Executive Summary: Concentrating Solar Power Impact on Grid Reliability

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NREL is a national laboratory of the U.S. Department of Energy
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NOTICE

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List of Acronyms

CAISO	California Independent System Operator
COI	California-Oregon Interface
CSP	Concentrating solar thermal power plant
DG	distributed generation, embedded PV
FFR	Fast frequency response
FRO	Frequency response obligation
GW	gigawatt
HVDC	high-voltage direct current
Hz	Hertz
mHz	millihertz
MVA	Megavolt ampere
MW	megawatt
NERC	North American Electric Reliability Corporation
PDCI	Pacific Direct Current Intertie
PFR	Primary frequency response
PV	Photovoltaic
ROCOF	Rate of change of frequency
SCE	Southern California Edison
SCR	Short-circuit ratio
SNSP	Simultaneous nonsynchronous penetration
WECC	Western Electricity Coordinating Council
WWSIS	Western Wind and Solar Integration Study

Table of Contents

Executive Summary 1
- Key Findings 1
  - Grid Build-Out to Support Added Solar and Wind Changes Transient Stability 1
  - Primary Frequency Response from Concentrating Solar Power Helps Meet Frequency Response Obligation 2
  - Fast Frequency Response from Solar Photovoltaics or Energy Storage Improves Frequency Nadir and Adds Margin Against Underfrequency Load-Shedding 3
  - Frequency Response from Concentrating Solar Power Can Substitute for Fast Frequency Response from Photovoltaics or Batteries 6
  - Available Dynamic Models Are Good, But They Have Some Limitations 9
  - Stability Implications of Concentrating Solar Power Compared to Photovoltaics Are Mixed, But They Are Not Decisive for the Conditions Studied 10
- Executive Summary Closure 11

List of Figures

Figure ES-1. Contribution of concentrating solar power governors and inertia to frequency response 3
Figure ES-2. Impact of fast frequency response timing on frequency nadir.. 4
Figure ES-3. The location of the event strongly affects the measured frequency during the first seconds. . 5
Figure ES-4. Relative benefit of concentrating solar power governors compared to fast frequency response.. 7
Figure ES-5. California's frequency response declines during sunset if headroom is depleted. 9
Figure ES-6. Transient stability of CSP compared to PV in a low-grid-strength location 11

Executive Summary

This study examines the impact of concentrating solar power (CSP) on grid reliability by investigating the dynamic behavior of the Western Interconnection under conditions of high solar and wind generation. *Reliability* in this case refers to the somewhat narrow context of stability: transient stability and frequency response; and control stability, especially that associated with weak grids.

The objectives of this study were to identify renewable energy penetration levels and mixes, severe disturbances, and load conditions where grid performance and reliability could be enhanced with CSP plants. Instantaneous penetrations of wind and solar—both photovoltaics (PV) and CSP—up to approximately 60% were considered. The focus is on situations in the Western Interconnection bulk power system during which variable renewable generation has displaced other (non-CSP) synchronous thermal generation under highly stressed, weak system conditions. Particular attention was given to impacts of frequency-responsive controls and synchronous generation characteristics.

This is relatively new ground for the industry, and this investigation is not a substitute for detailed planning, but the risks illustrated can be analyzed and mitigated. Tools, data, and the current state-of-the-art interconnection and bulk power system stability studies, if used following good system engineering practices as systems are built out, will ensure continued reliability of power systems.

Key Findings

Grid Build-Out to Support Added Solar and Wind Changes Transient Stability

Transmission added in solar-rich areas to avoid thermal and voltage violations, plus changes in dispatch and commitment (Section 2), have some effect on transient stability. The impacts are mixed, with some improvements and decreases (Section 5.2). No stability violations—noncompliance with Western Electricity Coordinating Council (WECC) criteria—were found for the primary fault-clearing cases tested (Section 5.2 and Section 10.2). As noted, good planning practice needs to be observed.

WECC-wide system inertia dropped up to 27%–32% from earlier light load planning cases. The earlier cases had less wind and solar generation and included synchronous generation, which was retired in the final study cases (Section 4.1). The lower system inertia did not present any significant stability or frequency response challenges.

We did not observe systemic issues related to frequency and transient stability resulting from the solar and wind build-out. That is, the overall behavior was similar in character to the present system. The system seems to better tolerate non-design-basis north-south separation with the grid additions (Section 6.6).

For the conditions studied, a simultaneous nonsynchronous penetration (SNSP) of approximately 70% (Section 4.3) did not have an adverse impact on system-wide transient stability (Section 5.2). Transient stability issues seemed to be rather localized (Section 10.2).

Primary Frequency Response from Concentrating Solar Power Helps Meet Frequency Response Obligation

Because CSP uses a conventional synchronous steam turbine generator system to produce electricity, it always contributes inertia when running. Further, depending on the design and operation of the plant, it can provide primary frequency response (PFR) via governor action. It is by no means ensured that CSP plants will necessarily provide this service. Steam systems and turbines must be designed with this capability in mind for best economy. This report provides some discussion and concepts for possibly squeezing additional frequency response out of steam systems (Section 8.1). The discussion includes the concept of a triggered, open-loop control based on the accepted practice of fast-valving special protective systems (Section 8.3).

