SAND2021-4022C

Particle CSP Plant: Quantifying System Benefits through Production Cost Modeling

Cara Libby,[1, a)] Qin Wang,[1] Aidan Tuohy,[1] Clifford K. Ho,[2] Bruce Kelly[3] and Henry Price [3]

[1]*Electric Power Research Institute (EPRI), 3420 Hillview Ave., Palo Alto, CA 94304 (USA).*
[2]*Sandia National Laboratories, P.O. Box 5800, MS-1127, Albuquerque, NM 87185-1127 (USA).*
[3]*Solar Dynamics, 1105 W. 11th Ct., Broomfield, CO 80020 (USA).*

[a)]Corresponding author: clibby@epri.com

Abstract. Next-generation central receiver concentrating solar power systems (Gen3 CSP) are targeting operating temperatures above 700°C and use of a closed Brayton power cycle with supercritical CO_2 (sCO_2) as the working fluid. These systems intend to deliver greater value through improved operating efficiency, dramatic cost reductions, and improved ability to provide grid benefits. EPRI conducted production cost modeling to quantify potential system benefits for a particle-based Gen3 CSP technology developed by Sandia National Laboratories. The model explores dispatch strategies for a Particle CSP Plant and determines changes in annual system operating cost, plant revenue, and locational marginal price (LMP). Sensitivity analysis is used to identify scenarios and market conditions in which the technology is competitive, such as high penetrations of variable solar photovoltaics (PV) and wind. The model is intended to quantify the unique value proposition for the Particle CSP Plant.

NOMENCLATURE

CFD	computational fluid dynamics
CSP	concentrating solar thermal power
DOE	United States Department of Energy
EPRI	Electric Power Research Institute
HTF	heat transfer fluid
LMP	locational marginal price
M	million
MWt	megawatt (thermal)
MWe	megawatt (electric)
PSO	Power System Optimizer
sCO_2	supercritical carbon dioxide
SETO	Solar Energy Technologies Office
SM	solar multiple
TAC	technical advisory committee
TES	thermal energy storage
WECC	Western Electricity Coordinating Council

INTRODUCTION

Current state-of-the-art concentrating solar thermal power (CSP) systems today are primarily comprised of parabolic trough technology using synthetic oil heat transfer fluid at temperatures near 390°C and molten salt central

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

receiver technology operating at 565°C. Both transfer heat to a traditional steam-Rankine cycle to generate power. Next-generation central receiver CSP systems (Gen3 CSP) are targeting operating temperatures above 700°C and use of a closed Brayton power cycle with supercritical CO_2 as the working fluid. These systems intend to deliver greater value through improved operating efficiency, dramatic cost reductions, and improved ability to provide grid benefits.

Under the U.S. Department of Energy (DOE) Concentrating Solar Power Generation 3 (Gen3 CSP) funding opportunity [1], Sandia National Laboratories is developing a particle-based Gen3 CSP technology. A conceptual drawing of the particle-based system is shown in Fig. 1. EPRI, working closely with Sandia, SolarDynamics, and the project technical advisory committee (TAC), conducted production cost modeling to assess the value of a Particle CSP Plant to a representative grid system. Study objectives included:

- Assess the relative value of particle-based CSP plant designs, plant configurations, dispatch strategies, and other characteristics from grid operator and plant owner perspectives
- Determine scenarios or market conditions in which particle-based CSP technology is competitive or provides greater system benefits
- Quantify the unique value proposition for a 100-MW Particle CSP Plant relative to an "Alternative Gen3 CSP Plant"

This effort was conducted early in the knowledge development stage of the Gen3 CSP technologies, before detailed designs, cost models, and performance models were available. As a result, much of the analysis is performed with preliminary data and relatively simplistic models, and thus the findings allow relative comparisons for an example grid network, and the absolute values presented are not broadly true or applicable to all systems. Full results are contained in a public EPRI report. [2]

