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Operation of Concentrating Solar Power Plants in the Western Wind and Solar Integration Phase 2 Study

Paul Denholm, Gregory Brinkman, Debra Lew, and Marissa Hummon

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Technical Report
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Abstract

The Western Wind and Solar Integration Study (WWSIS) explores various aspects of the challenges and impacts of integrating large amounts of wind and solar energy into the electric power system of the West. The phase 2 study (WWSIS-2) is one of the first to include dispatchable concentrating solar power (CSP) with thermal energy storage (TES) in multiple scenarios of renewable penetration and mix. As a result, WWSIS-2 provides unique insights into CSP plant operation, grid benefits, and how CSP operation and configuration might need to change under scenarios of increased renewable penetration. Examination of the WWSIS-2 results indicates that in all scenarios CSP plants with TES provide firm system capacity, reducing the net demand and the need for conventional thermal capacity. The plants also reduced demand during periods of short-duration, high-ramping requirements that often require use of lower efficiency peaking units. Changes in CSP operation are driven largely by the presence of other solar generation, particularly photovoltaics (PV). Use of storage by the CSP plants increases in the higher solar scenarios, with operation of the plant often shifted to later in the day. CSP operation also becomes more variable, including more frequent starts. Finally, CSP output is often very low during the day in scenarios with significant PV, which helps decrease overall renewable curtailment (overgeneration). However, the CSP plant configuration studied was not designed to minimize curtailment, implying further analysis of configuration is needed to understand the role of CSP in enabling high renewable scenarios in the western United States.

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1 Introduction

The Western Wind and Solar Integration Study (WWSIS), one of the largest regional solar and wind integration studies to date, explores some of the challenges and impacts of integrating large amounts of wind and solar energy into the electric power system of the West. The first phase (WWSIS-1) examined the hourly operation of the Western Interconnection with wind and solar penetrations up to 35% (GE Energy 2010). Phase 2 (WWSIS-2) (Lew et al. 2013) added several analysis components, including 5-minute dispatch simulations and analysis of wear-and-tear costs and emissions impacts of cycling the fossil-fueled fleet. WWSIS-2 also analyzed additional wind and solar scenarios, including larger amounts of solar. In addition, WWSIS-2 added significant amounts of concentrating solar power (CSP) 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, rapidly change output, and provide firm capacity. The ability to store energy for later use can be particularly valuable in high renewable scenarios during periods when there is limited correlation between the natural supply of solar or wind energy and electricity demand. The WWSIS-2 report provides some indication of the value of dispatchable CSP, but it does not provide detailed insights into how CSP plants are operated in the various scenarios. This includes both the plant operational characteristics, such as start frequency and use of storage, and potential benefits, such as provision of reliable capacity during periods of peak demand. A greater understanding of these issues could be important to CSP technology developers and system planners to maximize the value of CSP in an evolving grid with increased levels of variable generation resources, such as wind and solar photovoltaics (PV).

The purpose of this document is to provide greater detail in the operation of the simulated CSP plants in WWSIS-2 in all scenarios. (In this document we use the term CSP to indicate CSP with TES, as only CSP plants with TES were simulated in the study.) It makes the following observations based on results from the WWSIS-2 simulations:

- Use of storage by the CSP plants increases in the higher solar scenarios, meaning a greater fraction of solar energy is stored for use later in the day. CSP operation becomes more variable, including more frequent starts.
- In all scenarios, CSP plants generate at nearly full output during periods of peak net demand, providing high capacity value.
- CSP plants are often ramped during periods of high variability of wind and solar, thereby reducing the ramping requirements of conventional thermal and hydroelectric generators. Combined with the high capacity value, this implies these plants provide a potentially significant source of grid flexibility.
- CSP output is often very low during the day in the High Solar Scenario. This helps decrease overall renewable curtailment (overgeneration). However, the configuration studied may not be optimal for the High Solar Scenario, implying further analysis of CSP

plant configuration is needed to understand its role in enabling high renewable scenarios in the western United States.[1]

Section 2 of this document provides an overview of WWSIS-2, including the various scenarios evaluated and the implementation of CSP. Section 3 summarizes the CSP-specific results, including each of the four findings stated above. Section 4 concludes and suggests additional work to analyze the potential value and role of CSP in high renewable scenarios in the western United States.

[1] More recent analysis has demonstrated a higher economic value for plants with a lower solar multiple (Jorgenson et al. 2013; Jorgenson et al. 2014), but further analysis is needed to understand how different plant configurations would fit into an optimized portfolio.

2 Overview of WWSIS-2

WWSIS-1, released in May 2010, examined the viability, benefits, and challenges of integrating high penetrations of wind and solar power into the western grid. WWSIS-1 found it to be technically feasible if certain operational changes could be made, but it raised questions regarding the impact of cycling on wear-and-tear costs and emissions.

WWSIS-2 was initiated to investigate the detailed impact of wind and solar power on the fossil-fueled fleet in the West, including wear-and-tear costs and emissions impacts of power plant cycling. The Western Interconnection was simulated using a production simulation model (PLEXOS) including unit commitment, 5-minute economic dispatch, and power flow for a variety of scenarios in the 2020 study year. The basis for the model was the Transmission Expansion Planning Policy Committee's (TEPPC) 2020 Portfolio Case 1. Transmission was modeled zonally, using 20 zones based on the Western Electricity Coordinating Council Loads and Resources Subcommittee. Metrics such as production cost, generation displacement, emissions, starts, hours run, ramps, and reserve violations were used to assess performance of the scenarios.

WWSIS-2 modeled four renewable scenarios in the U.S. portion of the Western Interconnection, including the TEPPC 2020 "base" scenario and three 33% renewable scenarios:

- TEPPC Scenario (9.4% wind, 3.6% solar)
- High Wind Scenario (25% wind, 8% solar)
- High Solar Scenario (8% wind, 25% solar)
- High Mix Scenario (16.5% wind, 16.5% solar).

A capacity expansion model (the Regional Energy Deployment System) was used to select which regions were optimal locations for siting the wind and solar based on resources, load, and transmission (Short et al. 2011). Transmission was expanded to bring the new wind and solar resources to load. Existing fossil generators were not retired.

In each of the scenarios, the ratio of solar PV to CSP was about 60%/40% on an energy basis. Because this ratio of PV to CSP was fixed, the study did not consider the impact of different solar mixes on grid operation or system costs. PV included both distributed (rooftop) and utility-scale PV. CSP was deployed using performance characteristics based on a wet-cooled trough-type plant.[2] Additional details regarding implementation of CSP in the PLEXOS model is described by Denholm and Hummon (2012). The plant is configured with a solar multiple of 2.0, meaning the solar field provides the power block with twice the energy needed to operate at its rated capacity under reference solar conditions. Excess energy from the solar field is stored for later use. The plant is modeled as a "direct" thermal storage plant, where the heat transfer medium is the same as the storage medium, and as a result assumes no losses associated with

[2] This and other assumptions regarding plant type and configuration were based largely on data available at the time of the study. Additional plant types and configurations have since been modeled and have been incorporated into ongoing studies (Jorgenson et al. 2013; Jorgenson et al. 2014).

transferring thermal energy into or out of storage.[3] The plant assumes 6 hours of storage capacity at rated output, a minimum generation level equal to 14% of rated capacity, and the ability to ramp over its entire range in 1 hour. The plant also includes start-up losses but does not include additional operational parameters, such as part-load heat rate and other system losses, that have since been modeled (Jorgenson et al. 2013; Jorgenson et al. 2014).

CSP deployment scenarios are described in Table 1, with a map of deployment by scenario in Figure 1.

Table 1. Installed Capacity of CSP Plants in the Four Renewable Scenarios[4]

State	Installed CSP Capacity (MW)			
	TEPPC	High Wind	High Mix	High Solar
Arizona	472	3,303	9,374	9,644
California	3,221	2,469	3,594	9,197
Colorado	169	169	169	1,440
Nevada	334	439	562	672
New Mexico	156	156	298	574
Total	4,352	6,536	13,997	21,526

[3] More recent NREL analysis of CSP assumes a 2% loss rate for direct storage tower plants and a 7% loss rate for indirect trough plants (Jorgenson et al. 2013). Additional analysis of the operation and value of different CSP technologies and configuration is provided by Jorgenson et al. (2013) and Jorgenson et al. (2014).

[4] The peak output of these plants can be about 10% higher than the rated capacity The version of the System Advisor Model (SAM) used to generate the solar input profiles allows the turbine to run at 10% “over design” conditions during summer months. Reduced solar field parasitic loads will also increase he net plant output when dispatching solely from storage. These limitations have been addressed in more recent PLEXOS CSP dispatch simulations (Jorgenson et al. 2013).

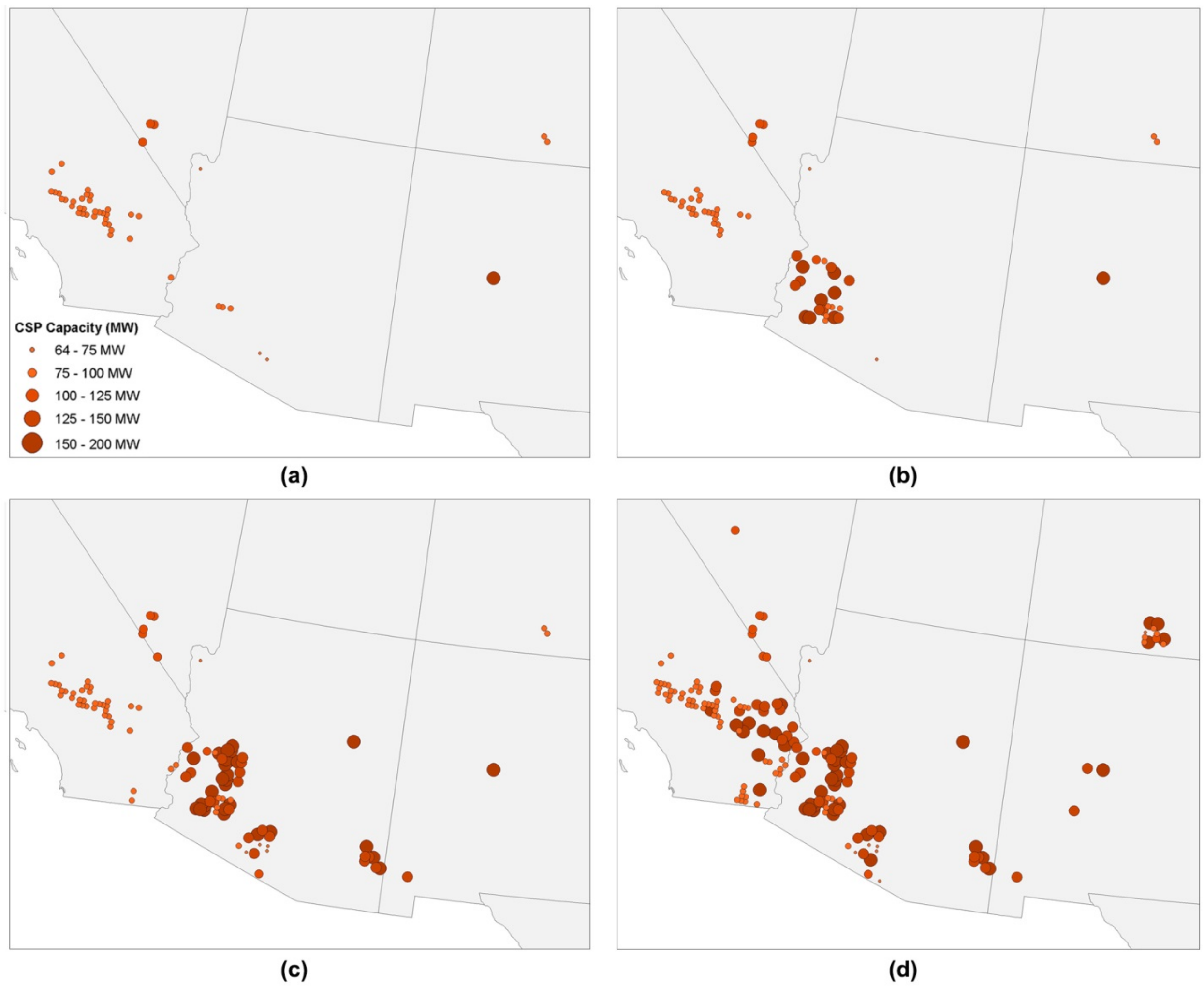


Figure 1. Regional deployment of CSP in the four WWSIS-2 renewable scenarios. (a) TEPPC; (b) High Wind; (c) High Mix; (d) High Solar

The PLEXOS model optimally dispatches all generators in the system (including storage) from the perspective of a system operator with the goal of minimizing overall system production cost. This means that all generators (including CSP) will operate to minimize the sum of system-wide fuel costs (both start and operating fuel) and variable O&M costs. Two unit-commitment cycles were simulated: a day-ahead (DA) "market" and 4-hour ahead (4HA) "market." The DA market is used to commit units with long start times or high start costs (coal, nuclear, and biomass generators), using a 48-hour optimization horizon. The extra 24 hours in the unit commitment horizon (for a full 48-hour window) also helps properly schedule storage (including CSP with thermal storage).[5] The unit commitment from the first 24 hours of each step was saved and input to the 4HA market. The 4HA market uses updated wind and solar forecasts and allows

[5] Without a longer look ahead, storage plants tend to fully discharge each day, not considering possible value to carry over storage to the following day. This is important for CSP when it is used to help address early morning ramps using energy carried over from the previous day, as observed in Section 3.3.

the combined-cycle, oil, and gas steam units to change commitment status in response.[6] The 4HA market was modeled in 24-hour windows. Results from only the first 4 hours from each run were saved for the real-time model, and the extra 20 hours in the unit commitment window helped optimally dispatch the CSP thermal storage. It was sometimes optimal for CSP units to store their energy and deliver it when prices were highest, which occasionally occurred during the load rise the following morning before PV generation began. This demonstrates the value of a 24-hour optimization window. Unit-commitment status from the 4HA market is then passed to the "real-time" economic dispatch simulations, which occur in 5-minute intervals. CSP plants were allowed to change output in the real-time simulations in response to local price variations resulting from forecast errors.

