The Increasing Value of Geothermal in the West

How geothermal now yields the highest economic value of any renewable resource in California and the surrounding region

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ABSTRACT

Since 2017, we have been evaluating the increasing economic value of geothermal energy to potential buyers in California and other Western states (Orenstein and Thomsen, 2017, Thomsen 2018a, Thomsen 2020). The updated geothermal value estimates in this paper are based on recent historical and forecasted wholesale energy, capacity, and renewable energy credit (REC) market prices, in addition to testing how geothermal costs affect selection in resource planning models. Current trends in wholesale prices for these products, reviewed in this paper, have confirmed that geothermal currently has a significantly higher economic value than a stand-alone solar PV plant in high solar regions such as California. While the value comparison between geothermal and renewable generation with energy storage (i.e., hybrids) is more complex, this paper and some of the prior ones also explore those relationships. As renewable penetration increases, planning models suggest that an incremental megawatt-hour (MWh) of geothermal displaces multiple MWh of solar and storage (Thomsen 2018b, 2021). This result shows the importance of combining wholesale market forecasts with planning analyses to fully understand geothermal's evolving value over the coming decades.

1. INTRODUCTION

Over the past decade, California and other Western states have accelerated their pace to achieve clean energy policy goals. California is arguably the most advanced, but many other states in the region are also rapidly expanding their clean energy portfolios. In 2021, the California Independent System Operator (CAISO) recorded annual renewable energy production of around 30% (CAISO 2022),[1] and the current expectation is that the state will achieve 60% renewable

[1] The CAISO accounts for around 80% of California demand.

energy production by 2030. Additionally, the CAISO expects to have 4 GW of new batteries on its power system by 2023, and state resource planning suggests up to 12-14 GW of energy storage by 2030 (CPUC 2022).

Geothermal was an early utility-scale renewable energy resource in the West, but for the past decade, development has lagged. That is now changing due to new procurement, resource planning selection, long-term reliability needs, and the lack of cost-competitive alternative clean energy resources that can provide firm carbon-free capacity.

This paper is the latest in a series analyzing geothermal valuation in markets and resource planning, beginning with Orenstein and Thomsen (2017) and continuing with Thomsen (2018a, 2018b, 2020, 2021). These prior papers include some findings not repeated here and can be reviewed separately. The price analysis methodologies, using different models, are not discussed in detail, but some references are provided.[2]

Because solar was the first new renewable resource to expand substantially in California and some other Western states, this paper continues the comparison begun in Orenstein and Thomsen (2017) of geothermal's market value compared to that of a stand-alone solar plant. The addition of energy storage on a stand-alone basis or integrated into wind and solar power plants improves their market valuation. Still, tremendous amounts of new energy storage will be needed to address operational and reliability needs over time. In contrast, geothermal energy obtains the average energy value across the entire year, which is already significantly higher than solar's energy value. Additionally, because it operates continuously throughout the year, geothermal obtains a high capacity rating, no matter the level of renewable penetration. Moreover, it has more reliable performance across the year than solar or wind hybrids with integrated storage since the latter utilize variable generation to charge the storage while geothermal has continuous operations. Due to geothermal's performance during the California blackouts of August 2020 (CPUC 2021), geothermal is now recognized and valued for its reliability during extreme weather and electrical events.

While not the cheapest renewable resource, geothermal now yields the highest economic value of any renewable resource in California and the surrounding region. This is due to its benefits quantified through wholesale markets and tradable credits, as well as its capability to support resiliency and reliability needs. These trends are significant because Load-Serving Entities (LSE) located in regions with wholesale markets analyze the contracted costs of new renewable resources and their future wholesale market value. This cost-benefit analysis is then used to rank alternative projects for procurement. For example, in the western U.S., the wholesale value ($/MWh) is what can be obtained for the energy (real power) delivered to the grid, as well as any other wholesale services (such as ancillary services), and resource adequacy (RA) capacity

[2] The models typically used for the types of valuation discussed in this paper typically fall into a few categories. “Price-taker” models use historical or forecast market prices or utility costs to develop an optimized value estimate for a resource but ignore the impact of that resource on the power system (the geothermal and stand-alone solar results in this paper used fixed production profiles but any resource with storage or which can otherwise be dispatched requires optimization). Power system models, notably the production cost models most commonly used for long-term forecasting, consider all resources when determining marginal hourly costs or shadow prices. In addition, capacity expansion models evaluate alternative scenarios for resource portfolio development, but generally are not used for market pricing analysis. See Warren *et al*., (2021) for model review in the context of geothermal evaluation.

obligations.[3] In addition, all renewable projects can obtain tradable renewable energy credits (RECs). The difference between costs and benefits is called the "net costs." Because of this calculation, in LSE procurement, a renewable resource with a higher contract cost will be selected over a lower contract cost resource if its net costs are lower.

This remainder of this paper examines the comparative value of geothermal when providing these market products and other capabilities, followed by an estimate of total economic value using different analytical methods.

