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The Increasing Comparative Value of Geothermal – New Market Findings and Research Needs

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ABSTRACT

In 2017, for the first time, the combined energy and capacity values of geothermal energy significantly exceeded the value of solar photovoltaic (PV) resources in California. In the first quarter of 2017, geothermal's wholesale energy value in southern California was $11-$13.50/MWh greater than solar PV. At the same time, utility estimates of marginal solar PV capacity ratings for the 2018 Resource Adequacy (RA) compliance period were between close to 0% and 20%, resulting in a capacity value difference of $1.40-$18.50/MWh between geothermal and solar PV. Over the next 5-10 years with current trends, geothermal will have a combined energy and capacity value of $22-37/MWh higher than solar PV using conservative assumptions. Additionally, geothermal provides other economic benefits, not monetized in this paper, that improve its comparative value, such as avoided renewable integration costs, operational flexibility and resource diversity. These calculations demonstrate that in Western US utility procurement, geothermal can compete with solar PV on a net cost basis, even as PV costs continue to decline.

1. Introduction

The Western US electric power system is undergoing many operational, reliability and market changes due to the rapid expansion of solar PV and wind. At the same time, utilities continue to procure other types of renewable resources, such as geothermal. Due to the location of geothermal projects, it is typically compared to solar resources in utility procurement decisions. This paper focuses on comparative value of these two resources in California. At low penetration levels, (e.g., under 5% of annual energy) solar in California has had a high energy

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and capacity value[1] because it generates during peak load hours. Until recently, geothermal baseload profiles obtained lower energy and capacity values because so much production was during “off-peak” hours, and innovation in geothermal resources, such as providing operational flexibility, was not yet seen as attractive to utility buyers. Because of these factors, geothermal resources have had difficulty in obtaining an accurate long-term analysis of their *net cost*, i.e., the economic benefits minus contract costs, as needed to compete with solar and wind in utility resource planning and procurement (Linvill et al., 2013; Thomsen 2013).

Research studies have long predicted that, as solar energy production increased in California and elsewhere, the energy and capacity value of additional (or marginal) solar resources would decrease and eventually be significantly lower than the value of other renewable resources, including geothermal (e.g., Mills and Wiser, 2012a,b; Linvill et al., 2013; Thomsen 2013). This paper shows that a reversal in comparative values[2] of geothermal and solar PV took place in California in 2017, and that geothermal’s comparative value will continue to grow with increasing solar penetration over the next decade.[3]

By analyzing wholesale market prices over the past few years, we find that the difference between geothermal and solar PV energy values in southern California have been increasing since 2014 and were $11-$13/MWh greater than solar PV in the first four months of 2017. Additionally, using California Independent System Operator (CAISO) simulations of energy prices for 2024 (CAISO 2014), where overgeneration affects up to 12 percent of hours annually, we find that the difference in energy value between geothermal and solar PV is over $18/MWh *without* assuming significant negative energy prices. The future comparative energy value of geothermal could be higher if negative prices due to overgeneration are persistent during solar PV production hours.

When comparing solar and geothermal capacity value in recent and future years, we used public data from different sources to estimate a range of $1.40-$18.50/MWh greater value for geothermal than solar PV. (CPUC 2017a,b; Astrape Consulting/Joint IOUs, 2017; CAISO 2017b).[4]

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[1] Unless otherwise noted, we use the terms value and economic benefit interchangeably in this paper. Economic benefit is defined as the monetized wholesale value of operational services as well as avoided capacity costs of existing or new conventional infrastructure, such as gas-fired generation. The term capacity rating refers to the percentage of the resource which is eligible to provide Resource Adequacy capacity; capacity value refers to the monetized value of that capacity. These terms are defined in more detail in subsequent sections.

[2] We define comparative value as geothermal value minus solar value; that is, the difference in value rather than the absolute value. The comparative value of geothermal can be increasing even as the overall price level is changing (e.g., as the average wholesale energy price decreases).

[3] We do not focus on wind valuation in the paper, which forecasting studies (e.g., Mills and Wiser, 2012a) predict could experience slightly less decline in economic benefits at high penetrations than solar PV, but which would still be lower value than geothermal over the long-term.

[4] This range reflects the difference in valuation depending on whether the avoided cost of capacity is based on bilateral market prices (the low end of the range) or the cost of new entry, typically a combustion turbine (the high end of the range).

These results suggest that the combined energy and capacity value of geothermal over the next 5-10 years will be $22-$37/MWh greater than the value of solar PV using conservative assumptions and forecasts. Also, utilities and regulators may assign additional monetary values to geothermal based on avoided renewable integration costs, options for operational flexibility, and geothermal's contribution to resource diversity. These results highlight the competitiveness of geothermal on a net cost basis despite continuing cost declines in solar PV.

This paper first describes the general cost-benefit equation used in renewable procurement, followed by comments regarding trends in resource cost and description of the benefits categories. The subsequent sections then focus on the methodology for calculating energy and capacity value and quantitative results, some general comments on other sources of potential value (including other operational services) and conclusions.

2. The Basic Cost - Benefit Analysis Framework

Most utility planning and procurement processes utilize variants on cost-benefit analysis, where the known and forecast economic benefits of alternative resources needed to meet load and policy objectives are subtracted from their known and forecast costs. The basic cost-benefit equation is structured as follows:

Net cost = Levelized Cost of Energy (LCOE) or Power Purchase Agreement (PPA) cost + integration costs - energy benefits - capacity benefits - ancillary services benefits.

We define these benefit components in section 4. When the costs are greater than the benefits, the difference is sometimes called the renewable energy premium.

3. Trends In Renewable Energy Costs

Geothermal resources are participating in an extremely competitive renewable energy market, and the calculation of comparative economic benefits is critical to proper valuation. Solar PV projects in the southwestern US have recent costs between $40-$50/MWh with subsidies (e.g., Bolinger et al., 2015). The lowest cost geothermal project with publicly available prices is the Ormat Nevada Geothermal Portfolio project with a cost of $75.50/MWh.