[6] Day-ahead and 4HA forecasts of direct normal irradiance were generated for CSP using a numerical weather prediction model.

3 CSP Operation

3.1 Overview of CSP Operation

A number of studies have demonstrated several of the key drivers behind how a CSP plant might be dispatched in different locations, under different market conditions (Madaeni et al. 2012; Denholm et al. 2013). The PLEXOS simulations in WWSIS-2 allow the CSP plants to be dispatched to maximize their value to the grid as a whole, minimizing the system-wide production cost. During each interval of the simulation, the plant can store some or all of the energy produced by the solar field or draw energy from storage. As a result, maximizing the value of a CSP plant often falls into achieving one or more of the following characteristics:

- CSP plants are dispatched to avoid the use of the highest-cost resources. These are often peaking plants that are needed during periods of highest demand.
- CSP plants are dispatched to manage the net variability on the system. This acts to reduce ramping requirements from thermal generators, decreasing the number of starts and part-load operation.
- CSP plants are dispatched to avoid generation during periods of very low energy value. In the extreme case, this means avoiding generation during periods where the supply of renewables exceeds the ability of the system to absorb that energy resulting in renewable curtailment (overgeneration).[7]

Each of the following sections examines in detail how CSP plants are operated to minimize overall production cost, achieving the characteristics described above. All results presented in this include only the U.S. portion of the Western Interconnection.[8] They also show how CSP operation changes in the various scenarios of increasing solar penetration, generally relying more on the use of energy storage and shifting energy to different times, often with more frequent starts and more variable operation.

3.2 Operation of CSP Plants to Provide Peak Capacity

One of the most significant benefits of CSP with TES is to provide firm system capacity by shifting energy to periods of peak demand. The ability of a CSP plant to provide firm capacity can be observed by its performance during periods of net peak demand—or the residual demand not met by variable generation resources, such as wind and solar PV. In the lowest renewable case (the TEPPC Scenario), there is a relatively small contribution of wind and PV. Figure 2 shows the aggregated load for the entire U.S. portion of the Western Interconnection during the week of highest demand in the TEPPC Scenario (July 24–30). It also shows the contribution from wind and PV and the corresponding net load.

[7] Overgeneration does not necessarily mean the supply of renewables exceeds the demand. It means the generation from renewables plus the minimum generation required from conventional generators exceeds demand. The minimum generation from conventional generators is a function of many factors, including generator flexibility (ability to vary output over various time scales), system reserve requirements, predictability of renewable supply, and local transmission constraints.

[8] There were no CSP plants deployed in Mexico or Canada in the WWSIS-2 simulations.

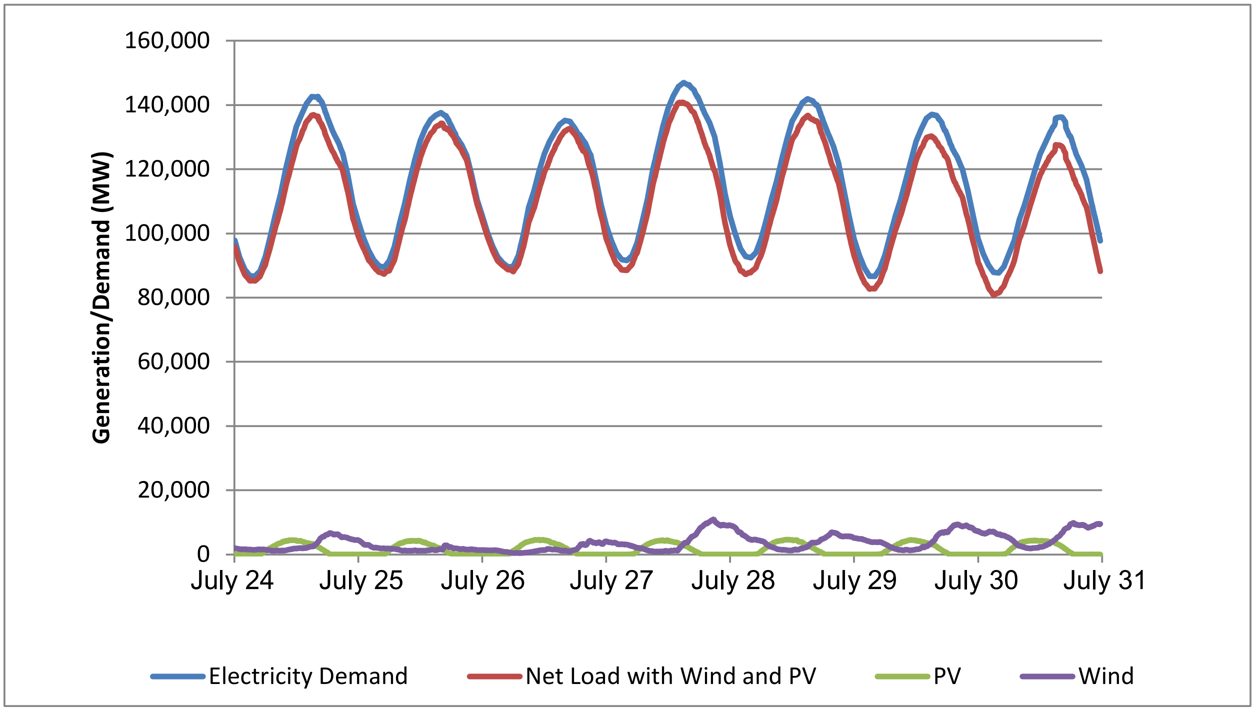


Figure 2. Load, PV, wind, and net load for the week of highest demand in the TEPPC Scenario

Figure 3 demonstrates the combined output of the CSP plants in the TEPPC Scenario during the same week. It also shows the thermal energy coming from the solar field (defined as electrical energy equivalent inflow, incorporating the efficiency of thermal to electrical conversion), or approximately the output of the CSP plants if they did not employ energy storage. These curves correspond to the right y-axis, with the net load shown on the left y-axis for comparison. It shows that the natural inflow of solar energy is not entirely coincident with demand, with an offset of about 4 hours. However, the use of storage enables the CSP plants to shift output to periods of highest net demand. The output of the plants is roughly equal to the "block" dispatch characteristic of previous studies of CSP operation in the summer (Sioshansi and Denholm 2010; Denholm et al. 2013.) The irregularities are due to the fact that each individual plant is responding to local needs, which are obscured by aggregating the plants together.

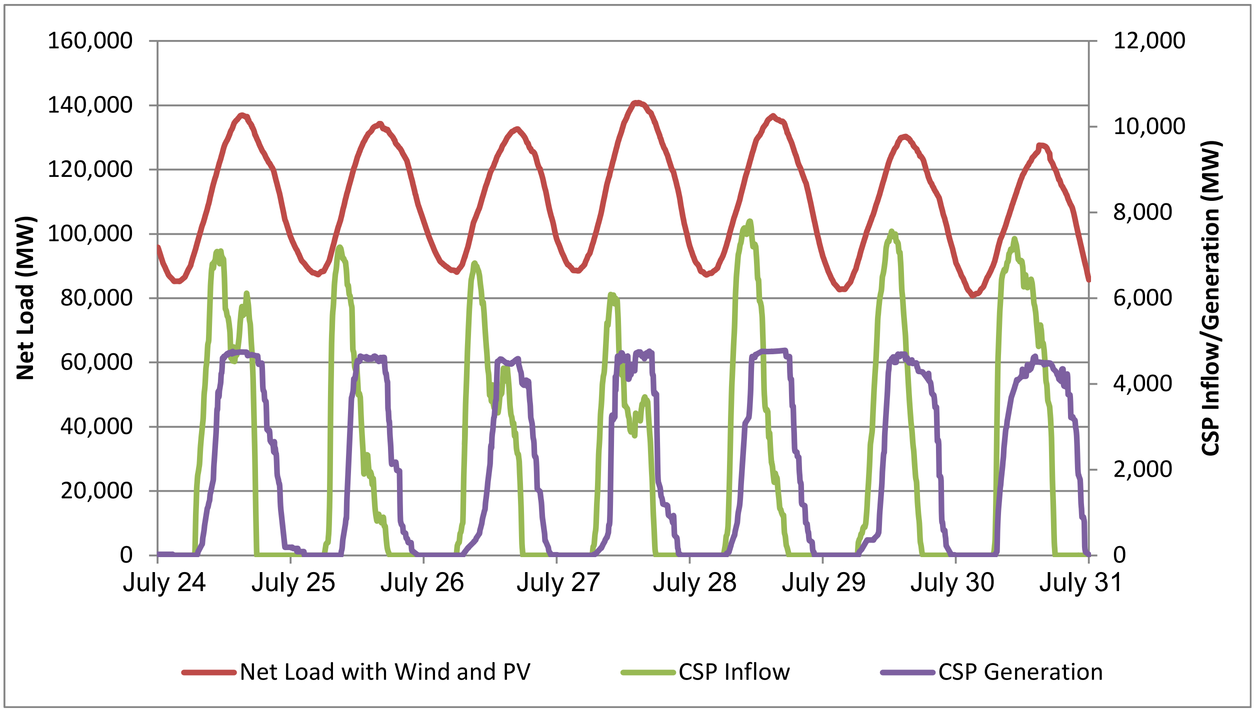


Figure 3. CSP dispatch for the week of highest demand in the TEPPC Scenario

While the previous figures provide the dispatch for all CSP plants aggregated, the dispatch of individual plants is fairly similar, with regional differences based on solar resource and local load patterns. Figure 4 illustrates the average dispatch profile for CSP aggregated to the state level over the entire summer period. The difference in timing is partially due to location, as the sun effectively rises earlier in Colorado than California because the output profiles are all synchronized to the same time (Pacific standard time).

