Impact of High Solar Penetration in the Western Interconnection

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Technical Report
NREL/TP-5500-49667
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Contract No. DE-AC36-08GO28308

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Prepared under Task No. SM101610

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Impact of High Solar Penetration in the Western Interconnection

Abstract — **The western U.S. has tremendous solar potential. However, the variability of power generation from solar plants presents an operational challenge for grid system operators. Experience in power grids with significant penetration of variable renewable generation (both solar and wind power) has shown that the operating flexibility of the balance of the generation portfolio is a key element in secure and economic operation.**

This paper presents an overview of the variable characteristics of solar power, as well as the accompanying grid performance and operational economics for a system with significant solar generation. The paper will show results of economic operational simulations of a very high solar generation future for the western half of the United States. The evaluated system is subject to significant dynamic operating constraints; and the analytical methods used account for the critical interrelationships between system security, solar variability, and imperfect solar forecasts.

I. INTRODUCTION

Today, the growth of solar generation is explosive in many countries around the world with a global average annual rate of over 30% per year. There are a wide range of environmental, social, technical and economic drivers that have resulted in solar as the fastest growing energy source in the US. With solar generation moving from a minor contributor to possibly substantial levels of penetration, a range of issues related to the operation and economic impacts on bulk power systems are rising in importance.

The issues associated with integration of solar generation are a subset of broader industry concerns with integrating variable renewable generating resources. To an appreciable extent, solar growth is following the route forged by the dramatic global growth in wind power.

Recently, the authors completed a large, multifaceted study called the Western Wind and Solar Integration Study (WWSIS) [1]. The focus of the WWSIS was to investigate the operational impact of up to 30% energy penetration of wind, plus an additional 5% energy production by solar generation in a large portion of the western part of the United States. The solar generation was composed of a mix of photovoltaic (PV) and concentrating solar power (CSP).

This paper presents the results of an incremental exploration that is based on the exhaustive work of WWSIS. It is considerably less broad in scope, and the focus is solely on behavior and challenges associated with solar generation. High solar penetrations were not examined in WWSIS due to lack of data and models for large-scale solar plants, but as these models are being developed, the fast pace of solar growth is demanding investigation in this area.

This paper provides a brief introduction to the scope of this incremental exploration, explains key aspects of the investigation and aspects of WWSIS that are necessary to understand the work reported here, inputs and scenario development, and the key findings. WWSIS provides more detail on all aspects of the two and a half year long study [1].

II. STUDY SYSTEM AND SCENARIOS

The entire interconnected grid of the western United States is modeled for the year 2017. This is the U.S. portion of the Western Electricity Coordinating Council (WECC), one of the major reliability regions in North America. The model includes details of load, all generation, and major transmission limitations. The focus of WWSIS and this exploration is on a subset of the grid that is operated by the WestConnect group of utilities in Arizona, Colorado, Nevada, New Mexico, and Wyoming[1]. A map of WECC and WestConnect is shown in Figure 1.

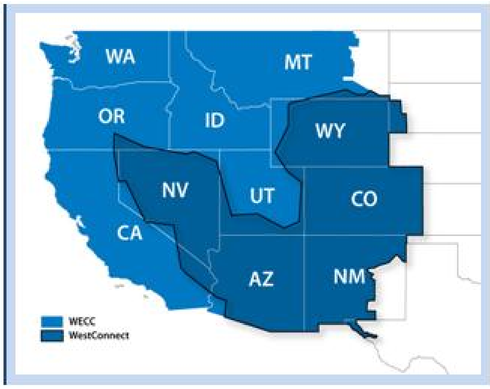

Figure 1 − Study Footprint Map; Western United States and WestConnect.

The overall study footprint consists of five areas that closely correspond to the state borders of Wyoming, Colorado, New Mexico, Arizona, and Nevada, as shown in Figure 1. Outside of the footprint, several additional areas, again roughly corresponding to state or regional borders, were modeled.

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[1] WestConnect also includes utilities in California, but these were not included in WWSIS because California had already completed a renewable energy integration study for the state.

The scenarios used in this paper are based on the WWSIS solar plant distribution that provided 5% solar energy in each of the five areas of WestConnect. In that base case, solar plant sites were selected in each area to reach a total of 5% of that area's annual load energy. Selection was made from about 260 candidate sites based on estimated energy production and market value of that energy. In the areas outside the study footprint, solar generation providing 3% of the load energy was selected from about 320 candidate sites.

While the focus of the study is on the footprint, it is extremely important to include solar resources in adjacent systems as well, in order to properly anticipate the inevitable interaction driven by weather conditions and time of day between the various areas that exchange power and resources.

The scenarios for this incremental exploration start with this nominal 5% solar case (3% outside of the footprint), removing all of the wind generation included in WWSIS. From that starting point, the power and energy of the selected sites are linearly scaled to meet 10%, 15%, 20%, and 25% penetrations. This is an imprecise approximation to how solar penetrations of this level would be realized. Additional solar plants would necessarily be in different locations, and exhibit temporally more diverse behavior. This simple approach gives a reasonable, but pessimistic, approximation of solar power production because it ignores that additional diversity and its smoothing impact on total solar power output.

Details of the scenarios are shown in Table 1. In this table, characteristics of the load, the 5% solar and 25% solar scenarios are summarized by area. The 10%, 15%, and 20% cases are linearly distributed between these two cases. In all scenarios, 30% of the solar generation was PV and 70% was CSP by energy. Since the PV and CSP have different capacity factors, the split in MW rating was 52% and 48%, respectively.

Table 1 − Power Ratings and Energy by Area, both Inside and Outside of the Study Footprint.

