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Dark Shadows

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Disclaimer

Acknowledgements

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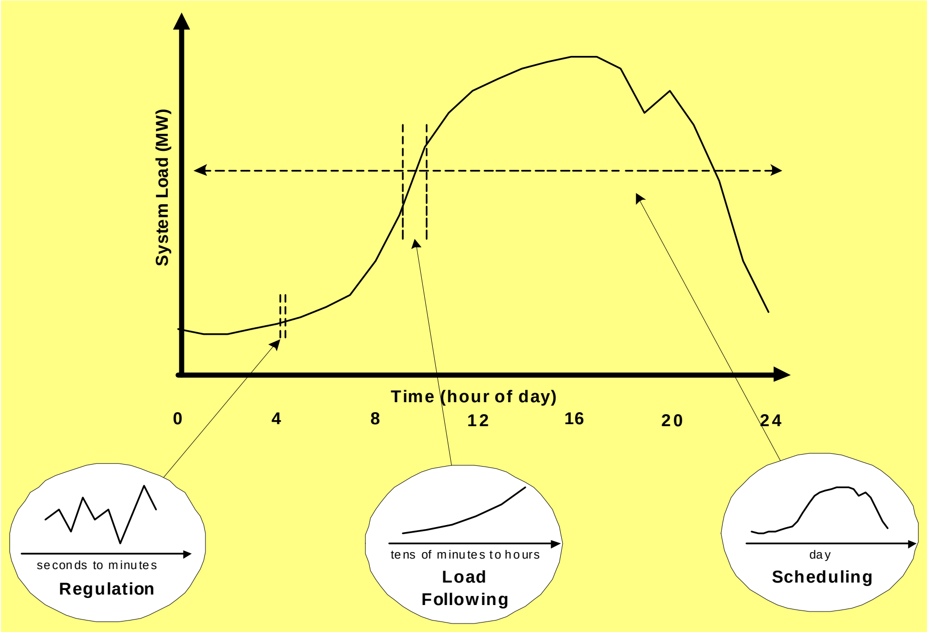
1. Introduction

The National Renewable Energy Laboratory, Sandia National Laboratories, the Solar Electric Power Association, the Utility Wind Integration Group, and the Department of Energy recently hosted a day-long public workshop on the variability of photovoltaic (PV) plants. The workshop brought together utilities, PV system developers, power system operators, and several experts to discuss the potential impacts of PV variability and uncertainty on power system operations. The workshop was largely motivated by a need to understand and characterize PV variability from the perspective of system operators and planners to avoid unnecessary barriers to the rapid development and interconnection of PV to the electric power system. Understanding PV variability will allow system planners and operators to develop effective measures to manage variability at different levels of PV penetration. The workshop generated considerable discussion on the topic and a number of lessons were learned by the end of the day. This article explores the issue of variability and uncertainty in the operations of the U.S. power grid and presents a number of the findings from the workshop.

2. Managing Variability and Uncertainty in Power Systems

Before focusing on the variability and uncertainty of PV plants, it is important to understand that variability and uncertainty are inherent characteristics of power systems. Loads, power lines, and generator availability and performance all have a degree of variability and uncertainty. Regulations, standards, and procedures have evolved over the past century to manage variability and uncertainty to maintain reliable operation while keeping costs down. There are many different ways to manage variability and uncertainty. Enforceable reliability standards, overseen by the North American Electric Reliability Corporation (NERC), generally focus on minimum performance standards for reliable operation. The standards, however, do not dictate *how* to meet many of the performance requirements. In general, system operators and planners use mechanisms including forecasting, scheduling, economic dispatch, and reserves to ensure performance that satisfies reliability standards in a least cost manner.

The earlier that system operators and planners know what sort of variability and uncertainty they will have to deal with, the more options they will have to accommodate it and the cheaper it will be to mange the system. Planners look years into the future to project needs for generation and transmission capacity, estimate cost effective expansion of supply options, and assess flexibility needs. Flexibility of the generation fleet is characterized in terms of parameters such as minimum start-up and shut-down times, minimum stable generation, and ramp rates. Closer in, planners will schedule units for maintenance or to be available to meet expected loads. These units are committed to generate electricity for a system in the hours to days unit commitment time scale. In the 10-min to hours time scale system operators will change the output of committed units to follow the changes in load throughout the day. More capacity than is needed at any particular time is committed to ensure that errors in forecasts or unexpected events can be accommodated without compromising reliability. In the tens of minutes time scale, system operators schedule adequate regulation reserves to track minute-by-minute changes in the balance between generation and load, Figure 1.



