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The Potential to Improve the Value of U.S. Geothermal Electricity Generation Through Flexible Operations

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Geothermal power plants have typically been operated as baseload plants. The recent expansion of wind and solar power generation creates a potential opportunity to increase the value of geothermal generation through flexible operations. In recent years, California's wholesale electricity markets have exhibited frequent, short-term periods of negative pricing, indicating that additional flexibility would be valued in the market. Here, we examine local nodal hourly price records at all geothermal plants located in the western United States. We describe how the frequency and temporal characteristics of negative pricing episodes have changed over recent years. Based on these price series, we calculate the value of multiple strategies of flexible operations. Additionally, we use the estimates of future prices, developed through a capacity-expansion model and a dispatch model, to explore how the value of such flexible operations might change along with further penetration of variable renewable power sources. Based on the historical pricing records, we find that simple curtailment of operations during negative pricing episodes could increase the average energy value by 1–2 \$/MWh and that allowing for increased production during limited high-priced hours, in addition to curtailment during negative priced hours, could potentially double the increase in value (up to 4 \$/MWh). The forward-looking simulations indicate reduced values of flexibility from geothermal power despite higher penetrations of variable renewable energy. This result highlights the possibility that increasing flexibility options throughout the system may counteract the influence of increased variable renewable energy deployment. [DOI: 10.1115/1.4048981]

Keywords: alternative energy sources, geothermal energy

1 Introduction

In most cases, geothermal power plants have historically been operated as baseload resources; in other words, they produce constant power at all times. However, the recent increases in variable generation sources, such as wind and solar, prompt the question: Could geothermal generation provide greater value to electricity markets by employing strategies that allow more flexible operations? Flexible operation is defined here as the ability to reduce output for periods of a few hours and, ideally, enhance the output during certain other hours. In this paper, we present an assessment of the value of flexibility across U.S. geothermal plants. We do not investigate the benefits of providing ancillary services but instead, focus only on the temporal changes to the energy value. We aim to provide results that are useful for early-stage guidance in the assessment of new strategies and technologies that allow for flexible operations.

This paper focuses on the existing U.S. geothermal electric power plant fleet and thus some context is useful. The U.S. generates more electricity from geothermal sources than any other country [1]. In 2018, the U.S. generated ~17 TWh of electricity from geothermal sources, which is about one-fourth of the amount of electricity generated from utility-scale solar power in the same year [2]. Within the U.S. lower 48 states all existing plants are located in western states, with most of the capacity located in California and Nevada.

In the U.S., the baseload nature of geothermal power has provided advantages but also challenges, as the periodic curtailment of geothermal power has occurred since the 1980s [3–6], prior even to the rise of wind and solar power as major sources of electricity. These early curtailments were driven by variation in demand and the availability of low-cost generation options, especially during years of abundant hydropower availability.

Beyond curtailment issues, increased variable generation impacts wholesale electricity pricing patterns and has led to an increased frequency of negative pricing events during times of high variable generation combined with relatively low electricity demand [7], for example during sunny spring days in California. Negative pricing episodes associated with increased variable generation are seen elsewhere in the U.S. as well as in Europe [8]. Multiple research efforts characterize the need for added flexibility with increasing renewable penetration [9–15].

While geothermal plants are somewhat shielded from hourly price fluctuations through long-term contracts, the value of geothermal generation could potentially be increased given the ability to respond to price fluctuations. Increasing flexibility has been identified as an important component toward increasing geothermal development in California [16,17]. Looking forward, current California law requires an increasingly carbon-free generation portfolio, with 60% of generation derived from renewable sources by 2030 and 100% carbon-free generation by 2045. While this provides an opportunity for low emitting geothermal generation, it also highlights the potential value of addressing flexibility, given the state's likely increasing reliance on solar and wind power.

Some geothermal plants have already instituted strategies to deliver electricity in a more flexible manner. In these cases, there

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was a tradeoff made between the added costs needed to prepare a plant to operate in a flexible manner versus the added value derived from flexibility. Urbank and Jorgensen [18] describe the systems modifications required at The Geysers to accommodate flexible generation: these include upgraded control valves and low-flow metering systems for the wells, automated chloride scrubbing systems, a turbine bypass, a make-up water system, and modifications to the H_2S burner systems for low steam/gas flows. When needed, The Geysers power plants in California can reduce output by roughly 350 MW (compared to 750–800 MW under normal conditions) for about 4–5 h [19]. The Geysers is limited in its ability to curtail by constraints related to maintaining well integrity and could reduce output even more if a turbine bypass system existed (a bypass system would allow the system to operate the wellfield separately from the turbine output). An interesting note about The Geysers is that a short-term increase (or "puff") in production has occurred after multi-week curtailment events [5]. Another example of flexible operations is the Puna geothermal field in Hawaii, where a bypass system has allowed the operators to curtail generation when needed—this type of operation is incentivized by the utility [20]. Matek [6] provides additional discussion of the operation of current geothermal plant technology in a flexible manner.

Our goal in this paper is not to evaluate the specific, existing, approaches to flexibility described above, but instead to provide a more generalized characterization of the value of flexibility for geothermal plants. We describe our methods for calculating value below, but for now, note that we define value based on hourly real-time pricing within the local wholesale electricity markets. We also note that we only look at the value of flexibility, but do not estimate the costs of adding such flexibility (consistent with our scope providing a general, not technology-specific, assessment of the value of flexibility). The purpose of such a general characterization is to help guide the development of strategies, technologies, and basic research that may enhance the value of geothermal electricity generation through facilitating flexible operations. There is another step that we do not address in this work, which is the translation of enhanced market value into power purchase agreements for geothermal-based generation. This research focuses on the identification of the value of flexibility, but not the practical aspect of recognizing that value within contracting procedures. It should be noted that flexibility, and options to enhance flexibility, are topics of interest across generation technologies, including thermal and renewable generation technologies, along with demand-side technologies, such as electric vehicles [21–24]. The ability of any one technology to increase flexibility has the potential to reduce the value of flexibility for other technologies.