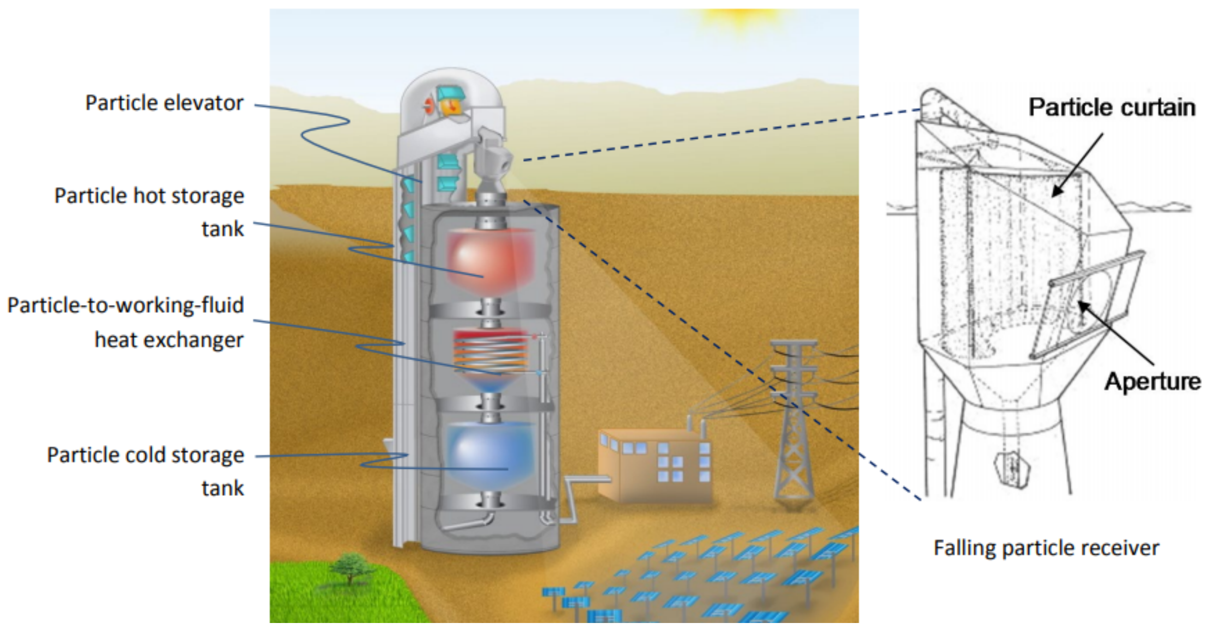

FIGURE 1. Sandia National Laboratory concept for particle system [3]

DIFFERENTIATING FEATURES OF PARTICLE-BASED GEN3 CSP TECHNOLOGY

The particle-based Gen3 CSP technology offers unique system benefits that may not be available to other Gen3 CSP technologies. Several differentiating features are identified in Table 1, and the first three key differentiators are explored in the production cost modeling to quantify the potential benefits: (1) short morning startup due to direct particle heating and reduced thermal mass of the receiver infrastructure; (2) high availability by avoiding forced outages due to leaks and freezing, enabling higher annual generation; and (3) modularity that allows plants to be sited closer to load centers (or industrial customers), which lowers transmission losses (or capital investments), and offsets high-cost generation. For this assessment, an "Alternative Gen3 CSP Plant" is defined to be identical to the base case Particle CSP Plant, with the same solar field and receiver efficiency assumptions, but with modifications that allowed quantification of changes in system benefits for a plant that does not offer these 3 features. Specifically, the Alternative Gen3 CSP Plant: (1) cannot utilize 30 minutes of low-irradiance energy in the early mornings, resulting in a slightly lower capacity factor; (2) based on data from Solar Two and commercial molten-salt tower experience, is assumed to have up to 18 additional forced outage days due to leaks and freezing, and; (3) is assumed to be sited at a location away from load centers, resulting in higher transmission losses.

TABLE 1. Summary of Particle CSP Plant Differentiators

Parameter	**Basis for Difference**
Forced Outage Rate	The Particle CSP Plant is expected to have comparable complexity to a trough plant, and therefore similar annual availability to a trough plant (95%). Based on data from Solar Two and commercial molten salt tower experience, liquid-based CSP technology may have up to 18 additional forced outage days due to leaks and freezing. If Particle CSP Plants can achieve fewer failure modes due to simpler design and greater maintenance accessibility, this may translate to higher availability than liquid-based Alternative Gen3 CSP Plants. While availability has not been validated for any of the Gen3 CSP concepts, the greater number of outages were assumed to be applicable to plants that use high-temperature ternary chloride salt in the receiver or indirect storage system.
Morning Startup	Compared to an Alternative Gen3 CSP Plant, the Particle CSP Plant is expected to offer ~30-minute shorter morning startup due to direct particle heating and reduced thermal mass of the receiver infrastructure. This low-irradiance production boosts the annual capacity factor by 0.5-1% relative to an Alternative Gen3 CSP Plant.
Modularity	Modularity of the Particle CSP Plant may allow plants to be evenly distributed throughout the system in areas with higher marginal prices, lowering transmission losses, offsetting high-cost generation, and providing inertia and other grid benefits. Liquid-based Gen3 CSP systems are typically larger to avoid freeze issues. System benefits of modularity would need to be weighed against higher capital and O&M costs and lower power cycle efficiency for smaller turbines, which were not considered in this analysis.
Capital Cost	In addition to lower TES costs, which could enable higher capacity factors, the particle system offers several other cost savings: • Gravity-fed particle receiver with refractory walls is potentially lower cost than high-temperature, pressure-welded tubular piping receiver designs that require skilled labor to construct; particle receiver refractory walls (pre-cast or shotcrete) may also provide opportunities for local manufacturing. • Single heat exchanger (vs. two for indirect Gen3 CSP systems with sodium-salt and gas-particle heat exchangers) • Particle storage is at atmospheric conditions and has no cover-gas or hermetic-seal requirement. The potentially lower TES cost allows oversized storage tanks and BOP to reduce clipping, enabling higher annual generation. • Modular design feasible using prefab components, shorter risers/downcomers with TES within tower structure, smaller N-field configuration, lower upfront engineering, and shorter time to build
O&M Cost	The simplicity of the Particle CSP Plant design may result in O&M cost savings compared to other Gen3 CSP concepts: • Lower routine maintenance requirements, i.e., fewer pumps, valves, motors, and heat tracing; no chemistry control or hermetic seals required • Greater accessibility for maintenance due to atmospheric pressure receiver, TES with no cover-gas or hermetic seals, fewer high-stress welds, use of skip hoist vs. pumps immersed in salt tanks to transport HTF, and inert HTF material that can be cooled to room temperature • Skilled labor requirements may also be reduced due to the simpler design