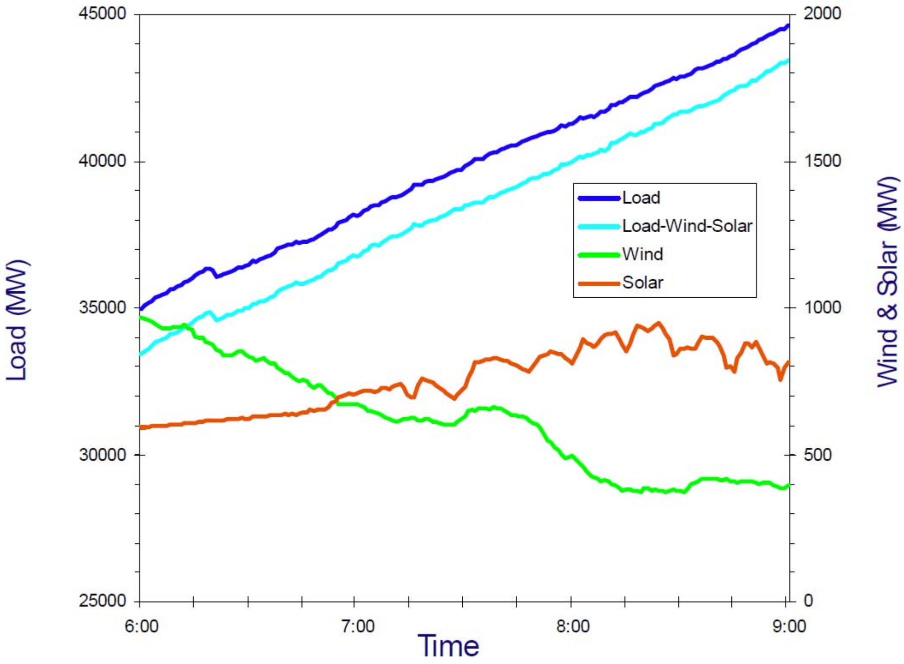
Source: Michael Milligan, NREL, presentation at PV Variability Workshop

Figure 1. Time scales relevant to operating power systems

Managing variability and uncertainty is easier and less expensive when transmission lines are used to aggregate several diverse sources of variability and uncertainty. The daily load shape that system operators use to plan for the real-time operation of the grid is dramatically smoother than the daily profile of an individual residential customer, due to the diversity of load usage among customers. Rather than being concerned with the timing and duration of each individual customer appliance, system operators know that the aggregate of all customers will follow a general trend that can be predicted and managed with relative ease. Similarly, experience with managing wind energy in several countries with high penetrations of wind indicates that aggregation of several diverse wind farms leads to much smoother wind profiles than would be expected from scaling the output of a single wind turbine (Holttinen et al., 2009).

3. Studies are Required to Characterize Additional Variability and Uncertainty of Photovoltaic Plants

The addition of variable generation to meet demand will increase the variability and uncertainty that must be managed by system operators and planners. Figure 2 shows data used in an integration study where flexible conventional generation is used during a morning demand ramp to meet the load or the net-load when integrating wind and solar. Integration studies characterize the additional expected variability and uncertainty in scenarios with high penetrations of variable generation. These studies also focus on strategies that can reduce the challenges and costs of integrating variable generation. A number of integration studies with large amounts of wind and some solar have evaluated the additional reserves required to accommodate the variable generation. The studies found, among other conclusions, that using forecasts of variable generation by system operators and decreasing the time between dispatch schedules for generation can greatly increase access to flexible generation (Kirby and Milligan, 2008). These measures reduce the costs of managing the net increase in variability and uncertainty from adding variable generation (Smith et al., 2007).



Source: Piwko et al., 2007

Figure 2. Detailed analysis of the challenges system operators must be able to manage in the California Intermittency Analysis Project (Piwko et al., 2007). Across all of the time scales identified in Figure 1, system operators use dispatchable resources to manage the combination of the load and the aggregate of all wind and solar plants.

Integration studies separate variability into different time scales as each is associated with different impacts, management strategies, and costs. The following list highlights general issues that are important for different time scales when operating power systems with variable generation:

- Power quality (e.g. voltage flicker) – seconds
- Regulation reserves – minutes
- Load following – minutes to hours
- Unit-commitment and scheduling – hours to days

Aside from the time dimension, it is also important to characterize variability along a spatial dimension. Problems with power quality are often managed within a single distribution feeder. The spatial scales of importance for power quality may be on the order of tens of square kilometers. On the other hand, balancing authorities must balance all generation and load within balancing areas that range from hundreds of square kilometers to tens of thousands of square kilometers. Arrangements that allow balancing authorities to exchange variability in ways that are beneficial to both balancing authorities, such as ACE Diversity Interchange (ADI), require understanding variability on the spatial scale of nearly an entire interconnection or hundreds of thousands of square kilometers.