We characterize the value of flexibility through two primary approaches. We look retrospectively at local, wholesale electricity pricing patterns near all geothermal plants in the U.S. Second, we use a price series from a capacity-expansion and a dispatch model to evaluate how the value of flexible geothermal operations may be enhanced in the future (nominally 2030) with greater penetration of wind and solar generation. Our goal is to provide a simple characterization of changes to price variability based on empirical historical records and based on the outputs of the forward modeling.

In the retrospective analysis, we evaluate price series spanning the years 2011–2017. We characterize the negative price episodes describing how these episodes change in frequency and quality over time. We estimate and compare the value of geothermal to wind and solar by matching price time-series to production estimates. We then estimate how several different flexible operational strategies can increase the value of geothermal generation. Note that in some regions renewable energy credits (RECs), which provide revenue in proportion to generation, provide an incentive to keep generating during some negatively priced hours. In California, and throughout the Western Electricity Coordinating Council region, RECs are mostly "bundled" within PPA contracts and so do not offer a separate revenue stream. We do not include RECs in our analysis.

It is important to note that we are not calculating expected revenue streams for geothermal operators. We are instead defining value, at each location and hour, as the real-time market price per MWh electricity delivered. This value metric is useful, as new long-term agreements with geothermal plants will respond to the price signals found in these markets. Additionally, they can provide some guidance as to the monetary value of strategies or proposed technologies that allow for a flexible generation. Additional discussion of the use of real-time market prices to define value can be found in the study by Mills et al. [7].

2 Methods and Data Sources

2.1 Geothermal Plants and Historical Pricing Data. We track 62 geothermal plants, as identified by the U.S. Energy Information Administration (EIA), many with multiple generating units, across California, Oregon, Idaho, Nevada, and New Mexico. These plants represent all the major geothermal electric power plants operating during the study period in the lower 48 states. To analyze the value of flexible operations at the location of these plants, we matched these plants to the nearest appropriate wholesale electricity node, and where applicable, we matched individual units to separate nodes. All nodes are either directly within the California Independent System Operator (CAISO) area or within the larger Western Energy Imbalance Market. In many cases, nodes are collocated with the geothermal plants, although for a minority of plants, the node chosen is some non-negligible distance away. Figure 1 shows the location and nameplate capacity of each plant and the associated nodes.

We analyze historical time-series of wholesale real-time prices at each node, sometimes called locational marginal pricing. Pricing data were collected and aggregated to the hourly time resolution by ABB as part of the "Velocity Suite" [25]. These pricing series represent the wholesale market value of electricity at the locations of each node and in the real-time market. They do not represent the price received by the associated geothermal plant, as individual long-term contracts would limit the immediate influence of real-time pricing fluctuations.

2.2 Future Scenario Modeling. A combination of a capacity-expansion and a dispatch model was used to develop future wholesale price hourly time-series for the CAISO region and each future scenario. This modeling exercise, and associated data, was developed previously and designed specifically to investigate how the increasing penetration of wind and solar would impact pricing patterns and thus the efficiency of electric sector decisions [26]. The specific models used were developed by LCG Consulting and included the Gen-X model for the capacity-expansion portion and UPLAN, a market dispatch model that includes co-optimization across the energy and ancillary services. The Gen-X model is used to simulate the change in capacity, additions, and retirements, based on minimizing total cost across the electricity sector through 2030. The Gen-X model was used to determine capacity for all generations other than wind and solar, as wind and solar penetration levels were prescribed. The UPLAN dispatch model simulated hourly prices based on details related to loading, generator physical and economic characteristics, transmission limits, and market structure. The model included the assumption that the share of renewables increased to the same levels in neighboring regions, thereby limiting the effects of inter-ISO transfers. The models did not perform a nodal simulation but instead simulated multiple zones throughout CAISO. As there was little difference in the price series between the zones, the results in this paper focus only on the system-wide price series. Seel et al. [26] present two sets of assumptions, the "balanced portfolio approach" and the "unbalanced portfolio approach." Our analysis focuses on the "balanced portfolio approach," which allows for renewable penetration to impact retirement decisions within Gen-X. Additional details are described in the study by Seel et al. [26].