	Load			5% Solar		25% Solar	
Area	**Minimum (MW)**	**Maximum (MW)**	**Energy (GWh)**	**Rating (MW)**	**Energy (GWh)**	**Rating (MW)**	**Energy (GWh)**
Arizona (AZ)	6,995	23,051	99,437	2,000	5,283	10,000	26,415
Colorado (CO)	5,204	13,115	70,080	1,700	4,005	8,500	20,025
New Mexico (NM)	2,571	5,320	31,260	700	1,894	3,500	9,470
Nevada (NV)	3,863	12,584	57,505	1,100	2,934	5,500	14,670
Wyoming (WY)	2,369	4,016	27,697	300	420	1,500	2,100
In Footprint	**21,002**	**58,087**	**285,979**	**5,800**	**14,536**	**29,000**	**72,680**

	Load			3% Solar		15% Solar	
Area	**Minimum (MW)**	**Maximum (MW)**	**Energy (GWh)**	**Rating (MW)**	**Energy (GWh)**	**Rating (MW)**	**Energy (GWh)**
California (CA)	27,110	75,039	354,891	5,400	15,286	27,000	76,430
Idaho (ID)	1,647	4,957	24,869	200	274	1,000	1,370
Montana (MT)	1,149	2,337	14,143	100	127	500	635
Oregon (OR) & Washington (WA)	14,278	30,953	178,359	1,300	1,645	6,500	8,225
Utah (UT)	2,263	7,274	38,022	500	1,240	2,500	6,200
Out of Footprint	**46,448**	**120,561**	**610,284**	**7,500**	**18,572**	**37,500**	**92,860**

Total	**67,449**	**178,647**	**896,263**	**13,300**	**33,108**	**66,500**	**165,540**

III. STUDY OBJECTIVES AND CONSTRAINTS

This study, like the preceding WWSIS, undertakes detailed analysis and modeling of the power system, but it was meant to provide insight and be a complement to other in-depth studies. This is not a transmission planning study, a cost-benefit analysis, a full-blown reliability study, nor a dynamic stability study.

In 2017, it is anticipated that WestConnect and WECC will operate differently from current practice. This study assumed the following changes from current operational practice: least-cost economic dispatch in which all generation resources are shared equally and not committed to specific loads; five regional balancing areas, instead of the 37 that exist today in WECC; and existing available transmission capacity, even though currently contractually bound, will be accessible to other generation on a short-term, non-firm basis.

There are also reasons that the study results tend toward the conservative. It did not model a more flexible non-renewable balance of generation than exists today or is presently planned for WECC. These levels of solar, if ever reached, are more likely to occur later than 2017 when the load is greater, the balance of generation may be more flexible, and more transmission may be installed. The solar dataset was conservative in terms of overestimating the actual variability found in measured solar plant output. Finally, the base assumption of $9.50/MBTU for gas means that gas is displaced, and that leaves relatively inflexible coal to accommodate the variability of the wind and solar power.

IV. CHARACTERISTICS OF SOLAR

A. *Types of Solar Generation*

Production of electricity from solar insolation takes several fundamentally different forms. Technologies that directly transform energy from incoming photons to electricity are p*hotovoltaic* (PV). Technologies that collect and concentrate thermal energy to drive any of a variety of heat engines or turbines are generally grouped as c*oncentrating solar plants* (CSP); they are also known as *solar thermal* plants.

The power production characteristics of each of these technologies have some important differences, which are examined below. However, all solar generation is dependent on the position of the sun which is perfectly predictable, but variable, and weather, which is not perfectly predictable. The simple reality that time of day and weather strongly govern system load means that analysis of grid performance and economics must include time-synchronized load and solar data.

B. *Photovoltaic Solar*

PV output varies with insolation. Output can be relatively steady during consistently clear or consistently overcast weather. Conversely, power output at a single PV installation can be highly variable on partly cloudy days, with intermittent and fast moving clouds. While these variations can cause local problems, only the coincident variation of many PV installations is of concern to the bulk system. As an example, Figure 2 shows 1-minute resolution PV output profiles representing relatively large regions under relatively volatile conditions [3]. The fastest variations tend not to be temporally coincident, but significant net variation is still possible.

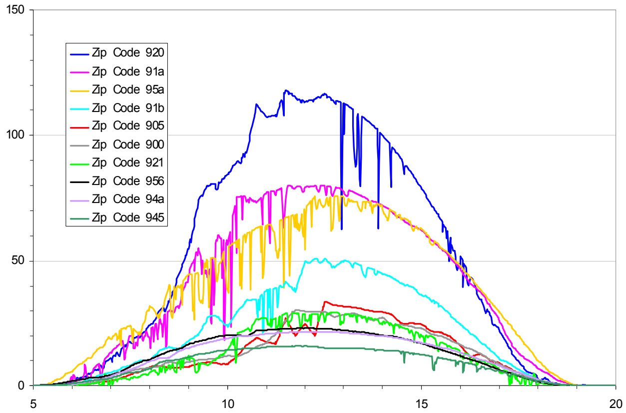

Figure 2 – Example PV Solar Zip Code Profile for a July Morning.

For the analysis reported here, a satellite cloud cover model was used to simulate the United States at a 10-km, hourly resolution [4]. PV was modeled in 100-MW blocks as distributed generation on rooftops because modeling information for large, central station PV plants was not available at the time of the study. Over 15 GW of PV plants were included in the dataset from which the 6,900 MW were selected for the 5% scenario.

C. *Concentrating Solar Power*

CSP is much less variable, because there is substantial thermal mass in the energy conversion system. An illustrative day of production from two large commercial CSP projects [3] is shown in Figure 3. The output rises in the morning to the plant rating and then declines in the evening. The ramp rates during the morning and evening periods are substantial, but otherwise the plant output is quite steady. This is characteristic of CSP steam thermal plants.