A fundamental challenge in integration studies is developing projections of the load and variable generation across all of these temporal and spatial scales for expected levels of variable generation that have yet to be experienced anywhere in the world. Integration studies for high-penetration scenarios of PV will require projections of variability from multiple GW of PV generation for both distributed PV and large utility-scale PV plants. Currently, wide-area solar data coverage is available with low time resolution or high time resolution data is available with limited spatial coverage. Solar data covering a large spatial extent is available from satellite images, but this data generally has an hourly temporal resolution. High-time resolution PV data and solar insolation measurements are available from individual points, but there are few networks with multiple time-synchronized PV or solar insolation sites. To develop projections of PV variability for integration studies analysts need to be able to model on the time scale of seconds to hours the output of:

- Large PV plants (~1-10’s of sq. km)
- Dispersed PV plants on distribution feeders (~10-100’s of sq. km)
- The aggregate of all PV plants that must be managed by system operators (~1,000-100,000’s of sq. km)

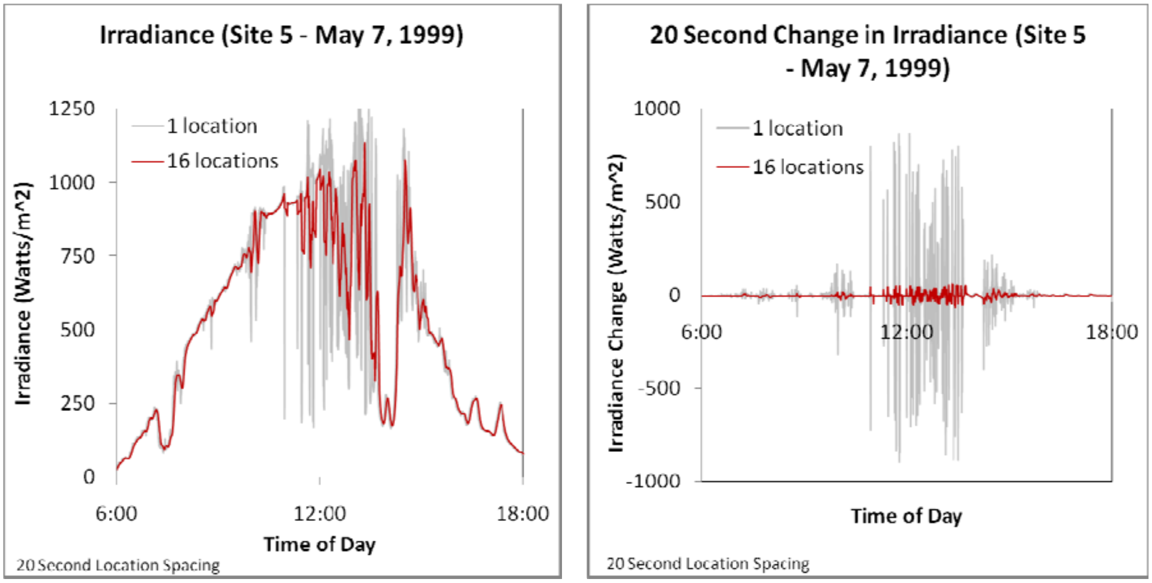
4. Lessons Learned from Analysis of Limited Existing Datasets Managing Variability and Uncertainty in Power Systems

4.1 Clouds can cause significant ramps in solar insolation and PV plant output

The output of PV plants is necessarily variable simply because the sun changes position throughout the day and throughout the seasons. The rising and setting of the sun regularly leads to 10-13% changes in PV output over a period of 15 minutes for single-axis tracking PV plants. Clouds, however, are largely responsible for rapid changes in the output of PV plants that concern system operators and planners. Changes in solar insolation at a point due to a passing cloud can exceed 60% of the peak insolation in a matter of seconds. The time it takes for a passing cloud to shade an entire PV system, in contrast, depends on the PV system size, cloud speed, cloud height, and other factors. For PV systems with a rated capacity of 100 MW, the time it takes to shade the system will be on the order of minutes rather than seconds.

4.2 Clouds are diverse

Unlike changes in the position of the sun which affects the output of all PV plants in a nearly uniform, highly correlated way, changes in PV output due to clouds are not driven by a similar uniform process. Clouds move across plants affecting one part of a plant before another or leaving some parts of plants unobstructed as the cloud passes. Clouds therefore cause diverse changes in PV output across plants and between separate plants. Just as electrical connections are used to aggregate diverse loads and conventional plants, electrical connections aggregate the diverse output of separate PV panels and blocks of PV panels within a plant or between separate PV plants. The degree of diversity between points or plants can be characterized by the correlation of simultaneous changes in the output. Similarly, diversity can be characterized by the relative reduction in the magnitude of ramps for the aggregate of multiple plants relative to a single point, Figure 3.

