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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-6A20-58186
March 2013

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. CP08.8301

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

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Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

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Acknowledgments

This project was funded by the U.S. Department of Energy Solar Energy Technologies Program. The authors would like to thank Craig Turchi for performing the SAM CSP runs. The following individuals provided valuable input and comments during the analysis and publication process: Adam Green, Udi Helman, Jennie Jorgenson, Shucheng Liu, Trieu Mai, Joe Stekli, and Frank Wilkins. Any errors or omissions are solely the responsibility of the authors.

Executive Summary

Concentrating solar power (CSP) with thermal energy storage (TES) is a dispatchable source of renewable electricity generation. However, the dispatchability of this resource is limited by the availability of solar energy. This makes it challenging to quantify the value of CSP and provide comparisons to alternative generation sources.

The California Independent System Operator (CAISO) has prepared a number of analyses of the grid operational challenges associated with the state's 33% renewable portfolio standard (RPS). These analyses, which used a commercial production cost model, created a publically available database of the CAISO system. This database can be used as a basis for analyzing the potential value of CSP with TES in California.

This analysis used the "Environmentally Constrained" 33% RPS scenario database in the PLEXOS grid simulation tool to estimate the value of CSP in avoiding conventional fossil generation, and compared this value to other sources of generation. To perform this analysis, we created a baseline scenario and added four types of generators, each in a separate scenario. The four generator types were photovoltaic (PV), a baseload generator with constant output, a CSP plant providing dispatchable energy, and a CSP plant providing both energy and operating reserves. Each generator added the same amount of energy (about 1% of annual demand) for an equal comparison of their value. In each case, we calculated the difference in production costs between the base case and the case with the added generator. This difference in cost was attributed to the added generator as its operational value to the system.

PLEXOS dispatches the hourly energy inflow of solar energy in the CSP plant to minimize the overall system production cost. The model considers the interaction of the California system with the rest of the Western Interconnection, and new generators within California can therefore affect the dispatch of coal, gas, and other generators throughout the West.

The operational value of each generator is associated with avoided fuel (and associated emissions) as well as reduced operations and maintenance (O&M) and power plant start costs. In addition to operational value, generators add capacity value to the system that can be estimated by examining generator operation during periods of high net demand. The CSP plants in this study provided energy during essentially all high net demand hours, implying a capacity credit similar to a conventional dispatchable resource. The corresponding value is typically determined by a proxy resource, such as a combustion turbine, or alternative market-based mechanism. In this analysis, we use a low capacity cost of \$55/kW-yr and a high cost of \$212/kW-yr.

Table ES-1 Summarizes the value estimated by combining the operational results from the PLEXOS simulations with capacity value estimates for each technology.

Table ES-1. Total Value Produced by Different Generator Types in the CAISO "Environmentally Constrained" Scenario

	Operational Value Per Unit of Delivered Energy ($/MWh)			
	Baseload	**PV**	**CSP (no Reserves)**	**CSP (with Reserves)**
Fuel	33.9	29.1	38.9	54.0
Variable O&M	4.7	4.4	5.2	6.0
Start	0.1	-2.3	2.1	4.7
Emissions	21.9	22.7	20.1	18.3
Capacity (Low / High)	6.3 / 24.7	10.7 / 41.3	13.6 / 52.3	13.6 / 52.3
Total	66.8 / 84.7	64.6 / 95.3	79.8 / 118.5	96.6 / 135.3

Overall, the analysis demonstrates several properties of dispatchable CSP including the flexibility to generate during periods of high value and avoid generation during periods of lower value. Of note in this analysis is the fact that significant amount of operational value is derived from the provision of reserves in the case where CSP is allowed to provide these services, adding about $17/MWh. This represents a substantial change in operational practice, including frequent operation at part-load. The incremental value of CSP with TES in this scenario was $30/MWh to $51/MWh compared to a baseload resource, or $32/MWh to $40/MWh compared to PV. This range depends on both the ability of CSP to provide operating reserves and the expected cost of new capacity.

This analysis also indicates that the "optimal" configuration of CSP may vary as a function of renewable penetration, and each configuration will need to be evaluated in terms of its ability to provide dispatchable energy, reserves, and firm capacity. As the net load variability increases with more renewable generation, CSP plants with different solar field sizes, amount of storage, and ramp flexibility may be best suited to enable integration of these variable-generation (VG) resources. This will also change the value proposition for CSP with TES. Future analysis will consider these elements under alternative RPS scenarios, including higher fractions of energy derived from renewable resources.

In summary, NREL has implemented a methodology for evaluating the operational impacts of CSP systems with TES within the PLEXOS production cost model. This model was used to quantify the additional value provided by this flexible resource as compared to baseload or VG resources. The model can be used to investigate additional scenarios involving alternative technology options and generation mixes, applying these scenarios within California or in other regions of interest.

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1 Introduction

The California Independent System Operator (CAISO) has performed a number of analyses of the grid impacts and operability of various scenarios associated with meeting California's 33% renewable portfolio standard (RPS) in 2020 (CAISO 2011a). These scenarios, developed by the California Public Utilities Commission (CPUC), have included various amounts of concentrating solar power (CSP). However, to date, the CSP plants in the scenarios evaluated by the CAISO have not included significant amounts of dispatchable thermal storage. As of early 2013, contracts with such plants have been approved[1] and there is increasing interest in the potential benefits offered by plants deployed with thermal energy storage (TES). CSP with TES is a dispatchable source of renewable energy and can provide valuable grid flexibility services including the ability to shift energy in time and provide both firm capacity and ancillary services. This flexibility can potentially aid in integrating variable-generation (VG) sources such as photovoltaics (PV) and wind and further reduce the overall production cost in a system when compared to a renewable portfolio of equal energy but without TES.

This document describes a preliminary evaluation of CSP with TES in the CAISO system, based on one of the scenarios developed for the 33% RPS study. CSP with TES was incorporated into the PLEXOS production cost model, and the differences in production cost were analyzed for the CPUC's "Environmentally Constrained" scenario.[2] Specifically, the incremental value of CSP with TES providing about 1% of CAISO demand was evaluated, and was also compared to PV and a baseload resource providing the same amount of energy. It should be noted that this work does not evaluate any of the capital or operational costs of any of the technologies evaluated.

Overall, the analysis demonstrates several properties of dispatchable CSP including its ability to generate during periods of high value and avoid generation during periods of lower value. Of note in this preliminary analysis is that significant operational value is derived from providing ancillary services that require frequent operation at part-load.

[1] The CPUC maintains a list of project status at http://www.cpuc.ca.gov/PUC/energy/Renewables/index.htm.
[2] PLEXOS is one of several commercially available production cost models. A list of publications that describe previous analyses performed with this tool is available at http://energyexemplar.com/publications/.

2 Simulation of CSP in the CAISO System

2.1 CAISO Scenarios

California has an RPS that requires 33% of all retail electricity sales to be provided by renewable energy by 2020 (CEC 2011). California has a number of renewable generation resources available including geothermal, hydro, and biomass; but two of the largest potential sources of generation—wind and solar—are VG resources that create challenges to cost-effective grid integration. As part of the effort to understand these challenges, the CAISO has studied the grid integration impacts and requirements of a 33% RPS, evaluating a number of scenarios largely formulated by the CPUC and California Energy Commission (CEC). These scenarios include projected load and mix of renewable generator types.

The CAISO has studied these scenarios using the PLEXOS production cost model. Production cost models simulate grid operation and can be used to help plan system expansion, evaluate aspects of system reliability, and estimate fuel costs, emissions, and other factors related to system operation.[3] The models have the primary objective function of committing and dispatching the generator fleet to minimize the total cost of production, while maintaining adequate operating reserves to meet contingency events and regulation requirements. Modern production cost models often include transmission power flow simulations to ensure basic transmission adequacy for the generator dispatch. Increasingly, these models are used to evaluate the impact of incorporating VG resources such as wind and solar.

The CAISO studies have evaluated a number of 33% scenarios, combining the projected mix of generators in California in 2020 with assumptions about changes in operating requirements due to renewables, and changes that may occur throughout the Western Interconnection (CAISO 2011a). Table 1 illustrates the renewable mix in four of the CAISO scenarios. The scenarios generated by the CPUC included various amounts of CSP. However, the assumed CSP plants included few with thermal storage; moreover, the plants that did include storage were simulated with a fixed dispatch that does not optimize their performance.

[3] These models are also used by wholesale market participants. In regions with wholesale power markets, production cost models can also be used to estimate market clearing prices on a short-term or long-term basis.