For purposes of this paper, we assume that the current cost difference between solar PV and geothermal contracts is $30-40/MWh, depending on location (e.g., the quality of the solar PV resource which geothermal is competing against). As a result, to compete with solar PV, a geothermal resource needs to demonstrate quantitative economic benefits which are equal to or exceed this cost difference, as well as provide other benefits which may be qualitatively assessed.

3.1 Net LCOE Estimates

A new factor in renewable procurement in California and elsewhere is the increased renewable energy curtailment as a persistent feature of resource operations (e.g., CAISO 2014, Denholm and Margolis, 2016). Utilities and renewable developers must consider how much energy will actually be delivered from the plant over the term of the contract.

To account for the forecast lost energy in the cost calculation, the utility or developer calculates an adjusted "net LCOE" as follows (see, e.g., Denholm and Margolis, 2016):

net LCOE = base LCOE/(1 – curtailment rate).

As solar PV penetration increases in regions such as California, curtailment has a significant cost impact on additional solar resources. For example, Denholm and Margolis (2016, pg. 10) outline a California 2030 scenario with 20% solar. In this case, if the base unsubsidized solar PV LCOE is $60/MWh, then an average curtailment rate of 4.6% results in an average net LCOE of $63/MWh, while a marginal curtailment rate of 26% leads to a marginal net LCOE of $81/MWh. At higher solar penetration, Denholm and Margolis simulate even higher solar curtailments, unless energy storage is added to the power system. While all renewable resources may face increasing curtailment during solar PV production hours, the effect of curtailment on geothermal is much lower on an average production basis, because it is producing most of its energy outside solar production hours.

If a net LCOE is calculated for a resource, then the analysis should not also add the energy value during the periods of curtailment (unless the resource is assumed to curtail to a lower operating level rather than completely back down). For example, if a resource is assumed to provide 80% of its total forecast output due to curtailment risk, and the curtailment hours are assumed to have negative market prices, then the resource's energy value should not be further reduced due to the negative prices. However, the energy and capacity value should be calculated for all the remaining production. In the remainder of this paper, we will focus on economic benefits without considering curtailment.

4. Background on Economic Benefits of Renewable Energy

This section provides background on the definitions of economic benefits of renewable energy and some methods for calculating those benefits, both in the current wholesale markets in California and as analyzed in different simulation studies of future conditions.

4.1 Categories of Economic Benefits

There are three major categories of economic benefits of renewable resources: energy (or active power), capacity and ancillary services. This subsection offers brief definitions and some explanation of modeling methods relevant to valuation of energy and capacity (discussion of ancillary services and integration costs follows in Sections 7-8).

4.1.1 Energy benefits

Energy benefits or value are defined here as either (1) the wholesale energy market revenue obtained by renewable generation, (2) the avoided energy production costs for a vertically integrated utility not participating in a market, or (3) the revenues obtained from marginal energy prices or avoided production costs calculated in a simulation model of a regional power system. In this paper, we focus on (1) and (3).

In the western U.S., the primary wholesale markets for energy with transparent prices are the CAISO markets and the Energy Imbalance Market (EIM). We use prices from the CAISO markets for energy valuation of type (1), while using simulated prices for the same region for valuation of type (3). The exact methods are described further in Section 5.

4.1.2 Capacity benefits

Capacity rating or credit is defined as the percentage of resource maximum output (MW) counted towards a region's resource adequacy requirement (which in California is determined the prior year for the next year)[5] or to a utility's long-term capacity needs.[6] Capacity benefits or value are the monetary value of that capacity in \$/kW or \$/MW in some period (typically month or year), or as averaged over a resource's energy production in that period (\$/MWh).[7] In utility renewable procurement, capacity value is typically converted into \$/MWh when calculating a total economic benefit for the energy being procured.

The monetary values selected for the capacity value calculation depend on whether the load-serving entity buying the renewable energy is assuming that the renewable resource is displacing an existing capacity resource or a new capacity entrant, which conventionally has been either a combustion turbine (CT) or a combined cycle gas turbine (CCGT). The net cost of a new capacity resource is calculated as the unit's annual fixed revenue requirement minus its expected energy and ancillary services revenues (e.g., CAISO 2017b). Historically, buyers have used forward capacity price curves, which assume that the renewable resource is displacing an existing capacity resource for several years, but in subsequent years, if there is sufficient load growth, it is displacing new capacity resources.

Because solar PV generation coincides with annual peak load hours based on the load shape in California and many other regions, the early penetration of solar PV obtained a high capacity rating, which was reflected in utility procurement valuations. Typically, the solar PV capacity rating was in the range of 65-75%[8] of maximum power output (MW), or higher, depending on actual or forecast solar irradiation at the project location and technology type (e.g., fixed or tracking PV). At the same time, geothermal has a higher capacity rating, generally getting around 90% or higher rating.

Despite the higher capacity rating, geothermal baseload energy historically had lower capacity benefits or value, because capacity value has to do with how much the buyer is paying for the resource's capacity rating over its entire renewable energy purchase. When calculating the net cost of renewable energy, the capacity value is calculated on the basis of total energy production procured. For example, in a particular year, the avoided capacity cost (\$/kW-year) is divided by the capacity factor[9] or forecast hourly production, multiplied by 8,760 hours and converted to \$/MWh. Counterintuitively, a geothermal profile with a 90% capacity rating (or higher) and a 95% capacity factor gets a significantly lower capacity benefit than a solar PV profile with a

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[5] Under the CPUC's Resource Adequacy program, the capacity rating is called the Net Qualifying Capacity (NQC); for details on the CPUC's Resource Adequacy program, see materials at http://www.cpuc.ca.gov/RA/.

[6] These ratings are calculated using several methods, including probablistic simulation models which evaluate the operation of all resources during hours of highest risk of loss-of-load, and simpler approximation methods. We discuss some of these further in Section 6.

[7] Some studies refer to the capacity rating as the capacity value. Please note the terminology in our paper.