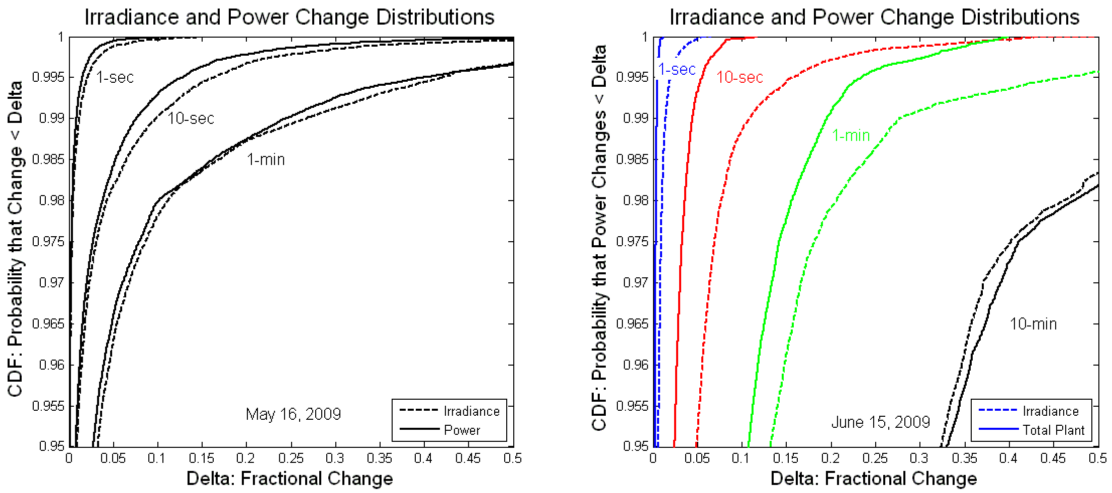


Source: Hoff and Perez, 2010

Figure 3. Aggregating the output of several different solar insolation meters illustrates the reduction in variability of multiple sites relative to a single site. The change in irradiance from one minute to the next (left) is dramatically reduced for multiple sites due to diversity.

4.3 Smoothing occurs within PV plants

Comparison of the variability of a solar insolation meter and a 30-kW PV plant in New Mexico shows that diversity, even within a small PV plant, can smooth rapid ramps relative to the expected ramps from just examining solar insolation. 1-second and 10-second ramps from the 30-kW PV plant are less severe than the ramps in the insolation meter, Figure 4 (left figure). 1-min ramps, however, are nearly identical between the two.

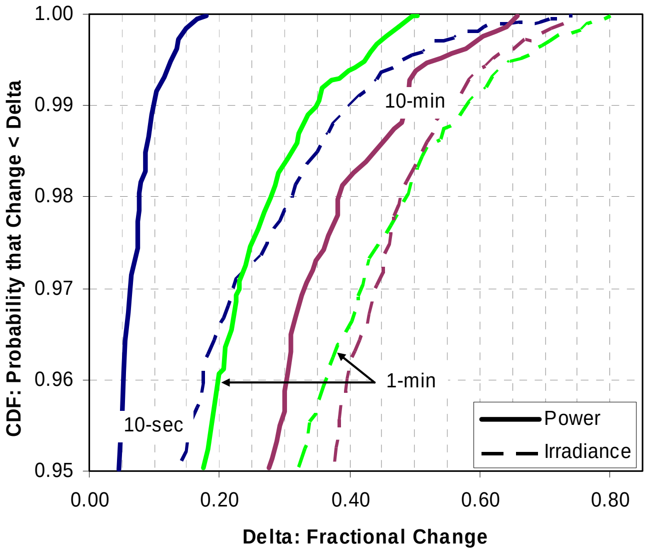


Source: Joshua Stein, Sandia National Laboratories, adapted from presentation at the PV Variability Workshop

Figure 4. Cumulative distributions (95th to 100th percentiles) of irradiance and PV power changes over various time periods during a single day from a 30-kW PV system (left) and a multi-MW PV system (right) show a reduction in variability between single point measurements (irradiance) and PV plant output (power/ total plant)