PRODUCTION COST MODELING METHODOLOGY

Production cost models simulate the operation of a power system by committing and dispatching a simulated generation fleet while maintaining power balancing, reserve requirement, and transmission line violation constraints, with the objective of minimizing system production cost. Normally, a production cost simulation only considers the production cost (unit startup and fuel costs), and not capital cost or fixed O&M cost. For this project, the "system" is a simplified area within the Western Electricity Coordinating Council (WECC) network model, depicted in Fig. 2, with 278 generation units (fossil, nuclear, wind, hydro, PV) [4] serving distributed loads with an aggregate peak of 8,192 MW. PV and wind represent 21% of total capacity in the existing model. While new CSP is not planned for this region currently, the existing system model was available for use in this study and includes some of the best CSP resource locations in California, Nevada, and Arizona.

In this study, the original grid system does not contain any CSP resources. Modeled scenarios include a single Particle CSP Plant with different designs and configurations, including baseload and peaker designs, and in some cases multiple Particle CSP Plants that are added to the system to understand potential impacts. The dispatch profile of the Particle CSP Plant(s) is affected by the other generators on the system. A simulation with a single Alternative Gen3 CSP Plant is run separately. Production cost modeling is useful for comparing relative differences across different CSP plant designs and configurations and understanding if particle-based systems may offer quantifiable benefits relative to Alternative Gen3 CSP Plant technologies. However, the analysis is not meant to be a financial study, and absolute numbers should not be reported, given the large number of model assumptions and approximations. Outputs of the model included in this analysis include annual system operating cost, plant revenue, and generation, which are defined below.

A Particle CSP Plant was incorporated into an existing commercial production cost modeling tool called Power System Optimizer (PSO) [5] that mimics grid operation with hourly resolution. PSO supports modeling of multi-level, nested time intervals with the ability to simultaneously optimize energy and ancillary services dispatch. The PSO modeling approach is a mixed integer programming algorithm, consistent with the one most independent system operators use.

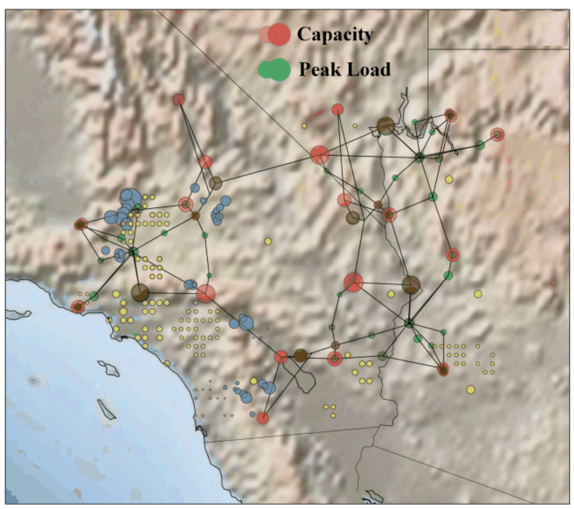

FIGURE 2. National Renewable Energy Laboratory (NREL) RTS-96 System

The key input to the model is time-series energy generation data available to the thermal energy storage system. Hourly profiles of available electrical energy inflow generated by the solar field and receiver were determined for three locations using weather data for the Solana Generating Station (Gila Bend, AZ), the Mojave Solar Project (Harper Lake, CA), and TMY2 data for Daggett, CA. SolarPILOT was used to model the Particle CSP Plant heliostat field, and iteration routines were used to calculate the irradiance on the aperture of the receiver over time. A validated model-based correlation for receiver efficiency calculated receiver thermal power using a polynomial function of the irradiance, wind speed, and wind direction. The correlations were validated using detailed physics-based computational fluid dynamics (CFD) models of on-sun receiver tests. [6] The base case Particle CSP Plant has a 100 MWe supercritical CO_2 power cycle with 50% nominal efficiency, based on DOE Solar Energy Technologies