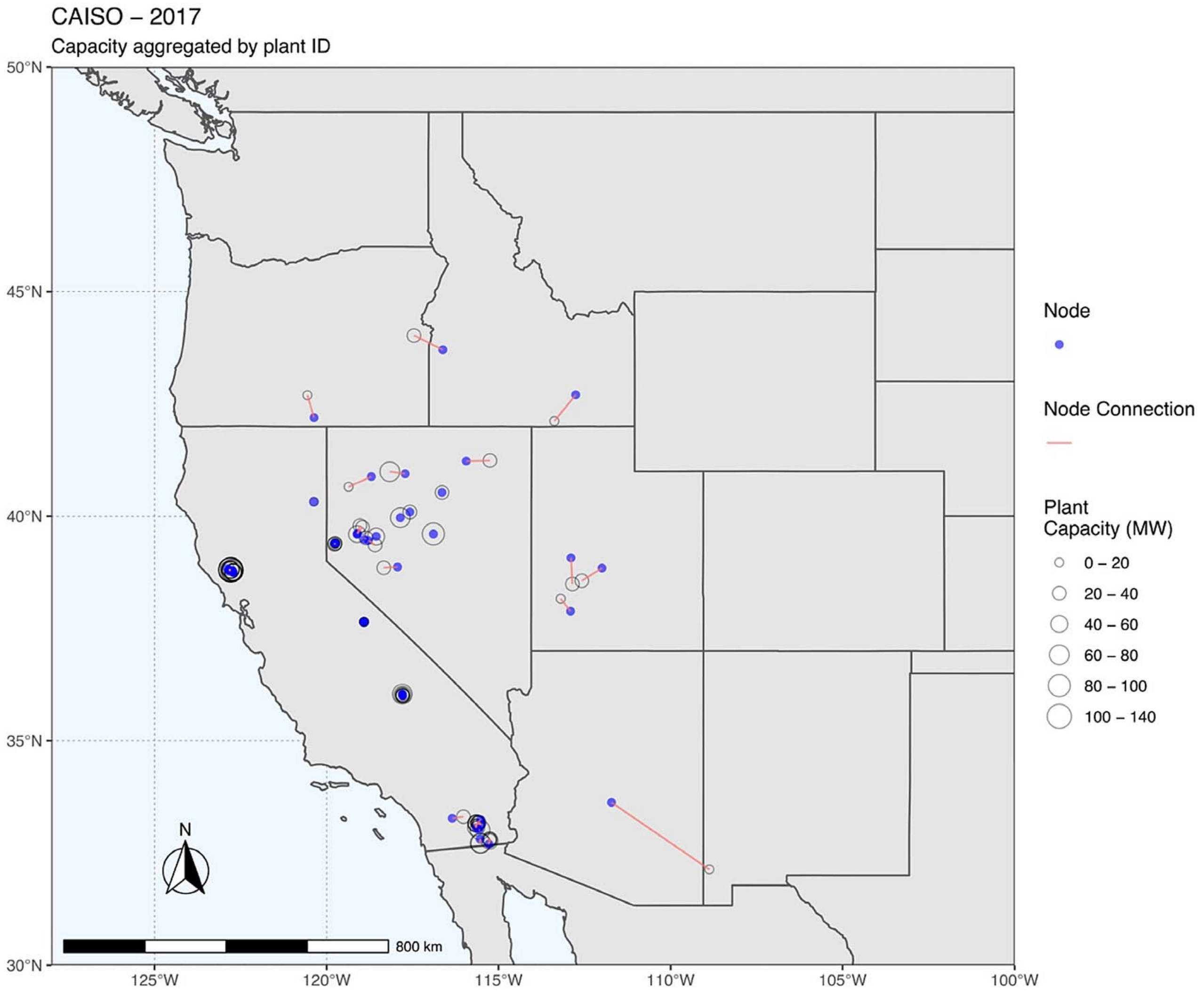


Fig. 1 Geothermal plants and associated nodes for value calculations. Note: The Node Connection line is not shown where plants and nodes are collocated. The Node Connection line does not represent a physical connection, it is a symbolic link.

2.3 Methodological Limitations and Caveats. One limitation is that prices are reported with an hourly resolution. Real-time markets resolve to sub-hourly time periods, and thus the price series, when averaged to an hourly resolution, may not allow us to fully capture all the value of flexibility. For example, the value of avoiding any negative price episode that lasts less than an hour will appear smaller than the true value of curtailing only for the negative portion of the said hour. Additionally, the real-time pricing series does not capture the capacity value and the value of other ancillary services. Although these other value streams are typically smaller than the energy value captured in the price series, for example, see Mills et al. [27], they are typically larger for geothermal power than wind and solar. However, while the omission of capacity and ancillary service value will have some effect on the comparison between the total value of wind, solar, and geothermal, it will have little impact on the relative estimates of the value of flexibility.

Another limitation is our assumption that plants have the capability to instantly ramp a large portion of their total capacity. We believe this assumption limits the complexity of our analysis without limiting the usefulness of our results. This assumption does mean that our flexibility value estimates will be biased high if ramping rates are slow compared to an hour (an example of a slow ramping rate, in this case, would be 30 min to reach its target capacity). As mentioned earlier, we are not attempting to exactly mimic existing geothermal technology, but there are examples of existing geothermal plants that have the significant ramping capability. For example, Linvill et al. [28] 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. The binary plant at the Puna field can ramp across its range of 22 MW to 38 MW at a rate of 2 MW/min (i.e., covering its full target range in 8 min) [20]. Finally, the Geysers plants, though not binary, have technology that allows them to ramp output at a high rate. Dobson et al. [19] document rapid power ramp rates (300 MW in 1 h) that have occurred at The Geysers in response to curtailment events.

The modeling of future scenarios has limitations as well, specifically, it assumes no addition of storage capacity beyond what is currently mandated. The future modeling does not allow for negative prices, but instead curbs generation until prices are positive at each hour. The future model does not provide details on location-specific patterns, which may also reduce the benefit of flexibility. The future modeling was nominally designed to represent 2030; however, given the recent regulations requiring 60% renewable penetration by 2030 may underestimate the total solar and wind penetration by 2030.

All of the flexibility models ignore the value of RECs, which provide some revenue even during zero or negatively priced hours. RECs reduce the overall value of flexibility; however, it was out-of-scope to explicitly include the analysis of RECs here.