[8] See, e.g., the CPUC RPS Calculator from 2010.

[9] The capacity factor is the percentage of the resource's maximum feasible energy production over a particular period (generally a year).

lower capacity rating and a much lower capacity factor (e.g., 15%-35%, depending on location) – as long as the solar PV resource is contributing to avoiding peaking capacity. This result was reflected in renewable valuations done for utility procurement and is found in several of the studies reviewed below.

4.2 Literature Review

There are now a large number of studies evaluating the comparative economic benefits of different renewable resources under alternative scenarios for regional power systems in the United States. Our focus here is on studies relevant to the primary locations for geothermal resources in the western states. Studies which examine changes in solar energy and capacity value in different future California and Western US renewable scenarios include Mills and Wiser (2012a, 2012b, 2014), Denholm et al., (2013) and Jorgenson et al., (2014), CPUC (2017a), and Astrape Consulting/Joint IOUs (2017). A few studies also show valuation of a baseload profile (e.g., Mills and Wiser, 2012a), as discussed further below. E3 (2014) and Denholm and Margolis (2016) did not perform resource valuation, but modeled very high renewable penetration scenarios and pointed out that at higher renewable penetration, solar PV would have a potentially much higher curtailment rate than a geothermal profile (for the reasons discussed above).

These simulation studies anticipated that as solar PV penetration increased and shaved the peak load, creating a "net load" shape, each additional tranche of solar PV resources would obtain a declining incremental or marginal benefit for energy and capacity. Mills and Wiser (2012a) showed that this relationship accelerates with continued solar PV expansion until incremental solar is no longer obtaining any additional capacity benefit (but continues to provide energy benefit). In a subsequent paper, Mills and Wiser (2012b) surveyed the literature on PV capacity ratings and showed a common result of decreasing capacity ratings with penetration.

In contrast, while baseload geothermal energy value fluctuates with changes in overall energy price levels, its capacity ratings remain constant because geothermal production is invariant to weather and because the resource is able to operate in all peak load or peak net load hours, no matter when they occur. That is, if a region or utility's new capacity requirements shift to the evening peak loads, a geothermal plant can serve those loads whereas a solar PV plant cannot (e.g., Mills and Wiser, 2012a).

With respect to geothermal valuation, Linvill, Candelaria and Elder (2013) and Thomsen (2013) surveyed geothermal attributes and developed a framework for comparative resource valuation, but did not include quantitative results on comparative energy or capacity values. They pointed out that geothermal attributes were not sufficiently captured in utility valuation methods. Nordquist et al., (2013) and Matek (2015) reviewed the literature and operational experience with flexible geothermal operations, but did not examine valuation.

Edmunds and Sotorrio (2015) conducted a quantitative analysis of potential geothermal value in the current and future CAISO ancillary service and ramping reserve markets. They conclude that current ancillary service prices are too low to merit geothermal participation at current PPA costs, as the ancillary service value would not compensate for lost contracted revenues. They forecast that ancillary service and ramping reserve prices may be substantially higher in future scenarios, opening up some opportunities for additional geothermal revenues when providing these services.

4.3 Mills and Wiser Results

Mills and Wiser (2012a) is the one research paper which did conduct a comparative analysis of economic benefits of different renewable resources and a baseload profile in a large number of renewable penetration scenarios. They developed a capacity expansion model with hourly dispatch of the California grid in 2030. While the simulation model is at a high level of aggregation and doesn't include a network, it provides insight into how renewable valuations can change as a function of penetration by different resource types. We also note that their model uses a scarcity price on energy to signal capacity needs, and hence average energy value remains higher than in a model with a separate capacity payment. This study was one of the earliest to identify that a baseload renewable profile would have a higher comparative value than a solar PV profile as solar PV penetration increased. In each scenario discussed below, the value of a particular resource is for a marginal addition to the scenario.

In their 2030 basecase (with only marginal renewables), Mills and Wiser calculate that a marginal solar PV resource has a \$37/MWh capacity value[10] and a \$54/MWh energy value, for a total of about \$89/MWh value (less some minor deductions for integration costs). In contrast, the baseload profile has a \$20/MWh capacity value and a \$50/MWh energy value, for a total of \$70/MWh. Solar PV thus has \$19/MWh higher economic value initially than the baseload profile.

As Mills and Wiser increase solar PV penetration in their model, comparative benefits change. In their 15% PV penetration case, solar PV has an \$8/MWh capacity value and \$45/MWh energy value, for a total of \$47/MWh. By 30% PV penetration case, solar PV has a \$1/MWh capacity value and \$27/MWh energy value, for a total of \$25/MWh. In both PV scenarios, the baseload profile held its original value of \$70/MWh. In the 15% PV case, the baseload profile is worth \$23/MWh more than the PV profile, and in the 30% PV case, the baseload profile is worth about \$45/MWh more.

While the model and scenarios developed by Mills and Wiser are stylized, their valuation results did anticipate the findings that we demonstrate in the next sections using actual and forecast energy market prices and updated solar capacity ratings and values. Arguably, given current market outcomes, Mills and Wiser's model was overly optimistic about solar PV economic benefits at high penetration, and their later papers have explored methods to mitigate the value decline with other measures, such as energy storage (Mills and Wiser, 2014).

5. Trends in Energy Benefits

The next sections turn to current market trends in comparative benefits, as well as some updated forecasts, beginning with wholesale energy benefits. Solar PV production in California is largely coincident with daily peak loads, and thus historically obtained a high energy value in California. More recently, there is enough solar production in California to dramatically reduce prices during these hours and shift the net load peaks to the early evening hours. In this section, we use

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[10] In both calculations, capacity value is based on the value of an avoided new combustion turbine.

both baseload and solar PV profiles, calculating their value using actual CAISO wholesale market prices for energy as well as simulated future prices.

