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RESEARCH DIGEST

The Value of In-Reservoir Energy Storage for Flexible Dispatch of Geothermal Power

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Geothermal systems making use of advanced drilling and well stimulation techniques have the potential to provide tens to hundreds of gigawatts of clean electricity generation in the United States by 2050. With near-zero variable costs, geothermal plants have traditionally been envisioned as providing "baseload" power, generating at their maximum rated output at all times. However, as variable renewable energy sources (VREs) see greater deployment in energy markets, baseload power is becoming increasingly less competitive relative to flexible, dispatchable generation and energy storage. Herein we conduct an analysis of the potential for future geothermal plants to take advantage of the natural properties of confined, engineered geothermal reservoirs to store energy in the form of accumulated, pressurized geofluid and provide flexible load-following generation. We develop a linear optimization model based on multi-physics reservoir simulations that captures the transient pressure and flow behaviors within a confined, engineered geothermal reservoir. We then optimize the investment decisions and hourly operations of a power plant exploiting such a reservoir against a set of historical and modeled future electricity price series. ***We find that operational flexibility and in-reservoir energy storage can significantly enhance the value of geothermal plants in markets with high variable renewable energy penetration****, with energy value improvements of up to 60% relative to conventional baseload plants operating under identical conditions. Across a range of realistic subsurface and operational conditions, our modeling demonstrates that confined, engineered geothermal reservoirs can provide large and effectively free energy storage capacity, with round-trip storage efficiencies comparable to those of leading grid-scale energy storage technologies. Optimized operational strategies indicate that flexible geothermal plants can provide both short- and long-duration energy storage, prioritizing output during periods of high electricity prices. Sensitivity analysis assesses the variation in outcomes across a range of subsurface conditions and cost 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 resource use 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.

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

Still, the economic outlook for geothermal power is unclear in a rapidly evolving electricity market. In addition to their large upfront capital cost, geothermal plants typically operate as "baseload" power plants, generating at their maximum rated capacity at all times. This has historically been a viable operating strategy, but shifting electricity market conditions driven by increased VRE deployment are eroding the economic value of baseload plants relative to more flexible alternatives. From an economic perspective, fast-ramping generators with low fixed costs, which can save money by conserving fuel and only generating when electricity prices are high, as well as energy storage devices that shift generation to valuable periods, can have a competitive advantage over baseload generators in a grid with significant VRE penetration.

In this study we evaluate the potential for next-generation geothermal plants to adapt to this shifting market paradigm by exploiting *In-Reservoir Energy Storage* (IRES), wherein geofluid is stored under pressure in a confined EGS reservoir and used to shift the output of a geothermal plant from one time to another. This technique has been demonstrated during EGS field testing in the past, and the present work represents the first ever analysis of its value for geothermal plants in future electricity systems.

Methods

Our peer-reviewed publication in the journal *Applied Energy*, summarized briefly in this research digest, uses numerical simulations and optimization modeling to assess the economic value of IRES for first-of-a-kind EGS plants under various electricity market scenarios and across a range of possible subsurface conditions. We further quantify the energy storage capabilities of EGS reservoirs and identify optimal operational strategies for plants with IRES.

We employ a bottom-up approach to modeling the performance of IRES, using multi-physics numerical reservoir simulations to develop a linear optimization model, which is in turn used to evaluate the economics of flexible operations. We use ResFrac, a commercial reservoir simulator, to simulate the pressure and flow behaviours within a flexibly operated EGS reservoir. We next develop and calibrate a linear optimization model capable of replicating simulation results and optimizing the operations and investments of a single flexible geothermal plant against a fixed electricity price series. The model optimizes geofluid injection and production rates at hourly intervals and oversizes the plant's generator, injection pump, and grid interconnection as appropriate to maximize profit. We compare the average energy value of a geothermal plant with IRES to that of a conventional plant across 16 historical and modelled future electricity price series and 16 plant performance sensitivity cases.