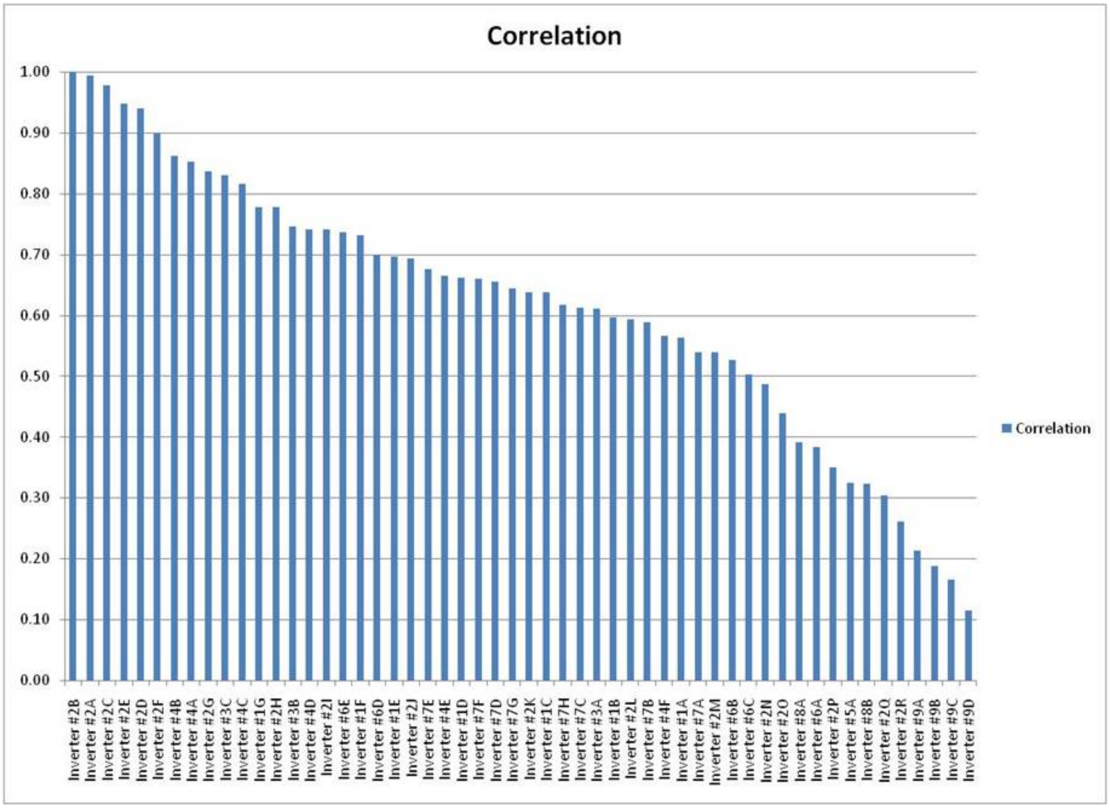
Comparison between variability observed in insolation meters and the output of larger multi-MW plants exhibit more pronounced reductions in variability. For example, output from a multi-MW PV plant of undisclosed capacity (>2 MW) shows the relative difference between ramps observed at a point (irradiance sensor) and power ramps from the entire plant decrease as the ramp duration increases, Figure 4 (right figure). Large 1-sec, 10-sec, and 1-min ramps in the multi-MW PV plant are approximately 60%, 40%, and >10%, respectively, less severe than observed at a point. The ramp distributions are nearly identical for 10-min ramps.

Other large PV plants exhibit similar behavior. A 75% ramp in 10-seconds observed by an insolation meter was associated with only a 20% in 10-second ramp in a different 13.2-MW plant in Nevada. A severe event that changed the output of an insolation meter by 80% in 1-min therefore led to only a 50% in 1-min change in the output of this plant and a 10-min change 65% in 10-min was slightly less severe than the 75% in 10-min change observed in the nearby insolation meter, Figure 5. 1-min changes in output of inverters within this plant were nearly perfectly correlated for close inverters, but inverters far apart within the same plant show correlation coefficients between simultaneous 1-min changes in output that drop as low as 0.1, Figure 6. The magnitude of the reduction in the maximum 1-min change in output therefore depends on the size of the plant. Increasing the plant size increases the relative reduction in 1-min changes in plant output, Figure 7. Similar smoothing behavior for short time scales is reported for the 25 MW DeSoto Next Generation Solar Energy Center in Florida (Kankiewicz et al., 2010).



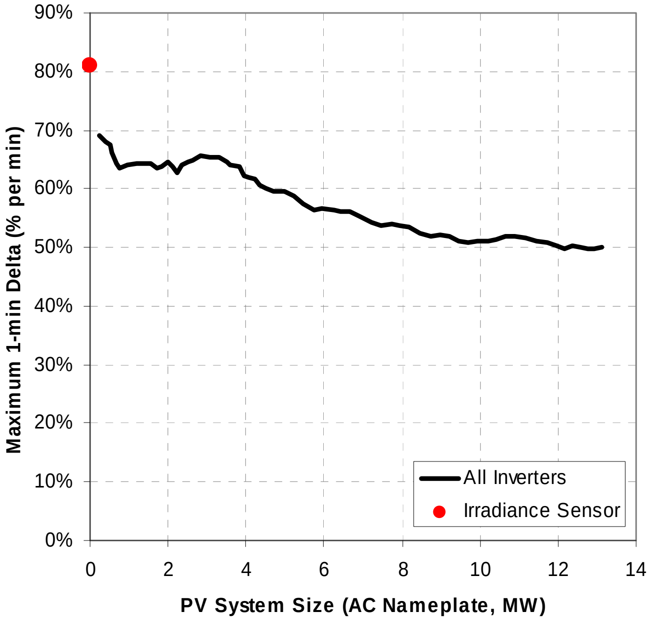
Source: Carl Lenox, SunPower Corporation, adapted from presentation at PV Variability Workshop

Figure 5. Cumulative distributions (95th to 100th percentiles) of irradiance and PV power changes over various time periods during a highly variable day for a 13.2-MW system.



Source: Carl Lenox, SunPower Corporation, presentation at PV Variability Workshop

Figure 6. Correlation coefficient of 1-min step changes in power output between different inverters (relative to Inverter #2B) within a 13.2-MW PV plant in the Southwest on a highly variable day.