5.1 Energy Value in Southern California, 2014-2017

There have been two dominant trends in the CAISO energy markets over the past few years. First, the average level of energy market prices has been declining due to low natural gas prices and increased renewable generation, and more recently higher hydro conditions. Second, the level of prices during solar PV production hours has been declining rapidly due to the rapid expansion of solar energy generation. From an initial level of less than 500 MW of solar in 2010, the California grid now has more than 14 GW of solar resources, including both solar PV and CSP, of which about 7 GW is behind-the-meter solar PV (CEC 2017). Much of this solar power directly or indirectly affects CAISO energy market prices.

When the average price level declines, all renewable resources have lower energy value; however, some resources face more significant value declines than others. In particular, solar PV is experiencing a more rapid value decline than geothermal, which obtains value outside the solar PV production hours.

To evaluate this trend, we used three solar PV profiles previously developed by the CAISO and the CPUC in the CPUC's long-term procurement planning process (LTPP).[11] We selected these randomly because they are at different locations and use different technologies (one uses single-axis tracking technology and the other two use fixed-tilt). We cross-multiplied these profiles by two different CAISO day-ahead energy market prices at aggregated locations[12] and normalized to $/MWh in market revenues. The results for 2014 through the first four months of 2017 are shown in Table 1 below. As can be seen, solar PV and geothermal energy values were approximately equal in 2014. Due to the increased solar PV production, the geothermal value was slightly greater than solar PV in 2015 (around $2-$3/MWh greater) and continued to increase in 2016 (around $4-$5/MWh greater) . In early 2017, the CAISO experienced low and negative prices in the day-ahead market during solar PV production hours, due to over-generation conditions related to high hydro, low loads and continuing solar PV expansion. Not surprisingly, in this period, the geothermal value increased substantially to $11-13/MWh over solar PV. We expect midday prices to rise later in the year, reflecting higher loads. However,

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[11] The LTPP is 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/.

[12] We used the South of Path 15 Trading Hub prices and the Southern California Edison (SCE) Location Aggregation Point (LAP) prices, all available on the CAISO OASIS site. Renewable energy contracts with California buyers differ in whether the seller is asked to settle financially at the nodal price, or at one of the aggregated prices (which reflect congestion from the node to aggregated location). Recent contracts we have seen asked the seller to specify whether the buyer should assume that energy is settled at the node where the generator is located or at either the trading hub or LAP. For that reason, we evaluated both types of aggregated prices for this review.

we do not yet know whether these energy value differences will increase or decrease over the full year.[13]

Table 1 – Difference in annual average energy value between geothermal baseload and solar PV ($/MWh) in Southern California, 2014-2017 (January-April), showing Trading Hub (TH) (SP 15) and SCE Load Aggregation Point (LAP) prices

	2014		2015		2016		2017 (January – April)	
	TH	***LAP***	***TH***	***LAP***	***TH***	***LAP***	***TH***	***LAP***
Average energy value ($/MWh)								
Geothermal baseload	$46.54	$48.04	$31.48	$32.59	$27.98	$29.04	$26.86	$27.28
Blythe Solar PV Solar PV_1	$46.72	$48.76	$29.10	$30.56	$23.87	$25.27	$15.60	$16.00
Solar PV Photovoltaic 2024	$45.51	$47.45	$28.26	$29.64	$22.99	$24.32	$15.62	$16.03
NV_WE	$45.42	$47.46	$28.16	$29.55	$22.80	$24.18	$13.29	$13.65
Difference in energy value between geothermal and solar PV*($/MWh)								
Blythe Solar PV Solar PV_1	-$0.18	-$0.72	$2.38	$2.04	$4.10	$3.76	$11.26	$11.28
Solar PV Photovoltaic 2024	$1.04	$0.60	$3.23	$2.95	$4.99	$4.71	$11.24	$11.25
NV_WE	$1.13	$0.58	$4.43	$3.04	$5.17	$4.85	$13.56	$13.62

***A negative sign indicates that solar PV is worth more than geothermal. Explanation of source data and methods in the text above.**

5.2 Energy Value Over the Next Decade

Simulations of the California grid in the future suggest the continued phenomenon of the rapidly expanding comparative value difference between geothermal and solar PV that occurred in early 2017. Prices in the solar PV production hours are low or negative, while late afternoon and evening prices reflect the dispatch of gas generation to meet the net load. It is expected that the trend shown here continues and that more hours will be persistently in over-generation conditions.

To test this, we used simulated southern California energy market prices from the LTPP models of 2024, issued in 2014. There were two scenarios utilized: a 33% RPS scenario and a 40% RPS scenario (as described in CAISO 2014). The prices included negative prices established by the curtailment cost assumed in the model. There was significantly more renewable curtailment in the 40% RPS scenario, affecting up to 12% of hours annually, but concentrated in solar PV

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[13] We note that the same solar profiles during Spring of 2016, which also experienced higher hydro conditions but less solar penetration, had both higher and lower average value when the full year was evaluated.

production hours.[14] We took a conservative approach, using results from the same simulation using a $0/MWh curtailment cost[15] assuming negative prices would not persist and be managed by the market.

For a perspective on the possible impact of negative pricing on comparative value, we then changed the $0/MWh prices to -$5/MWh and -$50/MWh.[16] Note that -$5/MWh is slightly above the *average* negative price in the day-ahead energy market price data during Spring 2017 which we used (which we calculate as -$4.26/MWh for the LAP prices), while most negative energy prices in the CAISO real-time market fall between $0 and -$50/MWh (CAISO 2017b).

Table 2 shows the 2024 results: when using the $0/MWh price during curtailment periods, the value difference between geothermal and solar PV in the 33% RPS scenario is $8-10/MWh (coincidentally similar to spring 2017 prices), while the difference in the 40% RPS scenario is $15-18/MWh. As might be expected, a slightly negative price of -$5/MWh does not greatly affect the comparative valuation when compared to the $0/MWh price. However, as prices become more negative during solar production hours, as reflected in the -$50/MWh price sensitivity, they affect solar energy value significantly more than geothermal value.