1. TRENDS IN COMPARATIVE ENERGY VALUE IN CAISO, 2012-2022

Wholesale energy is the primary product delivered by different generation sources (as well by energy storage when discharging) to meet demand for electricity. The Western U.S. market is mostly comprised of the CAISO market as well as the Energy Imbalance Market (EIM). Several primary factors have determined prices in the CAISO energy markets over the past decade: the price of natural gas, which primarily determines the generator bids which set market prices; the penetration of renewable energy, notably solar, which both depresses prices during some hours of the day and increases them at other times (during system ramps); increasing summer temperatures; and the availability of hydroelectric generation, which can swing from 5% - 15% of annual energy and can further lower prices during high hydro periods.

By 2021, CAISO had an average of 30% renewable energy, of which approximately half is from solar energy.[4] The progressive effect since 2014 of this steadily increasing renewable energy production on the daily profile of energy market prices is shown in Figure 1, which plots the hourly average day-ahead energy market prices in Southern California for selected years using the CAISO Southern California Edison (SCE) Load Aggregation Point (LAP) (average annual prices are discussed in the next section), a large zone which encompasses much of the southern part of the state. Solar generation depresses prices during the solar production hours in the middle of the day. It creates two system ramps when solar begins operations and drops off, with resulting price increases in those periods. In Figure 1, the year 2014 is shown for comparison since the impact of solar began after this year, and then includes the three most recent full years. The figure also helps illustrate that as solar generation expands, a stand-alone solar plant sees a declining value. However, this trend can fluctuate yearly; for example, in 2021, higher natural gas prices raised all energy market prices, including solar revenues, as shown in the green line.

[3] California has a Resource Adequacy (RA) capacity requirement, but not a centralized capacity market. Hence, utility buyers provide renewable projects with a capacity credit based on a combination of short-term bilateral capacity contract costs and long-term avoided costs of new capacity. This requirement can be monetized as capacity value (typically represented as $/kW-year and converted into $/MWh when resources are compared on an energy production basis).

[4] From 2012 to 2022, wind generation has fluctuated between 5-6% of annual CAISO energy production, with higher production in the latter years, geothermal generation has been between 4-5%, and the production of the remaining nuclear plant provides about 7-8%. Hydro has fluctuated between 5-15% in recent years. Natural gas production and imports make up the rest.