Findings

In-Reservoir Energy Storage (IRES) significantly enhances the value of geothermal power plants across a wide range of scenarios. Under baseline assumptions, and taking into account the additional capital cost required to increase the size of surface facilities, IRES increased the value of energy produced by geothermal plants in current electricity markets in the western US by 6-44%. For modelled price series reflecting a geospatially-abstracted national grid in the year 2030, the value of energy increased 3-26%.

Optimal operations with IRES enable geothermal plants to shift their generation to times when its value is maximized. Optimal operational profiles for plants with IRES indicate that geofluid production (and therefore power output) are reduced during times of low electricity pricing. Injection rates are often boosted simultaneously, taking advantage of reduced pumping power costs. Reservoir pressure accumulated during these periods is used to drive greater geofluid production during times when electricity prices are high, thereby maximizing revenues. We observe 'charging' and 'discharging' cycles hundreds of hours long.

Shifting power production with IRES delivers much greater value than curtailing geothermal output. Many existing geothermal plants are capable of operating flexibly by curtailing generation (shutting off). While they cannot recover lost generation, this strategy can help avoid economic losses during periods of negative electricity pricing. We find that IRES significantly outperforms a curtailment-only strategy in all cases, and delivers considerable value even in markets that do not feature negative pricing.

IRES is more valuable in electricity markets with high VRE penetration. We observe the greatest energy value improvements from IRES in markets with large amounts of wind and solar power. Conversely, markets with few VREs and relatively stable pricing show little value IRES. In modelled future scenarios where VREs make up 50% of installed generating capacity, geothermal plants with IRES are ~25% more valuable than their baseload counterparts.

Geothermal power plant surface facilities should be increased in size to take full advantage of IRES. Though binary-cycle geothermal power plants can accommodate marginally higher flow rates than their design point, we find that surface plants and other equipment are often increased in size to take full advantage of IRES and maximize value in certain hours. We observe flexible plant oversizing up to 161% of the capacity of a baseload plant operating at the same wellfield, as well as interconnection oversizing up to 93% and injection pump oversizing up to 636% of their respective baseload capacities.

Benefits of IRES are robust across a wide range of cost and subsurface performance parameters. We investigate the effect of variations in surface plant capital cost and O&M costs, maximum allowable reservoir pressure, rock matrix permeability, reservoir fracture conductivity, and number of fractures on the value of IRES. Across parametric variations, we find that improvements in the value of energy generation are generally within a few percent of their base case values. However, we do find that rock matrix permeabilities multiple orders of magnitude below our base-case value lead to notably reduced benefits from IRES. This finding suggests that subsurface conditions will need to be well-characterized in order to accurately assess a candidate site's flexible potential.

IRES enables geothermal plants to provide high-efficiency, long-duration energy storage at little to no additional cost. Due to non-constant electricity consumption by injection pumps resulting from changes in injection rate and reservoir pressure, we find that IRES round-trip efficiency is variable and can be optimized in response to specific market conditions. Typical RTEs observed in our study are in excess of 80%, roughly comparable to those of lithium-ion batteries and pumped hydro storage. In a series of controlled tests, we find that unmodified EGS reservoirs can store energy at these efficiencies over hundreds of hours, easily qualifying as "long-duration" or multi-day energy storage. Notably, this energy storage capacity becomes available at no additional cost with the construction of an EGS reservoir.

Overall, this study demonstrates that next-generation geothermal has the potential to offer significantly greater flexibility than has been previously assumed. By exploiting IRES, EGS plants can offer both clean, firm generation and high-efficiency long-duration energy storage. These capabilities can significantly enhance the value of geothermal plants in electricity systems with high wind and solar penetration. Though the modeling assumptions made in this study must be validated through extensive field testing, our results suggest that successful development of IRES could significantly improve the economics of next-generation geothermal plants.