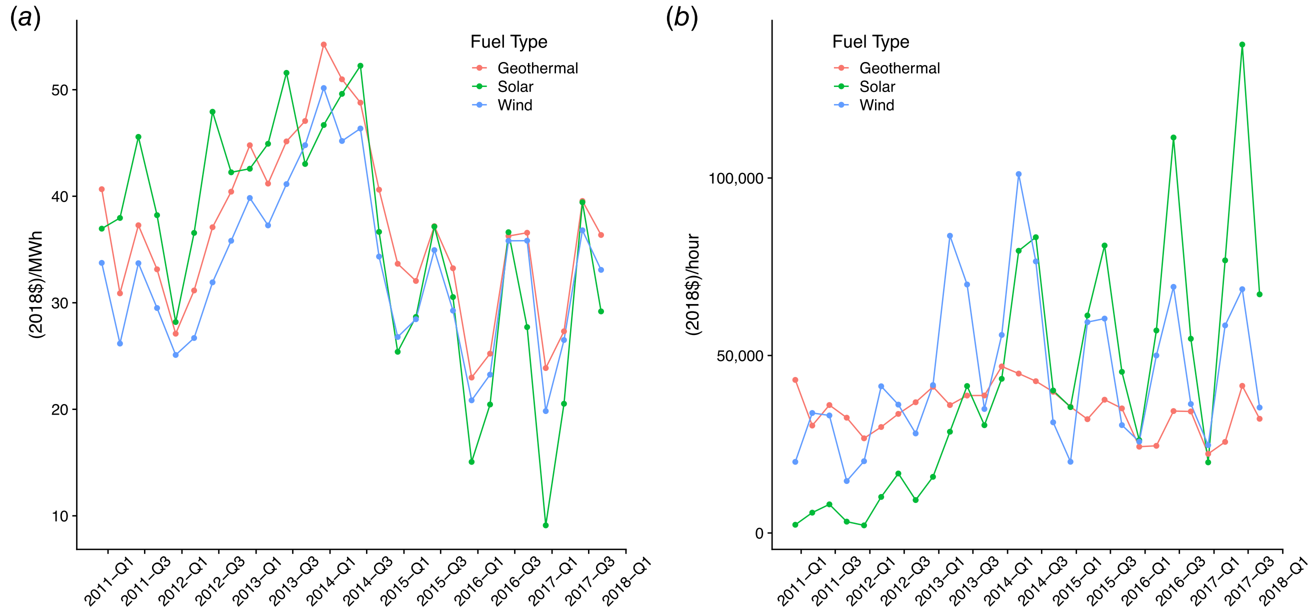


Fig. 2 The average monthly value of energy produced by various renewable sources: (*a*) the relative value (2018 $ per MWh generated) and (*b*) the total per-hour value (i.e., hourly generation × hourly price), both as average quantities across a month. The troughs on panel (*a*), seen in years 2015 and later, occur during spring, when high solar and hydro production is coupled with mild electricity demand. Note the "value" quantity only accounts for the energy component of the real-time wholesale market.

3 Characterization of Geothermal, Solar, and Wind Value Over Time

Often, the costs of geothermal electricity generation are compared on a one-to-one basis with the costs of other renewable generation sources. However, due to differences in the timing and availability of generation, the value created by each source can be quite different. Furthermore, the expansion of one type of generation can impact the value of generation from other sources differently. For example, Orenstein and Thomsen [29] find that recent pricing trends have increased the value of geothermal generation relative to solar generation in Southern California. Here, we analyze how the real-time market value of geothermal, solar, and wind energy has changed over time across all of CAISO.

The specific comparison here is based on the hourly energy component of the real-time wholesale price series. Average $/MWh values across each time period were calculated by weighting the hourly energy price component by the hourly generation for the technology type (geothermal, wind, or solar). Thus, these averages account for the underlying energy value but do not show value changes due to congestion or line losses (localized impacts on value are explored in the following sections). Note also that these values may not represent the full price that utilities, or others, are willing to set for long-term contracts, as there are additional considerations, such as the ability to hedge against potential future price fluctuations or regulatory requirements, which may lead purchasers to pay a premium over recent market energy prices. All values are reported in 2018$, and curtailment has been accounted for by adjusting total MWh generated to pre-curtailment levels. Note that curtailment data were available only for wind and solar generation and only for years in which it was reported by CAISO (i.e., 2015 and later).

Figure 2 shows both the relative value (in $/MWh terms) and the average per-hour value (generation × price). Value is partially a function of the amount of deployment of each generation type. Note that in recent years, the relative value of solar energy has declined the most and the value of geothermal energy has declined the least (see Fig. 2(*a*), and also Table 1), concurrent with the expansion of total solar generation (Fig. 2(*b*)). This pattern indicates that as solar capacity increases, the value of generation from all technologies is reduced while geothermal becomes relatively more valuable than solar. Note that at the beginning of the time period, solar generation was often more valuable, on a $/MWh basis, than geothermal, and that this ordering has switched by the end of the time period.

Table 1 The average annual energy value (2018 $/MWh) of generation produced by geothermal, wind, and solar in CAISO

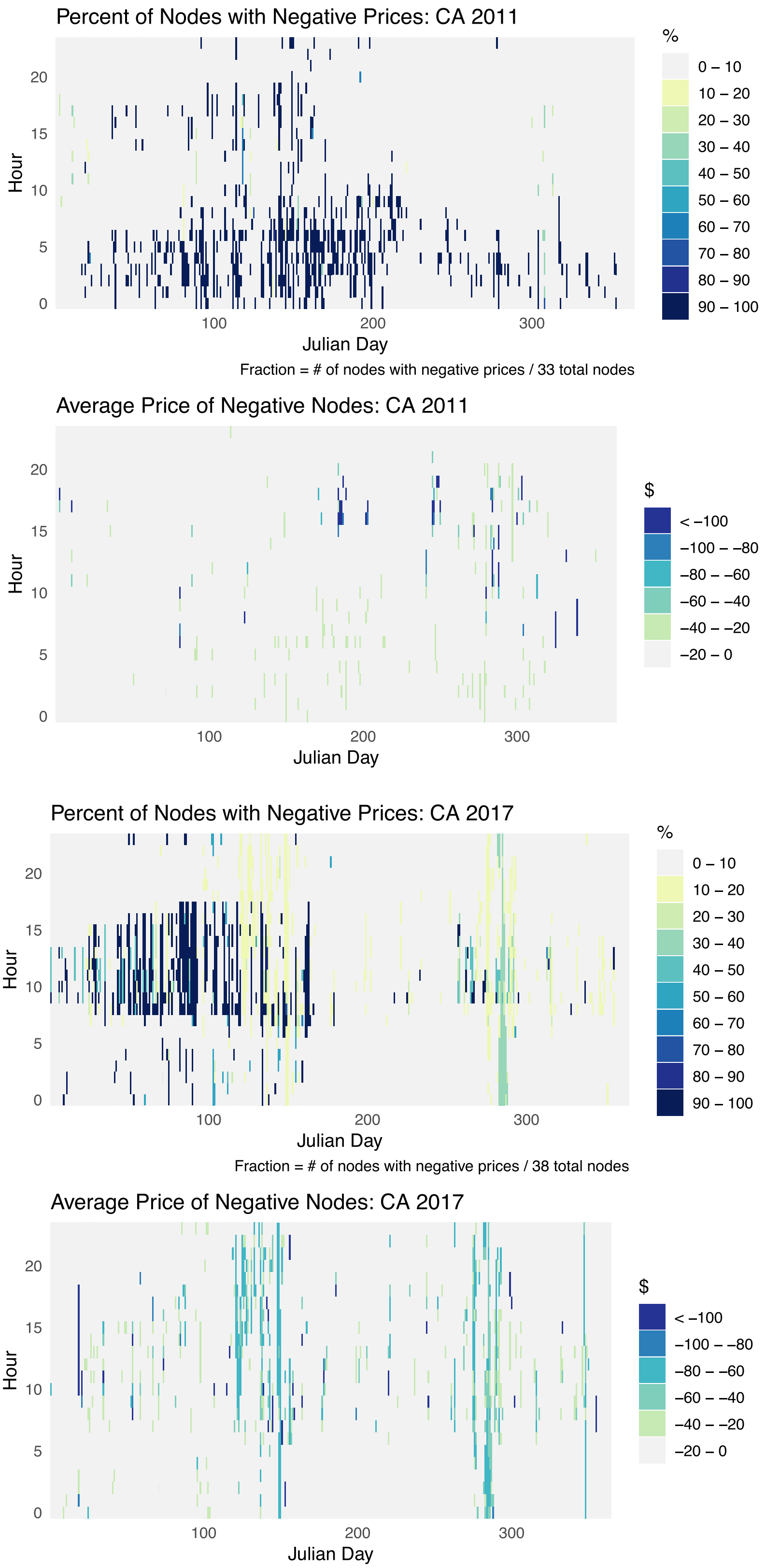
Year	Geothermal ($/MWh)	Solar ($/MWh)	Wind ($/MWh)
2011	35.5	40.4	31.7
2012	34.0	38.8	30.1
2013	44.5	45.4	40.9
2014	48.7	46.1	43.9
2015	34.0	30.3	30.6
2016	30.3	25.0	29.0
2017	31.8	24.6	29.1