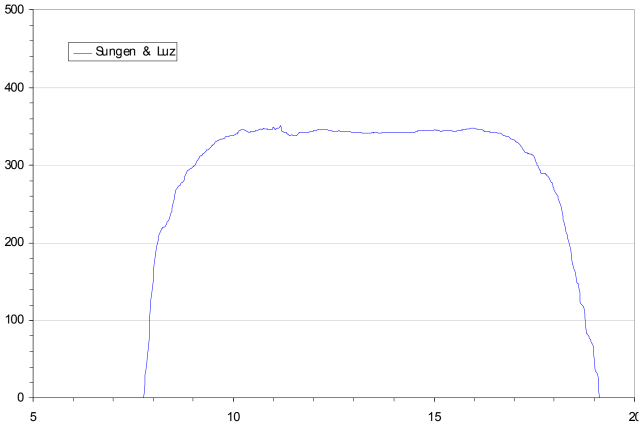

Figure 3 – Example Concentrating Solar Project Profile for a May Day.

The CSP in this study was modeled as 100-MW blocks of parabolic trough plants with six hours of thermal storage, which was dispatched to a typical utility load pattern. The candidate CSP plants were included in the dataset totaled over 200 GW, from which 6,400 MW were selected for the 5% scenario.

Other types of concentrating solar generation can have higher variability, because they have much less thermal mass. The power production from a representative day of operation of two Stirling solar plants [3] is shown in Figure 4. The variability is greater than the CSP plant, and is more like the output of PV. Stirling plants were not included in this study.

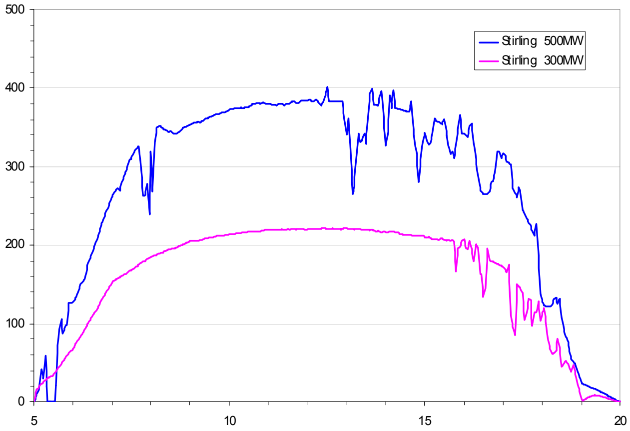

Figure 4 – Example Stirling Solar Project Profile for a May Day.

D. *Daily, Monthly, Seasonal, and Annual Characteristics*

The average January daily output shapes of the PV and CSP in the study footprint with 25% solar energy penetration are shown in Figure 5. The average January load shape is also shown.

On average, solar generation is increasing during a relatively flat load period after the morning load rise, and decreasing during the late afternoon/early evening load rise.

The PV production tends to peak about 6 hours before the load. CSP without additional thermal storage would show a similar average shape. However, the addition of thermal storage tends to shift some of the energy production closer to the peak load hours, resulting in a second peak in the CSP profile. This peak is still about 3 hours before the load peak. Managing the stored energy could provide additional operational flexibility, reduce system operating costs, and increase the value of the solar power. While redispatch of the stored energy was not examined at these penetration levels, it was part of the original WWSIS analysis.

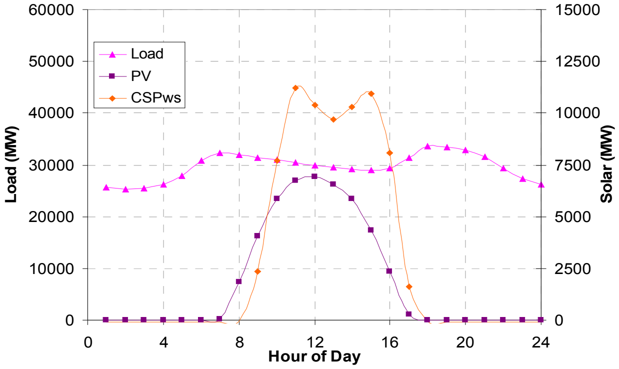

Figure 5 – Average January Solar Profiles.

The average daily PV and CSP shapes for other seasonally representative months are shown in Figure 6 to Figure 8. Again, these are for 25% solar energy penetration.

The double peak in the January CSP profile is also observed, to a lesser extent, in April and October. In all months, CSP production peaks about 3 hours before the load. PV production peaks 4-8 hours before the load.

On average, solar generation is decreasing during the late afternoon/early evening load rise. The morning increase in solar generation is more coincident with the morning load rise in April and July, and less so in October. Solar generation in April, with its generally clear skies, exceeds that of July, which is generally hazier.

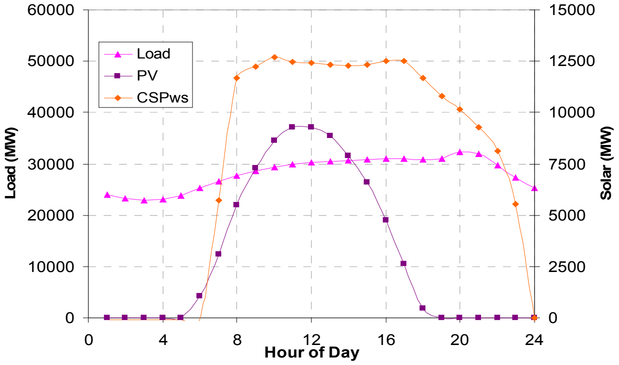

Figure 6 – Average April Solar Profiles.

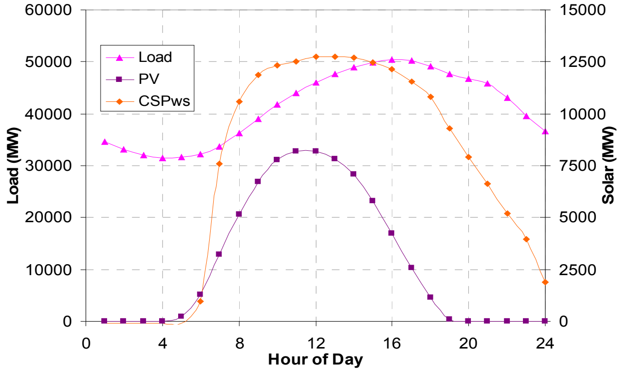

Figure 7 – Average July Solar Profiles.

