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Concentrating Solar Power (CSP) Plant Optimization Study for the California Power Market (CalCSP)

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Abstract. In the United States, many states are implementing goals to achieve 100% carbon free power generation by 2050 or sooner. California has one of the more aggressive goals to achieve 100% carbon free generation of its retail power sales by 2045. California has excellent solar resources, but to accomplish this goal, California's power utilities will need new zero carbon resources that can replace the natural gas units that they currently rely on for suppling power at night. Appropriately configured concentrating solar power plants with thermal energy storage are an option to serve this nighttime load. These plants would be designed to take advantage of CSP's low-cost thermal energy storage and collect and store energy during the day and then be dispatched to produce power at night. The U.S. Department of Energy has funded a study to identify the design of a CSP plant that optimally meets the evolving CA grid needs. This will be done by taking a fresh look at how CSP technologies can best be designed to meet the emerging nighttime market for carbon free power generation or zero-carbon firm resources. The paper provides an overview of the study and present preliminary findings on the California power market requirements, CSP configurations, technoeconomic analysis, siting opportunities, and key issues for CSP deployment in this market.

Keywords: Concentrating Solar Power (CSP), California, Power Market, SB 100, Renewable Portfolio Standard (RPS)

1. Introduction

In the United States, it is the states that primarily regulate the electric power generation sector often with support from the federal government via various subsidies and incentives. As a result, it is the states that drive the decisions and policies to encourage renewable electricity generation and the move to decarbonize the electric power sector. One of the primary policies that drove the deployment of renewable energy was renewable portfolio standards (RPS). These required a percentage of a utility's electric generation to come from renewable power sources. Growing interest in addressing climate change and eliminating carbon emissions has led many states to implement more aggressive clean energy targets. As of September 2020, 38 of the 50 states and the District of Columbia (Washington DC) have established an RPS or renewable goal, and in 12 of those states (and the District of Colombia), the requirement is for 100% clean electricity by 2050 or earlier.

1.1. California Senate Bill 100

California, located on the west coast of the United States, has a population of nearly 40 million, and has sites with excellent direct normal solar resources which are ideal for Concentrating

Solar Power (CSP) technologies. California is one of the states that has been more aggressively reducing carbon-based power generation. California Senate Bill (SB) 100, titled "The 100 Percent Clean Energy Act of 2018," established a landmark policy requiring that renewable energy and zero-carbon resources supply 100 percent of electric retail sales to end-use customers by 2045. As part of SB 100, California prepares periodic reports on how it plans to meet its carbon reduction goals [1]. According to the initial assessment report, in the "Core" SB100 scenario, California could require nearly 100 GW of new solar power (utility scale and customer rooftop), over 20 GW of new wind generation (on-shore and off-shore), and over 50 GW of energy storage, by 2045 to meet this goal. Because the SB 100 target is based on retail sales to end-use customers, the policy does not necessarily end the use of natural gas. While no new natural gas generation is assumed in the SB 100 Core scenario, much of the existing natural gas capacity is retained through 2045. As stated in the 2021 SB100 joint agency report, "generation of renewable and zero-carbon resources must be at least equal to retail sales by 2045, however natural gas generation can serve non-retail load or system losses" [1]. Several alternative scenarios are being evaluated in addition to the Core scenario including high electrification, no-combustion, availability of zero-carbon firm resources (in place of natural gas), and accelerated timelines. These result in increased deployment of renewable generation or in the case of zero-carbon firm resources could reduce or eliminate the amount of gas generation needed.

California did not include several technologies in its initial SB-100 modeling assessment and CSP was one of these. The reasons for not including CSP were:

> "Because of the higher costs relative to solar photovoltaic and wind energy, there is limited development potential, and solar thermal plants were ruled out of the modeling study. Concerns regarding the environmental impacts of CSP projects — including avian mortality from power tower flux and evaporation ponds — have also been a barrier to development, though recent technological and operation changes have reduced the mortality." [1]

As states move towards a goal of 100% carbon free power generation, utilities need resources that can replace the natural gas baseload, intermediate load, and peaking units that they rely on today for suppling energy and capacity and providing a reliable and stable grid. In the past with lower renewable penetration, the focus was on the least cost renewable energy. As variable renewable generation increased, the focus shifted to net load and meeting evening ramp rates. With the goal to eliminate conventional fossil generation, the question is how utilities can manage the grid with increasing variable generation. Figure 1 below shows an example of how the net California system load would look with double the 2020 renewable generation (solar, wind, and baseload renewables) for sunny spring, summer peak, and winter days. The conventional hydroelectric output is assumed to remain constant (an assumption that may be optimistic given the long duration drought facing California). The brown represents the remaining load to be served by current fossil, nuclear, and generation imported to the state. Although this is a simplistic analysis, it highlights the main issue facing California - meeting nighttime loads. For California to meet this need with solar, huge amounts of energy storage will be required as is seen in the SB-100 reference case. Appropriately configured CSP plants with thermal energy storage (TES) are an option to serve this nighttime load (Note: all references to CSP in the rest of this document, imply that TES is included).