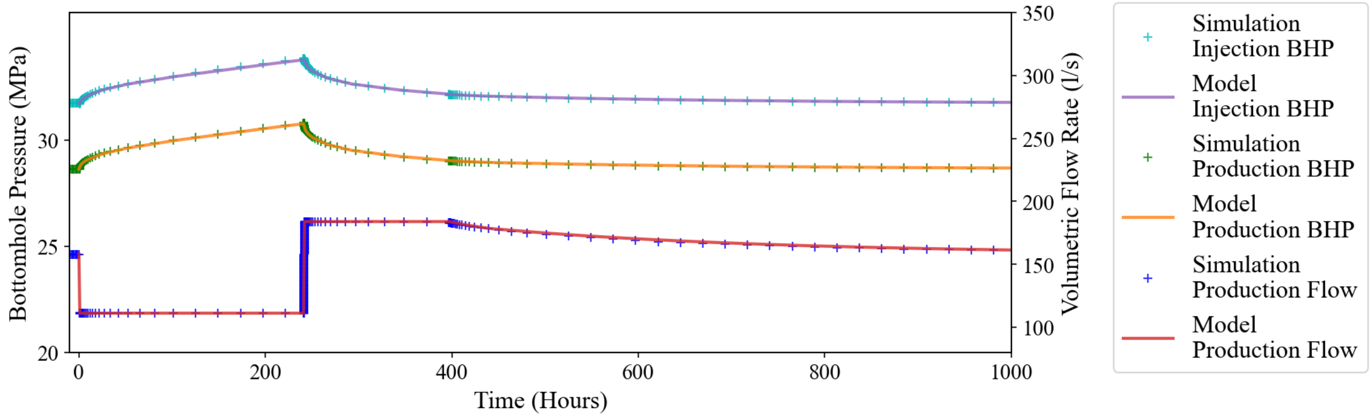

Figure: Reproduction of numerical reservoir simulation results in the linear optimization model. Both the model and the simulation execute a 240-hour 'charging cycle' where production flow rate is reduced below its steady-state value and injection rate is kept constant. This imbalance causes geofluid to accumulate in the reservoir and pressure to rise at the injection and production well bottomholes. After 240 hours the production well is opened up, and the accumulated pressure drives increased flow until the system re-equilibrates.