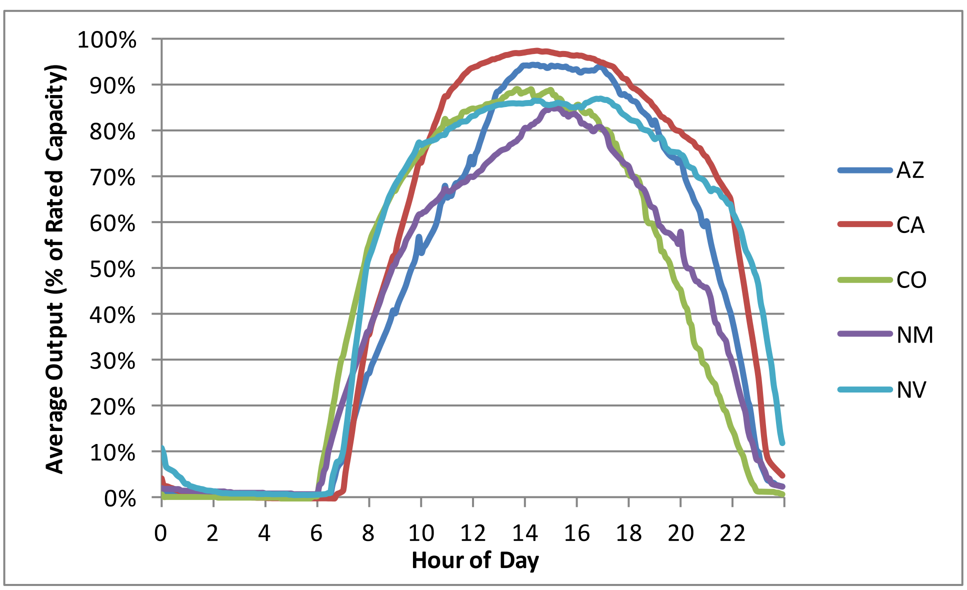
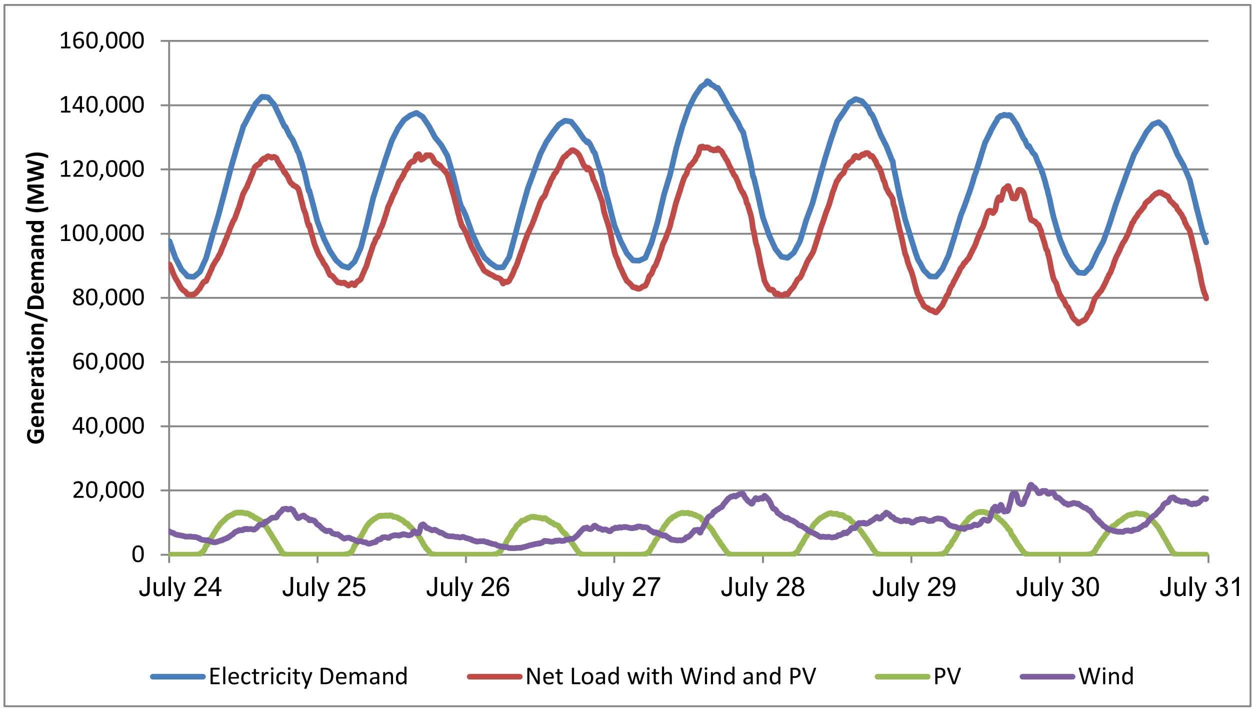


Figure 4. Average CSP dispatch profile in the summer aggregated to the state level in the TEPPC Scenario

As greater amounts of wind and solar are added to the system, the timing of peak demand can shift, potentially increasing the importance of energy storage in CSP plants. Figure 5 demonstrates this for the High Wind and High Solar Scenarios. Figure 5a illustrates the High Wind Scenario, which produces a relatively small shift in peak demand. Figure 5b, however, shows a much greater shift, with the peak net demand moving from about 2 pm to about 6 pm but also with a narrower peak window.



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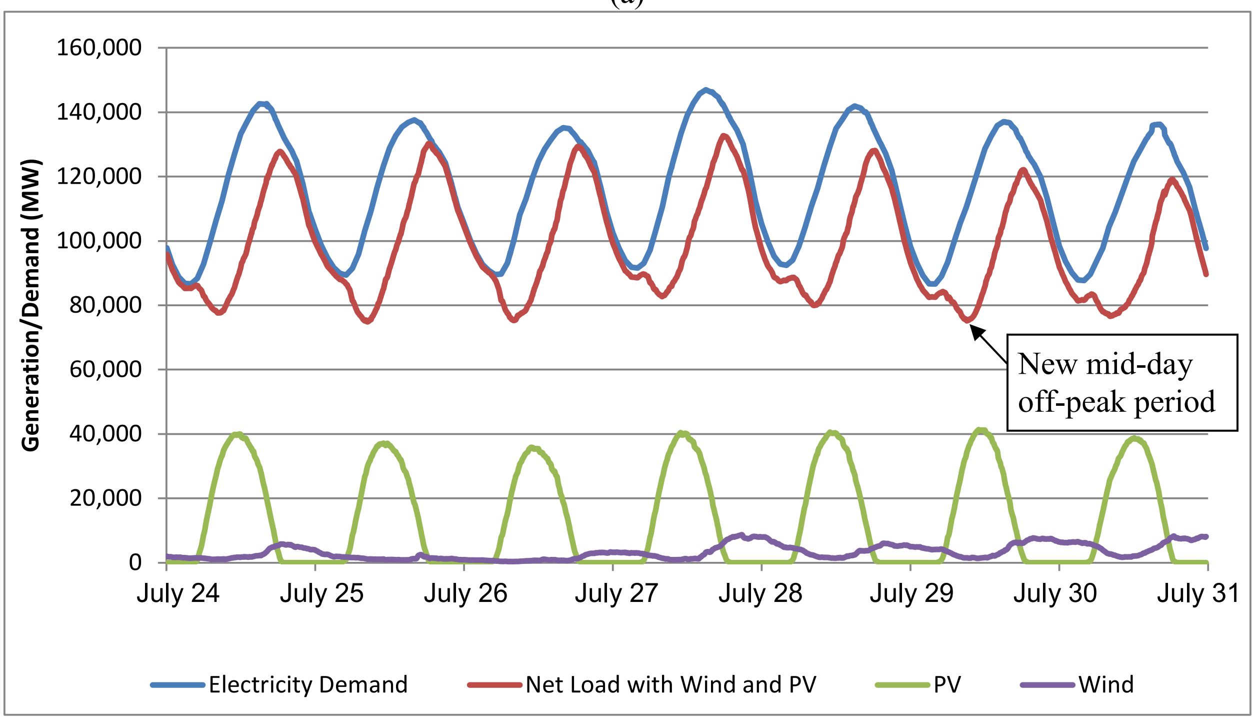
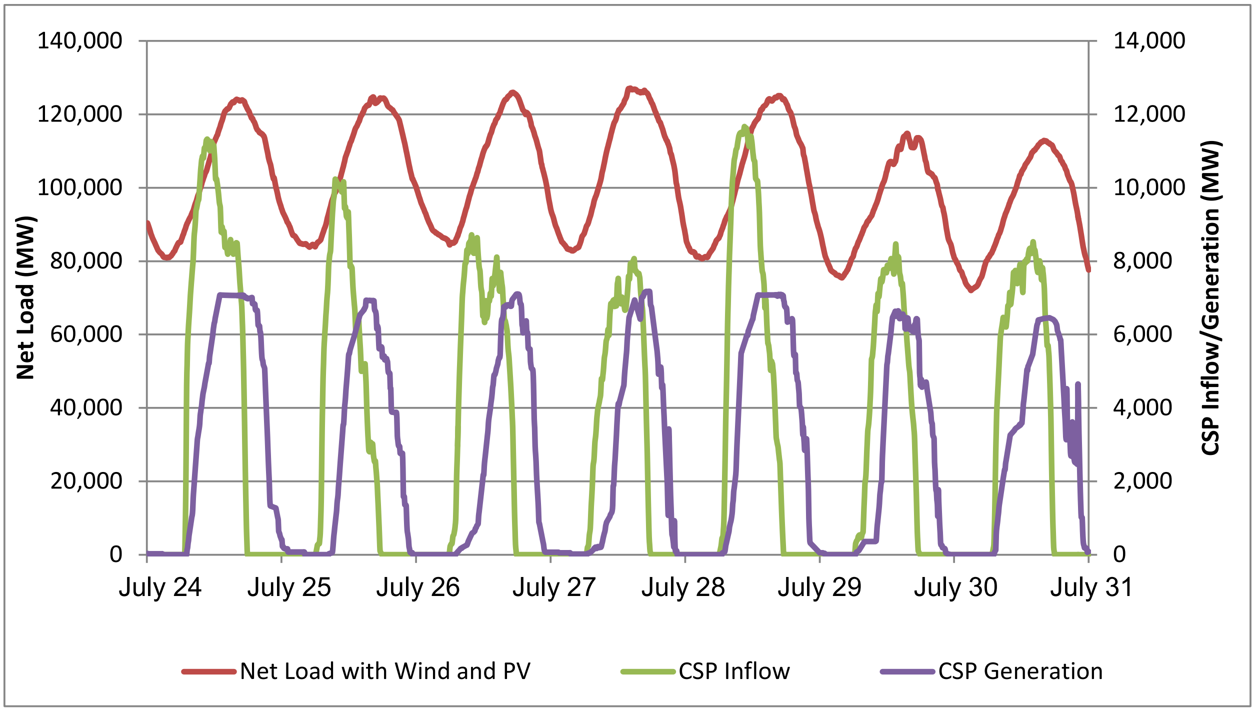


(b)

Figure 5. Net load profiles for the (a) High Wind and (b) High Solar Scenarios for one week in July

Figure 6 shows the corresponding CSP output for each of these two scenarios for the same period. It shows the significant shift in CSP generation to later in the day, particularly in the High Solar Scenario.



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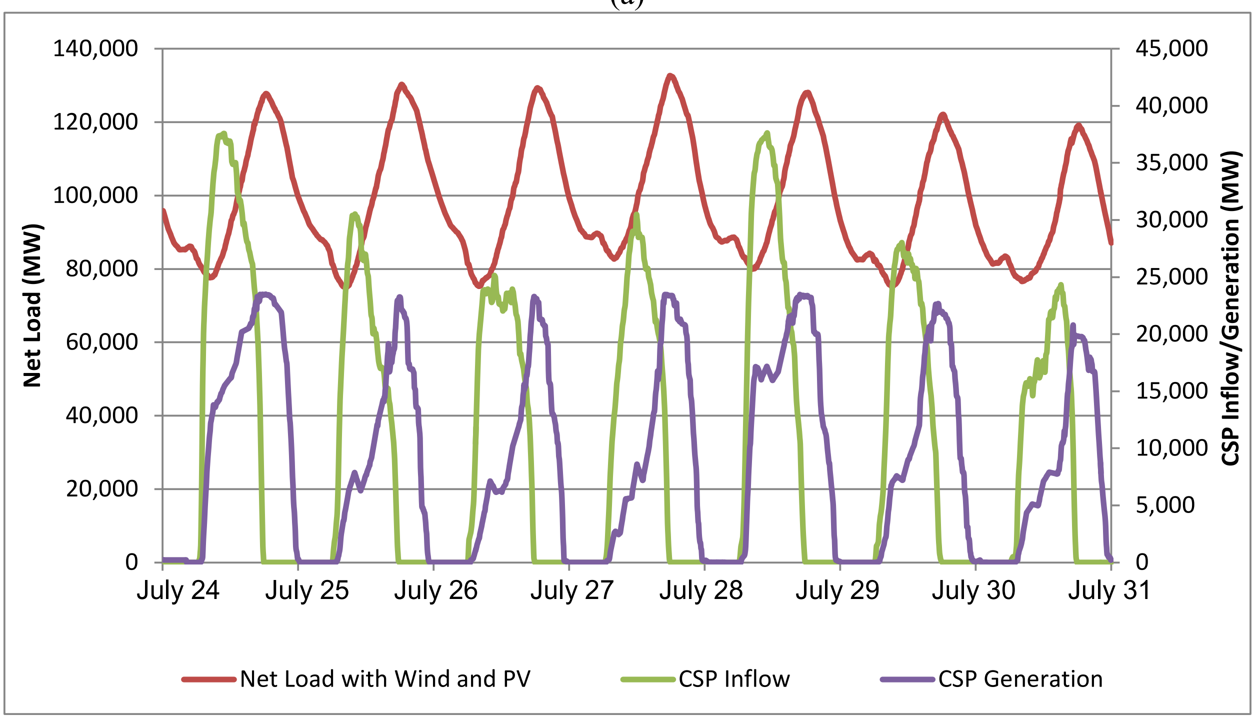


(b)

Figure 6. CSP generation profiles for the (a) High Wind and (b) High Solar Scenarios for one week in July

This shift in generation profile can be observed more directly by comparing seasonal average operation of the CSP plants. Figure 7 illustrates the average CSP generation profile for CSP plants in California during the summer. The output has been normalized for comparison, as the

High Solar Scenario has about three times the installed CSP capacity compared to the TEPPC Scenario. In the TEPPC Scenario, CSP generation typically peaks between 2 pm and 3 pm, compared to 5 pm and 6 pm in the High Solar Scenario. This is due to the large amount of PV generation that occurs during the earlier part of the day.