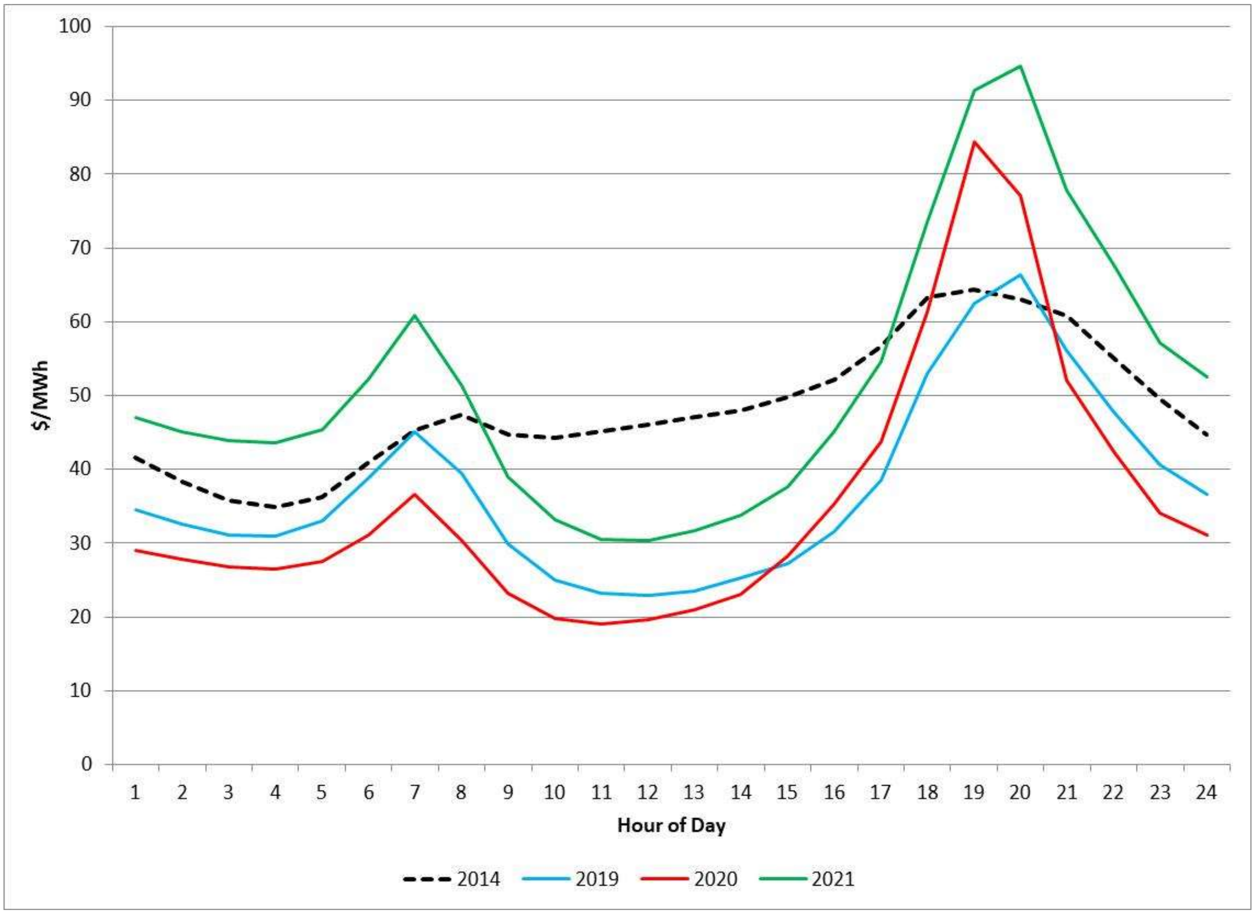

Figure 1 – Average day-ahead SCE Load Aggregation Point (LAP) Prices by Hour of Day, 2014 and 2019-2021

1.1 Trends in Annual Comparative Wholesale Energy Value

When buyers of renewable energy evaluate the economic benefits of alternative resources, there are two primary benefits to consider: wholesale energy and capacity. Beginning with energy, the best indicator of value is transparent energy market prices, which in the West are calculated at several thousand locations in the CAISO market and within the Energy Imbalance Market (EIM). A sample of these prices are used in this section to illustrate the energy value of different clean energy resources.

Geothermal energy value

There are two methodologies when modeling historical or planned geothermal energy production. One method is to use an actual historical or forecast profile for a particular plant, which depending on the plant may show different degrees of production variability as a function of ambient temperature. The other method is simpler, and assumes a profile where the plant operates at 90-95% of installed capacity in each hour (often referenced as a flat block). This analysis utilizes a flat block for calculating energy value, as do most planning models.

Figure 2 and Table 1 illustrate the results for geothermal energy value in southern California from 2012 to 2021. For this and all subsequent results below, we again use the aggregated

CAISO day-ahead[5] energy prices at the SCE Load Aggregation Point (LAP).[6] The figure and the table's first row show the geothermal energy value for a flat block of power all year.[7] As shown in the table, over these ten years, the average value has fluctuated between a low of $29.04/MWh (2016) to a high of $51.56/MWh (2021). The increase in the past year has been due to a combination of factors, most notably the rise in the price of natural gas and higher temperatures, increasing demand, particularly during the summer. The recent increases also offset the general trend in prior years toward lower average value due to increased renewable production and low natural gas prices.

Stand-alone solar energy value

In recent years, in California and other western markets, geothermal was typically compared to stand-alone solar projects in procurement, due to solar's high-value as a peaking resource. However, as solar penetration has increased, solar energy value has correspondingly declined. To evaluate these trends, we used three publicly disseminated solar PV profiles previously developed by the CAISO and the CPUC in the CPUC's long-term procurement planning process (LTPP).[8] We selected these three randomly from many profiles because they are at different locations and use different technologies (one uses single-axis tracking technology and the others use fixed-tilt). The method is simple: we cross-multiplied these profiles using the same CAISO day-ahead energy market prices for the geothermal valuation above. Then, we normalized to $/MWh in market revenues.

In Table 1, the second, third and fourth rows show the value of the three different solar PV profiles, while Figure 2 plots these for one of the profiles. The table's last three rows show the value difference between the geothermal and solar profiles, which is the geothermal value minus the solar PV value. When the number is negative, it indicates that solar is worth more than geothermal. When the number is positive, it indicates that geothermal is worth more than solar and the additional energy revenue that geothermal would have earned compared to solar PV. Each column represents the year being evaluated.

The table and figure show that average geothermal value has been getting steadily higher than a stand-alone solar plant. In 2012, the solar PV energy profiles evaluated were worth $3-4/MWh more than geothermal. This relationship changed in 2015, when geothermal production had slightly higher average energy revenue than solar for the first time, and the gap continued to expand each year. By 2021, geothermal would have earned $13-$15/MWh more than solar energy over the year due primarily to the high level of solar penetration over this period.

[5] Real-time energy market prices are not evaluated as these are only used to financially settle deviations from day-ahead schedules, which rarely impacts geothermal schedules, but may affect solar generation given forecast errors.

[6] In Orenstein and Thomsen (2017), we also showed the average energy value at the South of Path 15 Trading Hub (TH) which are not repeated here; the SP15 TH and SCE LAP calculations differ only is this because of the manner in which the aggregated market price is calculated based on the underlying locational marginal prices (LMPs). We found that the SP15 TH average comparative values were consistently $1-2/MWh lower than the LAP valuations, and do not repeat them here.

[7] In actual practice, geothermal energy value could be lower or higher than this estimate. For example, if the geothermal profile had lower production during the lower energy price hours of the day, which now coincide with solar production hours and higher ambient temperatures, but higher production during the higher evening price hours, then the average would be higher.

[8] The LTPP was an umbrella proceeding which has conducted simulation of future grid conditions; the LTPP is now folded into the CPUC's Integrated Resource Planning (IRP) proceeding. For more information see http://www.cpuc.ca.gov/irp/.

