electricity, right axis) as functions of total developable capacity for the three major electric grids serving the contiguous US. 'Low' and 'High' cost cases vary the baseline cost for the subsurface portion of an EGS power plant by -33% and +50%, respectively, to reflect remaining uncertainties. 'Near-field' EGS resources located close to natural geothermal reservoirs are highlighted.

EGS could achieve very large-scale deployment through learning-based cost reductions. Despite relatively high near-term costs, we find that EGS under baseline assumptions could achieve commercially competitive deployment in the early 2030s. These early developments in turn drive down costs, leading to greater deployment and further cost reductions (Figure 2, upper and middle panels). We find a long-run potential for 250 GW of EGS nationwide by 2050 at baseline costs and under current policies, with potential increasing to 750 GW under a net-zero carbon policy pathway. In this latter case installed EGS capacity in 2050 is more than seven times that of today's US nuclear fleet, and the technology provides roughly 1/5 of total national electricity generation. However, a combination of high near-term EGS costs and a lack of further policy support could stunt early learning and growth, limiting the technology's long-run relevance.

Successfully-scaled EGS brings wide-ranging benefits. By operating as a flexible, firm resource and shifting its generation to times when power is most valuable, EGS can act as a cost-effective compliment to cheap but variable wind and solar power. We find that the cost of achieving a net-zero carbon electricity sector is significantly reduced when EGS is available at scale and benefits from learning-by-doing (Figure 2, lower panel). In a zero-carbon grid, each GW of EGS can provide the equivalent system value of more than 3 GW of wind, solar, and storage.

EGS has the potential to become a nationally relevant electricity resource. If EGS costs follow a conventional learning trajectory, the technology could become a major source of electricity generation across the entire US, not just in the resource-rich western states as has been previously assumed. For example, in a case with baseline initial EGS costs and a net-zero policy trajectory (with a \$300/tCO_2 carbon price in 2050), more EGS capacity is installed in the Eastern US than in the West (Figure 3). While EGS power is still more costly in regions with lower-quality resources, learning-based cost reductions make the overall difference in cost between high-quality and low-quality resources smaller.

Long-run deployment outcomes are sensitive to uncertainties in the availability and learning rate of EGS, but less so to uncertainties in the cost of other technologies. If the 'learning rate' for EGS is reduced to half of our assumed value, then long-run deployment potential is reduced by more than half. Similar long-run outcomes occur if EGS power plants are not able to be operated flexibly, or if high-quality near-field resources cannot be successfully developed early on. Conversely, variations in the costs of wind, solar, batteries, hydrogen electrolysis, and competing clean firm technologies have almost no impact on EGS potential. The price of natural gas, which affects the cost of existing fossil-based firm power, does have a noticeable impact on the relative value of EGS in the near term.