Note: The "value" present only accounts for the energy component of the real-time wholesale market.

4 Characterization of Negative Pricing Episodes

Negative pricing episodes provide an incentive to reduce generation and generators that can seamlessly respond could capture this value. We look to characterize the negative price episodes that geothermal plants experience. Specifically, we characterize patterns at the subset of pricing nodes that are associated with geothermal plants. We are interested in a limited defining set of characteristics about these negative pricing episodes: their duration and starting point, and their magnitude (i.e., how negative is the price). We are also interested in how these patterns have changed over time.

We find, as evidenced in Fig. 3, the patterns of negative pricing that geothermal plants experience has notably changed between 2011 and 2017. In both years, negative pricing was most frequent during the spring and early summer, decreasing in the latter half of the year, coincident with the reduction in hydropower generation seen during the fall and winter. A difference is that, in 2011, negative pricing was clustered in the hours between midnight and about 7:00 am (local), while in 2017, negative pricing had shifted toward high solar hours. This shift is consistent with the closure of California's San Onofre Nuclear Generating Station in 2013 and the


Percent of Nodes with Negative Prices: CA 2011

Fraction = # of nodes with negative prices / 33 total nodes

Average Price of Negative Nodes: CA 2011

Percent of Nodes with Negative Prices: CA 2017

Fraction = # of nodes with negative prices / 38 total nodes

Average Price of Negative Nodes: CA 2017

Fig. 3 Negative price heatmap, 2011, and 2017

increase in solar power generation. Despite the shift in the starting point, negative episodes typically lasted only a few hours in both years. That being said, a minority (<30%) of geothermal plants faced a limited number of days (~10) where the majority of the hours had negative prices. Still, as Fig. 4 demonstrates the negative price patterns that geothermal plants encountered in 2017 were clearly one of repeated, short-duration, negative episodes influenced by the availability of solar and hydropower (along with the underlying seasonal and diurnal variability in electricity demand).