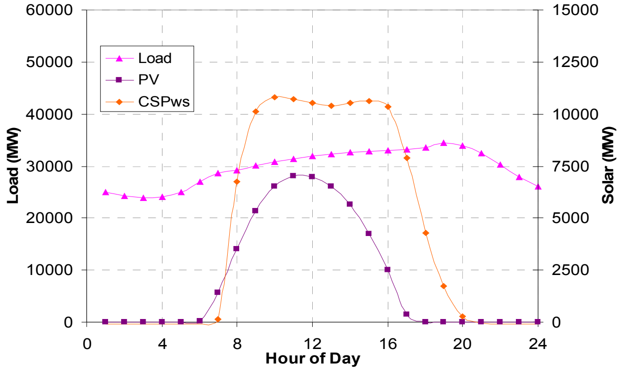

Figure 8 – Average October Solar Profiles.

The above discussion focused on average daily solar power profiles for representative months. The following discussion focuses on solar energy across months and years. The annual energy production for 2004, 2005, and 2006 in GWh are summarized in Table 2, along with the average of the three years and deviations from the average of the individual years.

Table 2 – Annual Energy Production.

Year	Annual Energy (GWh)	Deviation from 3 Year Average
2004	33610	1.54%
2005	32927	-0.52%
2006	32759	-1.03%
Average	33099	

Figure 9 shows the study footprint monthly solar energy for the three years. Similarly, Figure 10 shows the monthly solar energy as a percentage of load energy (i.e., penetration) for the same three years. For reference, the 25% annual energy penetration level is shown.

First, while there is relatively little total annual variation between years, there is significant year-to-year variation in the monthly energy. Second, 25% annual energy penetration is not 25% energy penetration at all times. In December, the energy penetration is about 12%. In April and May, the penetration is about 37%.

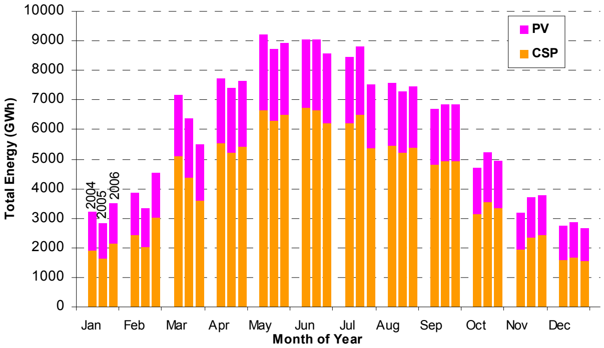

Figure 9 – Monthly Solar Energy for 3 Years.

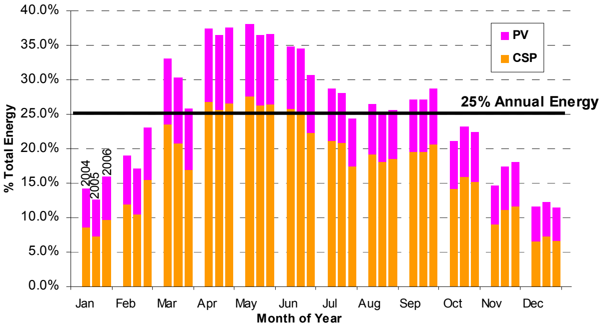

Figure 10 – Monthly Energy Penetration for 3 Years.

V. NET SYSTEM CHARACTERISTICS

The results presented in this section are for the entire study footprint.

The challenge to the power system is strongly correlated to the instantaneous penetration, i.e., the fraction of total system load that is being provided by solar generation at a given instant in time. Duration curves for hourly energy production *and* hourly instantaneous penetration are shown in Figure 11. The left vertical-axis scale applies to the energy production, and the right vertical-axis scale applies to the penetration.

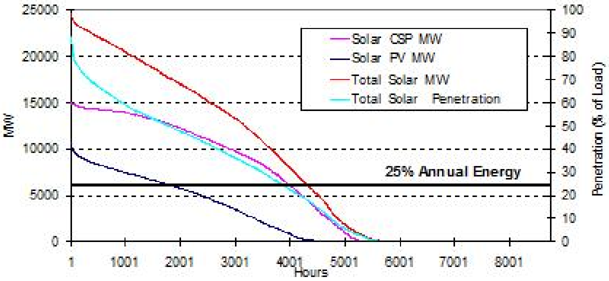

Figure 11– Solar Energy Production and Penetration Duration Curves.

The production of solar power will displace other non-zero marginal cost generation whenever the system can accept it. Thus, it is useful to view the solar generation as negative load, which combined with the actual system load, yields a “net load”; the power that must be supplied by other resources on the system. The instantaneous penetration of solar will be high when this net load is relatively low. Figure 12 shows the study area load duration curve, and then five net load-duration curves for progressively greater levels of solar generation. By the 25% case, roughly one-third of operating hours have net load levels lower than the base system minimum load. The extreme hour (8760) corresponds to highest penetration in Figure 11. During these periods, some energy will be exported, fewer other generation units will be committed, and the dispatch of committed generation will tend to be lower.

The variability of load and solar will drive maneuvering of the other generation resources on the system. When load and solar power are both increasing, the need for the other generation, i.e., that serving net load, to maneuver will tend to decrease. This is true for coincident decreases in load and solar as well. Figure 13 shows a year of hourly load and solar power changes for the 25% solar case. Hours of the year are segregated into four seasons with four colors. Concurrent positive changes in load and solar generation are shown in the 1st quadrant, and concurrent drops in the 3rd quadrant. Hours that have an increase in solar and drop in load are in the 2nd quadrant. Hours that have an increase in load and drop in solar are in the 4th quadrant. The dotted lines show loci of 5,000 MW changes in net load. Ordinarily, this is the condition that can cause the most operational concern, as the resulting increase in net load has the potential to stress the grid and operating reserves. Hours below the 5,000-MW line have net load increases greater than 5,000 MW, roughly the largest load increase ever seen by this system.