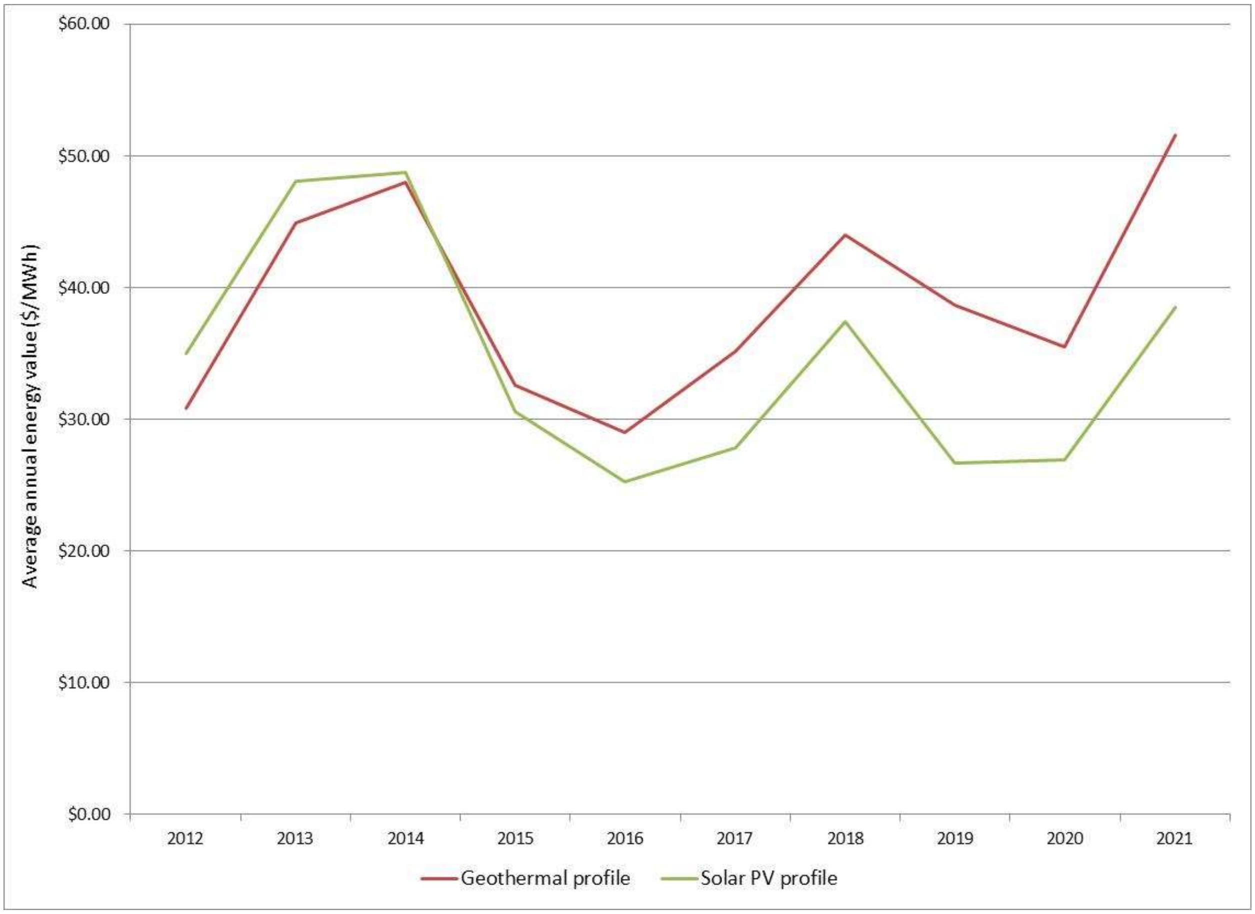

Figure 2 – Difference between average value ($/MWh) of geothermal and an illustrative stand-alone single axis tracking solar PV profile using day-ahead CAISO SCE LAP prices, 2012 - 2021

Table 1 – Difference in annual average energy value between geothermal baseload and three solar PV profiles ($/MWh) in Southern California, 2012 to 2021, using CAISO day-ahead SCE Load Aggregation Point (LAP) prices

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Average energy value ($/MWh)										
Geothermal baseload	$30.84	$44.94	$48.04	$32.59	$29.04	$35.21	$43.99	$38.67	$35.55	$51.56
Solar PV-1 "Blythe 2024"	$35.00	$48.09	$48.76	$30.56	$25.27	$27.82	$37.42	$26.70	$26.93	$38.48
Solar PV-2 "Photovoltaic 2024"	$33.84	$47.29	$47.45	$29.64	$24.32	$26.30	$34.71	$25.71	$24.22	$36.43
Solar PV-3 "NV_WE"	$34.78	$47.42	$47.46	$29.55	$24.18	$25.81	$35.23	$24.99	$23.77	$36.39
The difference in energy value between geothermal and solar PV* ($/MWh)										
Solar PV-1 "Blythe 2024"	-$4.16	-$3.16	-$0.72	$2.04	$3.76	$7.93	$6.58	$11.97	$8.63	$13.08
Solar PV-2 "Photovoltaic 2024"	-$2.97	-$2.35	$0.60	$2.95	$4.71	$8.92	$9.29	$12.96	$11.37	$15.13
Solar PV-3 "NV_WE"	-$3.94	-$2.48	$0.58	$3.04	$4.85	$9.39	$8.77	$13.67	$11.78	$15.17

*A negative sign indicates that solar energy is worth more on average than geothermal energy (due to the higher concentration of production in higher-priced hours in those years). All prices used for these calculations are downloaded from the CAISO OASIS website.