Table 1. Renewable Mix in CAISO 33% RPS Scenarios

Scenario	Region	Incremental Capacity (MW)							
		Biomass/ Biogas	Geothermal	Small Hydro	Solar PV	Distributed Solar	CSP [1]	Wind	Total
Trajectory	CREZ-North CA	3	0	0	900	0	0	1,205	2,108
	CREZ-South CA	30	667	0	2,344	0	3,069	3,830	9,940
	Out-of-State	34	154	16	340	0	400	4,149	5,093
	Non-CREZ	271	0	0	283	1,052	520	0	2,126
	Scenario Total	*338*	*821*	*16*	*3,867*	*1,052*	*3,989*	*9,184*	*19,266*
Environmentally Constrained	CREZ-North CA	25	0	0	1,700	0	0	375	2,100
	CREZ-South CA	158	240	0	565	0	922	4,051	5,935
	Out-of-State	222	270	132	340	0	400	1,454	2,818
	Non-CREZ	399	0	0	50	9077	150	0	9,676
	Scenario Total	*804*	*510*	*132*	*2,655*	*9,077*	*1,472*	*5,880*	*20,530*
Cost-Constrained	CREZ-North CA	0	22	0	900	0	0	378	1,300
	CREZ-South CA	60	776	0	599	0	1,129	4,569	7,133
	Out-of-State	202	202	14	340	0	400	5,639	6,798
	Non-CREZ	399	0	0	50	1,052	150	611	2,263
	Scenario Total	*661*	*1,000*	*14*	*1,889*	*1,052*	*1,679*	*11,198*	*17,493*
Time-Constrained	CREZ-North CA	22	0	0	900	0	0	78	1,000
	CREZ-South CA	94	0	0	1,593	0	934	4,206	6,826
	Out-of-State	177	158	223	340	0	400	7,276	8,574
	Non-CREZ	268	0	0	50	2,322	150	611	3,402
	Scenario Total	*560*	*158*	*223*	*2,883*	*2,322*	*1,484*	*12,171*	*19,802*

[1] CSP is referred to as "Solar Thermal" in the CAISO reports

For this analysis, we chose to evaluate CSP in the "Environmentally Constrained" scenario,[4] shaded in gray above. This scenario has a much greater contribution of PV than the other scenarios, reflecting various initiatives within California to promote distributed solar generation (CEC 2011). It also includes CSP, although it does not reflect the latest projections of CSP deployment such as plants with thermal storage that were approved by the CPUC in 2012.

2.2 Implementation of CSP Plants in PLEXOS

A separate document describes in detail our methodology of implementing CSP with TES into the PLEXOS production cost model (Denholm & Hummon 2012). This section summarizes this previous work.

A CSP plant with TES consists of three independent, but interrelated, components that can be sized differently: the solar field, which produces thermal energy from solar radiation; the thermal storage tank; and the power block, which converts thermal energy into electricity.

The plant modeled in this simulation is a parabolic trough system, which collects the sun's energy using curved mirrors that focus sunlight on receiver tubes that run the length of the solar field. The reflected sunlight heats a fluid flowing through the receiver tubes. This heat transfer fluid is passed through a steam generator, producing steam for use in a conventional steam-turbine generator. Another configuration currently being deployed is a tower system, which uses a large field of flat, sun-tracking mirrors known as heliostats to focus and concentrate sunlight

[4] The choice of this scenario was based, in part, on feedback from CSP industry stakeholders. As discussed in section 4, the relative values of different renewable source may be highly dependent on their relative penetration, and additional analysis is needed to evaluate the impact of different generator mixes.

onto a receiver on the top of a tower. Current tower systems use water or salt as the heat transfer fluid passing through the receiver. Thermal storage systems for trough plants and tower plants can be "direct," where the storage material is the same as the receiver heat transfer fluid, or "indirect," where the receiver fluid transfers its energy to the storage system using an intermediate heat exchanger.

Figure 1 summarizes the implementation of CSP with TES in this study. First, an hourly flow of solar-generated electric energy is produced using the System Advisor Model (SAM) (Gilman et al. 2008; Gilman and Dobos 2012) version 2012-5-11. This occurs outside the PLEXOS dispatch model. The CSP simulations used the wet-cooled empirical trough model (Wagner and Gilman 2011). The model converts hourly irradiance and meteorological data into thermal energy and then models the flow of thermal energy through the various system components, finally converting the thermal energy into net electrical generation output. Meteorological data were derived from the National Solar Radiation Database (NSRDB) (NREL 2007).

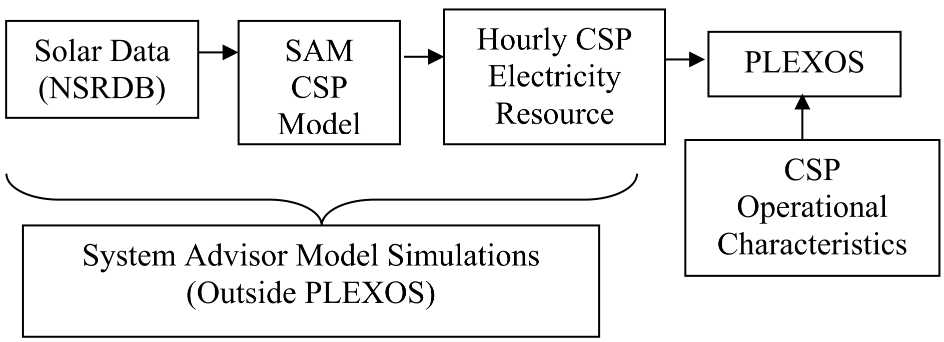

Figure 1. General process of implementing CSP

The "electrical equivalent" thermal energy generated by SAM is an input to PLEXOS, which dispatches this energy, along with the rest of the generation fleet, to minimize the overall system production cost. The actual dispatch of CSP energy in PLEXOS uses a modified form of its hydro algorithm to simulate storage, generator operation, and the effect of solar multiple. In each hour, PLEXOS can send solar energy directly from the solar field to the grid via a simulated power block, to storage, or a combination of both. The model can also choose to draw energy from storage. The ability to store energy is limited by the capacity of the storage tank, measured here in terms of hours of rated plant output that can be stored.

In addition to the hours of storage, a key parameter in the CSP simulation is the solar multiple (SM), which is a measure of the relative size of the solar field and power block, and is an important factor in determining a plant's capacity factor and effective use of solar radiation.[5] The solar multiple in PLEXOS was established by scaling the power block to some fraction of the maximum output of the solar field. For example, a SM of 2.0 can be simulated by setting the

[5] The solar multiple normalizes the size of the solar field in terms of the power-block size. A solar field with a SM of 1.0 is sized to provide sufficient energy to operate the power block at its rated capacity under reference conditions (in this case, 950 W/m^2 of direct solar irradiance at solar noon on the summer solstice). The collector area of a solar field with a higher or lower SM will be scaled based on the solar field with a multiple of one (i.e., a field with a SM of 2.0 will cover roughly twice the collector area of a field with a SM of 1.0).

maximum size of the power block to 50% of the maximum output from the CSP simulations from SAM.

The simulated power block includes the essential parameters of the CSP power block, including start-up energy, minimum generation level, and ramp-rate constraints. The model considers start-up losses in the dispatch decision by assuming that a certain amount of energy is lost in the start-up process. In this case, we used start-up losses equal to 20 MWh per 100 MW of plant capacity (20% of the energy required to run the plant at rated output for 1 hour) (Sioshansi and Denholm 2010). No additional start-up costs were attributed to the CSP plant. The power-block minimum generation level is assumed to be 40% of maximum. In the base case, we assumed a constant efficiency as a function of load (equivalent to a flat heat rate).[6] Sensitivity to this assumption is discussed in the Results section.

Several additional parameters are important to establish the ability of the CSP plant to provide grid flexibility and operating reserves. We evaluated two scenarios for CSP operation. The first case does not allow CSP to provide any operating reserves. In this case, the plant ramp rate was set to allow ramping from minimum (40%) to maximum in the 1-hour simulation period. The second case allows the plant to provide spinning, regulation, and load-following reserves. The plant was not allowed to provide non-spinning reserves.[7] For spinning reserves, the plant is allowed to provide reserves while operating at or above its minimum generation point. The ramp rate of the plant is set to allow ramping from minimum to maximum in 10 minutes. As a result, the plant can offer its entire operating range capacity (60% of its rated capacity when operating at minimum) as spinning reserves. No actual energy provision was assumed while providing contingency reserves. This is discussed in more detail in the Results section.

The ability to provide regulation reserves is constrained by the actual provision of real energy during any given time period. A plant providing regulation reserves is constantly increasing or decreasing output in response to a regulation signal. This means that at any given point, the plant is providing more or less energy than its scheduled energy output. As a limited energy resource, CSP cannot provide continuous “up” regulation services beyond what is being added to storage or what is held in storage during the “up” event. There are several approaches to simulating the provision of reserves with a limited energy storage device. One is to account for the real energy that would be dispatched by a plant providing up (or down) regulation.[8] An alternative approach used here is to assume symmetric regulation operation in a manner similar to simulation of

[6] Previous analysis of small steam plants and estimates of CSP performance indicate a relatively flat heat rate down to about 50%–60% of rated capacity, with a minimum generation point at 20%–30% of rated capacity (Denholm & Mehos 2011). So, our assumption of a flat heat rate will tend to overestimate CSP performance, whereas the assumed minimum generation point will underestimate performance. The impact of these assumptions is discussed in the Results section.

[7] Non-spinning reserves may require extended operation and may not be well suited to limited energy resources such as CSP. Regardless, the value of non-spinning reserves is typically very low (the average price in the base case was less than $1/MWh), so this assumption will have very little impact on the value of CSP—either in these simulations or in real market conditions.

[8] This requires an assumption about the amount of time the plant providing regulation actually spends providing energy above its normal dispatch point when providing up regulation (and below when providing down regulation). The net energy provided in each dispatch interval is then subtracted from the energy that could be otherwise dispatched (and compensated at prevailing market rates). We did not have this information, so pursued an alternative approach assuming approximately symmetric operation.

electricity storage devices (such as batteries) when providing regulation reserves. A conventional storage plant providing regulation reserves essentially operates at a zero output setpoint and then provides up regulation by discharging or down regulation by charging.[9] If regulation is a net-zero energy service over a relatively short time period, limited energy storage devices should be able to provide continuous regulation service.