The points below the 5,000-MW line in the 3rd quadrant are interesting. For these hours, the system load is dropping, but the net load is *increasing* faster than the fastest morning load ramp of the base system. Failure to forecast such changes could be operationally difficult.

The hours of extreme net load change in Figure 13 are due in part to the way the data for this exploration was created. The hourly energy production for the 5% scenarios was simply scaled up for the 25% case. This approach is overly conservative in that it loses the benefits of the increased spatial diversity that would accompany such a build-out and unrealistically increases the variability. Thus, the hourly variability would lower with a more geographically diverse build-out. This is a subject for further investigation.

In addition to being variable, the production of solar cannot be perfectly predicted. Forecasting solar production is receiving a considerable amount of attention in the industry. The state of the art has not progressed as far as that for wind generation. Nevertheless, as has been shown for wind power, forecasting of solar generation for high penetration systems will be required for economic operation. Figure 14 is the duration curve of the day-ahead solar forecast, actual production and the forecast error used in this study. The forecast used here is relatively crude, and could be expected to improve with technology. The combination of variability and uncertainty impacts the operation of the grid.

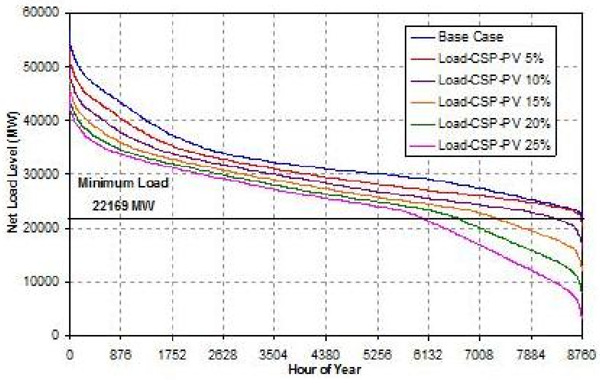

Figure 12 − Total Net Load Duration Curves.

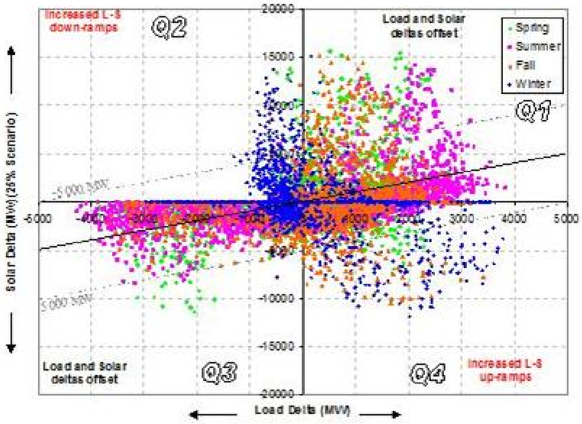

Figure 13 − Hourly Variability of Load and Solar Generation.

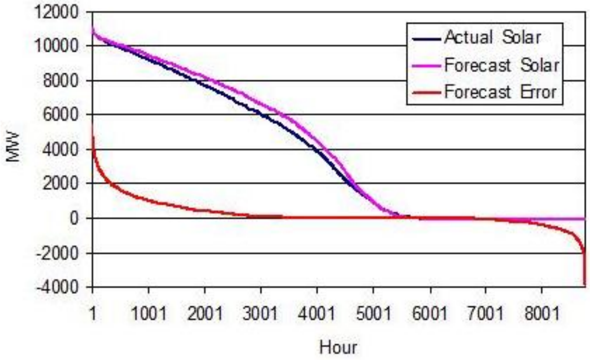

Figure 14 − Solar Actual, Forecast, and Error Duration Curves for 25% Solar Case.

VI. OPERATIONS WITH 25% SOLAR

The previous section examined the characteristics of solar generation on an annual, seasonal, monthly, and daily basis. These characteristics, including the variability and forecasts, were used in an examination of the operational impact of 25% solar penetration as presented in this section.

Production simulation analysis with GE's MAPS (Multi-Area Production Simulation) program was used to evaluate hour-by-hour grid operation of each scenario for 3 years with different solar and load profiles. WECC was represented as a set of 106 zones, which were grouped into 20 transmission areas. The following assumptions were made:

- All study results are in 2017 nominal dollars with 2% escalation per year;
- \$2/MBTU coal;
- \$9.50/MBTU natural gas;
- Carbon dioxide costs of \$30/metric ton of CO_2;
- Extensive balancing area cooperation;
- All units are economically committed and dispatched while respecting existing and new transmission limits and generator cycling capabilities and minimum turndowns;
- Existing available transmission capacity is accessible to renewable generation; and
- Generation equivalent to 6% of load is held as contingency reserves – half is spinning and half is non-spinning.

Figure 15 shows the aggregate generation dispatch for an example week in July without any solar. The top of the curve represents the total load plus exports for the study area. Each type of generation is represented by a different color. The nuclear units (black) have a constant output. The coal units (gray) have a nearly constant output, with some reductions during light load periods. The combined cycle units (purple) vary more than the coal, but still operate at consistently high output levels. Hydro (dark blue), pumped storage hydro (light blue), and peaking gas turbines (red) are largely operating during peak load periods.