Renewable generation with storage

As energy storage costs decline, geothermal is now more typically compared in planning and procurement to combinations of renewable generation with storage, including the various types of solar-battery hybrids now common in the western US.[9] The set of possible configurations for inverter-based resources is shown below, based on a table in Denholm *et al*., (2017):

Type of Coupling	Co-Located?	Point of Common Coupling	Energy Stored
Independent	No	None	Grid
AC-coupled	Yes	Transmission/feeder	Grid or renewable generator
DC-coupled	Yes	DC side of inverter	Grid or renewable generator
DC tightly coupled	Yes	DC side of inverter	Only renewable generator

In addition to needing to specify the type of configuration, the capacity (MW) of each component and duration (MWh) of the energy storage also needs to be determined, which may affect both energy value and capacity value, as discussed below. For energy value, having an associated storage capability will allow the operator to shift some production from the lower value solar production hours to higher value hours in the late afternoon or evening, subject to some efficiency loss. As such, a hybrid project would be able to achieve a higher energy value than a stand-alone solar project.

Modeling the energy value of clean generation with storage located separately and operated independently is relatively straightforward, and there are many available studies. In this case, the storage device is typically assumed to have unlimited energy to charge, while the renewable generation is modeled as a production profile; in a price-taker analysis, the energy value is thus the sum of the two (e.g., Gorman *et al*., 2021). On the other hand, modeling DC tightly coupled hybrid configurations can be more complicated because charging the storage system will be limited by the availability of energy from the variable renewable generator such as solar or wind. In addition, the value of the combined system will be a function of the project design, such as in the case of solar hybrids, the sizing of the solar field, and the relative power capacity (MW) of the solar and storage components, and the duration of the energy storage system (MWh). Generally, the energy value of tightly coupled hybrids is less than a roughly equivalent system design that is not tightly coupled (Gorman *et al*., 2021).

Gorman *et al*., (2021) find that in the CAISO energy market, from 2012 to 2019, the addition of battery storage to a tightly coupled hybrid PV system added between \$5 - \$10/MWh for energy alone (along with some capacity value discussed below). Our assessments have found similar results.

A geothermal hybrid with a co-located battery system that charges only from the generator would have some similar energy properties to a tightly coupled wind or solar hybrid but also

[9] In a recent survey, Gorman *et al*., (2021) find that "proposed development [of hybrids] is highest in the West, where 70%–90% of proposed solar is paired with storage (compared to 5%–20% in the East), suggesting a regional driver of co-location."

differences. Similarly to a solar hybrid, it will reduce geothermal plant output during the lowest price or utility cost hours and shift it to the highest price hours. The main difference is that it could operate in this fashion at all hours of the year, thus providing more operational flexibility and reliability to the power system than a variable energy hybrid, which may fail to sufficiently charge the storage system on some days—in the case of solar generation, particularly during the winter.

A further, critical limitation of a simple comparison of average energy value for individual geothermal and hybrid projects is that it does not capture that as the power system is transformed to meet decarbonization targets in planning scenarios it would take *multiple* solar with storage plants to replicate a baseload geothermal profile (see Thomsen 2020). To properly evaluate the resource choices for energy and capacity thus requires more advanced planning modeling than a simple project-level optimization based on historical or forecast prices.

Other technologies

There are a few other clean energy resources that are being evaluated in the West and could provide an alternative to geothermal by providing a firm but flexible energy production profile. Offshore and onshore wind energy has an energy profile that is more continuous throughout the day (without storage) but would require substantial additional capacity to ensure the production profile and, as discussed below, onshore wind located in California has a low capacity rating due to its lack of reliable performance during the state's peak load hours. In California and elsewhere, there is also policy support for green hydrogen, which would be a dispatchable generator that could compete as a firm or flexible resource. It would also have a marginal fuel price which would affect energy market value but is currently only considered in a few planning studies. New nuclear power is under consideration in some Western states, which could have a similar energy profile to geothermal. Finally, long-duration energy storage with several days duration has a high reliability and resilience benefit. There is preliminary data on how geothermal competes with these technologies in resource selection over the coming 10-20 years from some planning studies (see, e.g., the resource plans reviewed in Thomsen, 2021), generally as a function only of comparative forecast costs. The geothermal sector needs to continuously evaluate how geothermal resource attributes are being compared to these emerging alternatives.