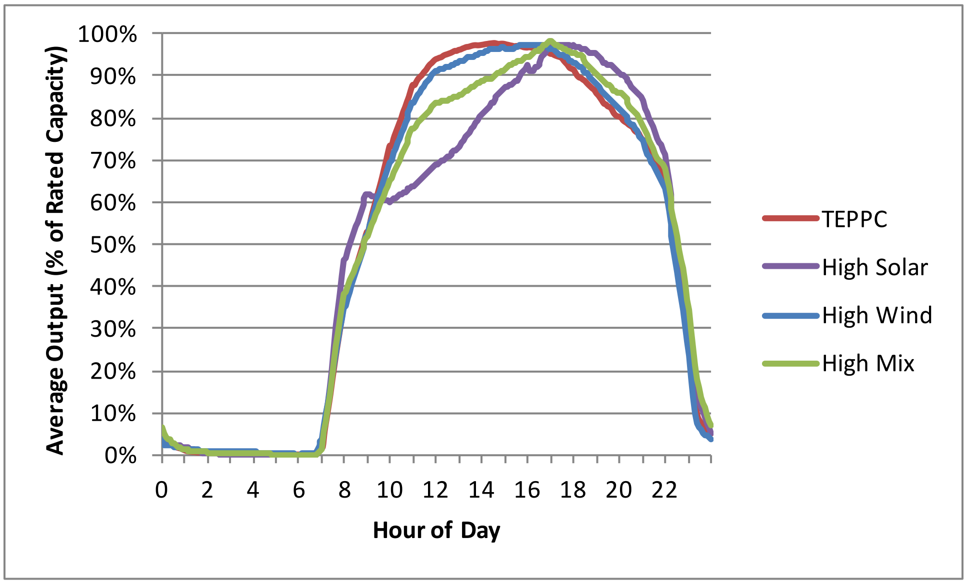
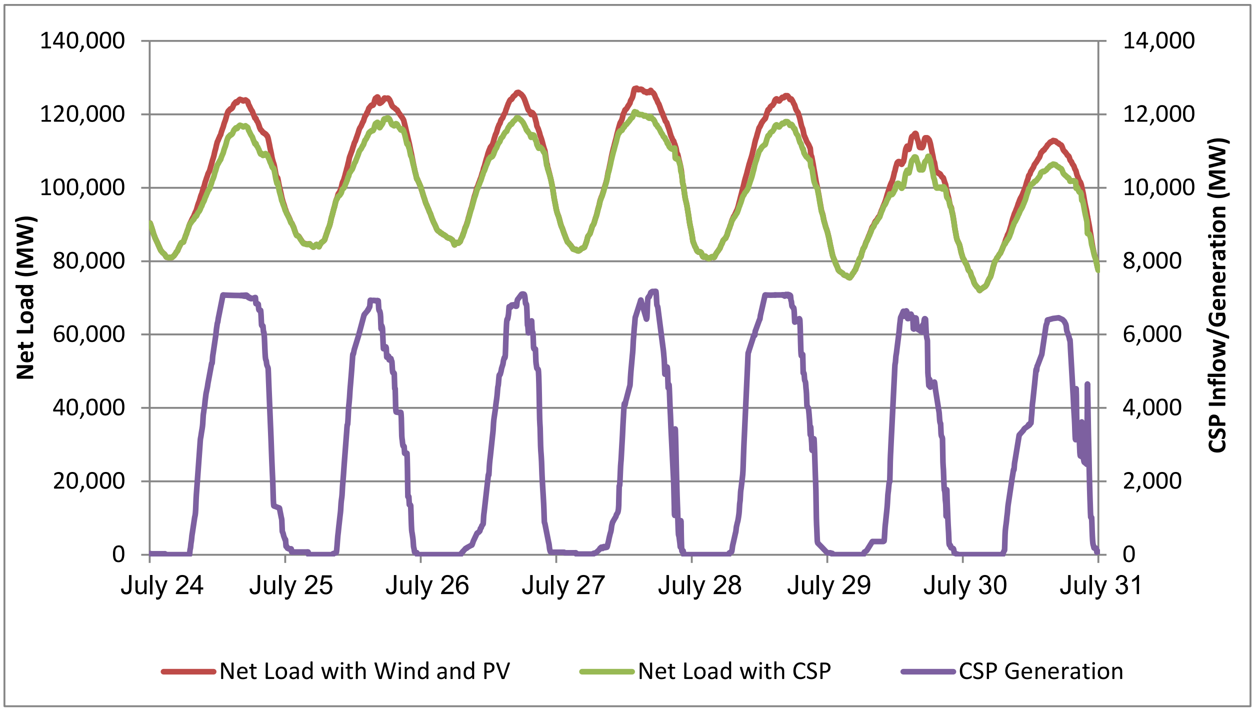


Figure 7. Average CSP dispatch profile in California during the summer

The effect of the CSP energy shift is to reduce the net load observed by the system in all scenarios, with CSP plants generating at nearly full output during periods of local and system-wide peak demand. Figure 8 illustrates the WECC-wide net load during the same period as Figure 7 with and without the CSP dispatch. It shows the significant reduction in demand that would otherwise need to be met with conventional generators. This supports previous (more detailed) analysis of the capacity credit of CSP plants, which finds that plants with several hours of storage have an effective load carrying capacity similar to conventional generation resources (Madaeni et al. 2012). The High Solar Scenario also demonstrates two other characteristics of CSP dispatch discussed in more detail in the following sections. The first is the reduction in system ramping requirements, as CSP plants reduce the overall ramp range and, in many cases, the ramp rate. The second is the general ability of CSP to avoid generation during periods of low demand. The net load curve with PV and wind (but before the addition of CSP) in the High Solar Scenario shows a new off-peak period that occurs in the late morning period after the sun rises (and significant PV production begins) but before load greatly increases. (This is easiest to observe in Figure 5b). Ideally, a CSP plant would avoid generation in this period in favor of later in the day. However, the configuration chosen for this study (solar multiple of 2 with 6 hours of storage) forces some of the CSP energy to be dispatched during this period, further reducing the net load during this new off-peak period in the late morning. This does not lead to significant operational challenges (or curtailment) in this scenario but points to the importance of evaluating various CSP configurations, as discussed in Section 3.4.



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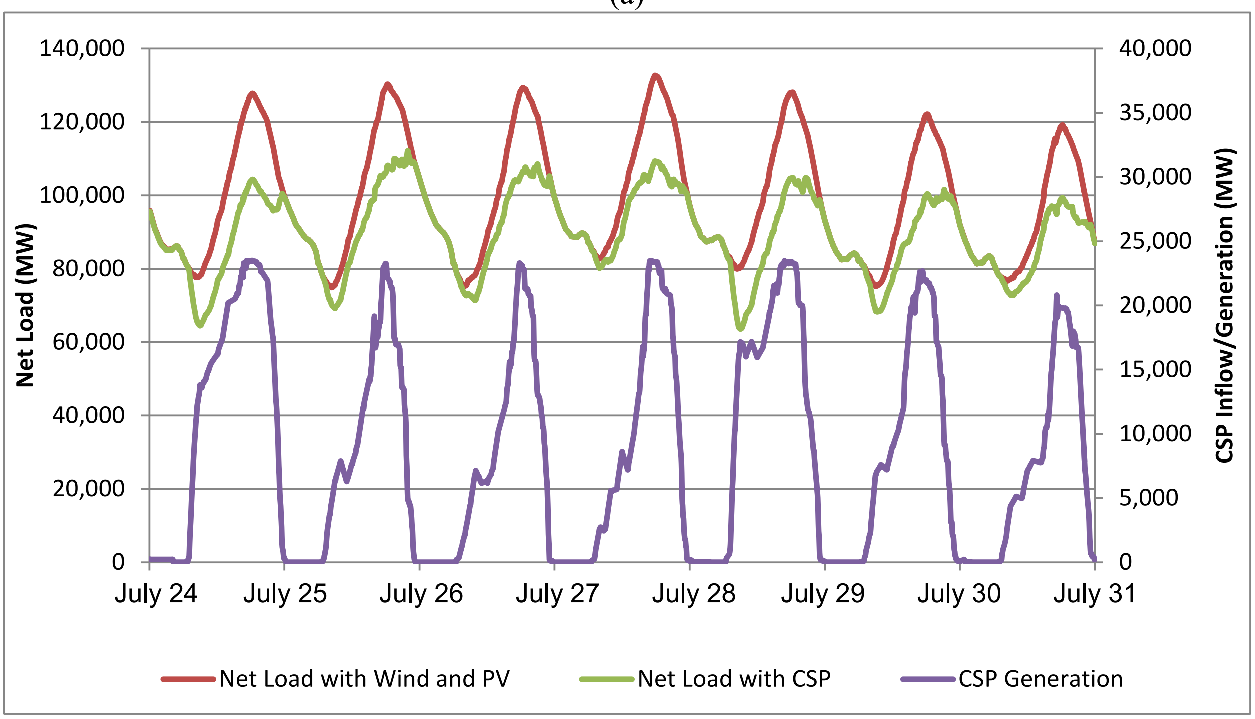

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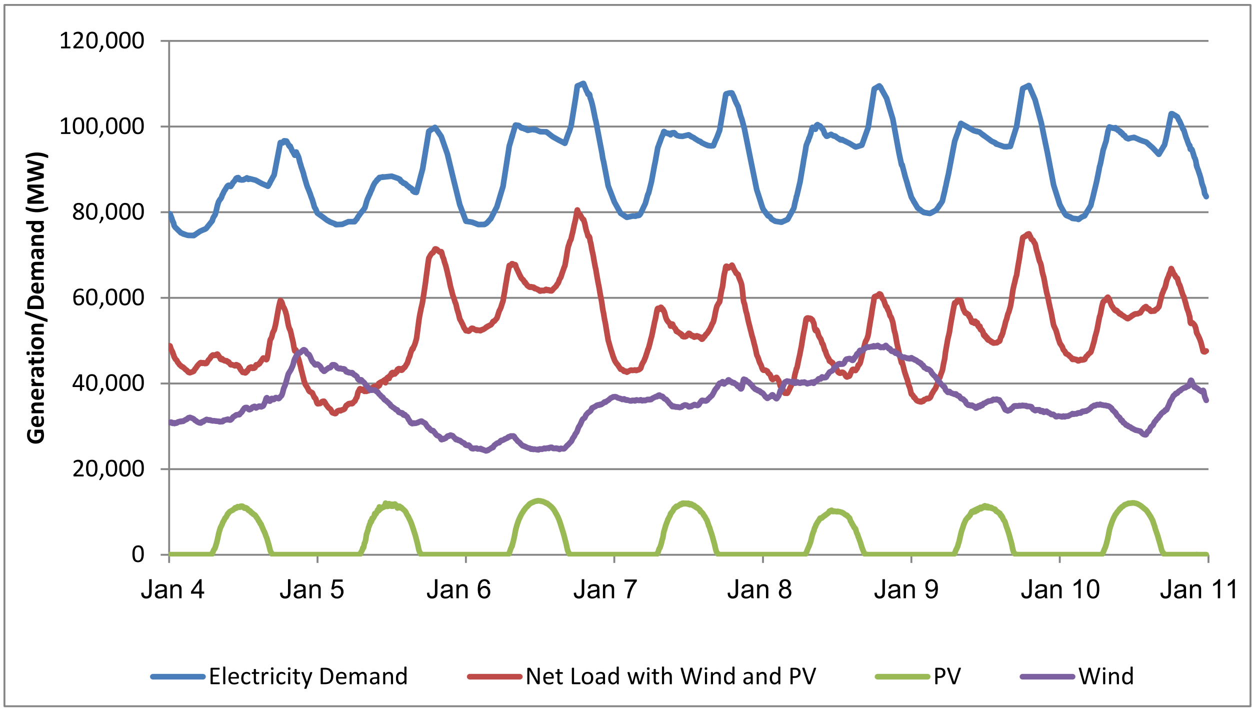
Figure 8. Net load before and after the dispatch of CSP in the (a) High Wind and (b) High Solar Scenarios from July 24–30

3.3 CSP Operation to Reduce Ramping Requirements

In addition to providing firm capacity, CSP can also replace the need for conventional generators to vary output during periods of high net load variability. This benefit occurs during all seasons, including periods with some of the highest instantaneous net load ramp rates (MW/minute) that occur near sunset on winter days. These ramp requirements are often associated with short duration peak periods. These winter peaks are much lower in magnitude than summer peaks, so typically do not drive peak capacity requirements. However, they often require the use of lower efficiency combustion turbines because the duration of the demand is not long enough to warrant starting a more efficient combined-cycle unit (exacerbated by the need for high ramp rates). This ramp requirement is increased in the High Solar Scenario.