We note that natural gas price assumptions in these 2024 simulations (CAISO 2014) are similar to those prices in 2014, and hence the market prices outside the solar PV production hours are more similar to 2014 CAISO prices than those in 2016-2017. If natural gas prices remain low in the future, then the forecast energy value difference could diminish; however, if there are more curtailment hours and if market prices become more negative, then the value difference could increase.

Our conclusion is that based on both current energy market prices and simulated future prices, a $10-$20/MWh difference in the energy value between geothermal and solar PV is reasonable for long-term contracts starting in 2017.

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[14] We also note that the curtailment results result even after the operations of the full 1.325 GW of new energy storage required under the California storage mandate. However, if the model is allowed to export surplus power to the rest of the west, curtailment declines.

[15] These price results are shown in Eichman et al., (2015).

[16] The original simulations were not re-run with these negative price assumptions, which would have marginally changed the number of simulated curtailment hours. For discussion, see Eichman et al., (2015).

Table 2 – Difference in simulated annual average energy value between geothermal baseload and solar PV in Southern California, 2024

	2024 - 33% RPS	2024 - 40% RPS		
Overgeneration price assumption:	***$0/MWh***	***$0/MWh***	***-$5/MWh***	***-$50/MWh***
Average energy value ($/MWh)				
Geothermal baseload	$43.11	$39.64	$39.09	$34.17
Blythe Solar PV Solar PV_1	$34.93	$24.36	$22.86	$9.60
Solar PV Photovoltaic 2024	$33.67	$22.92	$21.41	$7.85
NV_WE	$33.13	$21.48	$19.87	$5.41
Difference in energy value between geothermal and solar PV* ($/MWh)				
Blythe Solar PV Solar PV_1	$8.18	$15.28	$16.23	$24.57
Solar PV Photovoltaic 2024	$9.44	$16.72	$17.68	$26.33
NV_WE	$9.98	$18.17	$19.23	$28.77

***A negative sign indicates that solar PV is worth more than geothermal. Explanation of source data and methods in the text above.**

6. Trends in Capacity Benefits

The recent trends in solar PV capacity value parallel the changes in comparative wholesale energy benefits: while solar previously had a higher capacity value than geothermal, the opposite is now the case. In 2018 by most measures, marginal solar PV resources in California have very low capacity ratings and a lower capacity value than geothermal resources. This section explains the calculation of these comparative benefits.

6.1 Capacity Ratings in California, 2016-2018

The forecast of declining solar capacity ratings as a result of increasing solar penetration has now been realized in California. Section 5.1 noted the recent rapid increase in solar production in California. However, until 2014, the CPUC and its jurisdictional utilities used a solar PV capacity rating method which assumed that solar PV would be counted as a peaking resource despite the level of solar penetration.[17] Using this method, solar capacity value would continue to be higher than that of geothermal. In 2014, the CPUC began to calculate the solar PV and wind effective load-carrying capability (ELCC), a measure of capacity rating, using a probabilistic method which reflects the impact of penetration (e.g., CPUC 2017a). There are two ELCC ratings: the average ELCC, which is based on the contribution of the full solar or wind portfolio; and the marginal ELCC, which is the contribution of an additional increment of solar or wind. For utility procurement, the marginal ELCC is thus the relevant estimate (Astrape Consulting/Joint IOUs, 2017).

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[17] Called the exceedance method, this approach measured actual or forecast solar production which exceeded the 70th percentile value during a set of defined peak load hours.

In its annual RA proceeding, the CPUC disseminated draft ELCC results for 2016 and 2017 before adopting estimates for 2018, which are shown in Table 3 below (CPUC 2017a). These results show that as solar capacity increased each year, the calculated average and marginal solar ELCC declined. In 2016, the average solar ELCC was only slightly below the historical estimates cited above. However, the next two years show a rapid decline – more rapid than predicted in the earlier research studies. The estimate of a 45% average solar PV ELCC in 2018 is for the month of June; while this was the adopted ELCC, the CPUC also notes that if behind-the-meter PV is considered as well, the average for the full solar portfolio would be 33.5%. In other months of the year, the average solar ELCC is as low as 0% (January), meaning that solar does not provide any capacity contribution in those months while geothermal resources would always provide the same contribution.

For current utility procurement, accurate estimates of the marginal solar ELCC are needed when comparing this resource to geothermal. The CPUC did not itself identify the marginal solar ELCC for 2018, but several stakeholders provided their own estimates, including a joint estimate from the three California investor-owned utilities (IOUs), using the same ELCC model and consultant as the CPUC, as well as other approximation methods (Astrape Consulting/Joint IOUs, 2017). The Joint IOU report estimates marginal solar ELCCs for 2018[18] in the range of 11.5% - 21.49% in northern California, and 9.58% - 15.24% in southern California, with the lower end of the range corresponding to behind-the-meter fixed PV and the higher end to tracking PV. Using another methodology – a net load peak approximation method[19] – for calculating solar capacity ratings, the Joint IOU report finds lower marginal solar capacity ratings, in the range of 3.78% - 8.74% in northern California and 1.29% - 4% in southern California. The properties of these two methods are discussed further in the joint IOU report.[20] This range of very low marginal solar capacity rating estimates for 2018 suggests that geothermal capacity ratings should already be compared to a range of solar ratings from close to zero to no more than around 21.5%. The utility can determine whether to be more or less conservative in determining the appropriate metric or range for procurement decisions.

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[18] The 2018 estimates are based on a 33% RPS case.

[19] The net load peak approximation develops a net load curve for the utility (e.g., the CAISO “duck curve”), and evaluates how well marginal solar resources contribute to forecast peak net load requirements. This is a simpler method for calculating solar capacity ratings than the full ELCC model, and was presented as a check on the ELCC results.

[20] As discussed in the report, the net load peak approximation method is better at calculating the alignment of solar production with utility net loads, but may not reflect interactions between solar production and other resources, such as storage, being evaluated in the ELCC model.