1.2 Forecasts of Energy Value

The price trends in the CAISO market are forecast to continue and to be amplified with the continued penetration of solar and other renewable resources. We have evaluated several forward price curves over the coming 20 years offered by different commercial vendors and some in the public domain.[10] These forecasts differ concerning the analytical methods used, as well as particular assumptions about changes to the resource mix, input costs (such as fuel prices), and bounds on market prices. For example, some commercial price forecasts predict a continued increase in negative market prices in California due to growing surplus generation, while others do not. Adding a carbon tax or other cost on carbon will drive up energy prices but will also tend

[10] For example, in Orenstein and Thomsen (2017), we conducted an assessment using public data on simulated future southern California energy market prices from the CPUC’s long-term procurement planning models of 2024, which were issued in 2014. The simulated prices were lower than the actual prices in 2021, but the differences between geothermal and solar average revenues were similar, as a function in part of assumptions about negative prices.

to have a more significant effect on the prices outside the solar production hours. While these forecasts are proprietary and will not be reviewed here in detail, we find that they predict a continuation of the recent trends shown in the actual wholesale markets, and support an energy value difference between geothermal and stand-alone solar PV of $20/MWh, or greater, over the coming 10-20 years. Even with the planned and forecasted increase in energy storage, this trend will likely continue since there is much more solar in the forecasts than storage. At the same time, the energy value of stand-alone storage and some hybrids is also likely to continue to increase over time, reflecting the need for power in the late afternoon and evening periods. However, the number of solar and storage resources needed to shift energy across the non-solar hours will also increase, thereby allowing geothermal to remain competitive as an energy resource (see Thomsen 2021).

2. COMPARATIVE CAPACITY VALUE AND LONG-TERM RELIABILITY

The Western U.S. is currently experiencing a shortage of reliable capacity, which is causing emergency procurements in California. Its capacity rating is a significant economic benefit of geothermal in current and future renewable generation portfolios. Capacity rating here is defined as the percentage (%) of a maximum operating level (MW) that can be used to satisfy the Resource Adequacy (RA) requirements established by the relevant regulatory authorities, which in California are the state energy agencies. Geothermal's capacity rating remains stable over time on a seasonal or monthly basis. In contrast, the capacity ratings of variable energy resources like wind and solar are a function of their penetration in the power system. In particular, the capacity ratings for an additional or marginal solar plant are susceptible to the level of penetration of solar plants that came before it. At the same time, for both stand-alone solar PV and solar hybrids, it is also a function of the forecast levels of solar irradiation over the year. This has been demonstrated in many research studies and in the actual determinations in states with increasing solar penetration.

Geothermal capacity ratings

Geothermal capacity ratings depend on whether they are calculated for existing plants or for planning model purposes. For existing plants, the capacity rating is generally based on recent historical production data. For example, for each forthcoming RA compliance period, the CPUC calculates monthly ratings based on the plant production in the prior three years during the hours of 4 pm – 9 pm. For planning purposes, in the CPUC and most other resource planning studies reviewed around the western states, geothermal obtains a capacity rating of between 85-95%, depending on location (Thomsen 2021).

The reliable performance of existing geothermal during the California August 2020 blackout events was noted in the California root cause analysis (CAISO, CPUC, CEC 2021).[11] This performance also encouraged the recent CPUC initiative to expand geothermal procurement in California, as discussed below (CPUC 2021).

[11] Figures B.8 – B.11 in the report show that geothermal production met its resource adequacy capacity ratings during the peak stress hours in August 2020, with only a small fraction of geothermal capacity on outage, better performance on a proportional basis than the natural gas plants. See CAISO, CPUC, CEC (2021).

Stand-alone solar capacity ratings

Prior to the expansion of solar in California, for planning purposes, new solar plants were assumed to be peak shavers with a capacity rating of 65% - 75%, depending on location. As the solar expansion accelerated, this changed more rapidly than anticipated by planners. By 2017, the CPUC's Resource Adequacy (RA) program calculated an average solar PV Effective Load Carrying Capacity (ELCC)[12] of 57.8%, and a marginal solar ELCC for new plants of 37%. In 2018, the CPUC calculated an average ELCC of 45% for solar, but did not publish a marginal ELCC. In 2021, to inform its upcoming procurements, consultants to the CPUC calculated that the marginal solar ELCC in 2023 would be 7.8%. The CPUC has essentially discounted solar ELCC to approximately zero for longer-term planning purposes. This rapid decline in solar capacity ratings results from the rapid increase in solar production but was not anticipated in the prior years of renewable procurement when utilities selected high quantities of solar on a least-cost basis without fully considering its net economic benefits.

Energy storage and hybrid capacity ratings

Energy storage and hybrids have been a focus of analysis and procurement for the last several years. At the CPUC and in many utilities around the West, the power output (MW) that can be sustained for 4 hours from an energy storage system has been considered the capacity rating until storage penetration increases substantially. At a certain level of penetration, the duration of stand-alone energy storage needs to increase so it can provide resource adequacy outside of the peaking hours, up to some limit point where additional storage cannot add further to the reliability of the power system. The capacity rating for a hybrid system roughly tracks this logic and is considered by the CPUC to be the sum of the capacity ratings of its generation and storage systems up to the combined plants' interconnection capacity. Neither the stand-alone storage nor hybrid storage analyses in California currently consider the effect of energy limitations. However, the next phase of analysis is likely to address such energy limitations and create further adjustments in portfolio needs.