Rules allowing limited energy storage devices to provide regulation reserves should accommodate CSP plants, especially those with several hours of storage (CAISO 2011b). However, a plant providing regulation must operate with sufficient headroom in both the up and down directions so that its net energy when providing regulation services can be essentially zero. To constrain the CSP plant to an operation mode that allows a net-zero energy balance for regulation reserves, we set the minimum regulation point of the plant to 70% of maximum capacity. This means that the plant can provide up regulation services over 30% of its capacity (from 70% to maximum) and can provide down regulation services over 30% of its capacity (from 70% down to minimum).

For load-following reserves, we allowed the plant to provide both up and down services. We assume load following will be a net-zero energy service over time frames that allow a CSP plant to provide its full operating range for these services. Because load-following is a relatively new service without clearly defined market rules, additional analysis will be needed to evaluate the ability of CSP plants to provide load-following reserves.

The total up services offered by the CSP plant in any given hour was set to an amount equal to or less than its maximum capacity minus its current generation point. There were no cost penalties applied to the plant for offering operating reserves. This is particularly notable for regulation reserves, where generators often offer a non-zero bid price for providing regulation services due to additional wear and tear and heat-rate degradation associated with operating at a constantly changing setpoint. However, none of the conventional generators in the CAISO database have a regulation bid price (except for a few high merit order units that set a scarcity price). As a result, as long as the additional cost of providing regulation from a CSP plant is similar to a conventional unit, this should have no impact on the *relative* change in production cost associated with providing regulation reserves from a CSP plant. However, a CSP developer would need to consider these additional costs compared to the additional value generated by provision of reserves services. No minimum up or down time was modeled; however, the start-up losses tend to minimize frequent starts. This issue is discussed in more detail in the Results section.

The cost minimization routine in PLEXOS does not optimize the CSP operation from the plant owner's perspective, but optimizes the entire system to minimize the sum of several operational costs including fuel (and associated emissions cost), variable operations and maintenance (O&M), and start costs. However, the cost minimization routine tends to maximize the use of CSP during periods of highest system cost, therefore producing a plant dispatch that tends to maximize net revenue for the plant.

[9] In reality the setpoint would be a small constant charge (negative output) to compensate for round trip storage losses and any constant energy decay losses that will occur.

2.3 Analysis Approach

A number of methods can evaluate the economic benefits of an individual generator or generator portfolio. Our analysis was based on evaluating an incremental amount of CSP when added to an otherwise static generation mix. The operational value of CSP was determined by running a base case, and generating an overall system production cost. A new scenario was then created by adding CSP (or another generator type) and re-running the production simulation. The total difference in production cost can then be attributed to the CSP plant, generating an annual benefit. This benefit (in total dollars of reduced production cost) can also be divided by the annual CSP generation to derive a benefit per unit of generation ($/MWh). This same approach can be applied to multiple generator types to generate comparisons of relative value.

In addition to operational value, a capacity value can also be generated via a number of approaches, generally evaluating the coincidence of production during periods of highest net demand. This was also performed, and these two values (operation and capacity) can be added to produce an overall annualized value or value per unit of generation.

As described earlier, the overall framework of this study was based on an analysis of a CAISO 33% RPS scenario. When using a "difference-based" approach in a production simulation, sufficient generation must be added to produce a quantifiable impact on the system. For this analysis, we chose to add plants generating energy sufficient to provide 1% of CAISO demand. However, to be consistent with the 33% RPS, this 1% energy from CSP was added to a base scenario where 32% of the energy was derived from renewables. The same method was used to add PV and a baseload plant, as discussed below.[10]

More specifically, we started with a base scenario where we took the "Environmentally Constrained" case, and removed some PV from within the Southern California Edison (SCE) service territory. A total of 1,548 MW, producing 3,149 GWh per year was removed from the "SCE small PV" category in the CAISO database. This produced a 32% base case, to which various generator types could be added to analyze their value in achieving a 33% RPS. This 32% base case was run to establish its operational cost.

A total of four plant types were added to this scenario to determine their absolute and relative value.

1. CSP with TES. A 762 MW (net) trough CSP plant with a SM = 2 and 6 hours of storage. Although modeled as a single plant, this would likely be two or more smaller plants. From an operational standpoint, this assumption is slightly conservative, because smaller plants would provide somewhat additional dispatch flexibility. The minimum generation point of 40% corresponds to 304 MW, with the ability to ramp over its full range (458 MW) in one hour. The net generation (determined, in part, by the dispatch) was 3,050 GWh per year. This plant was allowed to shift energy but not provide reserves. The plant was added within the SCE service territory with performance based on the solar resource at 32.85 N Lat., -114.95 W Long.

[10] While each technology produced a slightly different total amount of energy, value of each was calculated on a per megawatt-hour basis as opposed to total system value. This normalization largely eliminates any effect caused by the small differences in annual generation.

2. CSP with TES providing reserves. This was identical to the previous case, but the plant was also allowed to provide load-following, regulation, and spinning reserves, constrained by the parameters described in section 2.2.
3. PV. This case evaluates the production difference associated with 1,548 MW (producing 3,149 GWh per year) of PV generation.[11] Note that this plant was "added" to the 32% case simply by running the actual CAISO environmental trajectory case. It should also be noted that a PV plant providing the same energy as the simulated CSP has about twice the installed capacity (1,548 MW of PV vs. 762 MW of CSP). This impacts the operational and net capacity value difference between PV and CSP, as discussed in the Results section.
4. Baseload Resource. This case evaluates the impact of adding a constant energy source providing 3,150 GWH per year, by adding a fixed, zero-cost generator with a constant output of 359 MW.

In addition to changing the generation mix, the operating reserve requirement was modified in the base scenario, because the change in PV penetration will change the variability and uncertainty of the net load. This variability and uncertainty drives the requirements for regulation and load-following reserves. The reserve requirements for each of the 33% RPS scenarios was originally calculated using a method and data sets described in CAISO (2011a). We did not have access to the code and some of the data sets used to generate these hourly reserve requirements. However, NREL has generated a similar statistical approach to calculate regulation and load-following reserves requirements described by Ibanez et al. (2012). To use an approach that most closely reproduces the original CAISO methods and results, we used the NREL methodology only to calculate the *difference* in reserves requirements associated with the base case (or the removal/addition of reserves associated with deriving 1% of CAISO energy from PV located in Southern California). This difference was applied to the original reserve requirements to evaluate the impact on production costs. We assume that the addition of CSP with TES or the baseload resource does not increase the reserve requirements. The system contingency (spinning) reserve requirement was not adjusted because proposed CSP plants are much smaller than plants likely to be the largest contingency on the system.

With the exception of the changes in the generation mix and CSP performance parameters, this analysis used the system characteristics as established by the CAISO PLEXOS model.[12] The model includes the entire Western Interconnection and assumes least-cost dispatch across the entire Interconnection (restricted by the modeled transmission capacity). Many of the regulatory, policy, and business practices that actually occur in the various balancing areas reduce the ability to achieve the "optimal" dispatch assumed in the model. In addition, to reduce model run time, power plants outside of California are modeled with fewer constraints on operation such as how quickly they can be started. Combined, these issues create a more flexible system than exists today. This likely reduces the value of flexible resources within California, but it is not possible to quantify the overall impact without additional analysis.

[11] This would consist of many smaller individual plants, but the PV is aggregated to a single output profile in the CAISO database.
[12] A more detailed description of the database, development, and assumptions is provided by CAISO (2011a).

Fuel prices were not modified. Natural gas prices in the CAISO database varied by region and by time within the single year of the simulation. For Southern California, the price ranged from \$5.6 to \$6.3/MMBtu. The CAISO database includes an emissions cost of \$36/ton of CO_2.

The analysis in this report was performed using PLEXOS version 6.207 R08 x64 Edition, using the Xpress-MP 23.01.05 solver, with the model performance relative gap set to 0.5%. Each yearly run was completed by performing four quarterly runs, with results summed to derive annual values.[13] To validate basic model performance, we compared our results from the CAISO's "environmentally constrained" case to published results. The total system-wide annual production cost calculated by the CAISO was \$18.63 billion.[14] Our result (performed on a more recent version of the PLEXOS software) was \$18.53 billion, or a difference of about 0.5%.

[13] The run time for each quarter was typically 20 to 30 hours.
[14] Personal correspondence with Shucheng Liu from CAISO on Feb. 25, 2013.

3 Results

3.1 Overview of CSP Operation

The general performance of CSP in providing dispatchable energy can be evaluated by examining its operation during periods of high prices. The marginal price of energy in a power system is driven by a combination of factors including load patterns, fuel prices, and system resources. In general, there are two daily load and price shapes common in many parts of the U.S. During the winter, loads and prices tend to have a bimodal shape, with a spike in the morning and larger spike in the evening. During the summer, loads and prices tend to have a smooth “sine wave” shape with loads and prices peaking in the late afternoon driven by air-conditioning demand.

The presence of wind and solar tends to change the traditional price/load relation curves historically observed. Because these sources have zero marginal cost of generation, they tend to reduce the marginal price of system generation during periods of strong wind or solar output. As the penetration of VG increases, prices are increasingly correlated with the “net load”—or load removing the contribution from wind and solar generators.

Figure 2 illustrates the price/load relationship for three days in the winter, starting on January 31. The data are for the SCE zone in the PLEXOS 32% base case simulation. The top curve is the total load, and the bottom curve is the wind and solar generation within the SCE zone. The VG curve shows the very distinctive solar generation in the middle of the day. This is subtracted from the total load to get a net load, or the load met by the rest of the system’s generators. This net load is strongly correlated with the price curve, showing a small price spike in the morning, and a much larger price spike in the evening. This price spike is due, in part, to the fact that solar generation is decreasing at the same time that demand for electricity is increasing, thus creating a significant up ramp in net demand.