Office (SETO) CSP guidelines for SunShot 2030 [7] and Gen3 targets. [1] The thermal-to-electric conversion efficiency, calculated according to [8], and cycle output power are calculated as a function of the dry bulb temperature. EPRI's stored-energy-dispatch strategy, in combination with the dry bulb temperatures from the weather file, determines the electric power supplied to the grid. Design parameters and operational characteristics specific to the base case baseload Particle CSP Plant are listed in Table 2.

TABLE 2. Production Cost Model Input Values for Base Case Particle CSP Plant

Design Parameters		Operating Parameters	
Power Block Capacity:	100 MWe	Ramp Rate (Load Changes):	10%/min
Receiver Capacity:	500 MWt	Min On/Off Time:	1 hour
TES Capacity:	14 hours	Startup Time:	Zero*
Solar Multiple (SM):	2.5	Losses:	TES: 2% Heat Exchanger: 1% Startup: 20% of rated power block capacity for 30 minutes

* The time-series energy inflow data already account for startup time. Only energy that can be utilized to produce electricity is included in the inflow data. For this reason, there is no additional startup time that needs to be built into the model.

PRODUCTION COST MODEL SIMULATION RESULTS

The outcomes of the production cost model include system benefit metrics as well as plant dispatch profiles and revenue. System operating cost refers to the fuel cost and startup cost of all thermal units. The Particle CSP Plant is assumed to have zero marginal operating cost since it does not have fuel costs and is staffed full time (i.e., all fixed O&M). When the Particle CSP Plant displaces fossil-fueled units, the system operating cost is reduced. Locational marginal prices (LMPs) are the system's marginal energy price reflected at different locations, or nodes, on the system. The price is determined by the marginal unit, which may or may not be the CSP plant. When the marginal unit is the CSP plant, the price of CSP is the settlement price, but even when the marginal unit is not a CSP plant, the existence of the CSP plant may impact the selection of marginal unit. The annual Particle CSP Plant revenue is calculated by the summation of the product of its nodal LMP and generation quantity in all hours. The average revenue per unit generation is the annual Particle CSP Plant revenue divided by the annual Particle CSP Plant generation. It is used to evaluate the average revenue of the plant for one MWh of energy produced in the market. A power-balance violation occurs when the system generation cannot meet the system demand. In the base case, only 0.047 MWh of balancing violation was observed for the year.

Fig. 3 shows an example dispatch profile (solid black) for the base case 100-MWe Particle CSP Plant for one week in August. The model optimizes dispatch for the whole system, based on the characteristics of the Particle CSP Plant and other units on the system. Hourly energy inflow data (dotted orange) is the energy available to the storage system and power block. The Particle CSP Plant operates at maximum capacity most of the time, cycling down briefly, and sometimes only to part-load, during off-peak hours in the early morning. After the inflow energy ramps down in the afternoon, the power block relies on stored TES energy to satisfy the evening peak demand period. The LMP (dashed blue) is typically highest at approximately 6-10pm, and twice during this week-long period it spiked around 7 pm.