Figure 9 illustrates the net load for a week period starting on January 4 in the High Wind and High Solar Scenarios. They show the morning load increase and a sharp narrow evening peak, often met by lower efficiency generators. Examining the normal electricity demand, of the 50 hours with the highest ramp rates, 47 occur from December to early February, typically at about 5 pm. The PV generation in the High Solar Scenario produces particularly sharp evening peaks but also introduces short morning peaks. The High Solar Scenario also creates a new paradigm for the definition of "on-peak" and "off-peak" as the mid-day period has a lower net load than during overnight hours.



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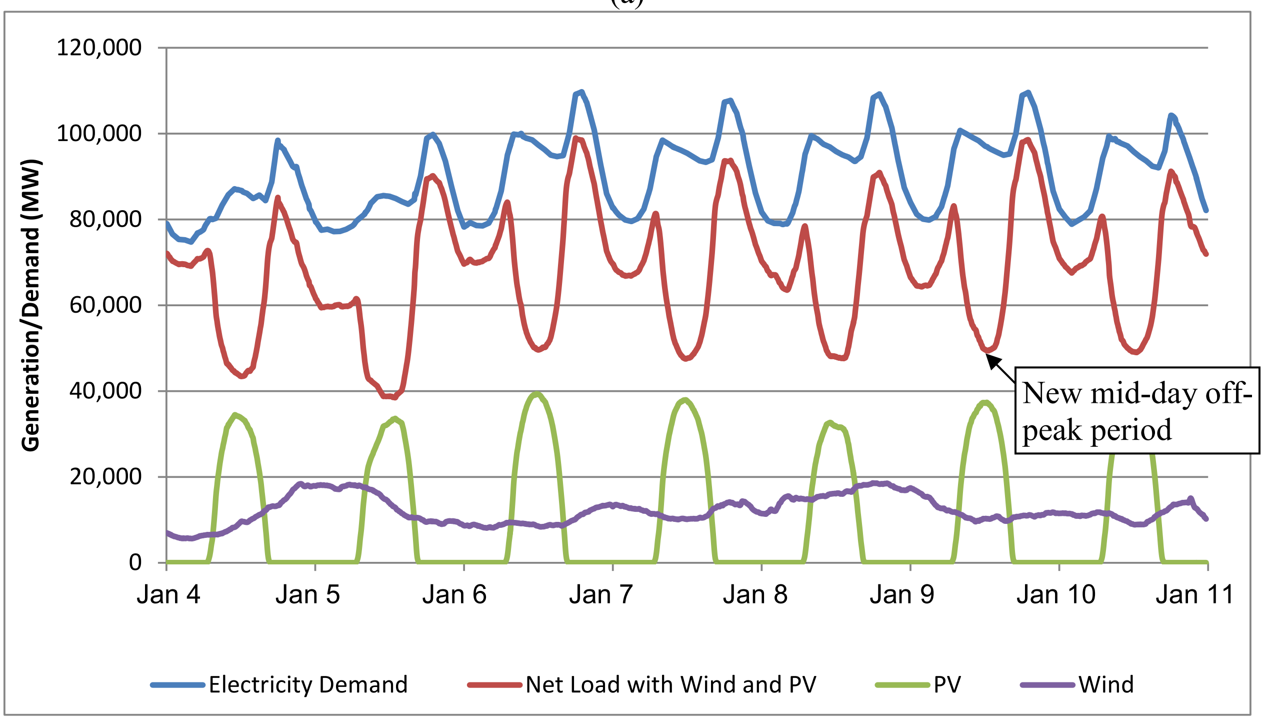


(b)

Figure 9. Net load profiles for the (a) High Wind and (b) High Solar Scenarios for one week in January

The impact of wind and PV on system ramping requirements is show in Figure 10. These values represent the average upward ramp rates of the normal load and net load (before curtailment) during each 1-hour interval equal to the rate (MW/minute) at which conventional dispatchable generation must ramp to meet the variability in the net load. Only 4,000 of the 8,760 1-hour periods are shown, as the remainders have very low ramp rates or are periods of down ramp requirements which are typically not as challenging as up ramp requirements. Of note is the limited impact in the High Wind Scenario. In this case, the PV penetration is insufficient to cause the dramatic drop in net load in the spring and winter compared to the High Solar Scenario, as shown in Figure 9. The High Solar Scenario creates much higher net load ramp rates during the period of normally high up ramp requirement (at about 5 pm), but shifted slightly on a seasonal basis to period of greater solar output (instead of peaking in December and January evenings the net peaks occur more often during November and February evenings).

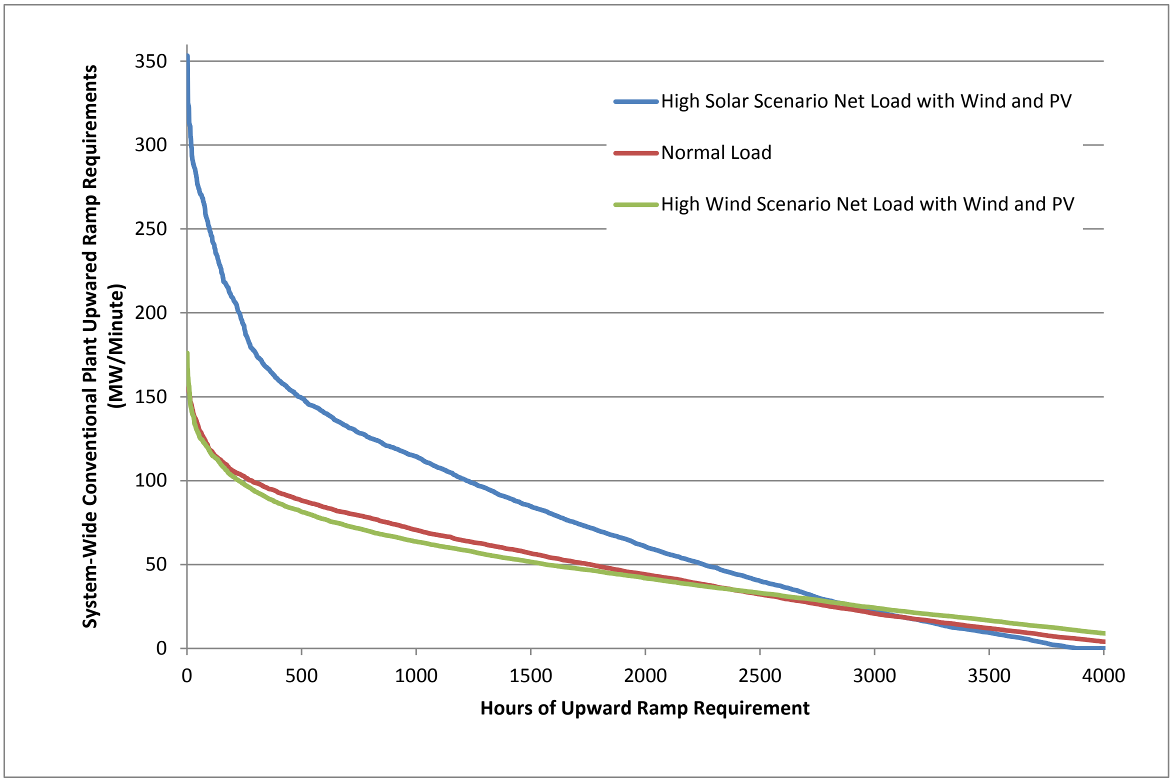
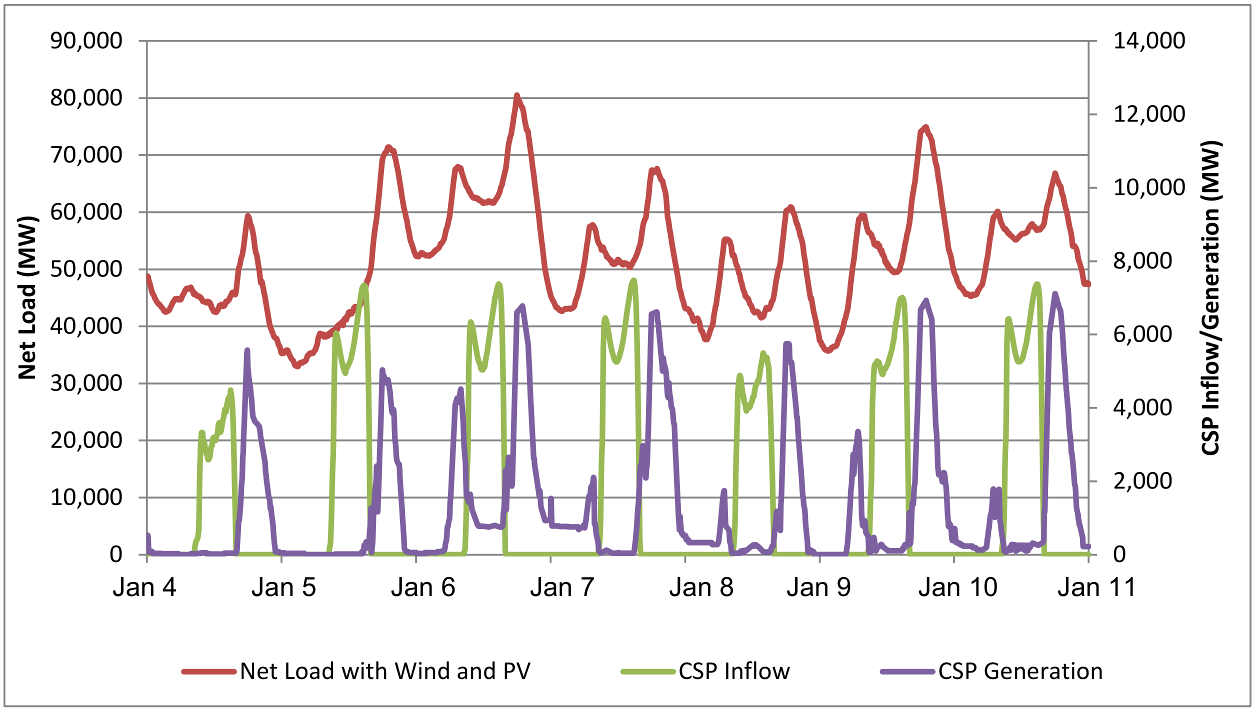


Figure 10. Upward ramp duration curve for the normal load and net load in the High Wind and High Solar Scenarios

The increased ramp rates demonstrated in Figure 9 and Figure 10 must be met by dispatchable resources. In both the High Wind and High Solar Scenarios, CSP plants are often dispatched to meet demand during the period of highest net load, avoiding the use of other thermal generators, including lower efficiency combustion turbines. Figure 11 shows the CSP generation during the two-week periods that correspond to Figure 9 . It shows a very different mode of operation in response to system demand compared to the summer operation observed in Section 3.2. The overall availability of solar energy is lower, and the plants tend to operate in a fairly narrow window, primarily generating at nearly full output during the peak period. However, the plants also often carry over energy to the following day to meet the morning load peak. During the overnight hours the CSP plants either operate at minimum generation levels or shut down completely. Overall, unlike operation during the summer, CSP plants in the winter generate in a pattern anti-correlated with solar availability.