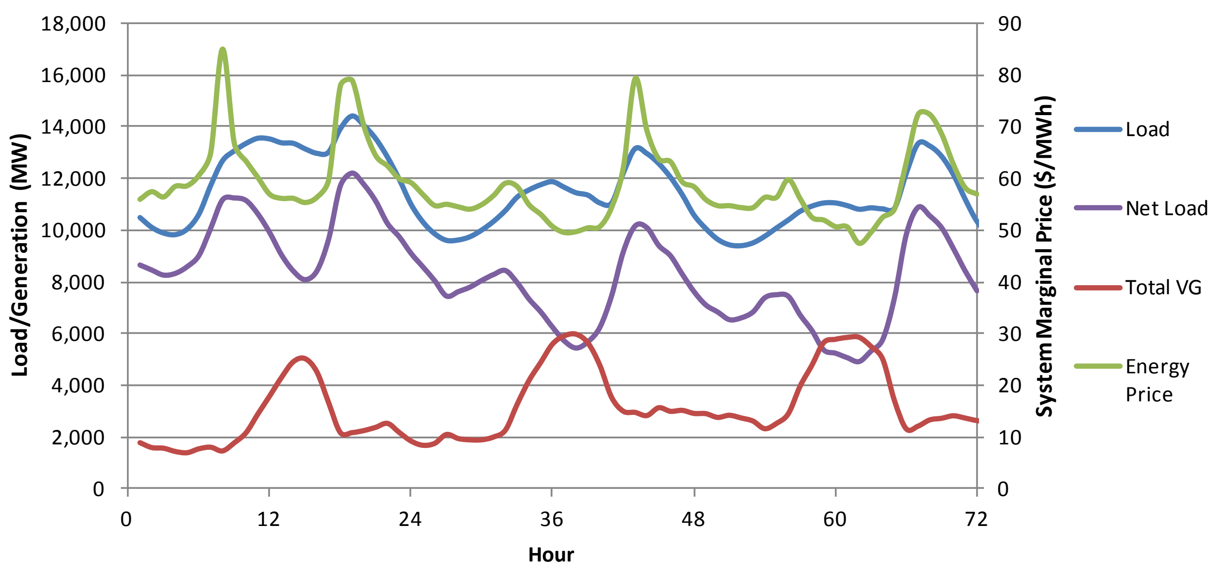

Figure 2. Base case price load relationships in the SCE Zone for three days starting January 31

Figure 3 shows the same relationships for the summer (starting June 24), again showing significant mid-day solar production, and reducing net demand in the middle of the day. This also moves the net load peak to later in the day during periods of reduced solar output. (Note the scale change indicating a much larger overall load due to significant demand for cooling in the afternoon.)

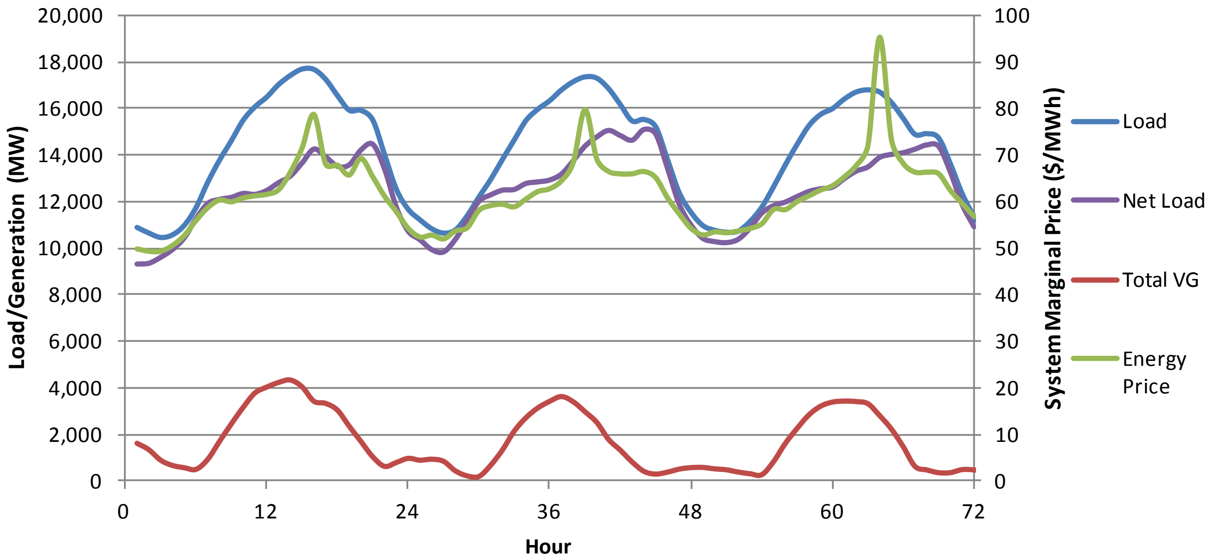

Figure 3. Base case price load relationships in the SCE Zone for three days starting June 24

Previous analysis has demonstrated that CSP dispatched to produce the highest economic value will follow the system marginal price shapes, and dispatches with two distinct patterns (Denholm & Hummon 2012). During the winter, the plant will start up using carried-over thermal energy from the previous day to meet the morning load peak. It will then often reduce output, or even turn off completely during the middle of the day, and increase output again in the evening. During the summer, the plant will operate continuously from morning into the evening, and reliably generate at maximum output during the peak demand that occurs in the late afternoon and early evening.

This analysis demonstrates similar operation in the CAISO simulations. Figure 4 shows an example of CSP operation during the same three-day period as in Figure 2. It shows the solar energy inflow, which is centered around noon, but also during periods of relatively low mid-day prices. The actual use of that energy (in red) shows the plant shifting energy to the evening and carrying energy over to the next day. It also shows the CSP plant reducing output substantially or turning off during the middle of the day.[15]

[15] Figure 4 combines the system marginal prices from the base case dispatch with the CSP results isolated from the simulation with added CSP. Because CSP itself affects the entire system dispatch, the actual system marginal prices from the CSP cases are slightly different. Also, the simulated dispatch represents a least-cost dispatch based on the various generator characteristics and constraints, and does not necessarily represent the dispatch that would occur under wholesale market conditions, which would have additional operating parameters and constraints such as conditions of power purchase agreements.

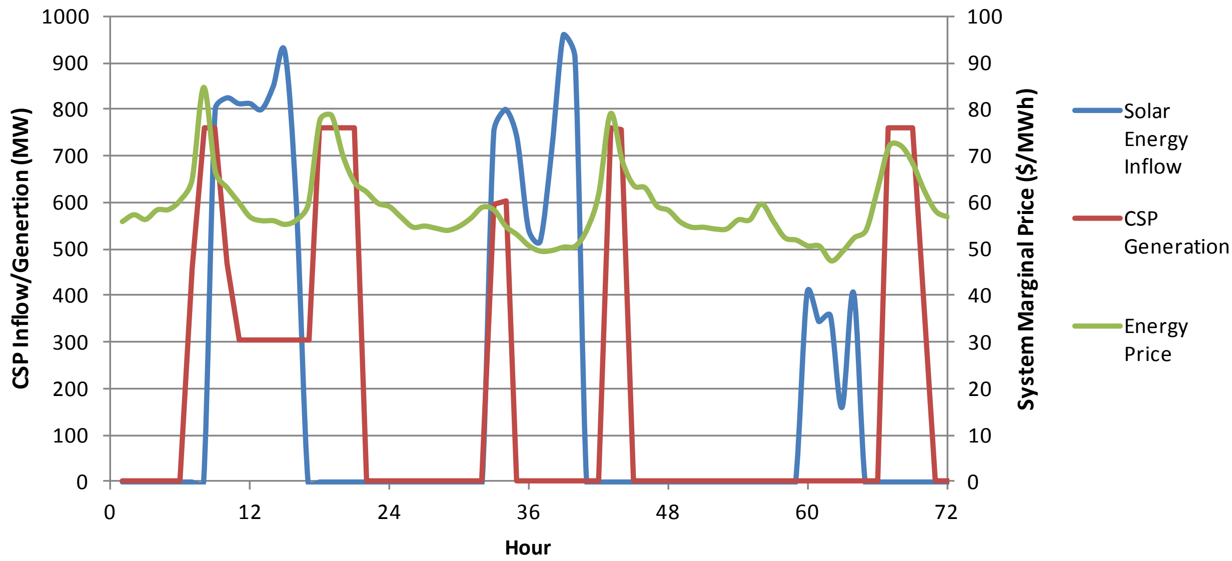

Figure 4. CSP operation for three days starting January 31 when providing only energy

Figure 5 shows CSP operation in the summer during the same period as Figure 3, demonstrating operation that is essentially centered around the period of highest value. The plant also operates at full output during nearly all hours of operation in these three days. Overall, when dispatched for energy only, the CSP plant typically operates at full output; in these simulations, CSP operates at full output during about 66% of the hours it is on line and generating at any level.