With respect to geothermal hybrids, a key difference is that such a hybrid would have a reliable generation source that would ensure its capacity ratings during periods of weather which diminish wind or solar generation, including periods of long duration energy shortfalls (NERC 2021). As such, the storage system would be used to increase the geothermal project's capacity value regardless of the season.

Monetary value of capacity

Renewable buyers credit new renewable resources with a monetary value for their RA capacity. This value is, in principle, either the prevailing bilateral capacity price in California over the near term, and/or the avoided cost of alternative generation if that is needed in later years over the contract term.

In recent years, the bilateral prices for capacity in California have increased, reflecting supply shortages, including those which resulted in the August 2020 blackouts. These capacity prices are reported annually by the CPUC (showing statistical averages) or by inquiries with capacity

[12] The ELCC is the capacity rating calculated using a probabilistic model.

traders. In 2021, an average price for system RA in California was around \$6.75/kW-month, which, when averaged over a geothermal baseload production profile, converts to around \$9.25/MWh. Orenstein and Thomsen (2017) estimated that the capital costs of a new combustion turbine, which historically has been used as a benchmark new capacity resource, would be similarly converted to around \$18.50/MWh when averaged over a baseload profile. Since new stand-alone solar has close to zero capacity ratings, these capacity valuations can be credited to geothermal and any resource, or portfolio of other resources, which are eligible as capacity resources (but not to stand-alone solar).

On the other hand, most procurement decisions to meet reliability needs are currently made in a resource planning framework, where geothermal is evaluated in comparison to alternative portfolios which may include solar and storage, as well as other resources. In these cases, the full capacity expansion model needs to be run with cost estimates for the eligible resources (Thomsen 2018b). The results of such analysis were discussed above and suggest that new geothermal will typically require multiple MW of solar and limited duration energy storage to replicate a geothermal profile. Hence, the cost comparison must be conducted within such a modeling analysis (e.g., Thomsen 2018b, 2021). In this case, the monetary value comparison is the cost of geothermal selected by the model compared to the cost of the alternative resources (see Thomsen (2018b) and CEC, CPUC, CARB (2021) for further analysis of how geothermal or equivalent firm resources substitute for solar and storage in planning models). In some scenarios modeled in CEC, CPUC, CARB (2021), lower cost firm and/or flexible resources could substitute for a very large capacity of alternative resources, indicating the potential for technology innovation and siting flexibility to improve geothermal competitiveness.

Resiliency and other new requirements for dependable capacity

The California blackouts of August 2020 (along with the more severe wildfire seasons) have demonstrated that new types of power system reliability conditions are emerging in the western U.S. due to climate change. These events, and the reliable performance of the geothermal fleet (CAISO, CPUC, CEC, 2021), were the primary drivers in the CPUC's subsequent decision to require procurement of 1 GW of new geothermal by 2026-2028 (CPUC 2021).[13]

These events and those elsewhere in the country are driving the current trend in resource adequacy and long-term reliability analysis of studies of resiliency. These studies are focused on the increased frequency of extreme, difficult-to-forecast events (wildfire risk, extreme storms, extreme temperatures), which may require sufficient resources to ensure reliable operations for multiple days or weeks (e.g., NERC 2021). This is driving an increased interest in geothermal, microgrids, long-duration energy storage with multi-day duration, green hydrogen fuels, and new nuclear power. The opportunity for geothermal is that most of these new technologies needed for reliability are still significantly higher cost than geothermal.

3. VALUE OF RENEWABLE ENERGY CREDITS

Renewable energy credits (RECs) are tradeable credits created when electric power has been produced from a renewable generator. In the western states, load-serving entities can buy RECs rather than directly contract for power to fulfill some percentage of their renewable energy

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[13] For additional details and context, see Thomsen (2021).

requirements, with rules depending on the state. In principle, the REC price is an indicator of another payment that a renewable generator could receive when selling its power (in practice, most geothermal contracts are bundled contracts for all attributes associated with the electric power).

REC prices are obtained through traders, some commercial publications and occasionally public sources. In 2021, we determined through trader quotes and some public sources that a common REC value was $14.50/MWh (not including any transaction costs). In commercial forecasts, the REC value is expected to be reduced over time as the costs of renewable power decline and the availability of surpluses increase. The REC value is not technology-specific and thus does not add value to any particular type of renewable resource based on its attributes.

4. VALUE OF GEOTHERMAL FLEXIBILITY

In addition to energy and capacity value, California regulators and system operators are also placing a higher value on operational flexibility as the power system transitions to high renewable penetration and decarbonization (Warren *et al*., 2021). There are two primary dimensions to the valuation of operational flexibility when considering geothermal. First, there is the impact on the avoided costs of operational needs when adding geothermal as a substitute for less flexible resources, such as solar power without energy storage. While difficult to calculate exactly, this value is clearly increasing in high solar penetration regions such as California, where solar ramps are increasing year to year and are forecast to continue to do so. This is an aspect of geothermal valuation which requires further analysis.