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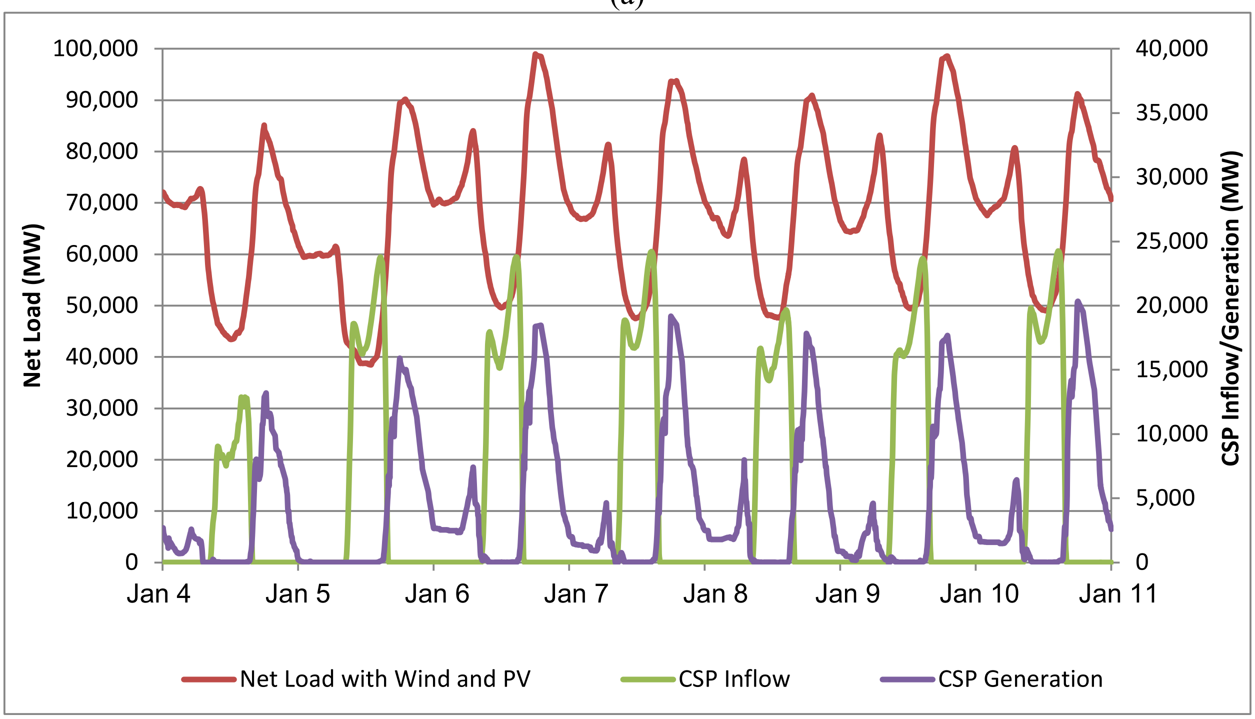

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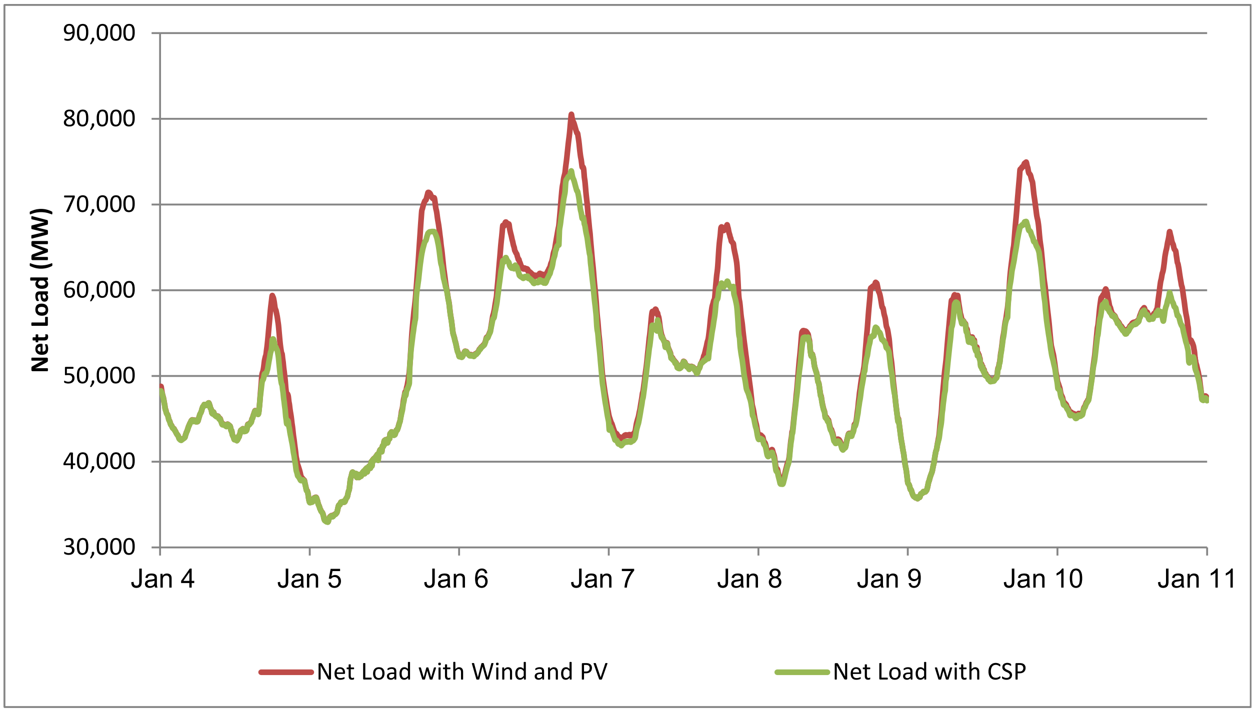
Figure 11. CSP generation profiles for the (a) High Wind and (b) High Solar Scenarios for one week in January

The net load shapes after CSP generation are shown in Figure 12. They show how CSP plants reduce the peak demand in both the morning and evening peaks, allowing a greater fraction of load to be met by more efficient units.



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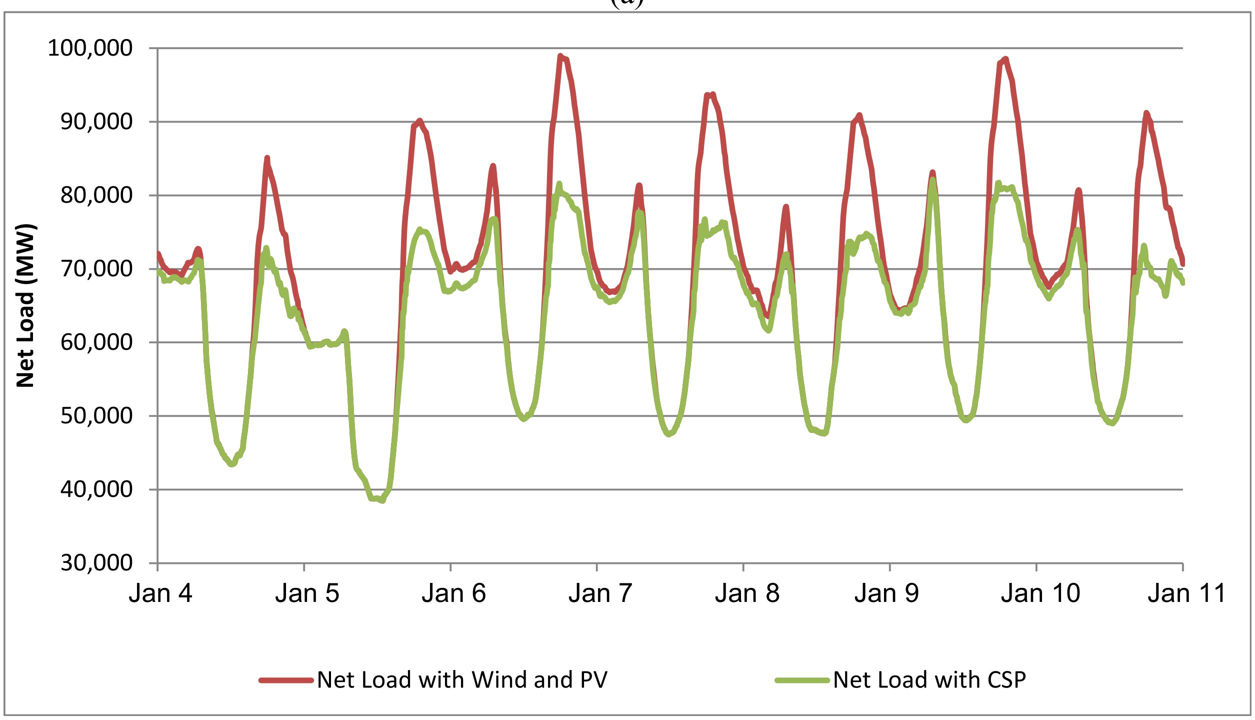


(b)

Figure 12. Net load before and after the dispatch of CSP in the (a) High Wind and (b) High Solar Scenarios from January 4–11

The impact on the net load duration curve is shown in Figure 13, demonstrating the reduction in overall upward ramping requirement that would need to be met by conventional resources. Only the High Solar Scenario is shown. The High Wind Scenario shows a similar but smaller benefit.

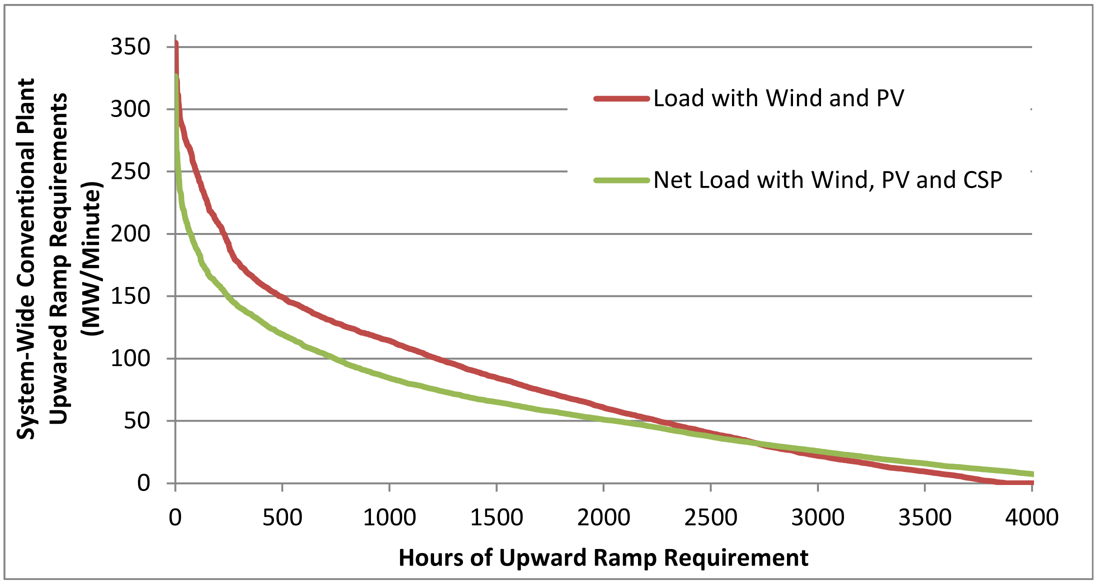
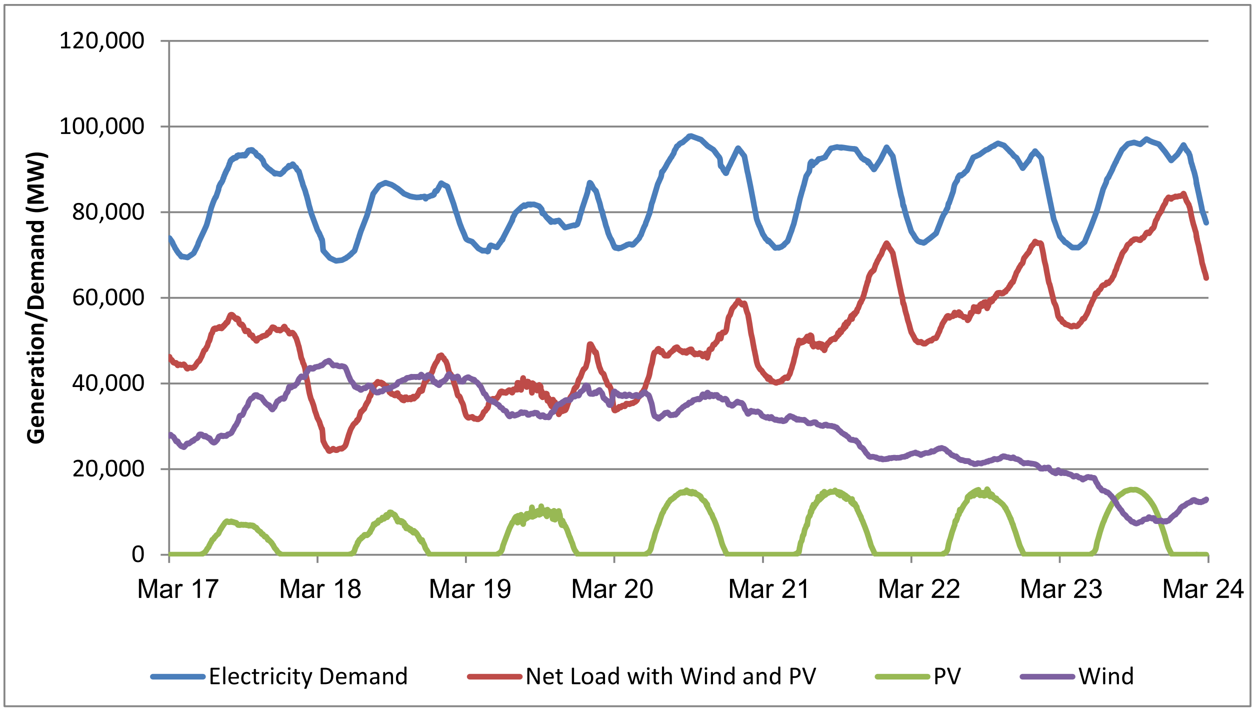