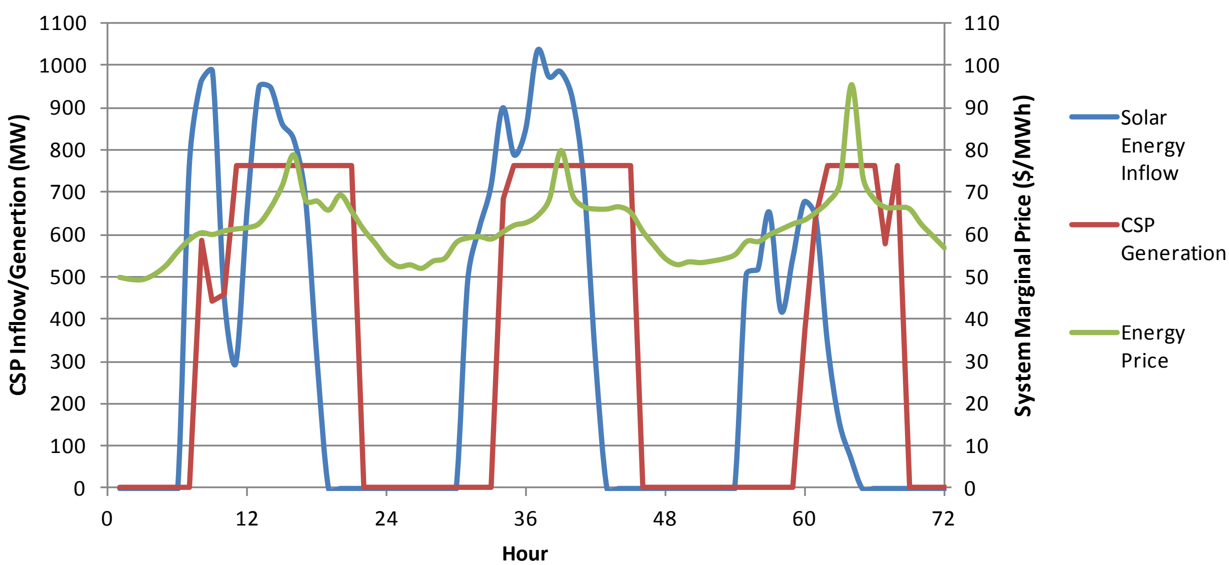

Figure 5. CSP operation for three days starting June 24 when providing only energy

Figure 5 shows some of the potential tradeoffs between the value of energy produced and the CSP configuration, including SM. At low penetration of solar, PV and CSP without storage are largely coincident with demand (and relatively high prices) during the summer. For CSP plants with storage and a SM of greater than 1.0, whenever the thermal output of the solar field exceeds the power-block capacity, energy must be stored, regardless of the system demand for energy or price.[16] As a result, the plant is forced to store this energy and generate at a later time, even if this later time has a lower demand or lower cost of energy. This is shown in Figure 5 on the third day in the afternoon when the energy inflow is coincident with an hour of high prices. A CSP plant with a low SM (or PV plant with similar profile) producing the same annual energy would sell more energy at periods of high prices than CSP with TES and a high SM. CSP with storage and the higher SM is forced to shift some energy to the evening when prices are slightly lower.[17] However, the higher SM allows for other services including provision of multiple reserve products and firm capacity, particularly in high VG scenarios, where the peak net demand for electricity has been shifted to later in the day. In addition, certain CSP designs may allow for higher SM and larger amounts of storage at relatively low cost.

This initial study indicates the need for additional analysis of possible changes in CSP configuration optimized for system-wide value, changes in operational value as a function of renewable penetration, and a more general analysis of various technology options for renewable integration. Figure 6 provide some indication of these issues and how they may change as a function of greater renewable penetration. It shows the marginal prices in the SCE zone in the base case and dispatch of both PV and CSP for a three-day period beginning on July 21. The rapid decrease in PV output, combined with high demand for electricity, creates a very high—but also, very short—price spike. This spike is caused, in part, by the need for operation of fast-ramping but relatively high-cost generators. As PV penetration increases, it will continue to reduce mid-day net load and shift generation requirements to those with greater ramp rate and range. The increased variability of the net load also increased the need for operating reserves during hours of high renewable output, creating additional opportunities for CSP plants capable of providing these services.

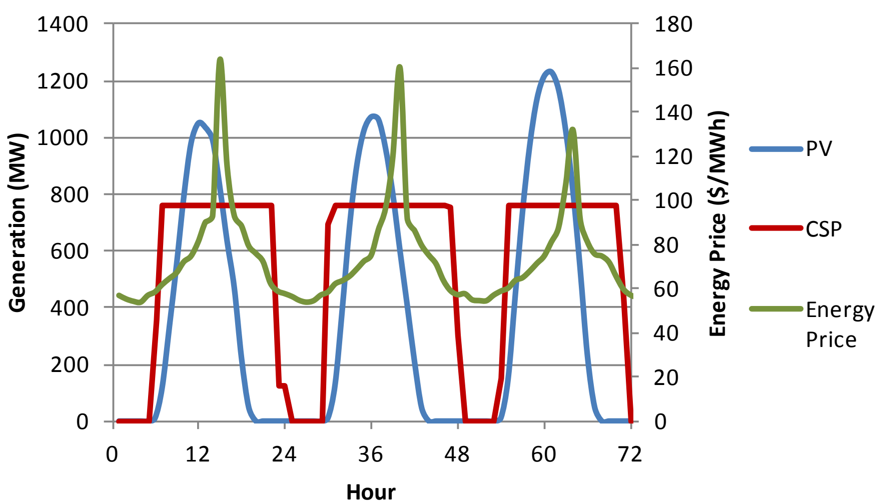

Figure 6. Dispatch of PV and CSP providing only energy during a three-day period beginning July 21

[16] This configuration also results in a small amount of unusable solar energy. During about 100 hours of the year, the energy inflow exceeds the power block while the thermal storage tank is full. In the simulated system, about 0.9% of the total potential thermal energy is curtailed.
[17] This result is due, in large part, to the combination of SM and amount of storage. A lower SM and fewer hours of storage would reduce this effect, but would be need to be analyzed on a case-by-case basis.

The operation of the CSP plant when allowed to provide ancillary services is substantially different from a plant providing only energy. Figure 7 shows the dispatch of CSP plants in the same time period as Figure 4, comparing an energy-only CSP plant (same as in Figure 4) and one allowed to provide reserves. It shows that the plant stays on longer and operates for more hours at part load. It also appears to "miss" several periods of high price, operating at much lower output during evening and morning price spikes.

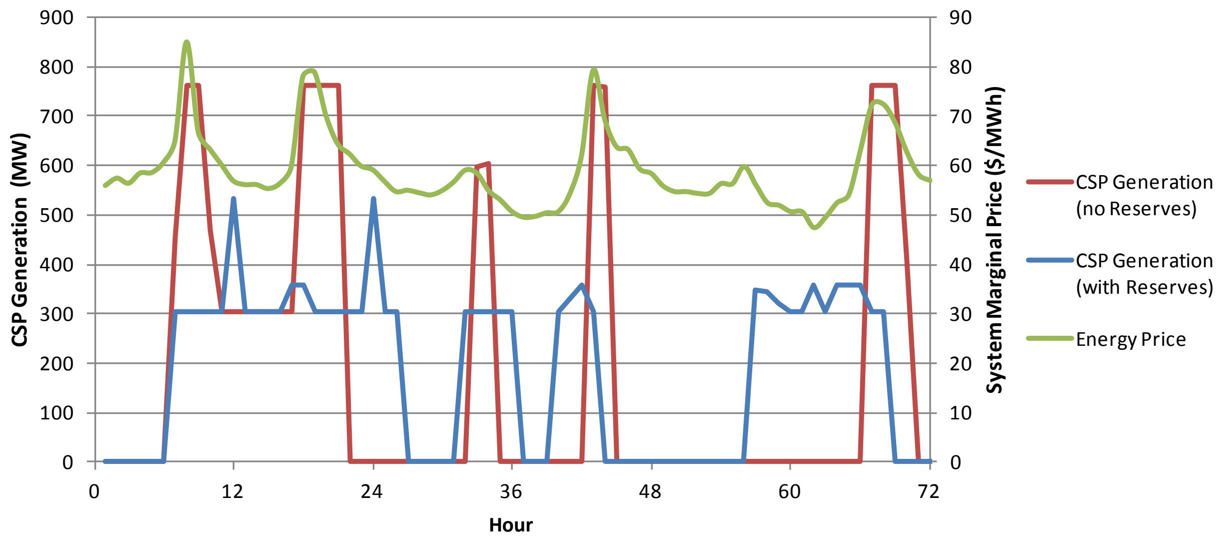

Figure 7. CSP operation for three days starting January 31 when providing only energy and providing both energy and reserves

During the summer, the plant also operates more frequently at part load, often generating less energy during periods of highest prices than when not providing reserves. The plant also often stays on line for extended periods (even when energy prices are relatively low), as shown during the overnight period of day 1 in Figure 8, which begins on June 24.