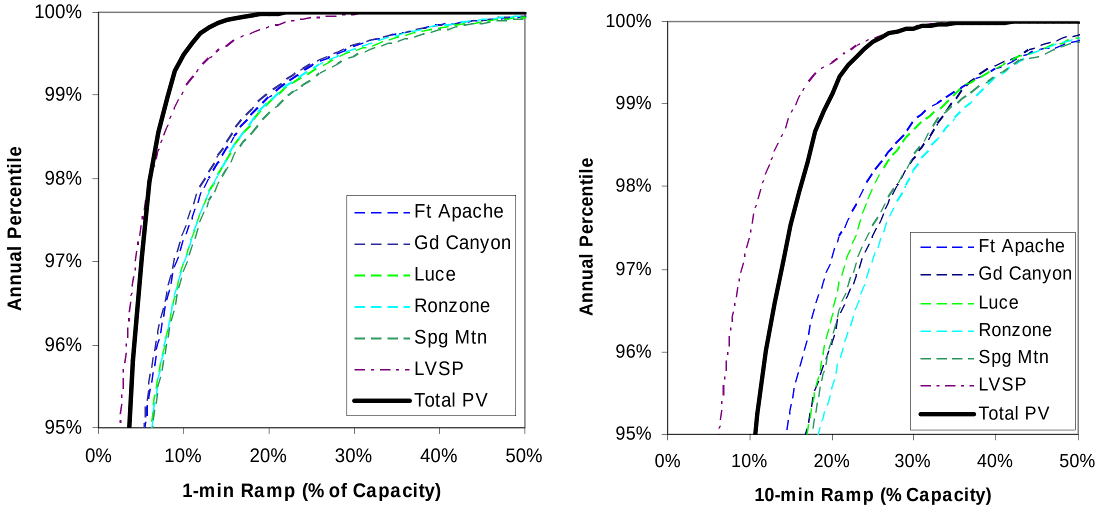
Source: Carl Lenox, SunPower Corporation, adapted from presentation at PV Variability Workshop

Figure 7. Maximum 1-min changes in the output of an irradiance sensor and aggregated blocks of a 13.2-MW PV plant on a highly variable day.

There are two key lessons from this analysis. First, diversity can occur even within plants and the amount of smoothing within a plant depends on the size of the plant. Comparisons of the variability of different technologies need to be done for plants of similar capacity to be meaningful. Second, for plants in the tens of MW scale, the output of an insolation meter will show distinctly more severe ramps in time scales up to about ten minutes than will be observed in the output of the PV plant. Changes in the output of an insolation meter for time scales longer than about 10-min however will be similar to the changes in the output of multi-MW PV plants. These observations are based on a limited sample of data, and should be verified with data from other locations.

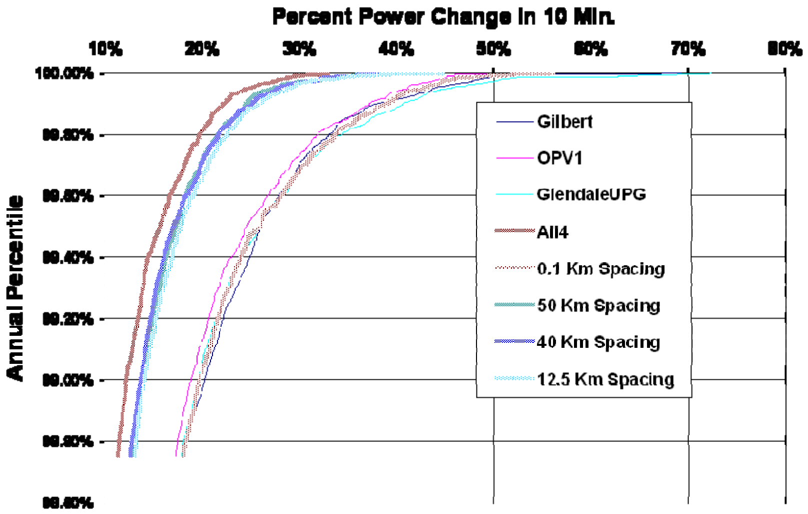
4.4 Diversity occurs between separate PV plants

While diversity over longer time-scales may be limited within multi-MW PV plants, analysis of a network of several time-synchronized solar insolation measurements in the Great Plains region of the U.S., six PV plants in the city of Las Vegas, four PV plants in Arizona, and two PV plants in Colorado indicates that smoothing can occur on even longer time-scales between separate plants. Aggregating six plants within a ~200 square kilometer area in Las Vegas greatly reduced not only the 1-min ramps but also reduced the 10-min ramps relative to the individual plants, Figure 8. Sixty minute ramps were smoothed, but to a lesser degree, with aggregation. Analysis of the 10-min ramps for PV plants located 12.5 km to 50 km apart in Arizona show on the order of a 50% reduction in the 99.7th percentile of the most severe ramps by aggregating any pair of sites, Figure 9. This is the reduction that would be expected if the 10-min ramps at each site were uncorrelated. Aggregating the output of two PV plants in Colorado 8.8 km apart (but along the same mountain ridge) showed a smaller reduction in 10-min ramps indicating that the smoothing benefit of aggregation may vary by region. Data sets from multiple regions need to be analyzed and compared to determine the extent to which local features affect the smoothing benefits of geographic diversity.