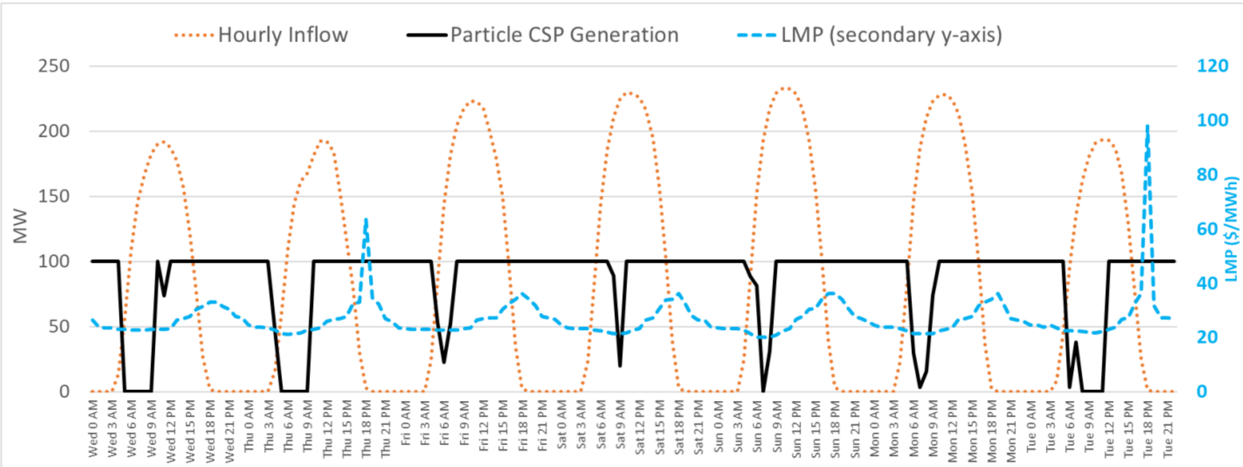

FIGURE 3. Example 1-Week Dispatch and Locational Marginal Price for Base Case 100 MWe Particle CSP Plant

Sensitivity Study

Table 3 shows the plant design, Particle CSP Plant capacity on the system, plant location, and renewable penetration sensitivity parameters that were considered. The middle column shows the base case values and the right column shows the range of values evaluated in the sensitivity analysis. For the base case and peaker designs, the solar field and receiver sizes are assumed to be the same. Gila Bend, AZ was selected as the base case due to availability of 5-minute weather data from the Solana Generating Station. Non-hydro renewable penetration on the grid system increases to 23% with the addition of a 100-MW Particle CSP Plant. Select results are presented here, and the full sensitivity results can be found in a public EPRI report. [2]

TABLE 3. Sensitivity Parameters

Parameter	**Base Case Values**	**Sensitivity Values**
Plant Design		
TES Capacity	1400 MWh (14 hours)	700 – 2000 MWh (4-20 hours)
Solar Multiple	2.5	3.0, 3.5
Dispatch Profile	Intermediate: 100 MWe, SM = 2.5, 1400 MWh (14-hour) TES	Peaker: 250 MWe, SM = 1, 1500 MWh (6-hour) TES
Unit Size	1 x 100 MWe (single tower)	10 x 10 MWe (modular)
Particle CSP Plant Capacity on System	1 x 100 MWe	20 x 100 MWe
Location	Gila Bend, AZ (Solana)	Harper Lake, CA (Mojave); Daggett, CA
Renewable Penetration	23%	50%

Fig. 4 shows the dispatch profile of the 250-MWe peaker during the same week as the 100-MWe base case plant in Fig. 3. The peaker does not operate as many hours, but it generates 2.5x more energy during the hours it operates at full capacity. From roughly 7am to 1pm when inflow energy is available, the plant stores the energy for later dispatch during peak hours in the evening. The LMP, an output of the model determined by the resource mix, changes because the Particle CSP Plant has changed from a baseload plant to a peaker plant. The generation of both Particle CSP Plant configurations follows the pricing signal very well, i.e., the plant generates when the LMP is high and goes offline when the LMP is low.

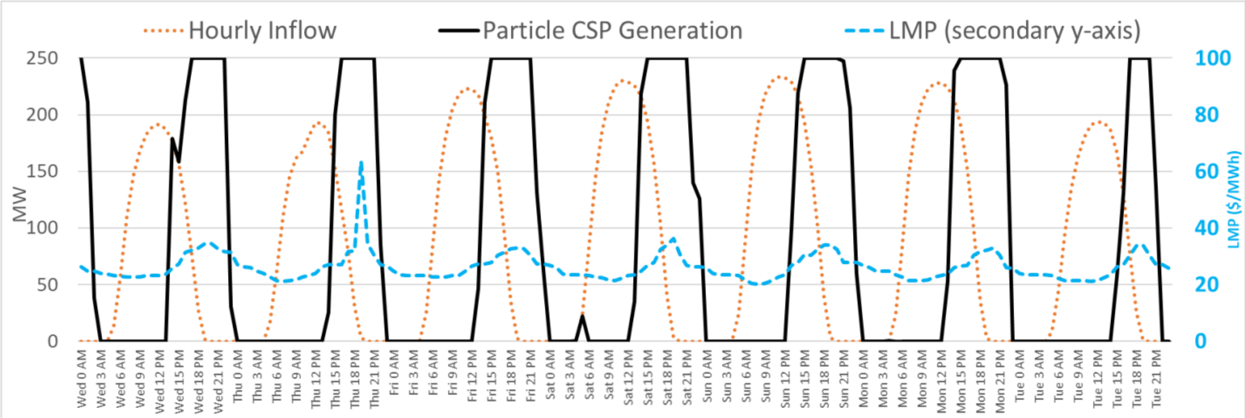

FIGURE 4. Example 1-Week Dispatch and Locational Marginal Price for Peaker 250-MWe Particle CSP Plant