Second, there is the direct economic value to a flexible geothermal plant when providing such operational flexibility into the wholesale market, or as required under a contract. A critical difference between newer geothermal plants and conventional "baseload" plants—like nuclear, some large coal plants, or some Western hydro during spring conditions—which need to operate at maximum production for purposes of efficiency or other constraints, is that geothermal plants using Ormat's technology can be dispatched downwards on an economic basis by system operators, and can also potentially provide ancillary services which require holding upwards reserves, including frequency regulation (e.g., Nordquist et al., 2013).

As the Western U.S. grid experiences increased operational needs along with a reduction in conventional flexible resources, such as gas-fired generation, geothermal may be able to compete with other new flexible resources to supply these needs. The basic economic requirement is that the lost opportunity cost of providing renewable energy – which in the California market is the net contract cost plus the cost of making up renewable energy credits (RECs), if needed – is lower than what the market (or utility) will provide for operational flexibility. This is already experienced at times on the California grid when energy and ancillary service prices spike over $100/MWh.

At the same time, new types of flexible resources, notably battery energy storage systems, are being added to the grid in California and elsewhere. There are thus two considerations for geothermal companies when offering operational flexibility: the trend in increasing operational needs and the expectation that new flexible resources will be added over time. We believe that, particularly in high solar penetration regions, there will be ongoing operational needs that energy storage will not fully address for at least the coming decade. As a result, it encourages the geothermal sector to become more proactive in developing innovative contracts which allow geothermal plants to provide operational flexibility.

5. WHOLESALE VALUE OF A MERCHANT GEOTHERMAL PLANT

Given the component elements discussed above, the total economic value of a geothermal plant can be estimated in a number of ways. One method is to estimate the recent and forecast value of a merchant geothermal plant, which is defined here as one which is developed on the basis only of wholesale market value and any other market-based credits (that is, without additional payments in long-term renewable contracts), incorporating energy, capacity, operational flexibility and RECs. As noted, this does not include the potential value of newer power system attributes not currently priced in the wholesale markets, such as resiliency and the related capability to provide sustained energy over multiple days. As reviewed in the prior sections, the wholesale value metric is useful as a baseline for contract pricing analysis. If the contract price is higher than the wholesale value, the difference is sometimes called the "renewable premium;" that is, it is what the buyer is willing to pay above market value to achieve a clean energy policy objective.

By our estimates above, a geothermal plant in southern California would have had a wholesale market value of around $75/MWh in 2021, which is higher than prior years due to the recent increases in energy and capacity prices. If this is correct, several recent geothermal contracts in the region would have been priced at around the actual wholesale merchant value, or even lower.[14] However, since wholesale prices fluctuate from year to year, there is no guarantee that this value will be sustained over the coming years. Hence, long-term contracts remain the primary mechanism for development of new geothermal. In addition, higher geothermal valuations can be obtained using planning models which evaluate the comparative costs of resource solutions.

6. CONCLUSIONS

Western U.S. power markets and resource procurement are changing rapidly due to the acceleration of policy goals and the influx of new renewable energy resources, especially solar PV and energy storage. This paper updates our assessment of the economic benefit of geothermal energy to potential buyers in California and the Western U.S., both in absolute terms and when compared to other eligible clean energy resources. Geothermal energy is valued primarily on the basis of recent historical and forecasted wholesale energy, capacity, and REC market prices. Geothermal also addresses emerging regional power system resiliency requirements needed for any increase in extreme events, such as not being highly variable due to weather and with unlimited energy production.

In 2021, we estimate that geothermal energy has a combined energy and bilateral capacity value about $25/MWh higher than solar PV. This value is closer to $33.50/MWh if the avoided cost of new capacity resources are considered. Based on commercial price forecasts, we expect this value difference to continue to increase over the coming decade.

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[14] According to the NREL ATB 2022, geothermal contracts signed between 2019 and 2021 in the western U.S. for which contract prices were publicly released, were between $67.50 - $74/MWh. See NREL (2022) and Robins et al, (2021).

For solar with storage, the comparison is more difficult, and the analysis requires considering planning scenarios. A project-level analysis using current data might suggest that the value gap with geothermal is reduced or fully closed. However, there are still differences between the resources which are relevant for planning purposes. For example, a DC-coupled solar-storage hybrid which charges entirely from the solar field will have significantly lower capacity value during winter months, when geothermal capacity value is unchanged.

Additionally, as renewable penetration increases, the costs of meeting future demand while replacing higher capacity factor gas and coal resources across the western states are expected to increase substantially. In the future decarbonization scenarios we have reviewed beyond 2026-2030 (Thomsen 2018b, 2021), in addition to excess solar and wind capacity, a lot of storage is required to shift sufficient energy to meet energy needs outside solar production hours. In these scenarios, we have found that geothermal is extremely competitive at LCOEs in the range of $75-$85/MWh .

The results reviewed here confirm that geothermal value is both increasing in absolute terms in recent years as power market prices rise and in comparison to alternatives in planning models. In addition, geothermal is well placed to address the emerging resiliency and resource adequacy challenges of the coming decade. The appropriate response of power system planners should be to conduct careful assessment of geothermal economic and reliability value and promote regional coordination to ensure efficient development of the regional geothermal resource.

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