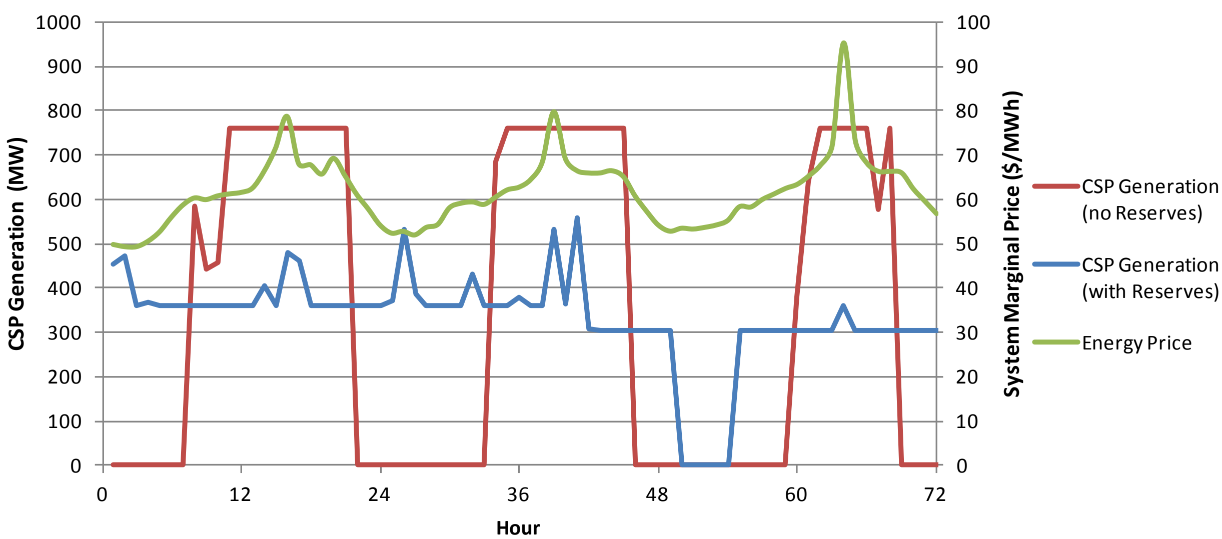

Figure 8. CSP operation for three days starting June 24 when providing only energy and providing both energy and reserves

The explanation for this mode of operation is due to the plant's ability to provide reserves by operating at reduced output. The plant stays on line during all hours because by operating at part load, it can effectively produce a large amount of reserves.

Table 2 demonstrates this operation in detail, using the results from the first day of the data illustrated in Figure 8 (June 24). Column 2 provides the marginal energy price for the SCE zone in the 32% simulation. It would be expected that the CSP dispatch would closely follow this value, and it does, as indicated in column 3 (CSP energy-only dispatch). The next column shows the energy-only "price-taker" revenue, if the CSP plant received this marginal price in a market setting (and did not negatively impact hourly prices).[18] The average value for this energy sold is $66.0/MWh. The next column shows the energy dispatch of the plant while producing reserves. The plant provides about 7% less energy (with the difference representing energy carried over to the next day) and at different times, including periods of low value. This plant also misses some periods of high value, such as when the plant generates at part load during hours 15 and 16. The energy-only price-taker revenue is about 15% less, and the average energy revenue is about $60.8/MW.

The next set of columns demonstrates why this is potentially an efficient use of the plant, showing the reserve price[19] and corresponding CSP provision. Although reserves prices (expressed as $/MWh or cost per unit of capacity for one hour) are much lower than energy prices, operation at part load allows substantial generation of reserve services. The price-taker value of reserves on this day of about $154K is greater than the $98K lost by not optimizing energy sales, and the plant providing reserves has a price-taker value about 9% higher than the energy-only plant despite selling less energy on this day. This simplified example does not include all the impacts of CSP plant dispatch, such as the price-suppression effect on both energy sales and ancillary service and the provision of down reserve services; however, it does illustrate the potential opportunities for CSP to increase its overall benefit to the system by operating at part load even during high price hours.

[18] In reality, CSP and other zero fuel-cost generators would suppress market clearing prices for energy (and reserves when providing them).
[19] This is a simple average of the three up services (regulation, load-following, and spinning reserves). The actual prices for each service are somewhat different, but this simplified table illustrates the general benefit of providing reserves.

Table 2. Hourly CSP Operation on July 29 When Providing Only Energy and Providing Both Energy and Reserves

Hour	SCE Energy Marginal Price ($/MWh)	CSP Energy-Only Dispatch (MW)	**Energy-Only Value ($K)**	CSP Energy Dispatch w/Reserves (MW)	Energy Value w/Reserve Dispatch ($K)	CAISO Avg. Reserve Price ($/MWh)	CSP Up Reserve Dispatch (MW)	Reserve Value ($K)	**Total Value with Reserves ($K)**
1	49.8	-	-	453	22.5	8.9	309	2.8	25.3
2	49.3	-	-	474	23.3	5.5	288	1.6	24.9
3	49.3	-	-	359	17.7	13.4	403	5.4	23.1
4	50.5	-	-	368	18.6	6.0	394	2.4	21.0
5	52.6	-	-	359	18.9	11.8	403	4.7	23.6
6	55.9	-	-	359	20.1	15.3	403	6.2	26.2
7	58.6	-	-	359	21.0	9.6	403	3.9	24.9
8	60.3	585	35.2	359	21.6	19.4	403	7.8	29.5
9	59.9	444	26.6	359	21.5	19.0	403	7.7	29.2
10	60.7	459	27.9	359	21.8	19.9	403	8.0	29.8
11	61.2	762	46.6	359	22.0	20.3	403	8.2	30.1
12	61.5	762	46.9	359	22.1	20.6	403	8.3	30.4
13	62.5	762	47.6	359	22.4	21.6	403	8.7	31.1
14	66.2	762	50.4	406	26.8	25.4	356	9.0	35.9
15	71.5	762	54.5	359	25.7	21.7	403	8.7	34.4
16	78.6	762	59.9	481	37.8	28.1	281	7.9	45.7
17	68.0	762	51.8	460	31.3	17.3	302	5.2	36.5
18	67.8	762	51.6	359	24.3	17.2	403	6.9	31.3
19	65.6	762	50.0	359	23.6	14.9	403	6.0	29.6
20	69.2	762	52.7	359	24.8	20.1	403	8.1	32.9
21	65.2	762	49.7	359	23.4	15.5	403	6.2	29.6
22	61.0	-	-	359	21.9	20.2	403	8.1	30.1
23	57.7	-	-	359	20.7	16.9	403	6.8	27.5
24	54.2	-	-	359	19.4	13.7	403	5.5	25.0
Total		**9,870**	**651.4**	**9,103**	**553.3**		**9,185**	**154.3**	**707.6**

Dividing this total revenue (from both reserves and energy) by the energy sold produces an average energy value of $77.8/MWh. However, the additional revenue associated with reserve provision is derived from the sales of capacity, not energy, so care should be taken in stating the origins of this system benefit. (This is another example of the challenges of using energy-only metrics such as levelized cost of energy, LCOE; the most extreme example would be in the case of a device that sells only reserves and no real energy, where its value on an energy basis would effectively be infinite.) Overall, the ability to sell reserves allows this limited energy resource to provide valuable services that require dispatchable capacity but little real energy. Over the year, the average capacity factor of the plant providing only energy is about 45%. Alternatively, the plant providing reserves (but the same amount of total energy) uses about 75% of its capacity, on average, for either energy or "up" reserves.[20]

It should be made clear that this use of CSP capacity is contingent on several factors. First, plants providing reserves obviously may be called to actually provide real energy during contingency events or when providing regulation up or load-following up services. As discussed previously, we assume that regulation and load-following are net-zero energy services and that market rules will allow limited energy storage devices to provide these services constrained by the operating range of the plant and time frame of these service requirements.[21] Contingency reserves present a slightly more complicated issue. Contingency reserves are not a net-zero energy service; while rarely called, they must be able to discharge energy for a time period determined by the ISO. This means that a CSP plant providing reserves needs to have enough inflow and stored energy in any given hour to meet both its energy obligation and the energy equivalent of its contingency reserve requirements.

This constraint was not explicitly enforced in the modeling simulations. To determine the magnitude of this impact, we examined the plant operation in each hour, and compared the total energy and contingency reserve committed to the actual energy inflow and storage. During 125 hours of the simulation, the CSP plant would be unable to meet its full contingency spinning-reserve obligation for a full hour. In terms of a reduction in potential benefits, the actual unfulfilled reserve obligation in MW-hrs[22] of capacity was about 1% of the spinning reserves provided by CSP.

As noted previously, the values in Table 2 do not represent the reduction in production costs actually simulated in the model, which would take into account the system re-dispatch that occurs as a result of the additional generator, and represents the difference between a price-taker simulation and a more detailed dispatch simulation performed here.

Overall, the use of CSP plants to provide reserves in this manner may represent a significant departure from previously assumed operational modes. As discussed earlier, plants providing only energy (not providing reserves) would be expected to generate at full output during a majority of hours when actually operating (in these simulations the plant was at full output during 66% of the hours when producing energy). The plant will also typically start once per day, and shut down in the overnight hours. However, when allowed to provide reserves, the least-cost dispatch results in the plant operating at part load for a large fraction of the time. So, although the plant is actually generating at some level about 80% of the time, it is operating at full output for only 11% of its on-line hours. The plant providing reserves also starts about 25% less than the energy-only plant, and it often remains on line for several days before shutting down.

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[20] To be clear, the capacity factor of the plant providing reserves as traditionally measured (annual energy actually produced divided by annual energy if running at max output for all hours of the year) is still about 45%. This means that a 100 MW CSP plant is on average producing about 45 MWh in each hour. However the energy plus reserves capacity factor of the plant when selling some combination of energy or reserves services is about 75%, meaning that on average a 100 MW CSP plant is producing 45 MW of energy service and 25 MW of zero energy reserve service.

[21] As noted earlier, market rules for load following have not been clearly defined and more analysis is required to determine the eligibility of CSP to provide this service.

[22] The unit of reserve capacity used in this report is MW-hr, or a MW of capacity held for one hour, which is different from MWh which is a unit of energy.

