ASSESSMENT OF A NEW SIMULATION APPROACH FOR ESTIMATING PV OUTPUT VARIABILITY FROM SATELLITE IMAGERY

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ABSTRACT

Uncertainty about the impacts of very large PV plants on utility operations is a barrier to building such plants. Output variability is of particular concern due to its potential impact on grid reliability and operations. Quantifying the impacts of proposed plants generally relies on simulating plant performance without the benefit of irradiance measurements at the proposed plant locations. Accordingly, methods for simulating irradiance are of great interest.

Sandia National Laboratories (SNL) has developed a relatively simple method to estimate one-minute power output from fleets of large PV plants. The method relies on generating artificial time series of irradiance from hourly satellite irradiance estimates (available nearly everywhere) and one-minute ground measurements of irradiance from analogue sites in the region [1]. When applied to the southern Nevada region, the resulting time series preserve basic statistics for irradiance and for changes in irradiance, and exhibit characteristics evident in measured irradiance from other regions. Here we investigate the dependence of the simulation on the available ground measurements. If ground measurements capture generic irradiance patterns, then the method could be applied to regions other than where the measurements were made. We use ground measurements from southern Nevada and Tennessee to simulate irradiance for a site in Florida, where we use hourly averages of ground-measured irradiance in lieu of satellite estimates. The simulation results compare poorly with ground observations of irradiance at a one-minute time scale. We conclude that our simulation method is not general in the sense that it appears to require irradiance measurements within the region of interest.

INTRODUCTION

In 2010, NV Energy began a study to quantify the effects on utility operations of different levels of utility-scale PV. In support of this study, SNL developed a method to produce time-synchronized, one-minute time series of power output for proposed PV plants at ten locations across southern Nevada. The NV Energy study is using the time series of power output to estimate increases in regulation and load following reserves at various levels of utility-scale PV generation.

Simulation of power output required generating artificial one-minute time series of irradiance. Our method for generating irradiance time series combines hourly satellite irradiance estimates, available at the plant locations, with concurrent one-minute time series of irradiance measured at other locations within the region. We applied the method to simulate one-minute time series of irradiance for ten locations in southern Nevada [1]. The simulated time series generally preserve statistics for irradiance at the target locations estimated from satellite data as well as statistics for changes in irradiance measured at other locations within the region. The simulated time series also display characteristics observed for irradiance measured in other regions. In particular, the correlation between the time series of changes in simulated irradiance for different sites decreases with increasing distance between sites and with decreasing time interval used to compute the changes in irradiance, a pattern observed for the Great Plains [2]. We concluded that the method produced time series that were reasonable for use in the NV Energy study.

We next investigated whether the ground measurements of irradiance from one region could be used to simulate irradiance in other regions. We hypothesized that the short-time scale patterns in the ground measurements, which result from the passage of clouds, may be sufficiently generic to be useful in simulating irradiance elsewhere. Alternatively, the method would require obtaining ground measurements within the region of interest. We tested the hypothesis by simulating irradiance for a site in Florida, using ground measurements of irradiance from southern Nevada and from Tennessee.

METHOD FOR IRRADIANCE SIMULATION

For the time period and locations of interest, we may obtain irradiance at hourly intervals estimated from satellite data (e.g., from SolarAnywhere™). Irradiance estimated from satellite data comprises an instantaneous observation of the spatial average over roughly 1 km^2 (one pixel) sampled from within a 20 x 20 km^2 area. Ground measurements of irradiance are typically one-minute averages at a single point. We assemble ground measurements of irradiance into a library of daily sequences and calculate the hourly averages of these sequences. We supplement the library with one year of daily clear-sky irradiance estimated using a clear-sky model.

For each day and location in the period of interest, we select one irradiance day from the library that best matches the hourly average irradiance, i.e., that minimizes the sum of squared differences in hourly average irradiance for that day. Using satellite-derived irradiance as the basis for choosing library days preserves seasonal patterns at specific locations as well as any correlation (or lack of correlation) among different locations.

When selecting irradiance days for different locations on the same calendar day, we developed a technique that prevents assigning the same library day to two or more locations, to avoid introducing perfectly correlated time series into the simulation results. The analysis reported here examined only one location, and this feature of our method is not used.