PFR from CSP benefits frequency response, improves the system nadir, and helps the system (and regions thereof, such as California) meet their frequency response obligations (FRO) (Section 9.3). The contribution of synchronous inertia is observable, but it not very important for the conditions and cases examined.

Tripping two of the Palo Verde Nuclear Generating Station units, for a loss of approximately 2,750 MW, is the design basis frequency event for WECC (Section 6.1.2). We have continued to use that event extensively in this study. Figure ES-1 shows three cases for that event run on the lighter load case (60% instantaneous wind and solar penetration for the U.S. WECC) that illustrate two separate points. The red trace shows the reference lighter load case. The CSP units are online contributing inertia, but there is no governor response. The blue trace shows the impact of enabling the governors on the CSP plants (per the model discussion in Section 3.2). As expected, both the frequency nadir and the settling frequency improve. The green trace shows the impact of replacing CSP with PV (so difference between this and the red case is the inertia of 10 GW of CSP machines). This case has the same 60% instantaneous penetration, but the SNSP is 70% because of the increased levels of inverter resources (Section 4.3). As expected, the CSP-to-PV case with less inertia shows a faster frequency drop, and the nadir occurs sooner and is approximately 1-mHz deeper. For this design basis case, the PFR is much more important than the inertia contribution (Section 6.3).

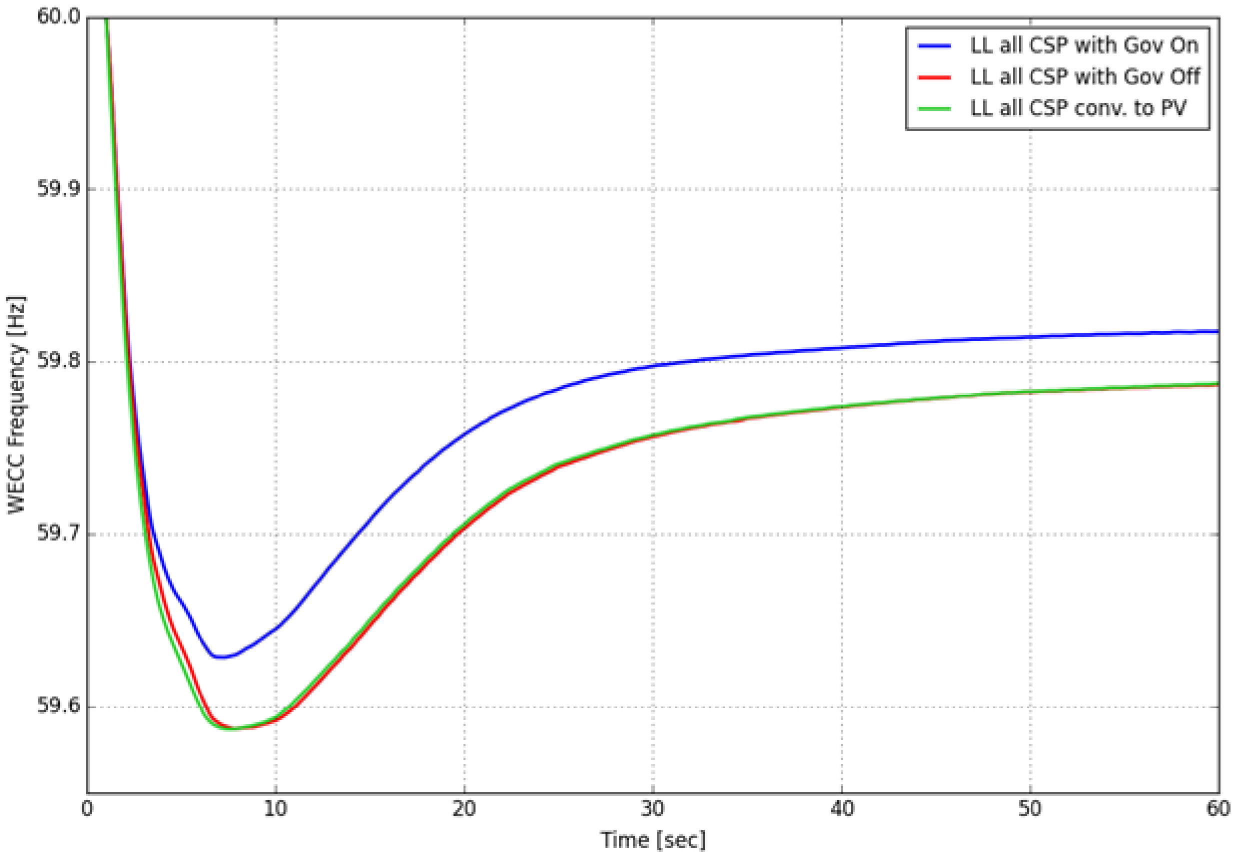

Figure ES-1. Contribution of concentrating solar power governors and inertia to frequency response

Fast Frequency Response from Solar Photovoltaics or Energy Storage Improves Frequency Nadir and Adds Margin Against Underfrequency Load-Shedding

The provision of fast frequency response (FFR) by utility-scale, transmission-connected PV or other inverter-based resources, such as energy storage devices, can improve the system frequency nadir and add margin against underfrequency load-shedding. FFR is the rapid injection of arresting power to the grid during the time immediately following a disturbance that unbalances the grid and causes the frequency to drop (Section 7.1). FFR slows the decline and helps make the minimum frequency better.