3.2 Operational Value

The qualitative overview of CSP operation presented in section 3.1 can be translated into the actual impact on system production costs. The operational value of each technology represents its ability to avoid the variable cost of system operations using the resource mix assumed in the scenario. The CAISO model tracks operational costs in four cost categories—operating fuel, variable O&M, start-up costs, and emissions costs. Operating fuel includes all fuel used to operate the power plant fleet while generating and includes the impact of variable heat rates and operating plants at part load to provide ancillary services. It does not include any penalties associated with loss of load or reserve violations, because there was no shortage of energy or reserves in any of the simulations.

Table 3 summarizes the results from the production simulations. It provides value per unit of energy delivered, calculated by dividing the difference in production cost by the total energy delivered to the grid by each technology.

Table 3. Operational Value Produced by Different Generator Types in the CAISO "Environmentally Constrained" Scenario

	Operational Value Per Unit of Delivered Energy ($/MWh)			
	Baseload	**PV**	**CSP (no Reserves)**	**CSP (with Reserves)**
Fuel	33.9	29.1	38.9	54.0
Variable Operations and Maintenance (O&M)	4.7	4.4	5.2	6.0
Start	0.1	-2.3	2.1	4.7
Emissions	21.9	22.7	20.1	18.3
Total	60.6	53.9	66.2	83.0

Table 3 demonstrates a relatively small increase in the operational value of an energy-only CSP plant compared to a baseload resource (about $6/MWh) or a PV plant (about $12/MWh), but a much greater difference when the CSP plant is able to provide reserves. Adding the ability to provide reserves increases the operational benefits of CSP by about $17/MWh, or a difference of about $22/MWh compared to the baseload resource and about $29/MWh compared to PV. A large fraction of the difference between the CSP plant with reserves and PV is the cost of starts, with PV increasing the net variability and reserve requirements, which increase the number of thermal plant starts. We assume CSP does not add to system reserve requirements and displaces thermal unit starts when providing energy, ramping, and providing reserves.

As discussed previously, several simplifying assumptions were made when simulating CSP, and these could have an impact on the calculated value, particularly in the case where CSP provides operating reserves. The assumption of a flat heat rate overestimates the performance of CSP at part load. This has little impact on the plant when providing only energy services, because the plant operates at nearly full capacity most of the time. However, when providing reserves, the plant operates at part load most of the time, and often operates at its assumed minimum. We examined the possible impact of part-load impacts by applying a polynomial heat-rate curve from Kearney and Miller (1988), where the efficiency at 40% load is about 7% lower than at full output. This curve was used to calculate the reduction in energy sales based on the marginal energy prices generated in the case with CSP. The reduction in CSP value was about \$0.8/MWh.[23]

The operational value calculated here does not include any costs associated with CSP operation. These include variable O&M, costs associated with CSP plant starts (excluding energy losses), and impacts of operating the plant at part load, including constant ramping during provision of regulation and load-following reserves.

The majority of the avoided costs is derived from reduced fuel use and associated emissions. The PLEXOS model tracks the total fuel used by all generators in the entire Western Interconnection. As discussed previously, the PLEXOS model generated by the CAISO includes the entire Western Interconnection, and there is substantial interaction between California and other Western states. The avoided fuel per unit of added generation can be tracked in the same manner as avoided costs. In each case, the total annual fuel offtake can be summed and compared to the case without the added generator. This difference is then divided by the total annual generation to produce the values in Table 4.

Table 4. Avoided Fuel Produced by Different Generator Types in the CAISO "Environmentally Constrained" Scenario

	Avoided Fuel Per Unit of Delivered Energy (MMBtu/MWh)			
	Flat Block	PV	CSP (no Reserves)	CSP (with Reserves)
Coal	2.7	3.5	2.0	-0.6
Gas	5.3	4.3	6.2	9.7
Total	8.0	7.8	8.2	9.1

Of obvious note is the fact that a generator located in California can avoid a substantial amount of coal generation despite there being no significant coal-fired generators within California. This is due to a combination of factors including the inherently interconnected nature of the Western Interconnection, significant imports of electricity into California, and the modeling assumption of least-cost dispatch throughout the West.

The relationship between imports and avoided fuel is driven by the patterns of generation, load, and CSP dispatchability. From roughly fall to spring, a significant fraction of the flat block and PV generation occurs during periods of moderate load and lower imports into the state of California (compounded by wind generation and large amounts of hydro generation in the spring). As a result, a large fraction of the flat block and PV generation avoids imports, as opposed to in-state gas-fired generation. These imports in the CAISO PLEXOS model are derived from a least-cost mix of generators, which often includes a substantial fraction of coal-generated electricity. During the first and fourth quarters, more than half of the fuel avoided by

[23] This calculation was not performed within the PLEXOS simulation. As a result, adding part-load heat rate to the model would result in re-optimization of the plant performance, which would likely reduce the penalty estimated here.

PV is coal.[24] Overall, this reduces the avoided-fuel value of PV, but increases its avoided emissions value, as observed by the higher value compared to CSP in Table 3.

In contrast, the dispatchability of CSP allows it to generate during periods of highest net demand, and it tends to avoid a higher fraction of in-state gas-fired generation. The dispatchability of CSP also increases the overall efficiency of system dispatch by providing rapid ramp rates and reserves. By smoothing the net load in California and reducing the number of partially loaded gas plants on line to provide ramping and reserves, it can increase the output of baseload units, including out-of-state coal-fired generators. Additional analysis is required to evaluate the potential limits on the market transactions effectively simulated in these scenarios. From a technical standpoint, the actual flexibility of the coal fleet in the Western states may restrict some of the operation assumed here.[25]

3.3 Capacity Value

The value calculated by a production cost model only addresses the variable operational value. Both CSP and PV have the ability to provide system capacity and replace new generation. However, the actual capacity value of solar technologies depends on their coincidence with demand patterns and how this coincidence changes as a function of penetration. A previous analysis of CSP plants with 6 hours of storage in California (nearly the same configuration evaluated here) found essentially 100% capacity credit using several years of data in historical systems (Madaeni et al. 2011). Capacity credit for PV generators varies depending on the year evaluated and module orientation (including the use of tracking technology), and it falls significantly as a function of penetration (Madaeni et al. 2012, Mills and Wiser 2012).

To estimate the capacity value of CSP in the 33% scenario evaluated in this report, we examined the performance of the generators during the periods of highest price, where price is used as a proxy for highest risk. Because we use only a single year of meteorology and load data, the results presented here are not generalized results; but they do provide at least some indication of the value of different generators types to provide reliable capacity. We use the capacity factor approximation, where the capacity value is approximated by the plant's capacity factor during a set of "risky" hours. A variety of analyses have evaluated the capacity factor approximation technique to determine the number of hours that can be used to approximate more complex reliability-based approaches (Madaeni et al. 2012). These analyses have evaluated from the top 10 hours to the top 10% of hours (876), with one study suggesting the top 10 hours is closest to more robust techniques (Madaeni et al. 2012). Figure 9 shows the average CSP capacity factor as a function of the number of hours considered using the results from the PLEXOS dispatch. For CSP with thermal storage, the number of hours considered appears to be largely irrelevant in the year evaluated. CSP plants were dispatched by PLEXOS to meet demand with essentially 100% capacity value during all high-priced hours. For PV, the capacity value is about 47% using the top 10 hours and about 40% using the top 1% of hours, using the AC rating of the PV system.

[24] This has been observed previously in simulations of California's interaction with the rest of the Western Interconnection (Denholm et al 2009)

[25] Since the CAISO PLEXOS model was released, the CAISO has changed coal plants outside California with capacities above 300 MW to include unit commitment, restricting them from rapid startup and ramping (CAISO 2011b). This change was not incorporated in the model used for this analysis.

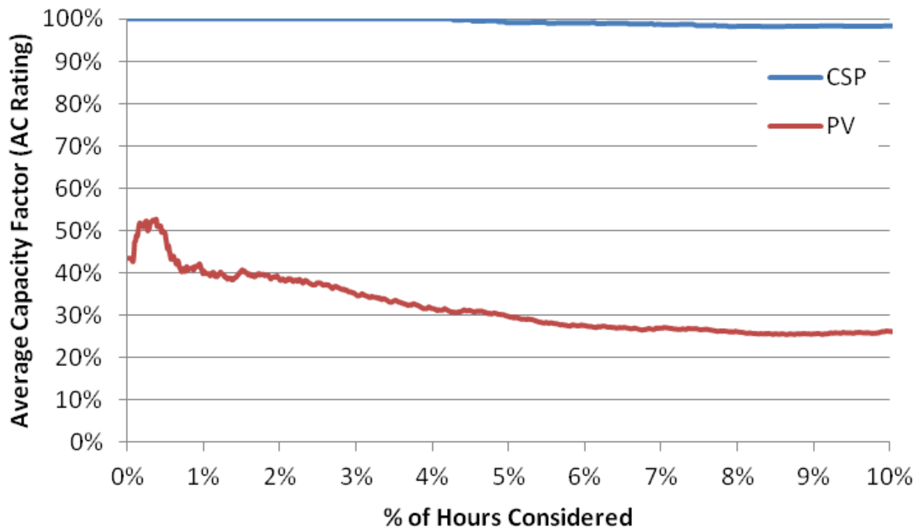

Figure 9. Average capacity factor of PV and CSP with storage during the top price hours

Table 5 summarizes the capacity value estimates from this analysis. The first row in Table 5 is the capacity credit in terms of fraction of rated capacity. This value assumes an equal outage rate for maintenance across technologies.[26] The second row translates this into an annualized value per installed kilowatt of the corresponding technology by multiplying the capacity credit by the low and high estimated annual value of a reference generator with 100% availability. There is a large range in estimates for the value of new capacity, with an extensive discussion provided by Pfeifenberger et al. (2012). We use a low value of \$55/kW and a high value of \$212/kW.[27]

Row 3 of Table 5 translates this value per installed kilowatt into a value per unit of generation. This is calculated by multiplying the value per unit of capacity by the total capacity credit (to get the total annual value of the installed generator), then dividing this value by the total energy production. This introduces a somewhat counterintuitive outcome, resulting largely from the impact of SM and the use of TES, as demonstrated previously by Mills and Wiser (2012). The PV plant has about twice the installed capacity as the CSP plant to provide equal amounts of energy, and about half the capacity value per unit of installed AC capacity; therefore, their net capacity value (as measured by unit of energy production) is similar.