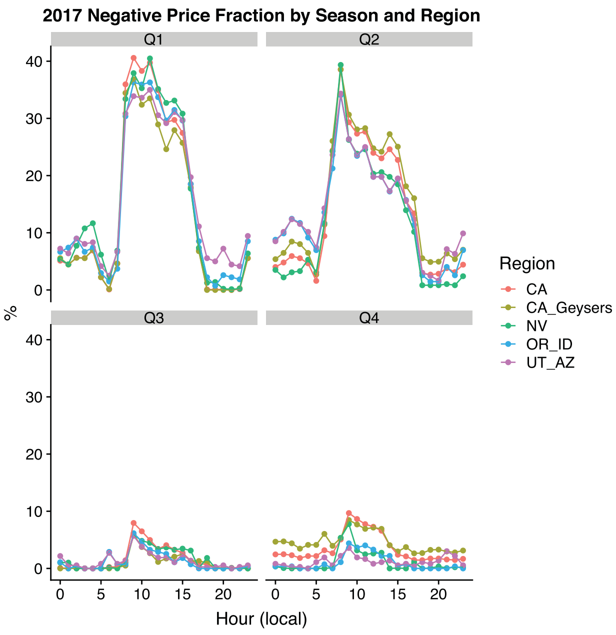


Fig. 4 Diurnal negative price variability by quarter, 2017

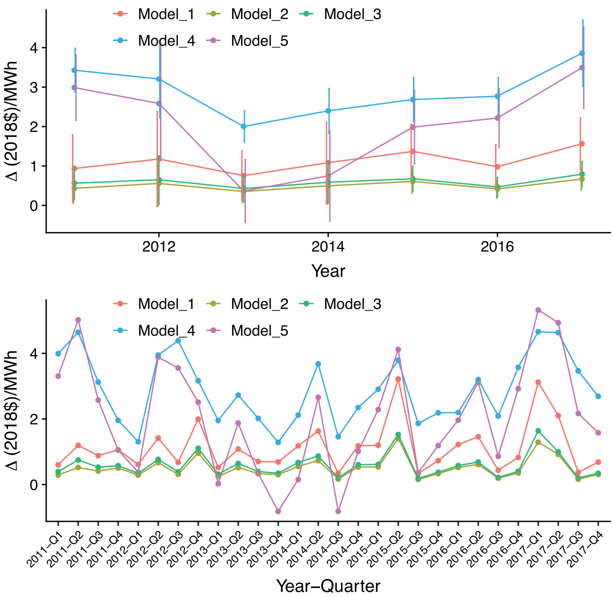


Fig. 5 Value of flexibility on (2018 $)/MWh basis

5 Historical Value of Flexibility Strategies

We chose five separate operational flexibility strategies to model (see Table 2). In each case, we compare the increase in value versus a flat-generation strategy (i.e., versus where output is constant and is not a function of price). A reminder that the strategies analyzed here are not supposed to represent a specific technology or plant but are designed to give us a general idea of the value of a variety of types of flexibility solutions. The simplest strategy, here called Model 1, is to reduce output every time the price becomes negative. In Model 1, we assume a plant can eliminate its output completely and indefinitely, thus eliminating all production during all negatively priced hours. Model 1 represents a situation similar to that of a new binary plant, planned and built with flexible operations in mind, which can achieve deep curtailment with little change to the capital cost. In Model 2, we place limits on the ability of a plant to ramp down its output, assuming that it can only reduce to 50% of capacity during negative hours, and do so for only 3 h in a row, after which it must run at 100% of capacity for at least 1 h. Model 3 is exactly like Model 2, however, Model 3 is allowed to increase production to 20% above capacity for the hour after running at 50%. Models 2 and 3 represent a situation that might be more similar to that of steam or flash geothermal plant, which may have technical limits to the amount to which it can curtail.

Models 4 and 5 are meant to represent bounding cases on the value of flexibility and potentially provide guidance of the value of developing new strategies or technologies to allow for greater flexibility in geothermal operations than is currently implemented. In Model 4, plants curtail their output by 50% in the lowest priced 4 h of each day and enhance their output by 30% in the highest priced 4 h of each day. Model 5 is the same as Model 4 except that plants curtail their output by 100% during the lowest priced 4 h of each day. In both Models 4 and 5, curtailment occurs in the lowest priced 4 h of each day regardless of whether or not those hours are negatively priced.

In the following value analysis, each of the models was computed at each of the existing geothermal plant locations; thus, we find a range of value enhancements depending on variations in the price series by location (see Fig. S1 available in the Supplemental Materials on the ASME Digital Collection). Although we model these strategies at each existing geothermal plant, we are not attempting to model specific output for these geothermal plants based on the unique characteristics of each plant; we are simply using these locations to gain a representative sample of the type of value changes that could be expected across geothermal locations.

We evaluate the change in value across the models in two ways. First, we look at the increase to average $/MWh versus Model 0 (see Fig. 5 and Table 3). In this calculation, we fix the total MWh generated (the denominator) to equal that of Model 0. By keeping the denominator consistent across all models, we account for lost revenue during modeled curtailment. In other words, even though Models 1 through 5 are operational for fewer hours than Model 0, we calculate the total average value of the models versus the total potential generation that could be achieved without curtailment.

Table 2 Summary of flexibility models

Model 0	Constant generation across all hours
Model 1	100% curtailment of all negative hours
Model 2	50% curtailment of negative hours, limited to three curtailment hours in a row
Model 3	Same as Model 2, plus 20% increase for the positive hour after a negative hour
Model 4	50% curtailment of lowest-priced four hours each day, 30% increase for the four highest-priced hours each day
Model 5	Same as Model 4, but 100% curtailment during the lowest priced 4 h each day

Note: In most existing plants, achieving 100% curtailment would require a turbine bypass system.

Table 3 Increase to $/MWh value by model, relative to Model 0, in 2017

	Annual (mean ± S.D.)	Q1 (mean)	Q2 (mean)	Q3 (mean)	Q4 (mean)
Model 1	1.6 ± 0.7	3.1	2.1	0.4	0.7
Model 2	0.7 ± 0.3	1.3	0.9	0.2	0.3
Model 3	0.8 ± 0.3	1.6	1.0	0.2	0.3
Model 4	3.9 ± 0.8	4.7	4.6	3.5	2.7
Model 5	3.5 ± 1.0	5.3	4.9	2.2	1.6

Note: All values in units of (2018 $)/MWh. Values shown are representative of the average (and standard deviation) across all geothermal plants.

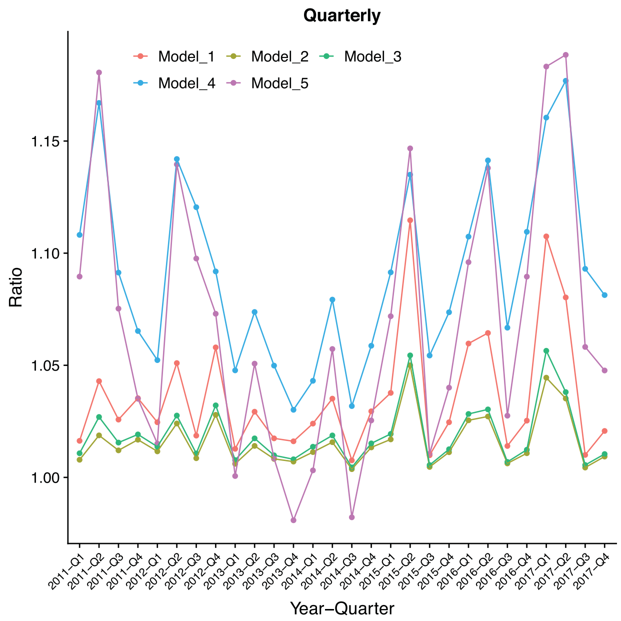


Fig. 6 Value of flexibility on per capacity basis

The second approach to investigate the value change is to calculate the ratio in total "revenue" between each model and Model 0 (see Fig. 6). Here, the total revenue is simply calculated by summing the product of hourly price and hourly capacity, where capacity is in the set 0.0, 0.5, 1.0, 1.2, and 1.3 depending on the curtailment or enhanced production by model and hour (e.g., a 50% curtailment would equal 0.5 capacity). Note that given current technology and operating practices, a short-term increase in output is unlikely to be feasible. These flexibility models are meant to provide a bounding case to investigate the potential for new technology or new practices to add value.