PV can be designed with FFR capability. This is particularly true for utility-scale PV. In the main report (Section 7.2), we include a detailed discussion of the fundamental concepts that allow PV to provide FFR. In brief, new controls, adaptive use of rating differences between PV inverters and panels, and possible transient overload of inverters can allow utility-scale PV to provide FFR.

Considerable effort was applied toward improving understanding of the timing and location considerations for FFR (Section 7.3 and Section 7.4). This study found that responding quickly after the disturbance produces improved performance (in terms of improved nadir), but responding within 1–2 seconds produces most of the of benefit. Faster response produces only marginally better performance and introduces robustness concerns.

Figure ES-2 shows the total results of a sequence of tests and the impact on the nadir as a function of timing. Higher nadir is better. The blue trace shows the base case without CSP governors enabled. The efficacy of the FFR is almost the same for approximately the first 3 seconds of the event, then the efficacy of the FFR drops to zero by the time of the nadir, indicated by the vertical red line. This is an important result that means that there is little systemic benefit in applying FFR with undue haste. Waiting for good information with which to make the decision to "trigger" the FFR has a small performance penalty and might produce significant robustness benefits.

The green trace presents the results in the case with CSP governors enabled. The impact of FFR timing on change in nadir is similar to the case without CSP governors enabled. The overall curve is better (higher) because of the CSP governor contribution, but otherwise the impact is very similar. This is another significant result. It shows that for a given operating condition, the beneficial contributions of multiple mitigations (in this case CSP governors *plus* FFR) are complementary and quite linear (they add up). This is not to say that the impacts are linear or uniform across very different operating conditions.

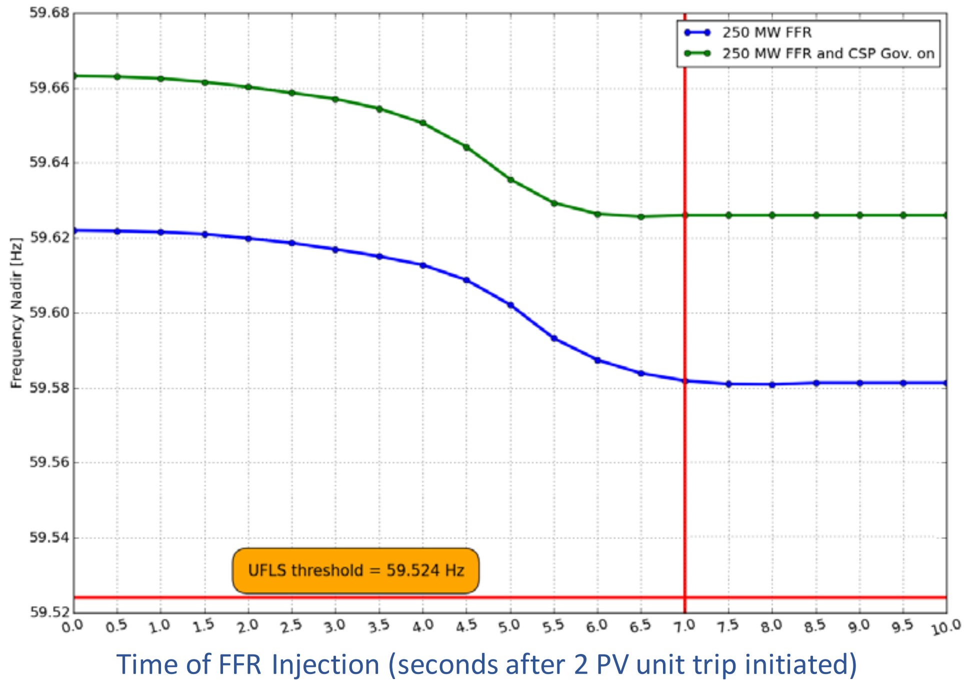

Figure ES-2. Impact of fast frequency response timing on frequency nadir

Further similar investigation showed that for energy-limited FFR (e.g., synthetic inertia from wind), the best efficacy is for FFR a few seconds into the event.