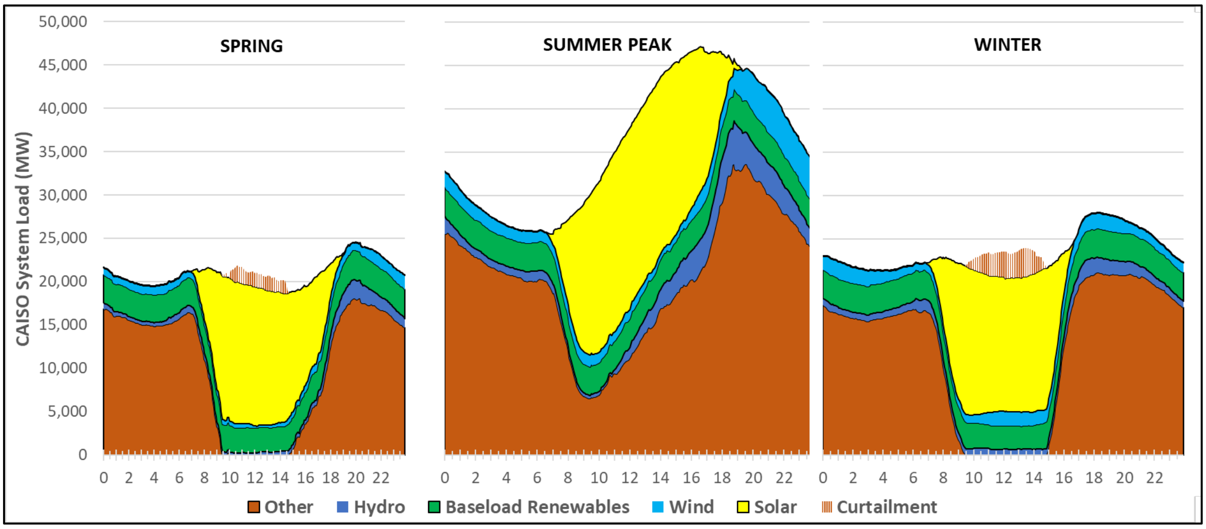

Figure 1. CAISO System Load with Double the 2020 renewable generation (solar, wind, and baseload renewables) Adapted from [2].

1.2. California CSP design study

The U.S. Department of Energy has funded a study to identify the design of a CSP plant with long duration thermal energy storage that optimally meets the evolving CA grid needs. This will be done by taking a fresh look at how CSP technologies can best be designed to meet the emerging nighttime market for carbon free power generation or zero-carbon firm resources. Specifically, it will rethink the designs of CSP plants to address the market requirements and to assess the technoeconomic performance of CSP technologies in these applications. The study will reach out to many of the important stakeholder groups in California and address real and perceived issues that stakeholders have with CSP technologies as identified in the SB 100 initial assessment report [1]. The study will attempt to learn from recent development experience in the United States and identify several areas that are well suited for the development of larger CSP power parks. Finally, the study will consider more innovative ways that CSP projects can be developed, financed, or structured to reduce their cost. This paper reports on the initial stage of this effort.

2. Power market requirements

To meet its SB-100 goals, California will require a massive expansion of photovoltaic (PV) and wind power in the state. Photovoltaics will provide most of California's power needs during the day. On-shore wind power is much more variable and may provide generation during the day or night, but often has extended periods of low generation. The state is considering new off-shore wind generation along the coast of California that will have more consistent wind resources. But this will take years to develop and permit. Battery technologies are one of the key technologies that California assumes will be needed to meet its nighttime generation needs. Batteries will be charged from solar and wind resources and used to supply power when wind and solar are not available. CSP with long duration energy storage could also be part of the technology mix. It is assumed that there is likely to be an excess of low-cost solar generation during the daytime from photovoltaic facilities. Thus, CSP plants would likely be designed to collect energy during the day and dispatch power at night. That is the general premise of this study, that CSP would be used as a nighttime generation or potentially as an evening peaking resource. CSP plants would need to be designed to reliably store energy during the day and dispatch energy when it is needed.