Table 4 summarizes annual system operating cost, plant revenue, generation, and the average revenue per unit generation for the baseload and peaker plant designs. As mentioned earlier, the system operating cost reflects the fuel cost and startup cost of all thermal units. The original grid without CSP has an annual system operating cost of $583.2 M. The operating cost with the peaker plant is $4.4 M lower than that of the baseload plant, indicating that the system can meet the demand with cheaper and/or less thermal generation with the peaker. This is also an indication that the peaker can provide more flexibility to the system than the base design.

TABLE 4. Annual System Operating Costs and Revenue for Base Case and Peaker

	Base	**Peaker**	**Difference**
Annual System Operating Cost ($)	566.7 M	562.3 M	-4.4 M (↓ 0.8%)
Annual Particle CSP Plant Revenue ($)	17.3 M	21.2 M	3.9 M (↑ 23%)
Annual Particle CSP Plant Generation (MWh)	679,532	679,513	-19
Average Revenue Per Unit Generation ($/MWh) *	25.5	31.2	5.7

* Ratio of Annual Particle CSP Plant Revenue and Annual Particle CSP Plant Generation

Annual plant revenue is a useful metric for CSP plant developers and investors. Quantifying potential changes in annual system operating cost may provide additional justification for CSP development in some regions. Fig. 5 and Fig. 6 show production cost modeling results for annual plant revenue and annual system operating cost, respectively. The Particle CSP Plant results in both charts are for plants in Gila Bend, AZ with 23% renewables penetration.

Annual plant revenue increases with larger solar field sizes (solar multiple) and modestly for larger TES capacities. It makes sense that plants that produce more electricity have higher annual revenue, which would be needed to help recover their higher capital cost. The peaker plant, which typically operates during high demand periods when market prices are higher, has 25% higher annual revenue than the base case plant. Since the peaker has the same heliostat field and receiver size as the base case plant, higher revenue may be needed to offset the higher cost primary heat exchanger and power block, which are not considered in the production cost modeling. However, the absolute numbers should not be used in financial comparisons due to the assumptions and approximations of the model. Modular Particle CSP Plants have roughly $1M lower revenue than the single tower design because they lower the average LMP. The Alternative Gen3 CSP results in the lowest annual revenue of the cases presented, likely due to lower annual generation and reduced availability.