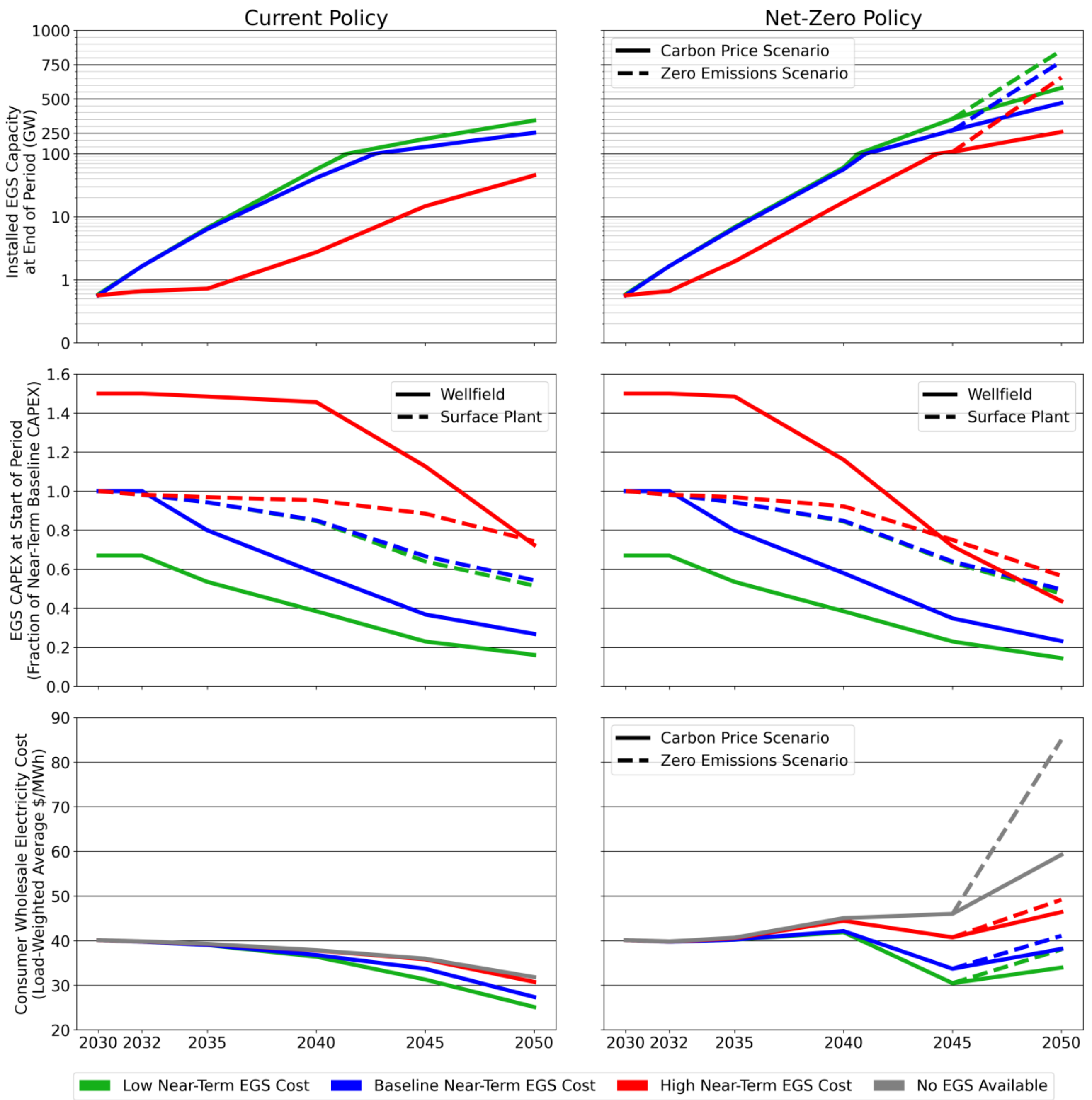

Figure 2: Trajectories of enhanced geothermal systems deployment, capital costs, and consumer electricity costs for current policy and net-zero policy scenarios and for three different EGS cost cases. For the net-zero policy scenario we include two alternative 2050 cases, one with a requirement for zero direct emissions and one that allows emissions subject to a $300/tCO$_2$ carbon price. EGS capacities in the upper panel are plotted on a logarithmic scale for values below 100 GW and a linear scale thereafter.

Learning dynamics could give EGS a long-run competitive edge. We find that EGS out-competes alternative clean firm technologies in scenarios where any significant amount of clean firm power is deployed, for two reasons. First, although EGS has higher *average* initial costs than nuclear SMR or Allam cycle gas technologies, the availability of high-quality near-field resources in the Western US allows it to more consistently achieve initial deployment and benefit from learning effects. Second, a higher assumed learning rate for EGS (resulting from its more modular nature) allows it to come down in cost more rapidly in scenarios where multiple competing clean firm technologies do achieve initial deployment, allowing it to eventually out-compete clean firm alternatives even in regions with lower-quality geothermal resources.

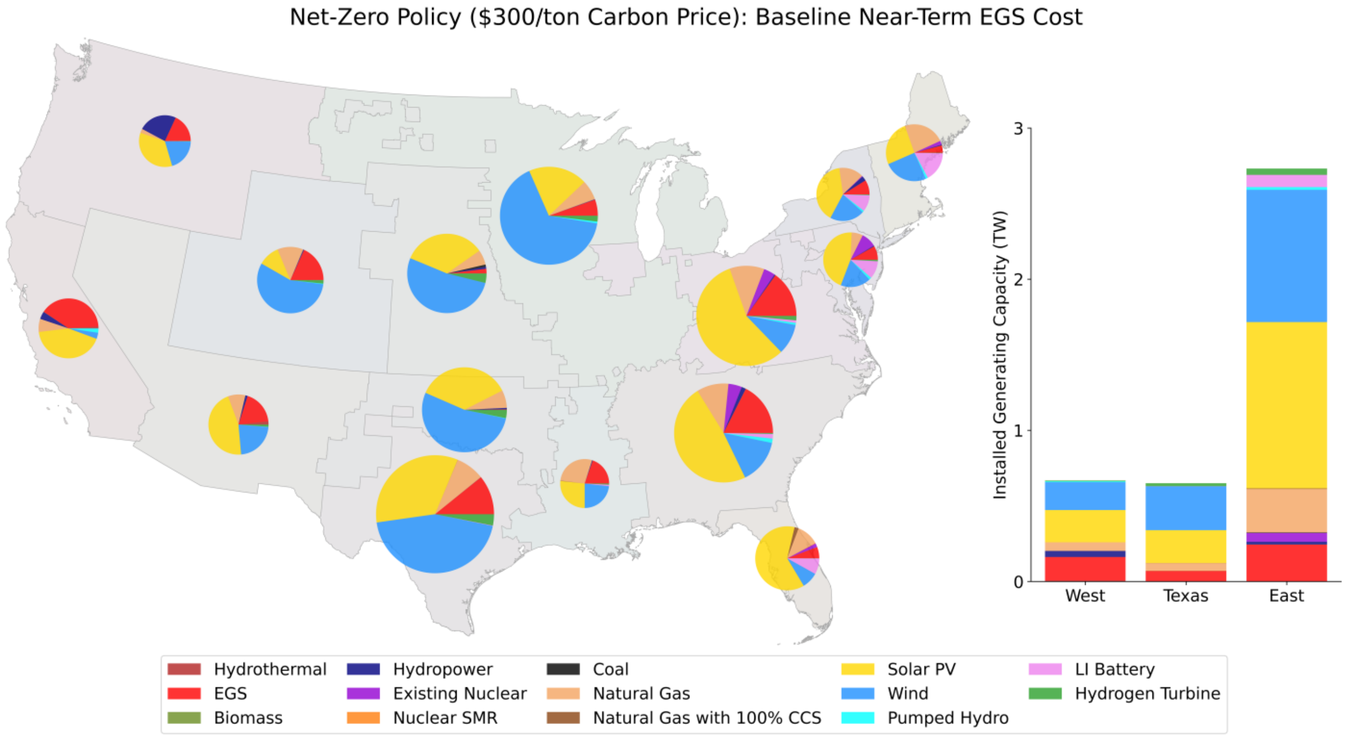

Figure 3: Final 2050 generating capacity mixes by model zone (left) and major regional grid (right) for a scenario with baseline initial EGS costs and a net-zero carbon policy trajectory culminating in a $300/tCO$_2$ carbon price. EGS makes up a larger share of capacity in western states where resource quality is highest, but total deployment is higher in the eastern half of the country.

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