To manage extended periods of low wind and solar resources, and to support grid reliability, California plans to rely on its current fleet of natural gas plants, albeit running at lower annual load factors. But to eliminate carbon emissions altogether, California will also need dispatchable carbon neutral technologies in its portfolio mix. These are currently thought to be combustion turbines fueled by carbon neutral (green) fuels or that sequester carbon from combustion. It is worth noting that CSP plants could also be hybridized with natural gas or green fuels to allow the plants to have 100% fuel availability, so even during an extended cloudy period, CSP plants could be used to provide a reliable source of capacity 24 hours per day, 365 days per year. The California SEGS parabolic trough plants, located at Kramer Junction, were hybridized with natural gas, and consistently demonstrated on-peak capacity factors near 100%.

2.1. NREL regional planning model

To understand the needs of the California grid as it experiences a massive expansion of variable energy resources and energy storage, the study will use the National Renewable Energy Laboratory (NREL) regional planning model (RPM). RPM is an integrated resource planning and dispatch tool for modeling regional electric systems [3, 4]. NREL has used RPM to model the expansion of power generation technologies in California and the entire western interconnection, including cases that look at California's SB 100 goals (Study of the Los Angeles Department of Water and Power pathways to a 100% renewable power system) [5]. One of the key advantages of RPM is that it allows detail to be added to the model to evaluate regions of interest. The RPM model can be used to evaluate what technologies are likely to get built in which regions to meet different policy objectives, where transmission should be expanded, and the cost and design assumptions required for CSP to be deployed. Transmission system capacity and access will be one of the key drivers for when and where new plants will be built. In this study, RPM will be used to predict in which regions photovoltaic plants will be built and where transmission is likely to be expanded. We assume that CSP plants can likely be co-located in the same regions where large PV facilities will be installed. The transmission system will need to be expanded to support power generation from the PV facilities during the day. This same transmission capacity is likely to be unused at night when the PV facilities are not generating, leaving the capacity available for CSP plants to use at night. RPM will be used to help validate this assumption and to help determine the design assumptions for CSP systems and to evaluate the cost assumptions needed in different CSP development zones of interest for gigawatts of CSP projects to be deployed to help meet the SB 100 goals.

3. Stakeholder engagement

One of the key goals of the study is to help inform stakeholders about the potential of CSP for California. Many of the key stakeholders that are planning for how California will achieve its SB 100 goals either do not have a good idea of the potential for CSP to support California's energy needs, or they may have pre-existing perceptions about the technology that may not be up to date. As a result, although CSP is acknowledged as a relevant technology for SB100, it has not been one of the primary technologies evaluated for meeting its targets. This project will reach out to the key stakeholder groups involved in plotting the path to address the SB 100 goals and will provide information to allow CSP technologies to be correctly evaluated against other technology options. The project has created a stakeholder advisory group (SAG) to provide input to the study and to review and provide feedback on the findings from the study. The SAG includes participants from key California agencies (California Public Utility Commission, the California Energy Commission, the California Independent System Operator, and the Department of Water Resources), several of the key utilities in the state, various environmental and advocacy groups, and several members from the CSP industry (including a plant owner and two CSP developer/technology providers). The goal was to create a diverse group with a range of perspectives to provide input to the study to see how CSP can support California's carbon reduction goals, to address stakeholder concerns about CSP, and to help develop concepts and scenarios for how CSP projects can be most cost effectively be developed in California. The project had its first meeting with the SAG in July 2022, where 18 of 22 members attended. The project team is conducting surveys of the SAG members to get formalized feedback and input to the study. The answers by 18 of the 22 SAG members to two key questions in the initial survey, are presented below.

Question: Which of the following technology issues could prevent CSP from being deployed? (Percent of respondents that agree or strongly agree)

The cost of energy from a CSP plant.	67%
The performance of CSP plants.	50%
The availability and reliability of CSP plants.	44%
The lack of developers and CSP industry in the U.S.	44%
The cost of operation and maintenance.	41%
The time it takes to develop and construct a CSP plant.	39%
The complexity of CSP plants.	28%

The cost of energy and the performance of CSP plants were the major concerns identified.