Figure ES-3 shows regional frequency measurements for two similarly sized events that are initiated at very different points in the system (Section 6.4). The blue trace (labeled 2PV) shows the trip of two Palo Verde Nuclear Generating Station units in Arizona, and the red trace shows an event in the middle of the Pacific Northwest. The location aspects dominate for approximately

2 seconds. Note, for example, how different the two events appear in the Northwest and Southwest. Even though these events are approximately the same magnitude from a frequency perspective, they look very different during the first 2 seconds. This represents an acute challenge for triggering control actions that are sensitive to initial frequency drop or rate of change of frequency (ROCOF). Specifically, local differences in frequency during disturbances suggest that triggering FFR should be no faster than 0.5 seconds. This is an important observation relative to the results of Figure ES-2 because those results show little benefit from faster triggering for these system-wide events.

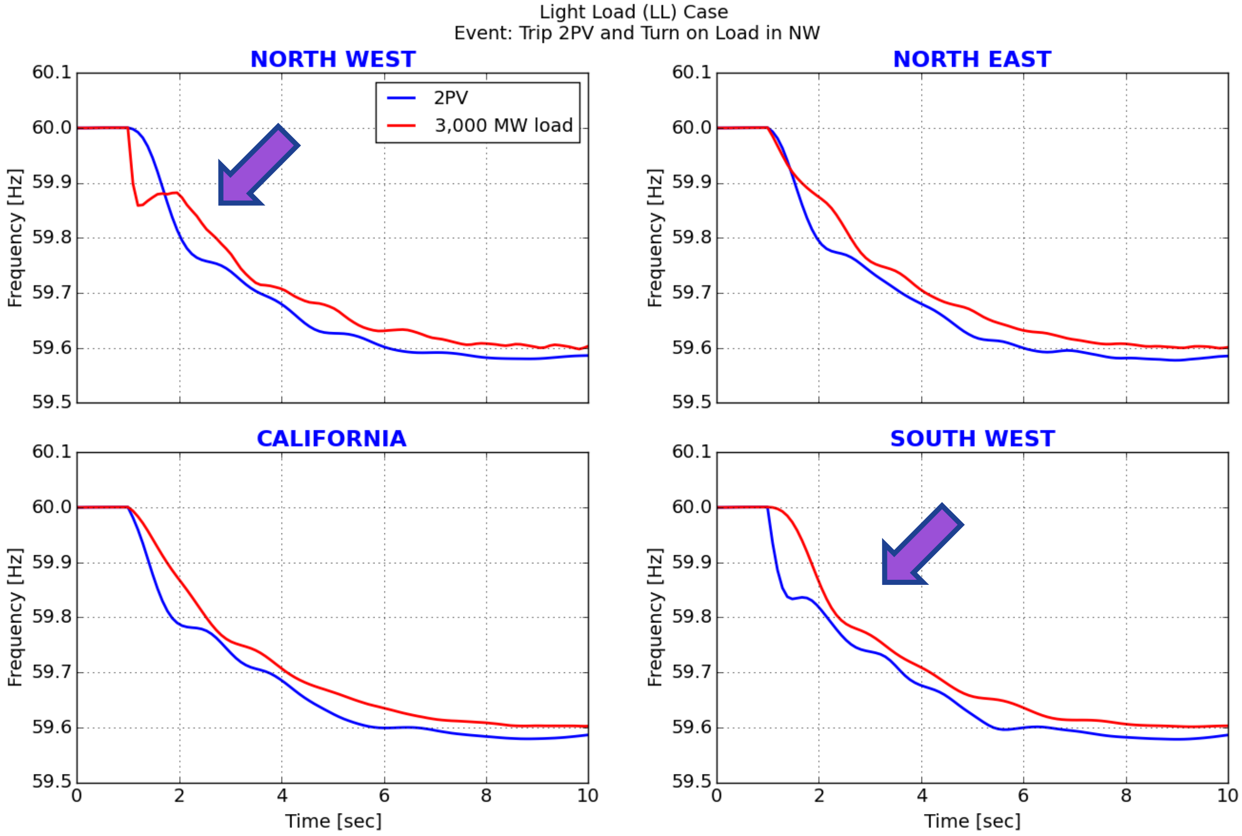

Figure ES-3. The location of the event strongly affects the measured frequency during the first seconds.

Investigation of the amount of FFR required to improve the frequency showed that the impact is relatively linear for small amounts. As the amount of FFR increases, the marginal benefit decreases. For the event and condition tested, FFR has good impact up to approximately 250 MW. The relative improvement declines for more FFR capacity; and for FFR greater than 500 MW, it immediately reverses the frequency decline, creating an inflection. The nadir is at the time of injection, and it does not change with increased FFR power. In the narrow context of arresting frequency and improving nadir, the contribution of the FFR is saturated and any FFR greater than 500 MW is wasted. This gives an interesting perspective: the event is approximately 2,750 MW, but more than 500 MW of FFR produces no additional benefit for this specific operating condition (Figure 65 in Section 7.4). The FFR works—*as always*—with the PFR from the committed generation that has active governors and headroom to act. The FFR does not impact the system in isolation, and the combination of the FFR and the amount and speed of PFR dictates the megawatt-level of this saturation point. For systemic events, the location of the FFR resources is not very important.