Source: Yih-huei Wan, NREL, adapted from presentation at the PV Variability Workshop

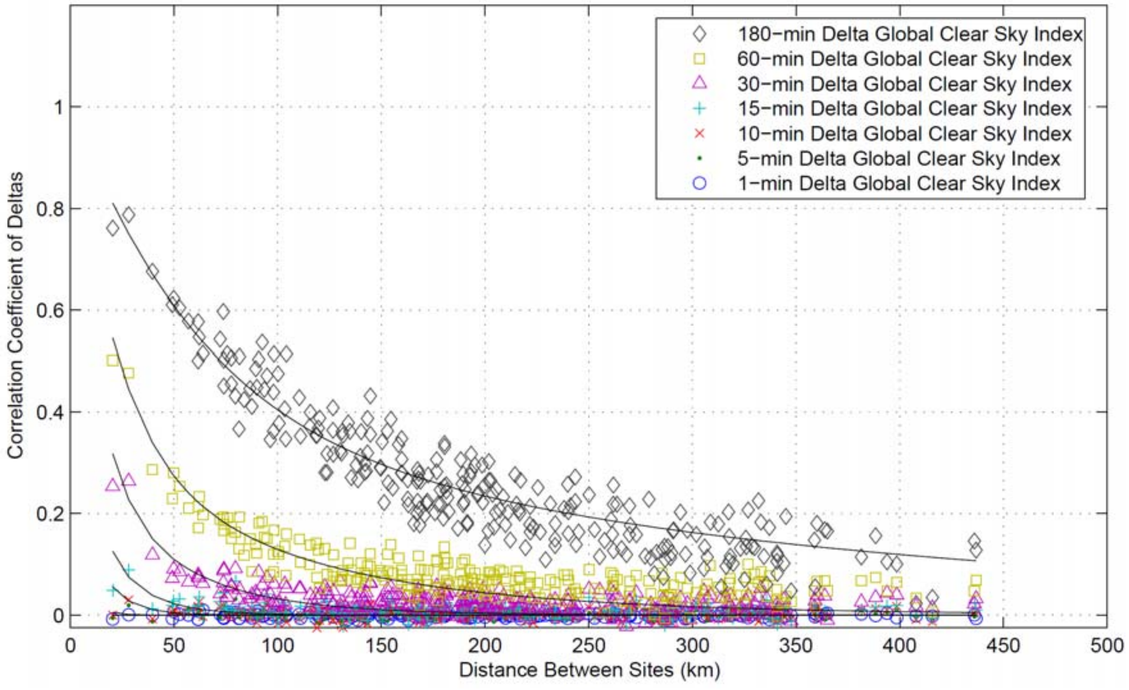
Figure 8. Cumulative distributions (95th to 100th percentiles) of six individual PV plants within a ~200 square kilometer area in Las Vegas and the aggregate of the plants demonstrate that aggregation greatly reduces the magnitude of extreme 1-min (left) and 10-min (right) ramps in the aggregate (Total PV) relative to the individual plants. Note that LVSP is a fixed tilt array while the remaining five plants are single axis tracking plants.



Source: Ray George, NREL, adapted from presentation at PV Variability Workshop

Figure 9. Cumulative distributions (98.6th to 100th percentiles) of ramps from individual PV plants in Arizona, pairs of variously spaced plants, and the aggregate of all plants (All4). Aggregating the output from pairs of PV sites 12.5 km to 50 km apart leads to a reduction in the magnitude of the 10-min ramps (as a percentage of the name plate capacity) relative to the individual site. Ramps are based on one year of 10-min data from one-axis tracking PV systems (courtesy Arizona Public Service Co.).

In the Great Plains, irradiance ramps over time scales of 30-min were uncorrelated for sites that were on the order of 50 km apart. Ramps over time scales of 60-min were uncorrelated for sites on the order of 150 km apart. Ramps over time scales 15-min and shorter were uncorrelated for all distances between sites down to the minimum spatial resolution of 20 km between sites, Figure 10. When ramps over a particular time scale are uncorrelated between all N plants, the aggregate variability is expected to scale with $1/\sqrt{N}$ relative to the variability of a single point. This diversity between multiple PV sites on all sub-hourly time scales needs to be accounted for in projections of variability that must be managed by system operators. Comparison of the variability of multiple solar insolation meters and similarly sited wind anemometers (scaled to create a time series of wind power output) suggests that the variability of several PV plants may be similar to the variability of several similarly sited wind plants for time scales longer than 10-15 minutes.



Source: Mills and Wiser (2010)

Figure 10. Correlation coefficient of step changes in the global clearness index (the ratio of the measured insolation to the clear sky insolation) for different distances between sites and different averaging intervals for the step changes (deltas).