Figure 13. Upward ramp duration curve for the net load with and without CSP dispatch in the High Solar Scenarios

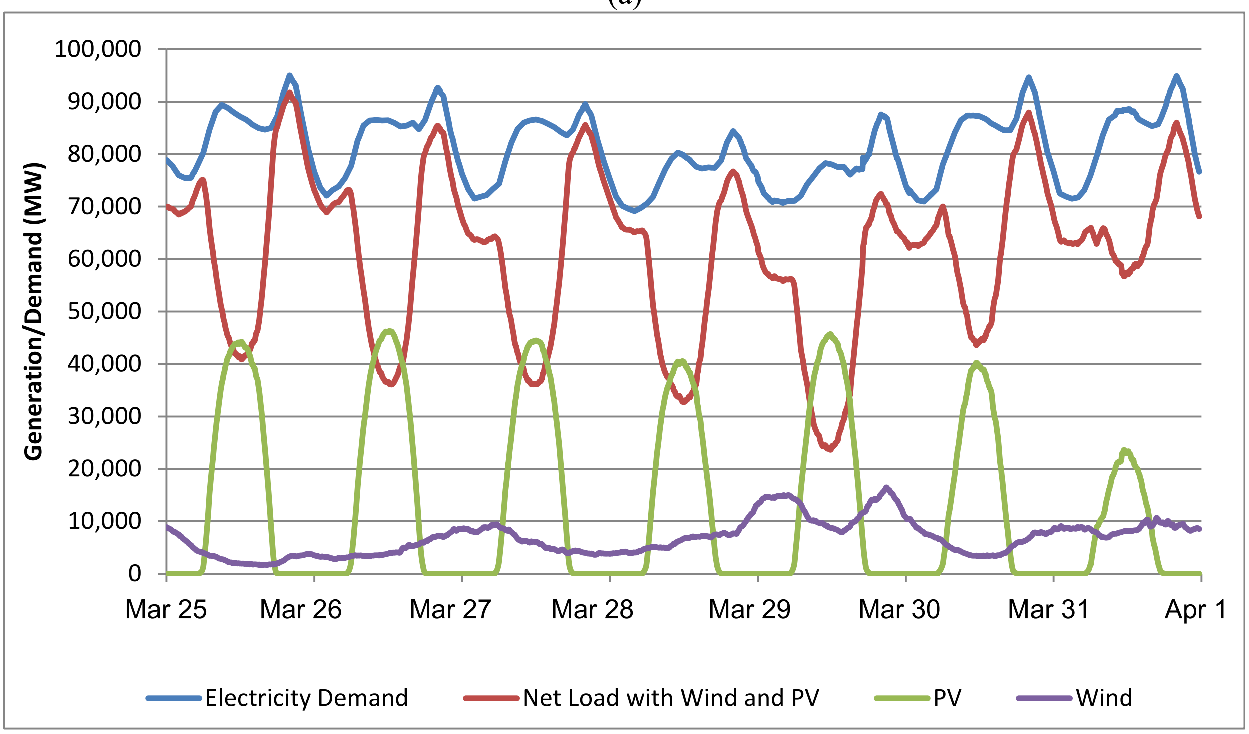
By shifting generation, CSP also avoids reducing net demand during periods of the new mid-day off-peak period, especially in the High Solar Scenario. This ability becomes particularly important in the spring as discussed in Section 3.4.

3.4 CSP Operation to Reduce Renewable Curtailment and Overgeneration

The WWSIS-2 scenarios demonstrate that spring presents the most difficult challenges in terms of potential curtailment. Curtailment is driven by a number of factors, including the coincidence of renewable supply with demand patterns as well as grid flexibility. Grid flexibility is driven by factors such as transmission capacity and generation mix, including the ability of conventional generators to ramp over a large range and at a high rate (NERC 2010). During the spring both wind and solar output can be relatively high, but mild weather produces some of the lowest load periods of the year. Figure 12 shows the net load profiles for the week with the lowest net load of the year, which occurs at about 2 am on March 18 in the High Wind Scenario and at about noon on March 29 in the High Solar Scenario.



(a)



(b)

Figure 14. Net load profiles for the (a) High Wind and (b) High Solar Scenarios during the week with the lowest net load

The High Solar Scenario produced more consistent low net loads and had the highest curtailment rates of the three WWSIS-2 high renewable scenarios at about 5% of total renewable potential. As a result, we focus on the operation of CSP in the High Solar Scenario.

As observed in Figure 12, the net load drops rapidly and to low levels in the middle of the day, followed by a significant up-ramp as solar production drops. In these cases, the net load drops below what the grid can reliably meet with the installed generation mix. Wind or solar energy must be curtailed so that the conventional generation fleet can maintain generation at some minimal level. The actual generation from PV and wind allowed by the grid in the simulations is shown in Figure 13, which shows significant curtailment.

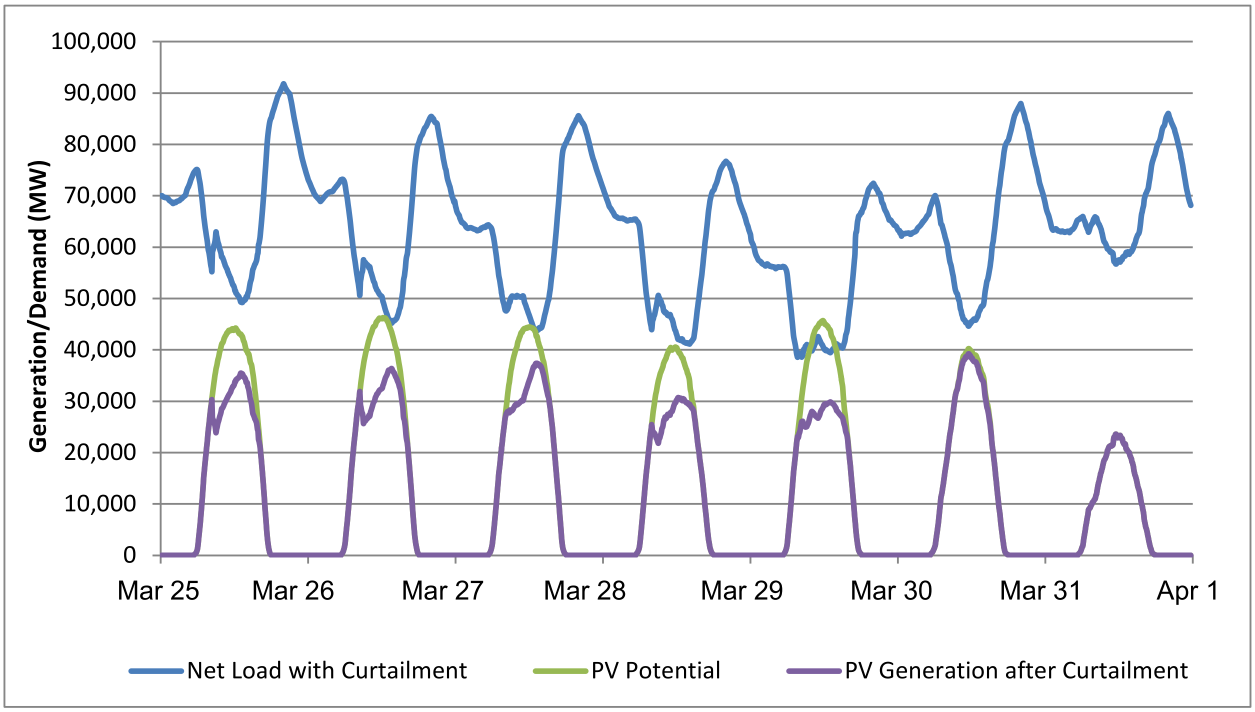


Figure 15. Net load for one week in March after curtailment in the High Solar Scenario

The flexibility limits that create this curtailment can be observed in Figure 14, which is a complete system-wide dispatch for the week of lowest net load in the High Solar Scenario. During periods of lowest net load, nearly all online thermal generation is generating at minimum stable levels around noon each day when PV output is the greatest but before load has peaked. This is most obvious on March 29 when the coal generation is flat. Significant solar energy is curtailed during the day as shown by the dotted line. This energy is curtailed partly because the start costs of coal generators do not justify turning them off in the morning and back on for the evening load peak.

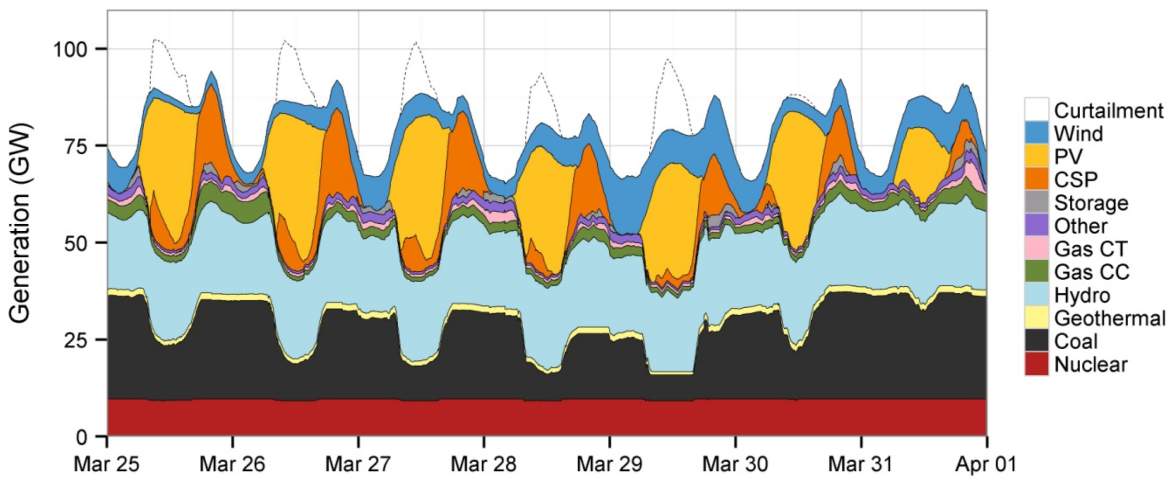


Figure 16. Dispatch stack for the week with lowest net load in the High Solar Scenario

CSP with TES can reduce curtailment in at least two ways. The first and most obvious is the ability of CSP to shift energy during times of low net demand. This operation can be observed in the CSP dispatch in Figure 14 and more directly in Figure 15, which shows CSP inflow and generation.

In the High Solar Scenario, CSP plants in the spring tend to start up in the morning, using as much solar energy as is possible before the large amount of PV generation exceeds what the grid can accommodate due to system flexibility limits. At this point significant curtailment of solar energy begins to occur. CSP plants reduce output or even shut down during the middle of the afternoon and the CSP plant stores as much as possible. It should be noted that this operation is based on a plant utilizing direct storage, capable of sending all energy from the solar field to storage, even during times of high solar field output.