Note that as (1) system inertia drops, (2) PFR becomes slower or scarcer, and (3) ROCOF increases, this inflection point becomes a larger fraction of the size (in MW) of the event. The authors have observed this in smaller systems with relatively low inertia. In the limit, as for example when a system approaches no inertia, the break point becomes equal to the size of the disturbance. That is, the FFR must fully, exactly, and quickly match the size of the disturbance to meet frequency performance objectives. The WECC system under consideration in this study is far from that point.

Frequency Response from Concentrating Solar Power Can Substitute for Fast Frequency Response from Photovoltaics or Batteries

Both CSP PFR and FFR from PV improve performance. These can be quantitatively compared (Section 8.2). In these cases, the benefit of frequency response from CSP is approximately equivalent to 3% of FFR from inverter/switched resources. That means, for example, that for each 100MW of CSP providing PFR, the equivalent of 3 MW of FFR is provided at that time. In this system, with approximately 10 GW of CSP, PFR on all the units would provide the same benefit for FRO as 300 MW of inverter-based FFR. Batteries or utility-scale PV, as discussed in Section 7.2, have potential to provide FFR. Obtaining FFR from these inverter-based resources will have accompanying costs, which might include costs of curtailment. The timing of available PFR or FFR will vary by resource. Both the amount (i.e., the number of hours per year that the service is available) and the timing (i.e., what hours the service is available) will be different by resource. Consequently, the overall (or annualized) economic value of the various alternatives derive from overall operational impact (i.e., over the full 8,760 hours of a year).

Figure ES-4 shows an example “equivalence” between the CSP governor and FFR. The reference case (black trace) is without FFR or CSP governor contribution. The blue trace shows the CSP governors enabled with no FFR, and the green trace shows 250 MW of FFR without CSP governors. The CSP governors produce a somewhat better frequency nadir than the 250 MW of FFR, giving an improvement equal to approximately 300 MW of FFR. The red trace is for both, showing that the impacts are additive.

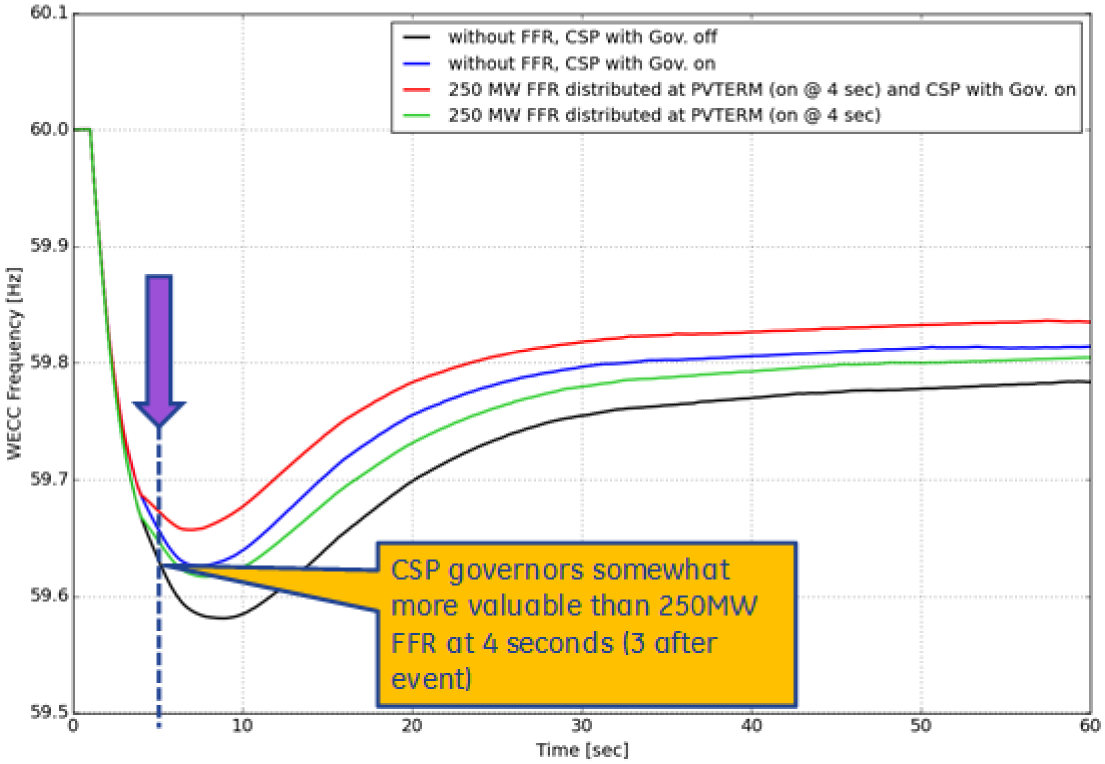

Figure ES-4. Relative benefit of concentrating solar power governors compared to fast frequency response

Tests on the use of fast-valving, open-loop controls on CSP showed that they might increase this benefit to approximately 4.5% (Section 8.3). Concepts were presented in the work for such controls, which would need further engineering design to ensure feasibility (Section 8.1).