Table 3 – Recent CPUC proposed and adopted solar PV ELCC ratings in California

	IOU Solar PV capacity	Average Solar PV ELCC	Marginal Solar PV ELCC from prior period
2016 RA Compliance period (draft)	5,914 MW	63%	
2017 RA Compliance period (draft)	7,424 MW	57.8%	37%
2018 RA Compliance period (adopted)	10,506 MW	45%	

Source: CPUC, 2017a.

6.2 Capacity Ratings Over the Next Decade

California entities have begun to evaluate long-term solar ELCCs. These estimates have not yet been approved by the CPUC and we do not review them in great detail, but they confirm the results of earlier research studies reviewed in Section 4. For example, the Joint IOUs study evaluates a 43% RPS scenario in 2026, and calculates a marginal solar ELCC of 4.16% - 8.28% in northern California and 2% - 3.91% in southern California (Astrape Consulting/Joint IOUs, 2017). These estimates are consistent with findings in prior research studies.

6.3 Comparison of Capacity Value

Using the methodology described above, applied to the recent estimates of solar PV ELCCs, marginal geothermal capacity values in 2018 (i.e., when converted to $/MWh) are higher than marginal solar PV capacity values.[21] As noted above, in California, capacity value in the short-term (e.g., 1-6 years in the future) is typically based on the avoided cost of existing capacity resources, while over the longer term, it is based on the avoided net cost of new capacity resources. The calculations are shown below.

6.3.1 Costs of Existing and New Capacity Resources

The 2016 CPUC RA Report (CPUC 2017a) finds that the average cost of bilateral RA contracts from existing resources is $37.20/kW-year when examining aggregated contracts over 2016-2020, while 85% of the contracts are at or under $50.28/kW-year. The weighted average of Local Resource Adequacy costs is about 31% higher than System Resource Adequacy (CPUC 2017a). For our purposes here, we simply use the average cost.

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[21] If the geothermal resource being procured is providing System Resource Adequacy but is being compared to a PV plant providing Local Resource Adequacy, then the value difference may be lower currently.

For new capacity resources, we use net costs calculated by CAISO, of $177/kW-year for a CT and about $10/kW-year less for a CCGT (CAISO 2017b).[22] CAISO (2017b) calculated energy and ancillary service market revenues for the CT in 2016 as between $4.80- $10.38/kW-year in NP15 and $12.50 - $17.29/kW-year in SP15, with the variation in each location reflecting assumptions about bidding and real-time market clearing. These market revenues are generally declining as energy prices decline. Hence, the *net* cost of a new CT is between $160-$172/kW-year in 2016, but probably higher in 2017 if energy market prices continue to fall.

6.3.2 Capacity Value Based on Avoided New Capacity Resources

We use these numbers and the formula for converting capacity ratings, capacity factors and avoided capacity costs to calculate the capacity value of geothermal and solar resources. Figure 1 below graphs some of our findings on capacity values in different years. All values in the figure use the 2016 avoided net cost of a new CT. The flat red line on the figure is the geothermal capacity value, which remains constant. The sloped blue line is the solar capacity value, reflecting different average and marginal solar capacity ratings and assuming that the solar capacity factor is 35%. The difference between these two lines is the difference in capacity value: on the left hand side of the figure, solar capacity value is higher than geothermal, while moving to the right, the value difference reverses as solar capacity ratings drop.

On the left hand side of Figure 1, we show the solar PV capacity value calculated using a 2010 CPUC estimate of its capacity rating of 65%. Although not shown in the figure, by our calculations, at around a capacity ratings of 32%, the capacity values ($/MWh) of the two resources are the same (due to the method for conversion of capacity value into $/MWh described above) regardless of the capacity resource being displaced. As marginal solar capacity ratings drop below 32% geothermal capacity value is greater than that of solar PV. (See Figure 1) The upper bound on the difference between geothermal and solar PV capacity value, when marginal solar PV has a *zero* capacity rating, is $18.50/MWh. This value is simply the estimated capacity value of geothermal resources under the stated assumptions.

6.3.3 Capacity Value Based on Avoided Existing Capacity Resources

Figure 1 does not show the same calculations for the avoided cost of existing capacity resources, as reflected in the bilateral contract prices. For a geothermal resource, the capacity value in terms of an avoided existing capacity resource at the average bilateral price would be $4/MWh. In parallel to our calculation shown in the figure, for a marginal solar capacity rating of 21.5%, the solar capacity value would be $2.60/MWh, resulting in a difference with geothermal of $1.40/MWh. When marginal solar capacity ratings trend to zero, geothermal value would remain at $4/MWh. Hence, we estimate the capacity value range in 2018 calculated with respect to avoided bilateral contract costs as $1.40-$4/MWh. This is the low end of our capacity value range.

6.3.4 Additional Sensitivities

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[22] Alternatively, the avoided new resource could be a 4 hour energy storage resource, which could have a similar net avoided capital cost to a CT in that time-frame and also provide energy shifting capability.

We also note that geothermal capacity value would be slightly higher if geothermal capacity ratings are higher than 90% or if net costs of new capacity are assumed to be higher.

As this section has made clear, solar capacity ratings as penetration increases is a subject of extensive research and comparative analysis. While there has been progress in the CPUC's Resource Adequacy program, further consensus on such ratings will facilitate appropriate comparison between geothermal and solar resources. A reasonable assumption in 2018 is that geothermal capacity value is higher than marginal solar PV capacity value, and possibly already as much as $18.50/MWh higher when the metric is avoided net costs of new capacity resources, with the upper bound estimate being more certain in future years with further solar expansion. Other factors, such as the amount of long-duration energy storage, will also affect these calculations over time.