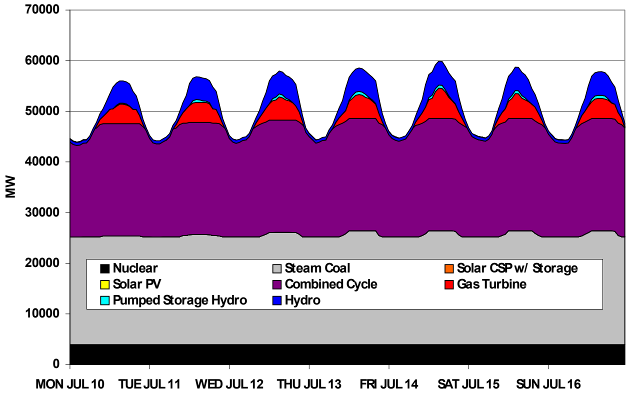

Figure 15 − Study Area Dispatch for a Week in July without Solar.

Figure 16 shows the aggregate generation dispatch for the same July week with 25% solar penetration. The PV (yellow) and CSP (orange) generation displaces about 10% of the combined cycle plants and all of the peaking gas turbine generation. The exports from the study area also increase substantially (54%, 767 GWh). Hydro generation is shifted to the latter half of the load peaks and into the subsequent load troughs. Coal generation sees more reductions, which are shifted into the morning load rise period.

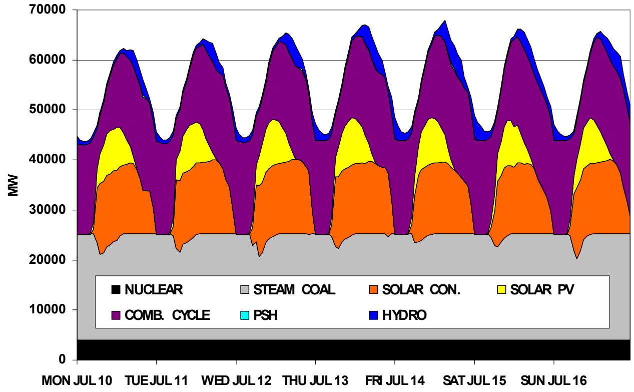

Figure 16 – Study Area Dispatch for a Week in July with 25% Solar.

Figure 17 and Figure 18 show similar information for an example week in April. The total load plus exports is about 75% of that in July.

In Figure 17, the nuclear units have a constant output, except for the start of a planned maintenance outage on Saturday. The coal units are also constant. The combined cycle units follow the load, but still operate at consistently high output levels. Hydro operates at all but the lowest load levels. No gas turbines operate.

Figure 18 shows that operating the system with significant solar generation is more challenging. Solar generation has displaced significant amounts of combined cycle generation. In fact, the combined cycle units are almost reduced to zero output during peak load periods. Many of the combined cycle plants see daily start/stop cycling. The coal units are also reduced during this time. That the coal is backed down mid-day is a marked contrast to minimum load challenges associated with high wind generation scenarios [1] that result in coal cycling during the night. The hydro generation has largely shifted to the load peak and into the subsequent load trough. And finally, gas turbines are necessary on days with actual solar generation below forecast or with peak loads occurring after the solar generation declines. While the impact of 25% solar on the thermal generators is not as challenging as the impact of 35% wind and solar investigated in WWSIS, there is still a significant impact on when and how other generators must operate to accommodate the solar power.

Nonetheless, the system can operate with balancing area cooperation. Without balancing area cooperation, operations during this week would be extremely difficult, if not impossible, for individual balancing areas.

The power system is designed to handle variability in load. With solar, the power system is called on to handle variability in the net load (load minus solar), which can be considerable during certain periods of the year.

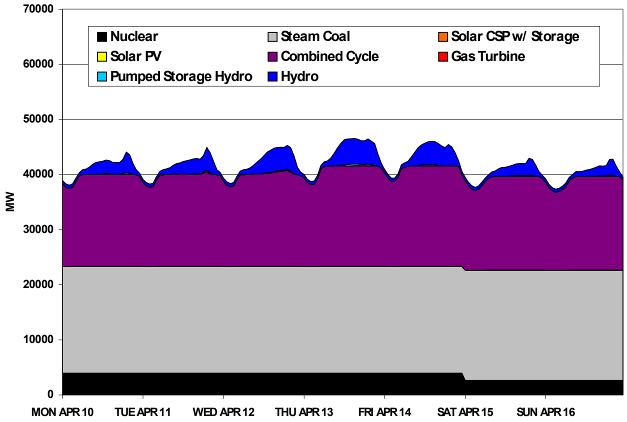

Figure 17 – Study Area Dispatch for a Week in April without Solar.

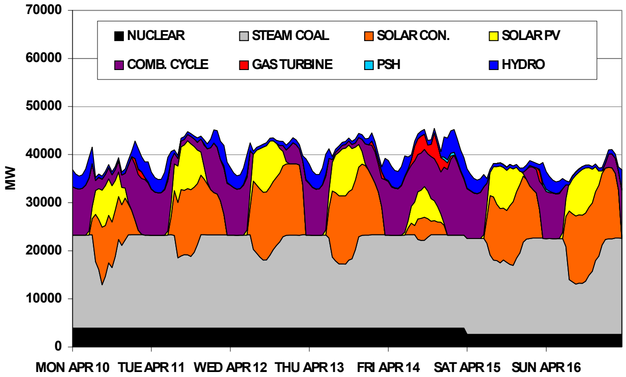

Figure 18 – Study Area Dispatch for a Week in April with 25% Solar.

The behavior of the combined cycle plants has potentially interesting economic implications. There is still a substantial amount of energy coming from them over the week; 984 GWh, or about 35% of the 2,822 GWh for the no-solar base case. However, they need to not only maneuver, but start and stop. Plants that have the capability to do so will be needed and will probably receive preferential commitment and dispatch. There is also need for peaking units during the poor solar day of Friday, April 14. This would be provided by gas turbines. Since significant energy is required during the week from combined cycle plants, the economics will likely favor flexible combined cycle plants. Ones that have the ability to start (and stop) by allowing their gas turbines to run in simple cycle quickly and on short notice, and ones with the ability to transition to more efficient combined cycle mode should the need for power persist, will be the ones that are dispatched.