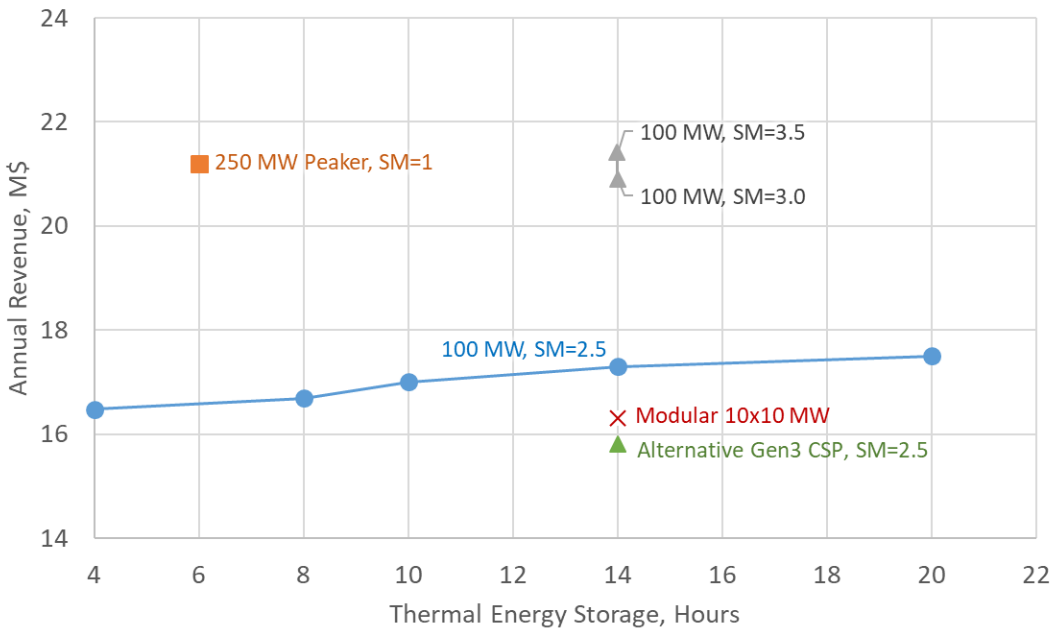

FIGURE 5. Annual CSP Plant Revenue

The trend in preferred designs is the same for annual system operating cost. Plant designs that produce more electricity displace more thermal generators, and thus reduce system operating costs. The annual system operating cost without any CSP units is $583.2 M (dotted black line). Adding an Alternative Gen3 CSP Plant reduces system cost by 2.6%, whereas the Particle CSP Plant reduces system cost by 2.8%. Increasing the Particle CSP Plant SM from 2.5 to 3.5 reduces system cost by 1%. Increasing TES capacity from 14 to 20 hours provides a negligible reduction. The 250-MW peaker plant, which generates 19 MWh more electricity per year than the 100-MW base case design, offers less than 1% lower system cost than the base case. Distributed modular Particle CSP Plants have nearly the same system cost as the base case; the primary system benefits provided by modular systems are a reduction in average LMP and less transmission congestion. The original grid had 1,757 binding events (congestion) for transmission lines[1], and with the ten modular units, this reduces the number of incidents by 1.2%, or 1,736 events, for the year.

[1] Transmission congestion exists when a transmission constraint (thermal, stability, security) is binding and causes alteration of the optimal dispatch of resources. At any time, multiple constraints may be binding on the dispatch. Congestion is generally an economic issue, not a reliability or security issue; a system can operate indefinitely in a state of congestion. Congestion causes nodal prices to diverge to reflect the optimal dispatch adjustments required to meet load while respecting all constraints.

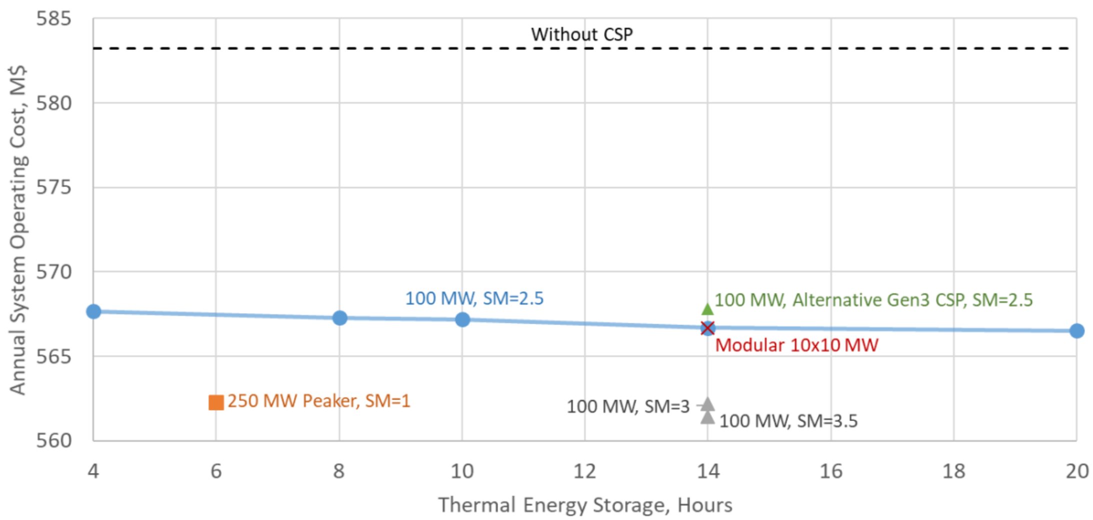

FIGURE 6. Annual System Operating Cost

CONCLUSIONS

Production cost model simulations were performed to determine dispatch profiles for the Particle CSP Plant for different design variants and grid system generation mix. Keeping in mind that the production cost modeling results are for a simplified network system, several key observations are offered about the relative value of different plant designs and deployment scenarios:

- *Particle CSP Plants reduce system operation costs*. Production cost simulation results show that adding one or more Particle CSP Plants reduces the system operation cost under all scenarios. For the modeled RTS-96 system, the annual reduction is approximately 6.5% higher for the base case Particle CSP Plant than for the Alternative Gen3 CSP Plant due to anticipated higher annual generation and greater plant availability.
- *Particle CSP Plants may offer higher annual revenue than Alternative Gen3 CSP*. For this grid system and the assumed capacity factor and availability benefits of the particle-based system, the Particle CSP Plant generated 9.5% higher annual plant revenue than the Alternative Gen3 CSP Plant.
- *Dispatch profiles can determine optimal TES*. Increasing the capacity of the TES system can increase the utilization rate of the energy. However, the marginal benefit keeps decreasing with incrementally higher storage capacity. For the RTS-96 system, the turning point is around 1,200 MWh. When the TES capacity is larger than this value, the Particle CSP plant dispatch does not change.
- *Increasing solar multiple provides modest reductions in system operation cost*. SM is an important design parameter because larger values correspond to more inflow energy for electricity generation, thus decreasing system operation costs. However, the marginal benefit declines with higher SM values. Increasing SM from 2.5 to 3.0 increases annual plant generation from 679,532 MWh to 807,634 MWh and reduces annual system operating cost from $566.7 M to $562.2 M (a reduction of 0.7%). Increasing SM from 3.0 to 3 increases annual plant generation from 807,634 MWh to 828,007 MWh and reduces annual system operating cost from $562.2 M to $561.4 M (a reduction of 0.14%).
- *Peaker plants may provide greater system benefits and significantly higher plant revenue than baseload plant designs*. The system operation cost for the 250-MW peaker plant design is $4.4M (0.8%) lower than the 100-MW baseload plant design. Plant revenue for the peaker is $3.9M (23%) higher than the baseload.
- *Multiple modular units can reduce locational marginal price (LMP) and transmission congestion*. Ten modular 10-MW Particle CSP Plants distributed throughout the grid system provide greater power system flexibility than a single-tower 100-MW plant design in one location, resulting in slightly lower system operating cost. The primary system benefits are a 15% reduction in LMP, which reduces plant revenue, and 1.2% fewer binding events (congestion) on transmission lines.
- *Additional Particle CSP Plant capacity increases system benefits*. The annual system operating cost increases roughly linearly as more Particle CSP Plants are added to the system. For the simplified network

model used in this study, increasing the number of 100-MW Particle CSP Plants from 1 unit to 5 units to 10 units increases the average revenue per unit generation. However, with 20 units the average revenue per unit generation has started to decline (to a value roughly equivalent to the 5-unit value), indicating that the optimal number of units falls between 5 units and 20 units. As the number of units increases, the number of hours in which the Particle CSP Plant units generate at the maximum nameplate capacity is reduced. For example, when the system has one Particle CSP Plant unit, the output is at the maximum limit (i.e., 100 MW) for many hours; when the system has 20 units, supply exceeds demand in some hours, and total CSP output is at the maximum limit (i.e., 2,000 MW) for fewer hours.

- *System benefits vary by plant location.* Energy inflow differs for each grid location due to solar resource quality and weather conditions. Hence, the impact on the power system and Particle CSP Plant revenue vary by location. The average revenue per unit generation is a good indicator to determine preferred plant locations. Gila Bend, AZ and Daggett, CA had nearly identical average revenue per unit generation, and Harper Lake was about 10% higher.
- *Particle CSP Plant value increases in regions with high renewable penetration*. There are more hours in which the system does not have sufficient flexibility to meet demand in grid systems with higher PV and wind penetration. Particle CSP Plants provide needed flexibility. Annual plant revenue for the Particle CSP Plant is 46% higher at a renewables penetration of 50% compared to the 23% renewable penetration case.

While production cost modeling results alone are insufficient to make technology design, development, and investment decisions, they can be used to inform these processes. This study provides insights on relative differences in annual system operating cost, Particle CSP Plant revenue, LMP, and other metrics for a variety of scenarios. This information can be used by system operators, utility planners, plant developers, investors, and other stakeholders to build an understanding of the potential value and benefits Particle CSP Plants may offer.

ACKNOWLEDGMENTS

This work is funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 34211. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

REFERENCES

1. "Generation 3 Concentrating Solar Power Systems, Funding Opportunity Announcement (FOA) Number: DE-FOA-0001697." U.S. Department of Energy, Sep. 11, 2017.
2. Particle CSP Plant: Insights on Market Adoption Pathways. EPRI, Palo Alto, CA: 2020. 3002020056.
3. Next Generation Receivers: R&D Virtual Workshop Series, U.S. DOE Concentrating Solar Power Program, Sandia National Laboratories (SAND2020-11936 PE), 2020.
4. Reliability Test System of the Grid Modernization Laboratory Consortium (RTS-GMLC). https://github.com/GridMod/RTS-GMLC
5. Power System Optimizer (PSO). http://www.enelytix.com/home/pso
6. B. Mills and C. K. Ho, "Simulation and performance evaluation of on-sun particle receiver tests," AIP Conference Proceedings 2126, 030036 (2019): https://doi.org/10.1063/1.5117548
7. SunShot 2030, DOE SETO. https://www.energy.gov/eere/solar/sunshot-2030
8. L. González-Portillo, K. Albrecht, and C. K. Ho, "Techno-Economic Optimization of CSP Plants with Free-Falling Particle Receivers," *Entropy* 2021, 23, 76. https://doi.org/10.3390/e23010076