Question: Which of the following are important siting issues for CSP? (Percent of respondents that agree or strongly agree)

Access to transmission.	83%
Availability of suitable land for CSP plants.	72%
The quantity of water used by CSP plants.	50%
The environmental impact of CSP plants.	44%
The effect of concentrated light flux on avian mortality.	44%
Reflected light affecting general aviation.	44%
The visual appearance of the illuminated receiver in operation.	39%
Department of Defense training flight routes.	39%
Possibility of heat transfer fluid leaks in parabolic trough plants.	28%

Access to transmission and identifying suitable land available for CSP were the major concerns identified.

4. CSP Technology comparison

This project will look at how the next wave of CSP projects located in or around California, could be optimized to support the needs of SB-100.

4.1. Commercial CSP technologies

This project will primarily focus on near-term commercial CSP technologies to evaluate which technologies and configurations are likely to provide the most value for future market needs. The initial stage of the project plans to consider the following CSP technologies.

Molten-salt tower (MST): The MST is believed to be the most economically competitive commercial CSP technology on the market with around 10 plants in commercial operation globally. Although the initial series of MST plants has experienced some availability issues, we assume that these issues are generally understood, and the next generation of MST plant should be able to avoid them. MST technology offers efficient and low-cost thermal energy storage which makes it ideal for peaking and night generation configurations that we assume will be needed. However, there are some concerns about potential avian impacts due to high flux zones of concentrated light, and concerns about the visual impact of the illuminated tower while the plant is in operation.

Parabolic trough (PT): PT technology using biphenyl-diphenyl oxide heat transfer fluid (HTF) is the most commercially mature CSP technology with over 80 commercial scale plants constructed and in operation around the world. PT technology is seen as a lower risk technology that can be more easily sited, but also more expensive that MST technology, due in large part to its more expensive indirect two-tank molten-salt storage technology. The main issue for trough technology is cost. This is primarily a consequence of the HTF which as a limited operating temperature of about 400°C.

4.2. Near-term advanced CSP technologies

Several advanced CSP technologies that have the potential to be deployed in the short term, the next 5 to 10 years, will also be evaluated. These include:

Hybrid configurations: Several recent studies have evaluated hybrid configurations that integrate CSP plants with PV and/or batteries have shown economic advantages compared with just PV + batteries [6]. CSP plants can also be designed to operate as dual fuel hybrids using natural gas, biogas, green hydrogen, or green ammonia allowing such plants to operate year-round with high availability.

Modular tower: A new modular tower technology that uses multiple small heliostat field/receivers and uses sodium as the HTF in the receiver to transport heat back to a central power plant where energy is stored in molten salt, is being developed in a reference facility in Australia [7]. If the modular design is successfully demonstrated and found to be cost competitive with MST technology, it addresses several of the siting and construction issues for larger MST solar fields. The reference facility will need to demonstrate that using sodium heat transfer fluid is an acceptable solution from a risk, reliability, and cost standpoint.

High temperature parabolic trough: Several higher temperature HTFs have been considered for parabolic trough technology. A new silicon based HTF allowing operating temperatures to be increased to 425°C or potentially 450°C has been found to offer marginally better economics compared to the current HTF. Switching to molten salt as the HTF in the solar field offers a potentially significant cost saving and efficiency improvement compared to the current HTF. However, molten salt has a high freeze point, so plants need to be designed to prevent and recover from molten salt freeze events. Like the modular tower, a reference plant would be needed to demonstrate the technology is sufficiently mature and cost effective to use at scale.

4.3. Reference technology

The project will compare CSP technologies and CSP hybrid configurations against PV + Batteries (PV+BESS) as this is the assumed reference from the Core SB-100 case.

5. CSP siting assessment

The study will evaluate regions in and around California to identify the most promising sites and determine if CSP would be able to be scaled up to be a significant carbon free power resource for California. The project will look for the best regions that provide the power needed, minimize cost and environmental impacts, consider other factors that might limit CSP development, and provide the most economic advantages to the State of California. One of the key questions is whether plants should be developed within California to provide the most economic benefit to the state, or to be developed outside of California to minimize impacts to some of the sensitive environmental zones in California, and to reduce the cost of power due to lower development and labor costs in neighboring states.

5.1. CSP development zones

The study has identified the following regions for CSP development with a goal to identify enough sites to develop at least 10 GW of CSP generation for California.

Mojave Desert region: The western Mojave Desert represents one of the premier locations for CSP plant development in California. The region has high direct normal irradiance (DNI) and significant existing high voltage transmission crossing the region. The Mojave has several large military bases and military aviation training routes which are a consideration for siting MST plants. The Mojave is home to several sensitive or endangered species that require special considerations.