From an operational perspective, these exploratory cases did not show any substantial adverse impacts in WestConnect up to the 25% case, given balancing area cooperation.

The impact on spot price is illustrated in Figure 19, which shows the spot price duration curve for Arizona, where a large portion of the solar generation and load in the study area resides. The figure shows that the addition of new, zero marginal cost resources will generally depress spot prices. However, a diminishing benefit is observed at high prices. This occurs at higher penetrations when high forecast errors (see Figure 14) cause expensive generation to be brought on line to make up for these large misses. This behavior is similar to that observed in high wind systems.

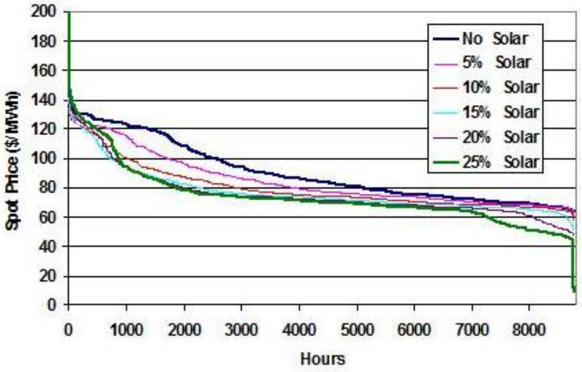

Figure 19 − Arizona Spot Price Duration Curves.

VII. BENEFITS OF 25% SOLAR

Given the fuel prices and carbon tax assumed for this study, solar generation primarily displaces gas generation nearly all hours of the year. Across WECC, operating costs drop by $13 billion/yr ($11 billion/yr in 2009$) from approximately $50 billion/yr ($43 billion/yr in 2009$). This represents about a 25% savings due to offset fuel and emissions (a $30/ton carbon tax is assumed). Figure 20 shows the overall impact on the operating costs of WECC for the various penetration levels with a state-of-the-art forecast. Figure 21 divides these values by the corresponding amount of renewable energy provided. In the 25% case, this equates to $83/MWh ($71/MWh in 2009$) of solar energy produced.

As one might expect, there is diminishing returns on incremental solar build-out when the incumbent generation portfolio remains fixed.

These operating cost savings would be applied toward the costs of the solar energy (which is primarily capital cost, not variable costs) and other necessary system infrastructure (e.g., transmission enhancements). Depending on the magnitude of the operating savings, they may or may not be sufficient to cover the costs.

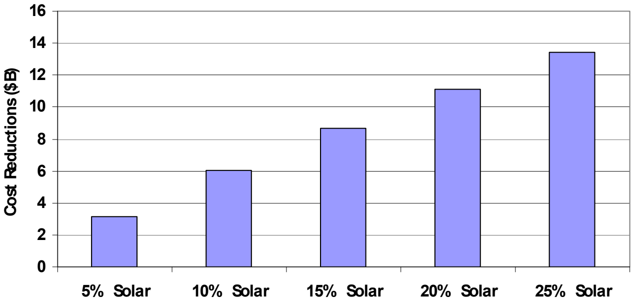

Figure 20 − Total WECC Variable Operating Cost Reductions.

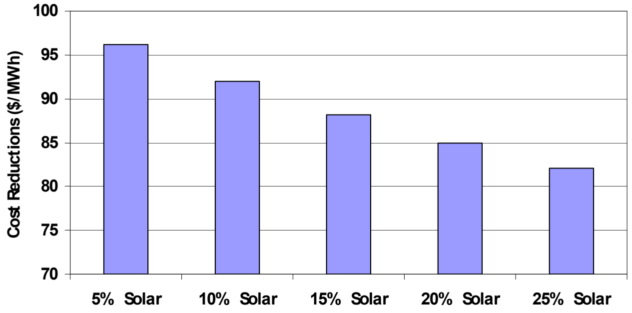

Figure 21− Operating Cost Reductions per MWh of Solar Energy.

Since the solar power is a marginally zero cost resource, the system will accept it whenever the spot price is positive and the system is capable, subject to reliability constraints. As noted above, this analysis assumes that all generation is responsive to price signals.

Figure 22 shows how other generation resources are displaced by the solar production. It is clear that there is nearly a 1:1 correlation between increased solar production and reduced combined cycle production. In the western U.S., for the fuel price and regulatory (i.e., carbon tax) assumptions of this study, gas generation was nearly always the marginal resource – that is, it is the first generation to be displaced by zero marginal cost resources.

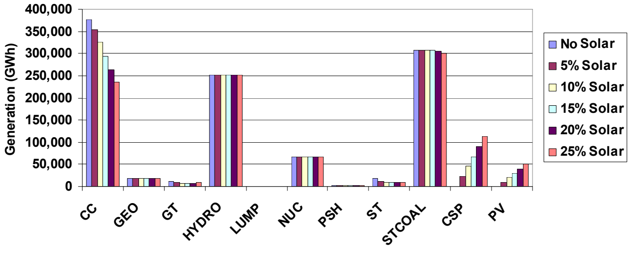

Figure 22 − Generation Displacement by Type.

Total WECC reductions in NO_x, SO_x and CO_2 emissions are shown in Figure 23. Total WECC reductions for the 25% case of CO_2 emissions were nearly 75 million tons per year, or approximately 15%. SO_x emissions would be reduced by approximately 15,000 tons (~2%) and NO_x would be reduced nearly 60,000 tons per year (~10%).

Again, the cost of fuel and carbon policy can strongly affect these results as well. If coal were on the margin more often, it would be displaced more frequently. The result would be further reductions in carbon and SO_x.