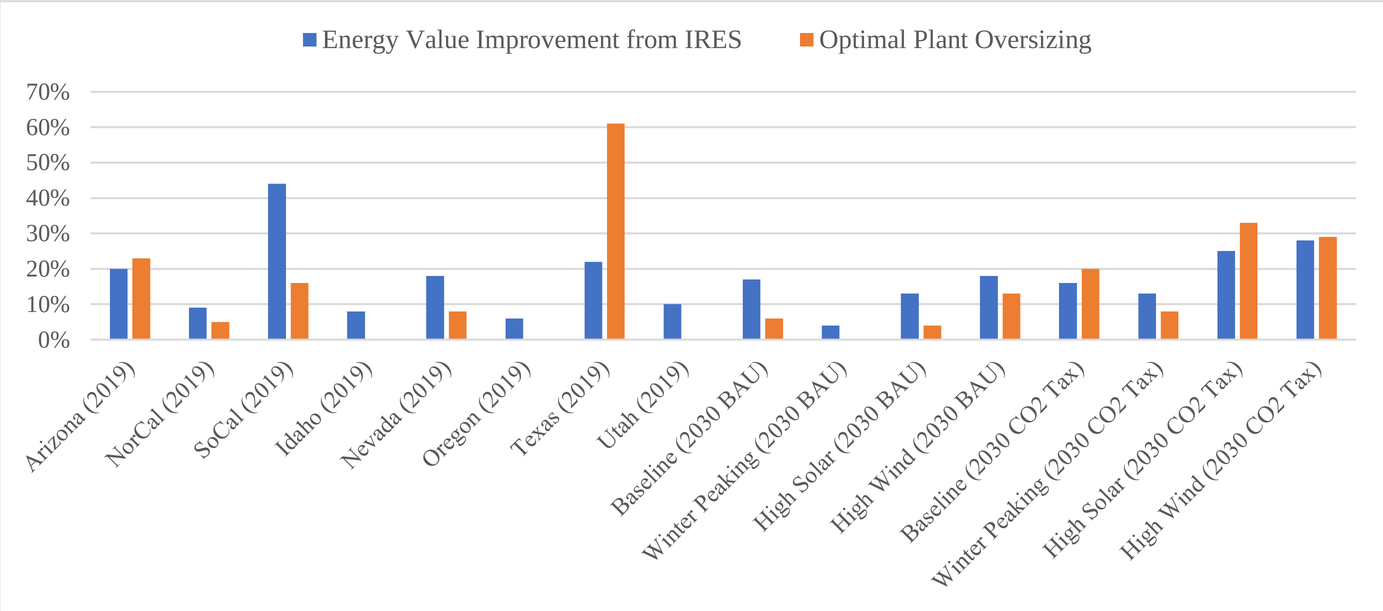

Figure: Energy value and optimal investment results for eight historical electricity price series and eight modeled future price series in the base case model. Energy value for a baseload plant is equivalent to the average of hourly electricity prices over a year. Energy value improvements from IRES are given in proportion to the baseload energy value for the same price series, and include the added costs of surface facilities oversizing. Optimal plant oversizing results are given in proportion to the capacity of a baseload surface plant operating on the same wellfield.

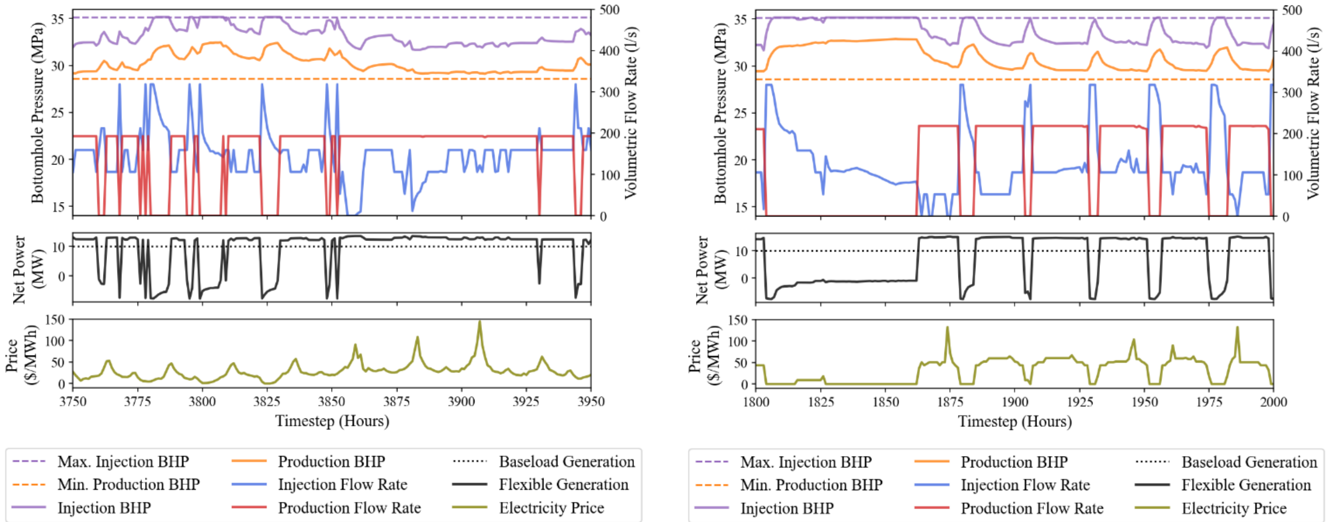

Figure: Optimal flexible operational strategies during selected 200-hour periods for the southern California historical price series (left) and a modeled future price series with a carbon tax and high wind penetration (right) under baseline assumptions. The upper section of each plot gives injection and production well bottomhole pressures and flow rates at hourly intervals. The middle section gives net generation under both baseload and flexible operating strategies, and the lower section gives hourly electricity prices.

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