4.5 Multiple methods are available for PV forecasting

Forecasts of PV output are required for days ahead down to hours and tens-of-minutes ahead. Forecasts should include information about the expected output and the degree of uncertainty in the expected output to indicate particularly volatile periods. Short-term PV forecasts are aided by the fact that clouds can be observed. Sky imagers near PV plants can be used to indicate approaching clouds and predict the impact the clouds will have on

PV output. Successive satellite images have been shown to yield useful information about the direction and speed of approaching clouds. For longer time scales, numerical weather models can be used to predict solar insolation out to multiple days (Lorenz et al., 2009). Forecasts are an important method for managing both the variability and the uncertainty of PV and should be incorporated into system planning and operations.

4.6 Grid events can impact the variability of PV

Step changes in PV output can occur from simultaneous inverter trips within the plant. Although inverter trip events are far less common than cloud-induced ramps, the severity and magnitude of trips exceed the observed severity and magnitude of ramps due to clouds. Currently, these trips are normal operation as inverters are designed to shut off when abnormal events occur on the grid and cause voltage or frequency deviations outside of a tolerance envelope. Tripping is presently required by IEEE Standard 1547 for PV (and other distributed generation) that is embedded on distribution systems. This requirement stems from safety concerns surrounding inadvertent islanding. However, an unintended consequence of these rules is that wide spread tripping of PV will occur for large grid disturbances such as transmission faults that depress voltages below existing tolerances over a wide geographical area in systems with large amounts of IEEE 1547 compliant embedded PV. Preventing large simultaneous inverter trips due to low voltage on the grid will require some reconciliation of rules like IEEE 1547, that mandate low voltage tripping, and FERC Rule 661a, that prohibit low voltage tripping for large scale generation. From a technology perspective, application of low voltage ride through (LVRT) techniques (such as those developed for wind generation) will be needed for PV inverter design. Voltage ride-through standards for PV are already in place in interconnection standards in Germany (Troester, 2009).

In addition to grid events, PV plants are subject to outages due to equipment malfunction or outages inside the plant similar to conventional generators. PV plant outages, like the outages of wind and conventional plants, should be planned for in the normal way that grid operators prepare for grid contingencies.

5. Conclusions

The PV Variability Workshop was the beginning of a dialogue that will need to continue between utilities, PV system developers and owners, and regulators to characterize PV variability and develop effective measures to manage the variability and uncertainty. The initial lessons learned from the workshop include:

- Rapid ramps are important to characterize and understand for PV, but in the end system operators need to maintain a balance between the aggregate of all generators and loads. Understanding the characteristics of aggregate PV output over large areas and correlation to load are critical to understanding potential impacts of large quantities of PV.
- PV variability can drive localized concerns, which typically manifest themselves as voltage or power quality problems. These issues are distinct from grid system

level issues of balancing, and ought not to be confused. Management and remediation options for local power quality problems are generally different than options for maintaining a balance between load and supply at the system level.

- The variability observed by a point insolation measurement will not directly correspond to the variability of a PV plant. A point measurement ignores sub-minute time scale smoothing that can occur within multi-kW plants and sub-ten minute smoothing that can occur within multi-MW plants. Extrapolation suggests that further smoothing is expected for short time-scale variability within PV plants that are hundreds of MW, but this needs to be confirmed with field data from large systems.
- Diversity over longer time scales (10-min to hours) can occur over broad areas encompassed by a power system balancing area. Data from the Great Plains region of the U.S. indicates that the spatial separation between plants required for changes in output to be uncorrelated over time scales of 30-min is on the order of 50 km. The spatial separation required for output to be uncorrelated over time scales of 60-min is on the order of 150 km. The assumption that variability on a 15-min or shorter time-scale is uncorrelated between plants separated by 20 km or more is supported by data from at least one region of the U.S. Additional data is required to examine this assumption in other regions with different weather patterns.
- Multiple methods will be used for forecasting solar resources at differing time scales. Clouds are the primary influence in the solar forecast. Over short time scales, it is important to recognize that clouds (and their rate and direction of movement) are visible to satellites and ground-based sensors. Over longer time scales clouds can change shape and grow or dissipate, so numerical weather modeling methods may prove necessary. As with wind forecasting, solar forecasting will benefit from further development of weather models and datasets.
- Photovoltaics fall under the broader category of variable generation. The experience with managing wind variability and uncertainty will benefit solar integration efforts. Where appropriate, unified approaches for managing variable generation will ease integration issues.

The most important lesson from the workshop, however, is that the dialogue regarding PV variability requires, above all else, additional time-synchronized data from multiple PV plants and insolation meters over spatial scales ranging from sq. km to greater than 10,000 square kilometers. The data will need to cover at least a year and should be synchronized with comparable load data in order to understand the net impact on the variability that must be managed by the system operators. Certain questions, particularly questions concerning power quality and regulation reserves, will require data with as high of a time resolution as multiple seconds. Analysis of data from multiple time-synchronized PV plants will allow detailed evaluation of the degree to which rapid ramps observed in point measurements will be smoothed by large PV plants and the aggregation of multiple PV plants. Such studies will help remove unwarranted barriers to interconnection and provide the basis for setting appropriate interconnection standards that will allow solar energy from PV plants to reach significant penetration levels.

Acknowledgements

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