Thermal storage should help the sustainability of PFR, and it might help the speed of response (Section 9.4). Again, more detailed design is required.

The Benefits of Frequency Response from Concentrating Solar Power During Sunset Can Be Substantial and Might Represent Valuable Options During the Neck of the Duck Curve

One challenge that has surfaced for systems with high levels of solar is managing the system as the sun sets and there is a drop in solar generation. As the solar power drops, there are potential issues with exhausting other resources. Thus, this concern is not about high instantaneous penetration but rather what might happen shortly afterward, as the sun sets. We looked closely at California for insight, but the issues are more general, and the findings apply to other parts of WECC and to other systems around the world that have or might have high levels of solar generation (Section 9.1).

The lighter load case is a reasonable proxy for operation during the low net load condition that precedes the start of sunset. During the time frames that are the focus of this study, one of the most pressing concerns that accompany sunset from high solar, light load conditions is frequency response (Section 9.2). During sunset, the system needs to meet the rise of net load by (1) dispatching committed generation that has headroom and (2) committing (starting) additional resources.

Exercises aimed at improving understanding of the relationship between this net load following and the depletion of generation headroom that accompanies the upward dispatch were pursued. To that end, the work took the extreme case of looking at what happens if all the loss of solar generation is followed by resources that are already committed in California. Two sets of initial conditions were considered: (1) the lighter load case and (2) a sensitivity case in which more solar, less wind, and less initial synchronous resources were available (Section 9.3).

In the sequence, the utility solar generation production across WECC, both PV and CSP (if deployed without storage), is ramped down uniformly to reflect the drop in insolation that accompanies sunset. At each step along sunset, WECC, California, and other frequency response performance was tested with the Palo Verde Nuclear Generating Station trip events. The committed gas-fired thermal generation, including combined-cycle steam, in California is dispatched upward. This continues until these units are effectively out of headroom and cannot further increase output. At that point, the California hydro with headroom is dispatched upward. The distinction might be important because when modeling hydro we assume that there is sufficient water (and headroom) to allow this upward dispatch. A much closer look at the hydrology would be needed to confirm this. As noted in this work and in earlier WWSIS work, the contribution of California hydro to meeting the California Independent System Operator FRO is significant under these study conditions. Closer inspection of the actual capability and performance of these hydro plants is warranted

One set of results is shown in Figure ES-5. The figure shows California's frequency response (as mandated by the North American Electric Reliability Corporation) in units of MW/0.1 Hz[1] compared to the amount of solar generation lost in WECC because of sunset. For the sequence for the sensitivity case (Low Load, Low Frequency Response), California was initially out of compliance. This means that the potential value from adding CSP governors is high. A comparison set of cases on the low frequency response sensitivity was run with all CSP governors enabled (the purple trace). The benefit to California is substantial, initially adding 150 MW/0.1 Hz of frequency response to California. California can meet its frequency response for up to 1,500 MW of sunset (blue arrow). A linear extrapolation (orange dotted line and arrow) suggests that enabling the governors on all new CSP in this case is "worth" approximately 2,500 MW reduction in utility-scale solar generation due to the sun setting.

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[1] Meaning MW of response per 0.1 Hz change in frequency