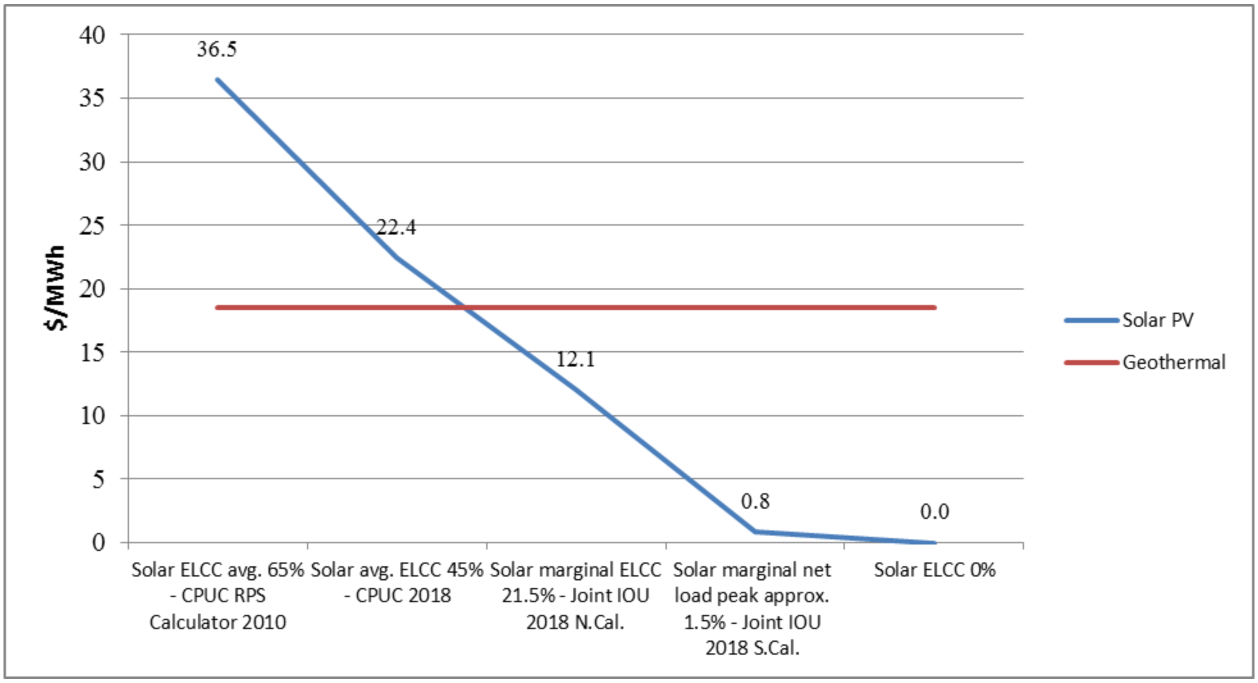

Figure 1 – Comparison of geothermal and solar PV capacity values in California when displacing a new CT, using different metrics

6.4 Flexible Capacity

Flexible capacity is a category of capacity introduced by the CPUC and CAISO in 2015 and intended to provide a forward requirement for resources which can meet emerging operational needs. The initial definition for flexible capacity is the capability to support a 3-hour sustained ramp, meaning that the resource can follow the CAISO dispatch instruction, in either the upward or downward direction, over that period.

Currently some geothermal plants in California are qualified as effective flexible capacity.[23] If selected as a flexible capacity resource, a geothermal plant would have to schedule itself to be available for ramping to the CAISO during the defined ramp periods. This could entail significant geothermal curtailment in the late afternoon, as the ramping needed in that period from a generator would be to follow the system net load ramp in the upwards direction and the resource would need to be backed down to its minimum operating level in the prior hours. Solar PV plants providing flexible capacity would have a variant of the same requirement, backing down earlier in the afternoon to reduce the rate of the system ramp and hence creating a much greater curtailment rate over total production. Hence, being selected as flexible capacity would increase the contracted costs of these resources. However, we do not currently have any data on these costs. A useful research study would be to clarify the expected operations of a geothermal plant providing flexible capacity to the CAISO.

7. Value of Ancillary Services and Operational Flexibility

Ancillary services and other types of services which require operational flexibility, such as ramping reserves, are a small component of electric power systems by economic value (CAISO 2017b), but one which is steadily more significant in regions with high renewable penetration. As the California grid reduces its reliance on natural gas generation to provide these services, a new generation of clean resources will have opportunities to participate in these markets. These include energy storage, demand response and renewable resources.

While wind and solar PV resources are increasingly being equipped to provide ancillary services (CAISO, 2017a), geothermal can follow the system operator dispatch signal within a known range and without the need for production forecast (or recharging, like energy storage). Hence, it has some operational advantages which need to be evaluated further to understand comparative value. We noted the study by Edmunds and Sotorrio (2015), which is a useful starting point for examination of potential geothermal economic benefits.

7.1 Frequency Regulation

Frequency regulation (or just regulation) is a balancing service conducted on time frames of 2-6 seconds, depending on the region. The regulation control signal is used to increase or decrease generation or load to balance the system in between real-time dispatch instructions (which are typically on a 5-minute basis). Geothermal has been used to provide frequency regulation in Hawaii (Nordquist et al., 2013; Matek 2015). At this stage, while CAISO Regulation market prices (which on average were $8-11/MW in 2016, but are much higher during certain peak load and system ramp periods) generally remains insufficient to elicit geothermal participation (see, e.g., Edmunds and Sotorrio, 2015), the geothermal sector should prepare to provide this service if opportunities emerge over the next few years.[24]

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[23] These include Calpine's Geysers units; see Final Effective Flexible Capacity List for Compliance Year 2017, available at http://www.caiso.com/planning/Pages/ReliabilityRequirements/Default.aspx.

[24] For CAISO, average Regulation Down prices were $3.13/MW in 2015, and $8.34 in 2016; average Regulation Up prices were $5.50 in 2015 and $10.84 in 2016; average Spinning Reserve prices were $3.68/MW in 2015 and $5.65/MW in 2016. See CAISO (2017b).

In the CAISO markets, there are separate Regulation Up and Regulation Down products, meaning that a resource which is dispatched at its maximum operating level can provide only Regulation Down, while a resource at its minimum operating level can provide only Regulation Up. A resource can also provide both up and down regulating ranges. This approach is useful for baseload geothermal plants, which could offer to provide Regulation Down and only be curtailed if the market price is sufficient. Alternatively, a geothermal plant could be backed down to follow both an upwards and downwards regulating signal.