The average increase to $/MWh is larger in Models 1, 4, and 5 compared with Models 2 and 3. The driving factor of these differences is that Models 2 and 3 only allow for 50% curtailment during negative price hours, whereas Models 1 and 5 allow for 100% curtailment during targeted hours. Note that there were enough negatively priced hours to allow for Model 1 to produce a significant increase to value only through curtailment. Model 4 includes 50% curtailment during low price hours but also includes enhancement of the peak value hours each day. Thus, we find that the value of flexibility is sensitive to the magnitude of curtailment allowed as well as the timing and size of any generation enhancements. Model 3 provides a similar but only slightly higher boost to average value compared with Model 2, indicating that the mean price during hours directly following negative price episodes are, on average, not much higher than the mean of all prices.

The greater value of Models 4 and 5 indicates that curtailment of negative priced episodes only captures a fraction of the potential value of the flexibility that could be achieved through limited increases to output during non-curtailment hours. The consistency in value between Models 2 and 3 indicates that to gain significant value through flexible operations that temporarily increase output, the timing of such an increase would need to be detached from the timing of any curtailments. Figure 5 also demonstrates that Model 5 can produce less value than Model 0 in the situation in which negative prices are infrequent, such as during particular quarters in 2013 and 2014.

The value of the flexibility models is not uniform across plants. For example, Table 3 shows standard deviations that are 22% to 42% of the mean values. We see that, in 2017, the value increase for Models 4 and 5 is most pronounced for plants within the state of Nevada and Imperial County in Southern California. Figure S1 displays a map of the value increase by model for 2011 and 2017. In 2011, the value increase is less concentrated in certain regions. The reason why certain regions have higher flexibility value is complex and involves multiple factors that influence local pricing, such as local demand profiles and transmission limitations, as well as the type of nearby generation resources.

The average $/MWh value is useful when comparing against estimated average levelized $/MWh costs associated with a flexibility strategy. As described above, another aspect to investigate is the change to the total value or "revenue" associated with each scenario. Figure 6 shows the ratio of revenue between each model and Model 0. In most years, Models 4 and 5 provided the largest increase in revenue. However, it is possible for Models 4 and 5 to reduce revenue in the case with few or no negative prices. In that case, the curtailment would reduce generation during positively priced hours and lead to lost revenue. We see that for limited periods in 2013 and 2014, Model 5 did indeed limit revenue compared to Model 0. During 2016 and 2017 however, Models 4 and 5 both increased total revenue within the range of 2 to 20%, with higher values observed in 2017. In rough terms, Model 1 provided a boost in revenue of roughly half of Models 4 and 5 in 2016 and 2017. This points to the added value of not just curtailment but load enhancement during peak price hours.

6 Future Value of Flexibility Strategies

Between 2013 and 2017, there has been a steady increase in the value of flexibility at geothermal plants. Given this trend and the expected continued increase in solar and wind resources, we examine the value of flexibility in modeled future scenarios. We analyze four future scenarios (nominally 2030) with different levels of renewable generation incorporated in each scenario. Three of the scenarios model expansion of solar and wind resources so that solar and wind account for a combined ~40% of total generation within the scenario modeled. To reach the ~40% penetration level, one scenario relies primarily on solar, one relies primarily on wind, and one relies on a balance of both solar and wind. The fourth future scenario holds wind and solar close to 2016 levels but allows the demand, non-renewable supply, and other factors to evolve to 2030 in the same manner as the other three scenarios. This fourth future scenario will be referred to as the "Low VRE" scenario, where VRE stands for variable renewable energy. See additional details in Sec. 2.

The value of flexibility found in these scenarios should not be directly compared to the recent historical price trends. One important difference between the modeled outputs and recent pricing patterns is that the model does not allow for negative pricing as it assumes generation is curtailed until a positive price is generated. The model also includes expansion to transmission through the region but does not include expansion to storage resources such as batteries. The elimination of negative pricing and the expansion to transmission indicate that the future modeled here is already more flexible than today's system. Thus, to gain insight from this modeling exercise, we must look at the difference in the value of flexibility between the renewable expansion scenarios and the Low VRE scenario, as opposed to comparing directly to recently observed values. This comparison is analogous to the question: How will the value of flexibility change as significant additional wind and solar resources come online? Additionally, because the model prevents the existence of negative prices, we evaluate a slightly different strategy for flexibility than the strategy used with the historical data.

Figure 7 shows the average diurnal pattern in wholesale energy prices by season and scenario. We see lower prices across all hours in the solar and wind expansion scenarios and each scenario has significant midday drops in price during all seasons. The solar expansion scenario shows the largest price reductions during midday and the largest daily price swings in general. We can see from this figure that the future scenarios represented are quite different in pricing patterns from the scenario in which solar and wind deployment are held constant.

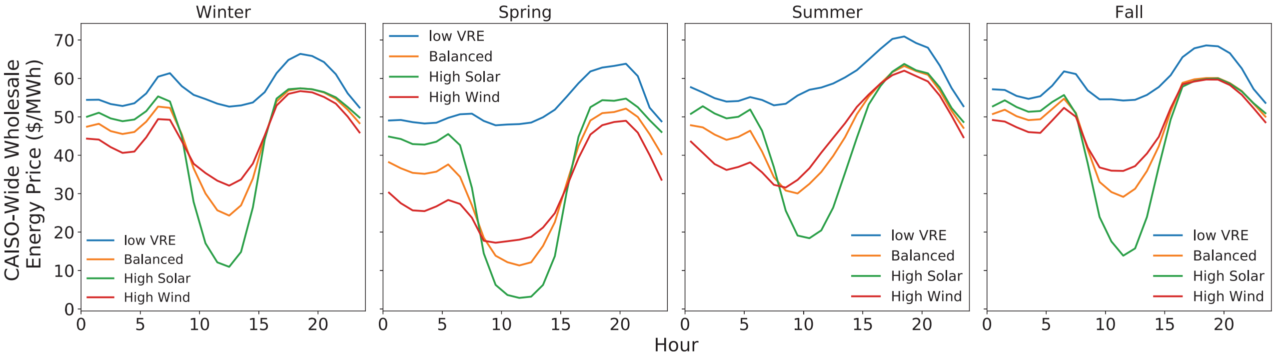


Fig. 7 Modeled average wholesale price under higher penetrations of renewable energy, shows reduced daytime prices with higher penetrations of solar compared to 2016 levels