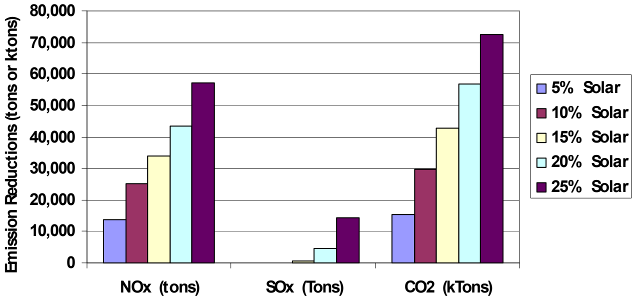

Figure 23 – Reduction in Total System Emissions.

VIII. CAPACITY VALUE OF SOLAR

Resource adequacy analysis involves loss-of-load-expectation (LOLE) calculations using the Multi-Area Reliability Simulation program, MARS. The capacity value of variable resources, including solar, tends to decrease with increased penetration. This is because the contribution to system adequacy has an important temporal component that yields diminishing returns for additional resources of similar time dependence.

An LOLE analysis was not conducted in this analysis. However, LOLE was performed in WWSIS [1] to determine the capacity value of both the wind and solar generation of that study. The capacity impacts of different types of intermittent renewable generation are different. PV tends to have peak output somewhat before system load peaks, whereas CSP with storage can be shifted to reduce the peak loads. The capacity values for 5% solar from WWSIS were about 30% for PV and about 92% for CSP. These values will decrease with increasing penetration, and the value of CSP will be significantly affected by the amount and use of thermal storage.

IX. COMPARISON TO WWSIS RESULTS

While this exploration is much less comprehensive than that of WWSIS, a few notable points of comparison arise.

Since solar is only producing power about ½ the time, instantaneous penetrations during the day at 25% energy can be very high.

Compared to wind, minimum generation problems can still occur with solar, but penetration levels need to be pretty high. Minimum generation issues occur in the middle of the day, not at night.

Hourly variability with solar can be substantial. This warrants closer investigation since the scenarios with penetration greater than 5% lack the benefits of spatial diversity that would come with these large build-outs.

Use of peaking units to meet substantial forecast misses occurs with both solar and wind, but for the solar cases, the misses tend to be mid-day.

This exploration did not examine sub-hourly performance and reserves issues. Similarly, it did not specifically identify impacts or shortfalls of contingency reserves. Results of WWSIS suggest that more sub-hourly reserves will be required, and that sub-hourly scheduling is likely to be needed. WWSIS results also suggest that inclusion of demand response as a resource for contingency reserves is likely to be effective and economic.

X. KEY FINDINGS AND CONCLUSIONS

The technical analysis performed in this exploration, in conjunction with the results of WWSIS, shows that it is operationally feasible for WestConnect to accommodate 25% solar energy penetration, assuming the following changes to current operational practice and infrastructure could be made over time:

Operational practice should:

- Substantially increase balancing area cooperation or consolidation, real or virtual;
- Increase utilization of transmission;
- Enable coordinated commitment and economic dispatch of generation over wider regions; and
- Incorporate state-of-the-art wind and solar forecasts in unit commitment and grid operations.

Additionally, from the more detailed examination undertaken in WWSIS, it is expected that the following operational and infrastructure changes will be necessary*:*

- Commit additional operating reserves as appropriate;
- Use operational flexibility of solar plants;
- Increase the flexibility of dispatchable generation where appropriate (e.g., reduce minimum generation levels, increase ramp rates, reduce start/stop costs or minimum down time);
- Build transmission as appropriate to accommodate renewable energy expansion; and
- Target new or existing demand response programs (load participation) to accommodate increased variability and uncertainty.

XI. ACKNOWLEDGEMENTS

This work was made possible by foundational support from the United States Department of Energy through the National Renewable Energy Laboratory. Readers should visit the NREL website: http://www.nrel.gov/wind/systemsintegration/wwsis.html

Contributions from WestConnect members, 3Tier Group, Northern Arizona State University, Exeter Associates, State University of New York at

Albany/Clean Power Research, members of the WWSIS technical review committee and GE associates are gratefully acknowledged.

XII. REFERENCES

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. **REPORT DATE** *(DD-MM-YYYY)* December 2010	2. **REPORT TYPE** Technical Paper	3. **DATES COVERED** *(From - To)*

4. **TITLE AND SUBTITLE** Impact of High Solar Penetration in the Western Interconnection	5a. **CONTRACT NUMBER** DE-AC36-08GO28308
	5b. **GRANT NUMBER**
	5c. **PROGRAM ELEMENT NUMBER**
6. **AUTHOR(S)** Debra Lew (NREL) Nicholas Miller, Kara Clark, Gary Jordan, and Zhi Gao (GE Energy)	5d. **PROJECT NUMBER** NREL/TP-5500-49667
	5e. **TASK NUMBER** SM101610
	5f. **WORK UNIT NUMBER**
7. **PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	8. **PERFORMING ORGANIZATION REPORT NUMBER** NREL/TP-5500-49667
9. **SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**	10. **SPONSOR/MONITOR'S ACRONYM(S)** NREL
	11. **SPONSORING/MONITORING AGENCY REPORT NUMBER**

12. **DISTRIBUTION AVAILABILITY STATEMENT**

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT** *(Maximum 200 Words)*

This paper presents an overview of the variable characteristics of solar power, as well as the accompanying grid dynamic performance and operational economics for a system with significant solar generation. The paper will show results of economic operational simulations of a very high solar generation future for the western half of the United States.

15. **SUBJECT TERMS**

Grid integration; solar power; transmission; power system operation; reserve requirements; GE Energy.

16. **SECURITY CLASSIFICATION OF:**			17. **LIMITATION OF ABSTRACT**	18. **NUMBER OF PAGES**	19a. **NAME OF RESPONSIBLE PERSON**
a. **REPORT**	b. **ABSTRACT**	c. **THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		19b. **TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18