Imperial Valley region: The Imperial Valley at the southeastern corner of California, next to the Mexican border, is agricultural land that receives its irrigation water from the Colorado river. The region is likely to see reduced allocation of irrigation water in future years freeing up land for potential solar development. Recent years have seen a significant amount of PV development. The DNI is slightly below that of the Mojave Desert and is a lower desert which is generally about 5° to 10°C hotter than the Mojave Desert.

San Joaquin Valley: The San Joaquin Valley is part of California's central valley and stretches from the Tehachapi Mountains north of Los Angeles up to Sacramento. Largely agricultural, the area is some of the most fertile and important farmland in the world. This region is also under pressure from water resource limitations. The solar resource is about 15% lower than the Mojave Desert. The southern end of the Valley has slightly better DNI and has a lot of oil and gas development (extraction) in addition to agriculture which means it has an existing skilled workforce potentially in need of transition to non-extraction jobs.

Desert Regions: The desert regions in the state are generally environmentally sensitive areas or are protected areas that cannot be developed. However, there are a couple Bureau of Land Management (BLM) solar enterprise zones and BLM variance lands where CSP projects could potentially be developed. This region has solar resources nearly on parr with the Mojave Desert. There are several high voltage transmission lines running through the desert region. Development in these areas is likely to take longer and be more costly.

Arizona & Nevada: California currently imports approximately 25% of its power from neighboring states. As a result, significant transmission already exists to import power into California and plans exist to upgrade many of those lines. Much of this imported power is currently generated by natural gas. As California weans itself off natural gas, this transmission will be available to import solar power from the surrounding states. There are large developable areas with good DNI in both Arizona and Nevada that could be used for CSP projects. California plants to input wind power from New Mexico and Wyoming.

5.2. Screening of site characteristics

A screening study will be conducted to identify potential sites in the CSP development zones. The list below highlights the key issues to be considered for identifying sites for CSP plants.

- Solar resource / wind & seismic loads
- Site topography / geology / hydrology
- Land use & ownership
- Environmental / cultural / economic considerations
- Department of Defense & Federal Aviation Administration airspace restrictions
- Site infrastructure: transmission, roads, railroads, water, natural gas
- Proximity to labor, services to support construction and O&M

- Review of development and permitting requirements
- Technology specific: visual impacts, avian concerns, HTF leaks.
- Former "energy community" as defined in the Inflation Reduction Act

6. Technoeconomic analysis

A technoeconomic analysis will be conducted in two steps. In the initial phase, a screening study will be conducted to compare the performance and economics of the identified technologies. From this, a single technology will be selected for more detailed and careful analysis in the second phase. For the initial screening study, two reference sites in California, a high solar resource site in the Mojave Desert, and a lower resource site in the California central valley but that is less constrained by transmission for power to reach the central and northern portions of the state, will be used to compare the technologies. The operational requirements will be developed based on the NREL RPM modeling results and with input from the SAG. This will define the specific plant operating dispatch profile, plant availability, and start-up or ramping requirements. Preliminary analysis and feedback indicate that the nighttime generation profile from sunset to sunrise is clearly of interest. The NREL System Advisor Model (SAM) [8], will be used to conduct the technoeconomic analysis of the technologies including performance modeling and financial analysis.

The key to the comparison of the technologies and likely the greatest uncertainty in the analysis are the cost assumptions to be used for each technology. Under normal circumstances it is challenging to develop accurate cost models, but with the current inflation and supply chain issues following the COVID 19 pandemic, accurate cost comparisons become even more challenging. The authors plan to use pre-COVID pricing of technologies where possible and attempt to get as much consistency as possible between the cost model assumptions for each technology. In the end, some level of price forecasting will likely be necessary. We plan to use stochastic analysis to evaluate the potential cost ranges of competing technologies. The authors have developed detailed cost models for molten-salt tower [9] and parabolic trough technologies [10] from prior efforts. We propose to update these using input from global CSP projects using data provided by industry participants in the study.

The second phase of work will use the selected CSP technology to conduct a more detailed design optimization and assessment of the cost and performance at a selected site in each of the CSP development zones. The analysis will look more carefully at the plant performance and evaluate design options that could improve the performance or reduce the cost of power from CSP.

Data availability statement

Data and information on the CalCSP study can be requested from the authors.

Author contributions

Hank Price performed writing – original draft of the paper, and conceptualization and supervision of the CalCSP project. Dr. Frederick Morse performed writing – review and editing of the paper and is leading the interaction with California stakeholders.

Competing interests

The authors declare no competing interests, except to encourage the development of CSP in the United States.

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