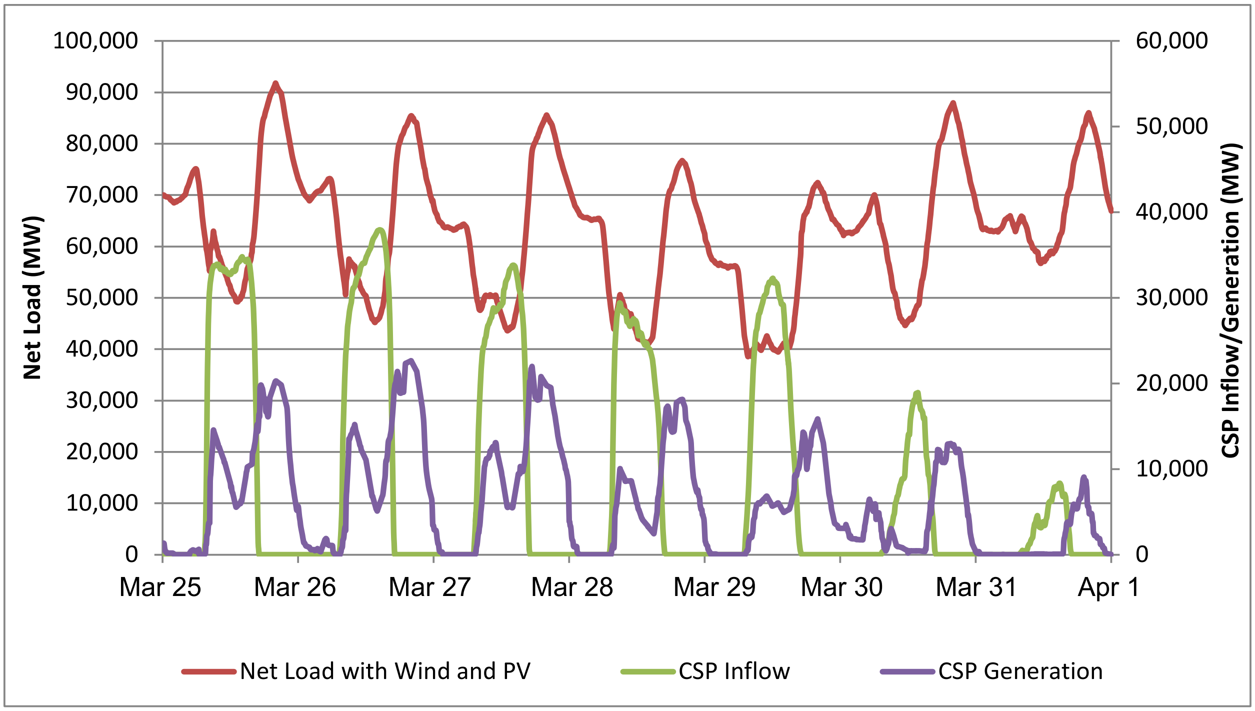


Figure 17. CSP generation profiles for the High Solar Scenario for the week with lowest load

The shift in generation from CSP plants by reducing mid-day output is one of the more significant changes in CSP operation observed between the WWSIS scenarios. Figure 16 provides the average dispatch profile during the spring season in Arizona for the High Wind and High Solar Scenarios. It shows the CSP plant shifting as much energy as possible to the evening hours in an attempt to avoid curtailment. However, the ability of CSP to avoid curtailment is limited by the configuration of the CSP plant modeled in the study. In all scenarios, the CSP plant configurations are the same—a solar multiple of 2.0 with 6 hours of TES capacity. In this configuration only 3 hours of incident solar energy (at reference conditions) can be stored by the plant. While reference conditions typically do not occur for several hours, this limited storage capacity has a clear impact on the ability of CSP to shift energy during periods of low net demand. Because the modeled CSP plants cannot store a greater fraction of the incident solar energy, this leads to some production during periods of low demand (further reducing the net load) but also resulting in curtailment of CSP generation. (This explains why the area under the High Solar curve is lower than the High Wind curve.) This also introduces more frequent starts, with the average plant (of all plants in the study) increasing starts from about 1.4 times per day to about twice per day during this period.

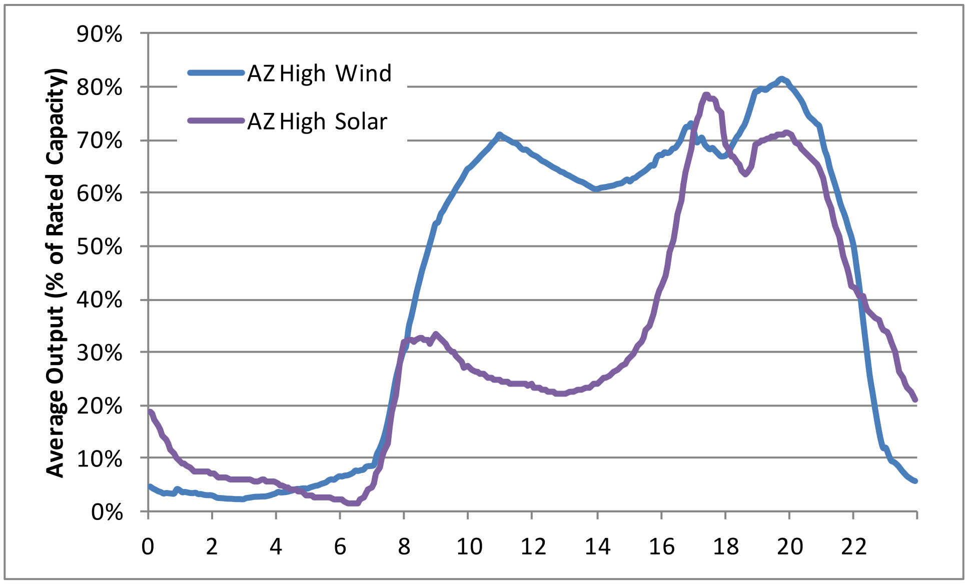


Figure 18. Average CSP dispatch profile in Arizona during the spring for the High Wind and High Solar Scenarios

Figure 17 shows the resulting net load and another indication of the impact of the CSP configuration used in WWSIS-2. Unlike in the winter scenario, where all energy is shifted to peak periods, a CSP plant with a solar multiple of 2.0 and 6 hours of storage is required to generate some energy during the new mid-day off-peak period, further reducing the net load and increasing potential renewable curtailment.

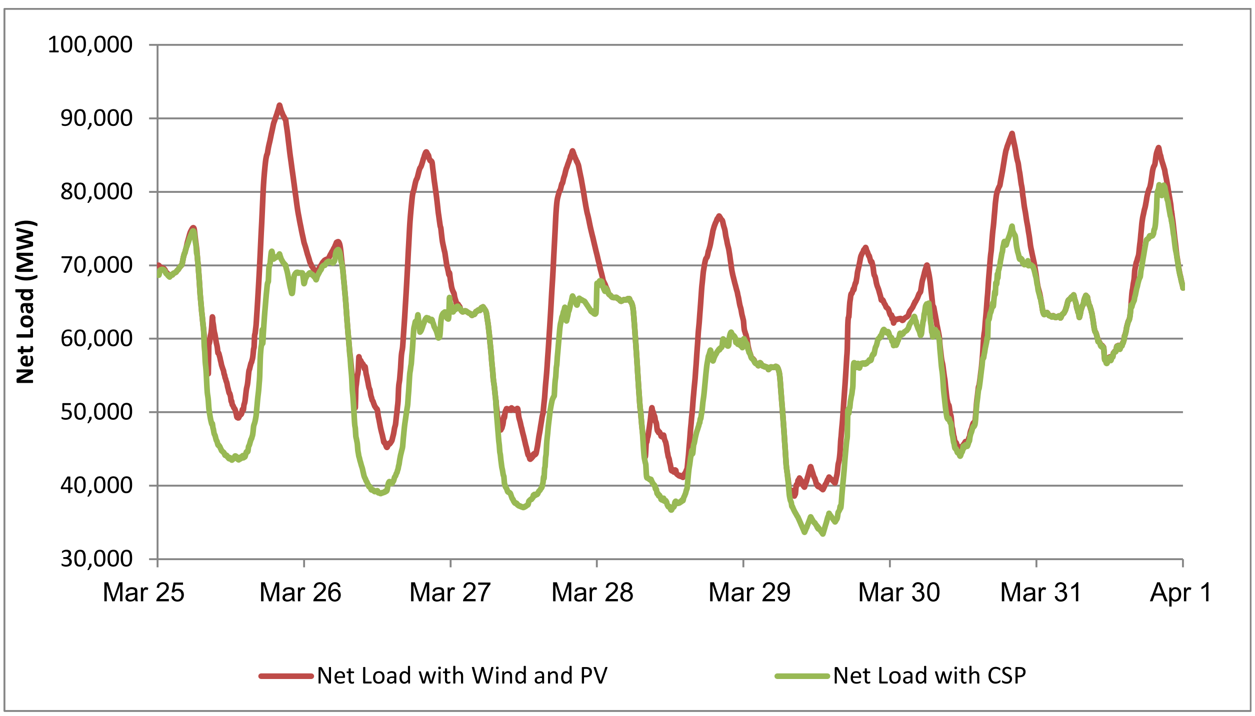


Figure 19. Net load before and after the dispatch of CSP in the High Solar Scenario for the week with lowest load

While the WWSIS-2 results clearly show the importance of energy shifting to avoid curtailment, there is another potential impact of CSP on grid flexibility. The dispatch in Figure 14 (and many of the other figures of net load in this analysis) shows the need for rapid ramping capability at sundown when PV output drops. Much of this ramping capability is based on operating units at part-load or quickly starting units. The rapid ramping of the CSP plants observed in the WWSIS-2 simulations replaces ramping capacity that would otherwise be provided by conventional units. If these units were required to operate at part load, the system might not have been able to reduce generation as much during the middle of the day, leading to greater curtailment. This issue was not examined explicitly in the WWSIS-2 scenarios, as it would require running scenarios with and without CSP. However, other analysis has indicated this could potentially reduce curtailment (Denholm and Mehos 2011) and further examination of this "portfolio" benefit of CSP is needed.

Overall, these results indicate that CSP is a potentially important tool to avoid "overgeneration" events where renewable energy supply exceeds demand, considering grid flexibility limits. However, this will require further examination of different CSP plant configuration, as well as their associated costs and benefits. In the High Solar Scenario, a large fraction of CSP generation is curtailed in this spring period due to the limited thermal storage capacity and high solar multiple. However, increased storage capacity needs to be compared to its cost, particularly when this capacity might only be needed for a few weeks or months when the most significant mismatch between solar energy supply and demand patterns occur.

4 Conclusions

WWSIS-2 evaluated four different penetrations and mixes of variable generation, and as a result, it shows how CSP operation may change as the grid mix evolves. Examining the operation of CSP plants as modeled in this study in detail, we observe the following:

- Variation in CSP plant operation is driven mostly by the increases in solar penetration. In the lower penetration of solar, optimal CSP operation is observed to be similar to previous analysis. This includes a "block" dispatch in the summer and a diurnal peaking dispatch in the winter.
- In the higher penetration of solar cases, operation of CSP begins to shift to later in the day with greater use of energy storage, more frequent starts, and lower generation in the middle of the day.
- In all scenarios evaluated, CSP plants are able to reduce the net peak demand, demonstrating high capacity credit and the potential ability to replace conventional capacity.
- CSP plants with rapid ramping capability reduce the need for operation of peaking units during all seasons, including winter when short-term peaks are often observed.
- CSP plants with TES can avoid curtailment of mid-day solar, which becomes more important with increased PV penetration.
- The optimal configuration of a CSP plant can vary depending on the mix of renewable generators and grid flexibility requirements. In particular, as solar penetration increases and the net load becomes "peakier," lower solar multiples might be needed to maximize the flexibility of CSP to effectively respond to system variability. This optimal configuration must be balanced against the increased cost of delivered energy due to lower utilization of the plant. This "net-benefit" will be addressed in future studies.

Overall, this study observed a number of quantifiable benefits of CSP with TES. However, several aspects of CSP's ability to help integrate renewables (including both PV and wind) need further analysis to understand the potential contribution of CSP to overall system flexibility. In particular, the role of CSP in lowering minimum generation constraints and provision of fast ramping capability and other ancillary services will need further analysis in scenarios comparing CSP to other grid flexibility options.

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