We examine one strategy for flexibility (here called "curtail and enhance"), which is similar to Model 5 from Sec. 5. In the "curtail and enhance" model, we allow geothermal plants to curtail all output from the four lowest priced hours and increase output by 30% during the four highest-priced hours of each day, but the curtailment and enhancement are only activated when it increases mean value for the day compared to flat generation. The value of the flexibility model, calculated as the increase in average wholesale price over the simple mean of prices through the year and seasons, is shown in Fig. 8. We note that the value of flexibility in the low VRE scenario is effectively zero, much lower than the 2017 flexibility values for Models 4 and 5 from Sec. 5. This indicates that this future model system values flexibility less than the current system, even under the case without expansion of wind and solar beyond 2016 levels.

The three VRE expansion scenarios all show a positive value of flexibility (Fig. 8). The Curtail + Enhance model increases value by 1 $/MWh (compared to flat generation) under the high solar scenarios on an annual basis. The High Wind and Balanced scenarios show an increase in the value of 0.4 and 0.5 $/MWh, respectively, from the Curtail + Enhance model. Thus, we see that high solar futures create a future with the greatest flexibility values. Flexibility is valued most during the springtime in all scenarios.

This future modeling indicates that the value of flexibility is sensitive to system transmission and the curtailment patterns of all technologies. The future modeled here, with increased transmission and flexible curtailment, leads to a lower value of flexibility for geothermal power compared to today's value of flexibility. Although it is unclear if the levels of transmission will expand at the rate implied by the modeled future scenarios, there are indications that other sources, which were not modeled, may provide grid flexibility in the future. Specifically, battery storage is expected to expand dramatically in the near future, for example, in CAISO, 50% of proposed wind projects and 67% of proposed utility-scale solar projects include a hybridization component, most often battery storage [30]. Additionally, new strategies for demand response, such as "shift" strategies, in which load is shifted from one time of day to another, have the potential to provide important load flexibility resources at low cost [31]. So, while the exact transmission scenarios described by the modeling here may not come to pass, it is clear that there are many possibilities for new flexibility options.

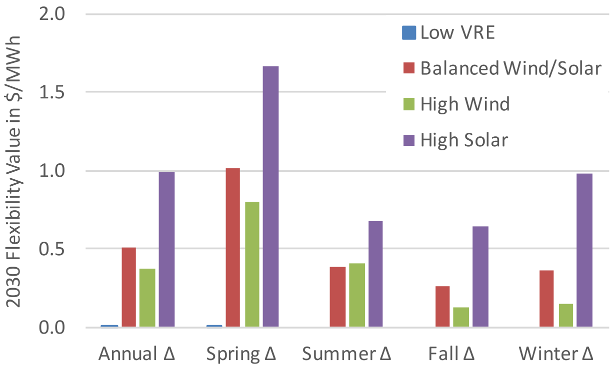


Fig. 8 The increase in the average value of generation in 2030 with a flexibility strategy compared to constant generation. Note: the low flexibility values shown here (low compared to current flexibility value) are due to a modeled future with enhanced system flexibility compared with today's system (i.e., additional transmission and additional curtailment of renewable generators).

7 Conclusion

In 2017, an always-on geothermal plant in California would have produced electricity with an average energy value of 31.2 $/MWh, about 30% more than the energy value of California solar power. This has not always been the case, e.g., the 2011 solar generation had a greater energy value than a geothermal generation. The swap in the ranking of energy value between the technologies is a function of the large and recent increase in solar generation.

The pattern of negative pricing at geothermal plants has also changed between 2011 and 2017, with negative pricing hours clustered during sunny hours in recent years rather than during the night in older years. This change is expected given the retirement of nuclear capacity along with the growth in solar capacity. In both years, negative pricing episodes most often lasted only a few hours at most and were concentrated in the first half of the year, coincident with relatively high hydropower generation.

The energy value of geothermal generation could be increased further through flexible operations. Based on 2017 pricing patterns, we found that geothermal plants could increase the energy value by roughly 2–4 $/MWh depending on the amount and type of curtailment and enhancement allowed in the flexible operations strategy. The strategy that increased value the most allowed for increased production during some hours and complete curtailment during other hours of each day. However, a simple strategy of curtailing only negative priced hours added 1.6 $/MWh to the average value of generation.

A forward-looking analysis found that in a future where solar power accounted for 30% of total generation in CAISO, the value of flexible generation strategy that relied on curtailment and increased production during peak price hours was roughly 1 $/MWh. This relatively low value of flexibility (compared to the recent market value described above) reflects a modeled future in which the electrical systems have been built to ensure greater flexibility (i.e., additional transmission resources have been included, and curtailment of generation across multiple technologies has become more standard). Although a future with such a flexible system is not a sure bet, this modeling exercise demonstrates that increased value in flexibility is not necessarily fated to accompany increased variable renewable penetration.

Currently, some geothermal plants can be feasibly operated in a flexible manner through the use of curtailment. Geothermal plants are not typically operated in a manner that allows for increases to output, such as is suggested by the design of a subset of the flexibility models in this paper. The analysis here suggests that both curtailment and enhancement can add value to geothermal generation, and combined may be able to increase total theoretical revenue from energy sales on the wholesale market by an order of 10%. This analysis did not focus on testing the value of specific new technologies or strategies to increase flexibility. Instead, this analysis is meant to provide information about the character of negative pricing episodes and the value of the flexibility that can be useful across a broad set of new technologies and strategies. The value streams described here can be used to determine, during an early stage of development, the cost versus value tradeoff of new flexibility strategies and technologies for geothermal plants.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper.

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