[26] Because outages are not considered, the capacity values reported here correspond more closely to an “equivalent conventional power” metric where PV and CSP have the same forced outage rate as a conventional generator. If the outage rates are not the same, this could increase or decrease the capacity value metric. For comparison, a forced outage rate in the range of 5%–10% is commonly used for combustion turbines (a typical proxy resource for capacity planning purposes). If the forced outage rate of a CSP plant is the same as a combustion turbine, this means there is no net impact on the relative capacity value for comparison purposes. Alternatively, the outage rate of a PV system is likely lower than that of a conventional thermal generator or CSP plant, therefore adding slightly to its capacity value relative to these technologies.

[27] The low value is based on the Capacity Procurement Mechanism described in section 43.7.1 of the California Independent System Operator Corporation Fifth Replacement FERC Electric Tariff, April 1, 2011 (http://www.caiso.com/Documents/CombinedPDFDocument-FifthReplacementCAISOTariff.pdf). The high value is the calculated annualized cost of a combustion turbine described in section 1.3 of CAISO 2012b. These values assume that all sources of capacity are functionally equivalent, and place no additional value on generators with different flexibility characteristics such as ramp rate or start-up time.

Table 5. Capacity Value

	Flat Block	PV	CSP with TES
Capacity Credit (%)	100	47	100
Capacity Value (Low / High) ($/kW)	55 / 212	26 /100	55 / 212
Capacity Value of Energy (Low / High) ($/MWh)	6.3 / 24.7	10.7 / 41.3	13.6 / 52.3

3.4 Total Value

The total value of the different generation sources is the sum of the operational value and capacity value. Figure 10 summarizes the values for the different cases by combining the operational value from Table 4 and the capacity value from Table 5.

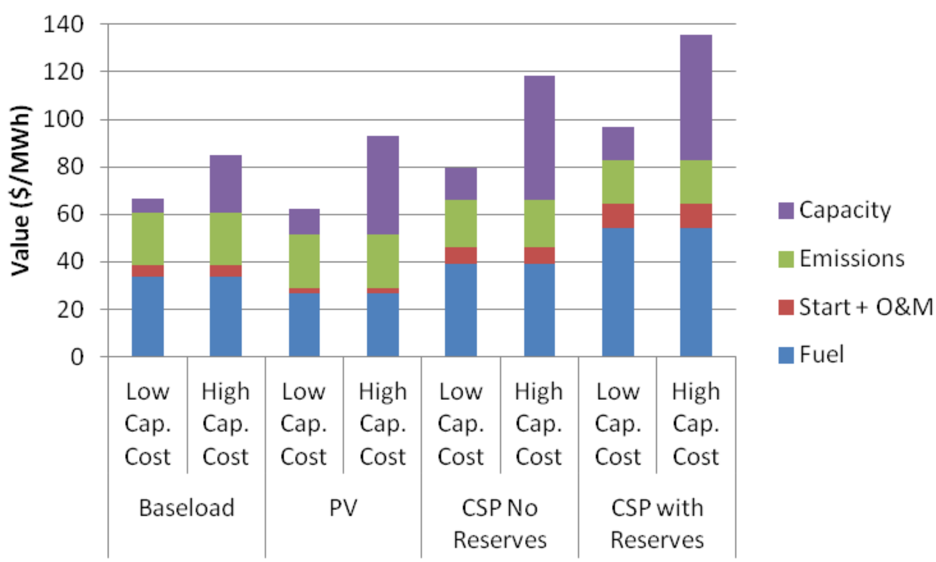

Figure 10. Total value of generation sources in the CAISO Environmentally Constrained Scenario

The overall value of CSP in this analysis ranges from about $80/MWh to about $135/MWh. The range is driven by assumptions about the ability of CSP to provide operating reserves and the cost of alternative generation capacity. The ability to provide reserves added about $17/MWh, assuming that CSP plants have rapid ramp rates while operating at part load. The cost of new capacity (which may include consideration of the actual flexibility provided by new capacity) provides the largest range, with the high-capacity cost case adding about $39/MWh of value compared to the low-capacity cost case.

This variation in total value for a CSP plant also produces a large range in the value difference between CSP and the other generator types considered. Compared to a baseload plant, this difference ranges from $30/MWh to $51/MWh, whereas the difference between CSP and PV ranges from $32/MWh to $40/MWh.

4 Study Limitations and Future Work

This analysis provides a preliminary estimate of the potential value of CSP in the CAISO 33% RPS simulations. However, there are several limitations of this study that will be addressed in future analysis.

1. The plants modeled in this study are wet-cooled, trough-type plants. Alternative configurations, such as dry-cooled towers, are already being deployed in California, and will have a different generation profiles. The impact of direct vs. indirect storage also needs to be evaluated.
2. The plant in this study has a SM = 2.0 with 6 hours of storage. Alternative configurations may provide a more optimal mix of energy and capacity services for the requirements of the system as a whole.
3. This study evaluated a single RPS scenario. Additional generation mixes should be considered, as well as other RPS scenarios. This also includes RPS scenarios of greater than 33%. These higher RPS scenarios should evaluate changes in operating reserve requirements, as well as the potential impact of increased curtailment rates that result from over-generation conditions during periods of high renewable supply. The specific changes in system flexibility (and possible role of CSP) required to minimize curtailment should be evaluated. In addition, higher renewable penetrations may significantly change both the value of CSP and the optimal configuration of CSP plants.
4. The simulations were performed at an hourly level and did not consider additional ramping that would result at higher time resolution due to solar, wind, and load variability. Furthermore, although load-following reserves were held to account for solar forecast error, these reserves were not dispatched. Sub-hourly economic dispatch simulations would evaluate some of the changes to generator operation in response to forecast error and increases in net load variability.
5. Additional analysis is needed of the ability of CSP to provide reserves. This includes the additional costs of operating at part load and providing regulation reserves (particularly compared to other plants). A better understanding of the constraints associated with limited energy resource providing ancillary services is also required.[28]
6. Many of the model simplifications needed to produce acceptable run times may affect the value of system flexibility. Sensitivity to these simplifications, such as optimization of units outside the Western Interconnection should be considered.
7. Additional sensitivities are needed around the price of natural gas.
8. This simulated dispatch assumes that the CAISO essentially controls CSP plant operation as opposed to self-scheduling, or simple block dispatch that would be less optimal from a system perspective. This essentially established a best-case scenario for the value of CSP and additional analysis is needed to determine the value of optimal dispatch and any market changes needed to enable optimal dispatch of CSP resources.

[28] Additional discussion of CSP providing ancillary services is provided by Usaola (2012).

5 Conclusions

CSP with TES creates a dispatchable source of renewable energy. However, this dispatchability is constrained by the hourly flow of solar energy. As a result, modeling its value is challenging and requires chronological simulation to assess its value in providing energy, ancillary services, and firm capacity.

In this preliminary analysis, CSP was incorporated into the CAISO's environmentally constrained 33% RPS case and its value compared to a baseload resource and also to PV. The energy-shifting value of CSP with TES was about $6/MWh higher than a baseload resource and about $12/MWh greater than the PV resource. The difference relative to PV is influenced by the coincidence of solar supply with demand, which will change as a function of penetration and also potentially to the operational restrictions resulting from the high SM assumed in this analysis. A lower SM may be more optimal in the scenario evaluated, but the relative value of CSP and optimal CSP configuration will likely vary with the increase of renewable penetration and the decrease in coincidence of solar energy supply with net demand.

When CSP is allowed to provide operating reserves, its operational value increased by about $17/MWh (producing a total difference of $22/MWh compared to the baseload resource and $29/MWh compared to the PV generator). The ability to provide reserves appears to have a significant value, but will require a different operational approach for CSP—greater operation at part load and more frequent plant cycling. The additional costs of this operation, which were not evaluated here, could reduce the net benefits of CSP providing operating reserves.

Finally, in the single year analyzed, the capacity value of CSP with TES is expected to be very high, because an appropriately scheduled CSP plant would have energy available during essentially all the highest-priced demand hours of the year. The additional value provided by CSP dispatchability will depend largely on the assumed cost of alternative capacity.

Combined, the operational and capacity value of CSP calculated in this analysis ranges from about $80/MWh to about $135/MWh. This represents an incremental value of $13/MWh to $51/MWh compared to a baseload resource, or $15/MWh to $40/MWh compared to PV.

Additional analysis is needed to provide additional validation as well as explore the sensitivity of these results to additional technologies and scenarios. The relative value of dispatchable resources such as CSP with TES would likely increase as a function of VG penetration. A key element of future analysis will include exploring alternative CSP technologies and higher renewable penetration scenarios.

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