A large solar PV project in the CAISO has recently completed a demonstration project which included providing regulation (CAISO 2017a). We encourage CAISO to similarly conduct a demonstration project with a geothermal resource providing regulation.

7.2 Contingency Reserves

Spinning and non-spinning reserves, collectively operating reserves, are dispatchable reserves held for generation during system contingencies.[25] Resources held on contingency reserves must keep the required headroom to provide energy. For a renewable resource, this would require operating at below maximum operating level. Unlike frequency regulation, all energy held back to provide this reserve is curtailed. If CAISO spinning reserve prices increase as higher cost renewable energy and energy storage displaces natural gas generation, there may be sufficient value for geothermal participation. Similarly to the Regulation markets, the highest prices are likely to take place in the ramping hours and evening peak loads. In those hours, there could be future opportunities for geothermal participation.

7.3 Ramping Reserves

Ramping reserves are additional ramping capability reserved by the system operator for real-time operations. Currently, only the Midcontinent ISO (MISO) and CAISO have implemented such reserves. In the CAISO markets, where they are called the Flexible Ramping Product (FRP), upward and downward FRP reserves are set-aside in the real-time markets on a 15-minute and 5-minute basis. The reserve clearing prices are set by resource offers for energy; that is, there aren’t separate ramping offers. To be selected to provide ramping reserves, resources have to be already in the bid stack for real-time energy dispatch, and the clearing price for the ramping reserves reflects the re-dispatch opportunity costs of the marginal unit placed on reserve. To participate in these CAISO markets, the geothermal unit could, without much risk, initially submit a sufficiently high bid to back down the resource in real-time economic dispatch. A demonstration project with a geothermal resource would also be helpful to evaluate such subhourly dispatch operations.

7.4 Integration Costs

The new operating conditions being created by expansion in production from variable energy resources – wind and solar – has resulted in an increased procurement of frequency regulation

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[25] In the CAISO, the operating reserve requirement is a formula based on the largest single contingency and other factors and typically amounting to about 1,700 MW per hour. For eligible resources, the contingency reserve quantity is the range which can be provided in 10 minutes, often cited as the unit ramp rate x 10 minutes and bounded above by the unit maximum operating level.

and ramping reserves in some regions, including in the CAISO markets. For example, in 2016, CAISO increased its procurement of frequency regulation by 19% for Regulation Up and 28% for Regulation Down compared to 2015, and costs of ancillary services roughly doubled (CAISO 2017b). While these changes may be transitory, many studies suggest that additional frequency regulation will be procured in the future (e.g., CAISO 2014). California also has a flexible capacity requirement, as described above, to facilitate meeting ramping requirements. Additional operating reserves may be needed in the future, such as frequency responsive reserves and inertial responsive reserves. Provision of these additional reserves have a variable cost which can be estimated using market prices or through simulation and potentially fixed costs of flexible capacity.

In principle, buyers of renewable energy in California and elsewhere assign integration costs when ranking alternative purchases of (non-dispatchable) wind and solar energy but do not assign such costs to non-variable resources, such as geothermal. This value difference varies, from low integration cost approximations adopted at the CPUC, which range from $2-$4/MWh for wind and solar, to higher estimates seen in some utility integrated resource plans. Mills and Wiser (2012b) found that Western utility resource planners used estimates of variable solar integration costs in the range of $1.25-$11/MWh, primarily based on “rules of thumb” due to lack of operating experience. We note that the adjusted LCOE discussed in Section 3 is a type of integration cost, because some curtailed renewable energy will be caused by the inflexibility of existing conventional generation.

In this paper, we do not make a specific recommendation on integration costs to be used when comparing a geothermal resource to a solar PV or wind plant. However, if the net costs of geothermal and these competing resources are close, utilities should evaluate integration costs to assist in the procurement decision.

8. Conclusions and Research Needs

This paper has reviewed some of the literature on comparative renewable resource valuation and updated the estimates of current energy and capacity values using current energy prices and capacity ratings from the California power markets and regulatory agencies. We focused on comparing geothermal and solar PV economic benefits. Early papers on renewable valuations forecast that while solar PV initially had significantly higher economic benefits than geothermal (as measured on an energy and capacity basis), as solar penetration increased, geothermal value would eventually be greater than solar PV. We demonstrate that this result is now evident in the California markets.

Our findings show that on a combined energy and capacity basis, geothermal is worth as much as $12.40-$32/MWh more than solar PV in the 2017-2018 timeframe.[26] As we look to the coming 5-10 years, many factors will change in the California and regional power system. Most studies forecast that solar energy will continue its expansion and that energy value during solar

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[26] The low end of this range assumes a value difference of $11/MWh for energy and $1.40/MWh for capacity, based on avoided costs of existing capacity; the high end assumes a value difference of $13.50/MWh for energy and $18.50/MWh for capacity, based on the avoided net costs of new capacity. All numbers are found in Sections 5-6.

production hours will continue to decline. The 2024 simulated energy prices we used suggested that geothermal energy values could reach up to $17/MWh greater than solar PV even if prices during solar overgeneration periods do not become negative. Similarly, when solar PV capacity ratings are zero, then using the avoided net cost of a new CT, the difference in capacity value could also be $18.50/MWh. For these reasons, we find that geothermal energy and capacity value are likely to be at least $37/MWh greater than solar PV within a few years.

In addition, utilities and regulators should further evaluate geothermal's value when avoiding the integration costs of variable energy resources, its potential contribution to operational flexibility, and possibly other factors, such as benefits of resource diversity, which we did not analyze here. These factors, and others, are likely to drive the value difference above $40/MWh.

To build upon this analysis, we suggest additional research into geothermal operations when providing frequency regulation or real-time economic dispatch and ramping reserves in California and additional public analysis on scenarios for future market prices in the 10-20 year timeframe. Moreover, research is needed to clarify geothermal operations as flexible capacity resources. We believe that further analysis on the market costs of additional ancillary services and ramping capability to integrate wind and solar could clarify trends in integration costs.

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