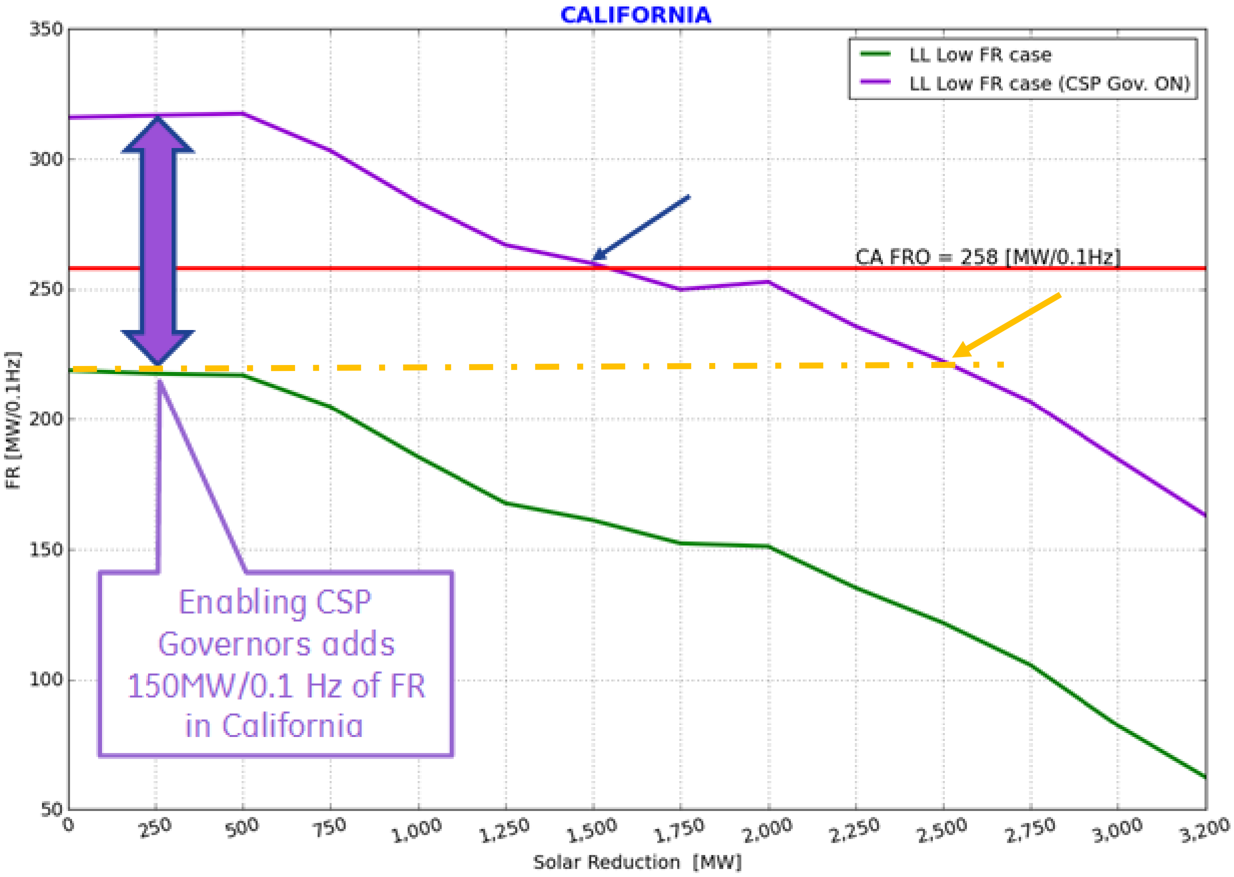

Figure ES-5. California's frequency response declines during sunset if headroom is depleted.

Better dynamic response is also similar to effectively postponing sunset because it provides a frequency response benefit, such as retaining headroom. In this construct, the possible fast valving discussed in Section 8.3 is "worth" approximately 1,700 MW of sunset above and in addition to the approximately 2500MW benefit shown in Figure ES-5. This is a nontrivial contribution to California's "duck curve." But whether such capability is possible hinges on whether control and/or thermal storage can be used to extract better, i.e., faster and more sustained frequency, response from CSP.

Although these specific results are based on one sequence in California, directionally the results are applicable to any solar-heavy system facing declining frequency response during sunset. Further discussion is provided in Section 9.

Available Dynamic Models Are Good, But They Have Some Limitations

Validation of the dynamic stability models for the CSP thermal plant showed good correlation to field tests. CSP models lack modeling detail needed for testing the dynamic impacts of thermal energy storage (Section 8.1). Approximations showed significant promise, but more detailed modeling efforts are required for definitive quantitative results (Section 8.2 and Section 8.3).

Utility-scale PV models might be optimistic for weak grid conditions. In particular, generic models might not accurately capture fast voltage and fast regulator stability concerns under short-circuit conditions below equipment specifications. Generic models might show good performance when the application behaves poorly in low short-circuit ratio (SCR) situations. The minimum system strength specified by the converter supplier can provide guidance for when different models and tools are required (Section 10.2).

Displacement of fossil-fueled generation by renewables increases dependence on hydro and makes modeling fidelity for hydro plants more important (Section 9.3).

Stability Implications of Concentrating Solar Power Compared to Photovoltaics Are Mixed, But They Are Not Decisive for the Conditions Studied

Short-circuit strength is one proxy widely used to screen for location-specific weak grid stability concerns. Further, SNSP is an emerging metric of systemic concerns about stability with high levels of inverter-based resources. A range of tests and screening for both metrics were pursued. One important finding was that short-circuit levels in the solar-rich areas tended to increase because of added transmission necessary to connect the new solar power plants without violating local voltage and thermal constraints. The added transmission tends to offset effects of decommitting synchronous generation. The only concerns identified tended to be very localized. These were sensitive to the fact that system strength declines as PV is substituted for CSP (Section 4.2).

Because SCR is a key metric for concern about inverter-based generation instability, a deliberately challenging test was devised in which the grid was degraded by removing one of the 230-kV lines providing egress for the power from the solar power plants. In this case, the SCR before the fault is 2. Figure ES-6 shows a comparison of two cases with the system degraded. The voltages in the upper set of axes show the CSP in blue and the utility-scale PV in red. The power swings of the local solar power plants are shown in the next two sets, with the CSP synchronous machines swings in the middle and the PV power on the bottom. The swing of the synchronous CSP machines is somewhat greater. Both cases meet WECC criteria (Section 10.2.2).

As the fault becomes longer, voltage recovery will degrade. Eventually, voltage recovery will violate criteria, or synchronous CSP machines will lose synchronism. Inverter-based generation, including PV, will tend to tolerate longer faults (discussion in Section 10.2.1).

The lowest grid strength here (i.e., SCR of approximately 2) is where inverters for stiffer grids might misbehave. Stress tests in simulations, where PV inverters were provided with control setting characteristics of very stiff (high short-circuit strength) systems, showed instability like that observed in the field; however, this class of instabilities is outside of the accuracy of positive sequence simulation (transient stability) tools. More sophisticated analysis is required for evaluation and mitigation (Section 10.3).

Solar-exporting areas generally showed better transient stability, i.e., reduced swings and better post-fault voltage recovery, with PV compared to CSP. No transient stability issues that resulted in violation of WECC criteria were observed for primary cleared faults regardless of the type of solar generation (Section 10.2).

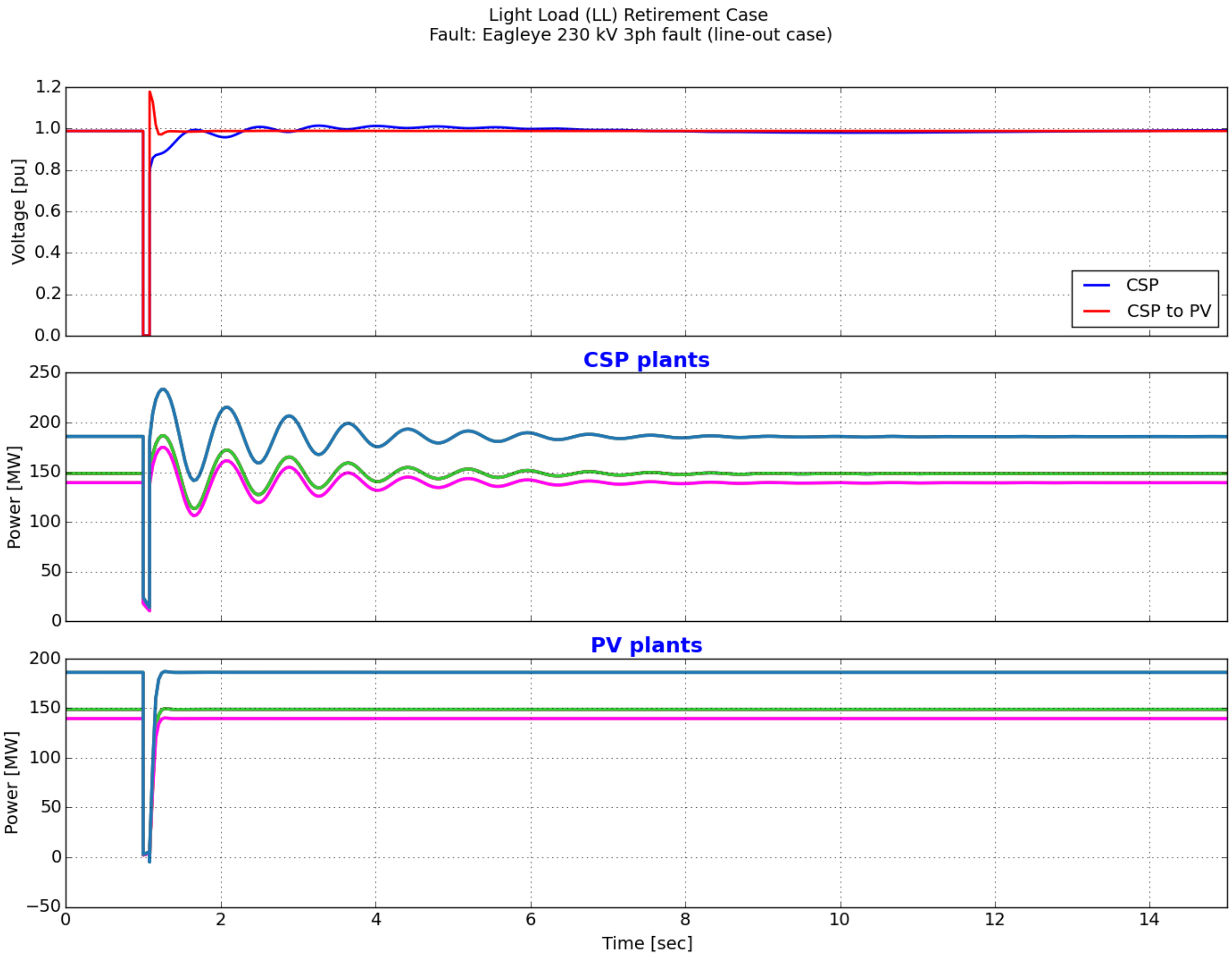

Figure ES-6. Transient stability of CSP compared to PV in a low-grid-strength location

The range of tests performed here did not show evidence of any widespread concerns about a weak grid, high SNSP, or low short-circuit levels for the predominantly utility-scale PV case. These cases do not provide observable motivation to prefer synchronous CSP instead of inverter PV regarding system transient and voltage stability.

Executive Summary Closure

This investigation shows that integrating large amounts of solar power in the WECC system for the conditions studied does not present any obviously intractable challenges. We find that frequency response can be aided significantly by frequency-sensitive controls on CSP and PV solar. Stability problems, including those anticipated around weak grid issues, were not substantial.