SIMULATING IRRADIANCE FOR FLORIDA

Ideally we would have obtained satellite-derived irradiance for the selected site in Florida at which we also have one-minute ground measurements of irradiance for the purpose of validating the simulation method. Satellite data from Florida for the time period of interest is available for a fee. We decided, however, to forego the fee and instead represent a "perfect" satellite model by using hourly average irradiance values calculated from the ground data. This decision eliminates one source of uncertainty associated with the modeling method, which is the uncertainty in the translation models that convert satellite data to irradiance.

Replacing the satellite data with these hourly averages, we applied our method to simulate irradiance at this location, using two libraries of irradiance days. One library is assembled from seven ground sensors operated by the Las Vegas Valley Water District (LVVWD) between 2006 and 2008; the second library is assembled from data collected by Oak Ridge National Laboratory (ORNL) in Tennessee (2008 to 2010 obtained from NREL's Measurement and Instrumentation Data Center). We then compared the simulated irradiance to the collocated ground observations in Florida.

Figure 1 displays measured one-minute irradiance (blue) from the Florida site for 16 days, and calculated hourly average irradiance (red). These plots illustrate the one-minute signal that we are trying to simulate, based on its hourly average values. Observations include several complete clear days (e.g., days 3 and 4), days with brief periods of clouds (e.g., days 1 and 2), days with persistent, variable cloudy conditions (e.g., dyas 13, 14 and 15) and an overcast day (day 6).

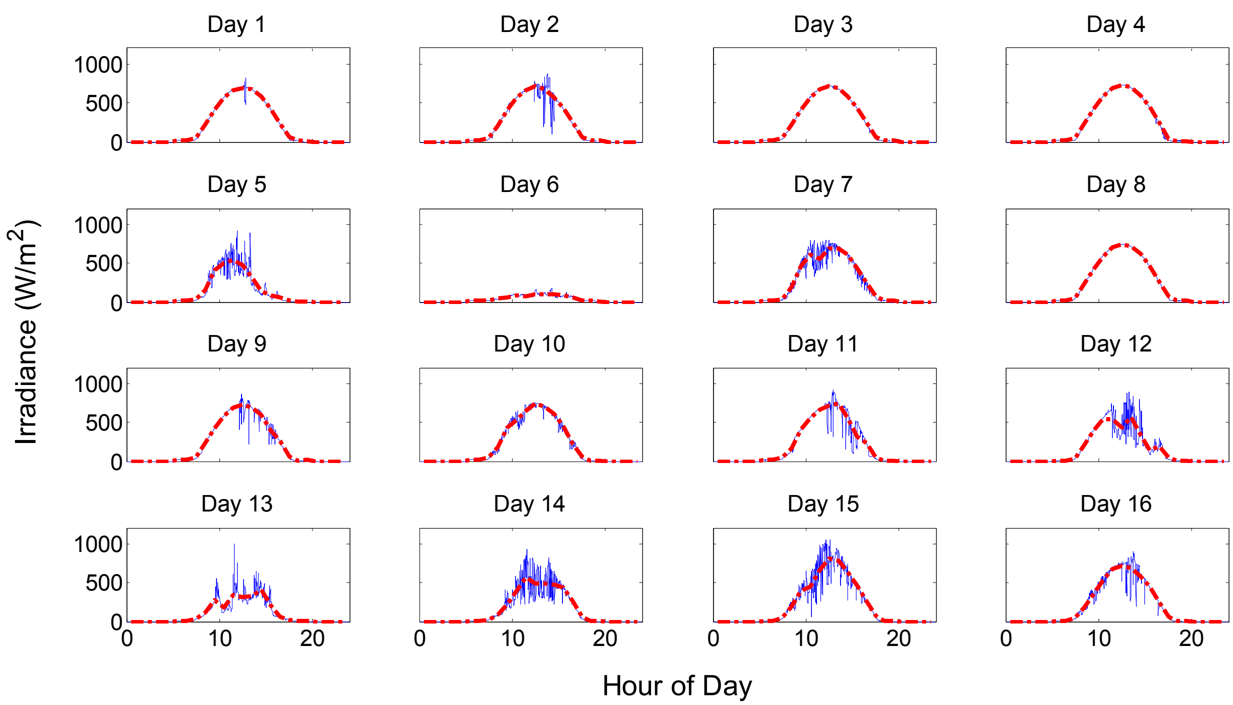

Figure 1. Measured one-minute irradiance (blue) and hourly averages (red) at the Florida site.

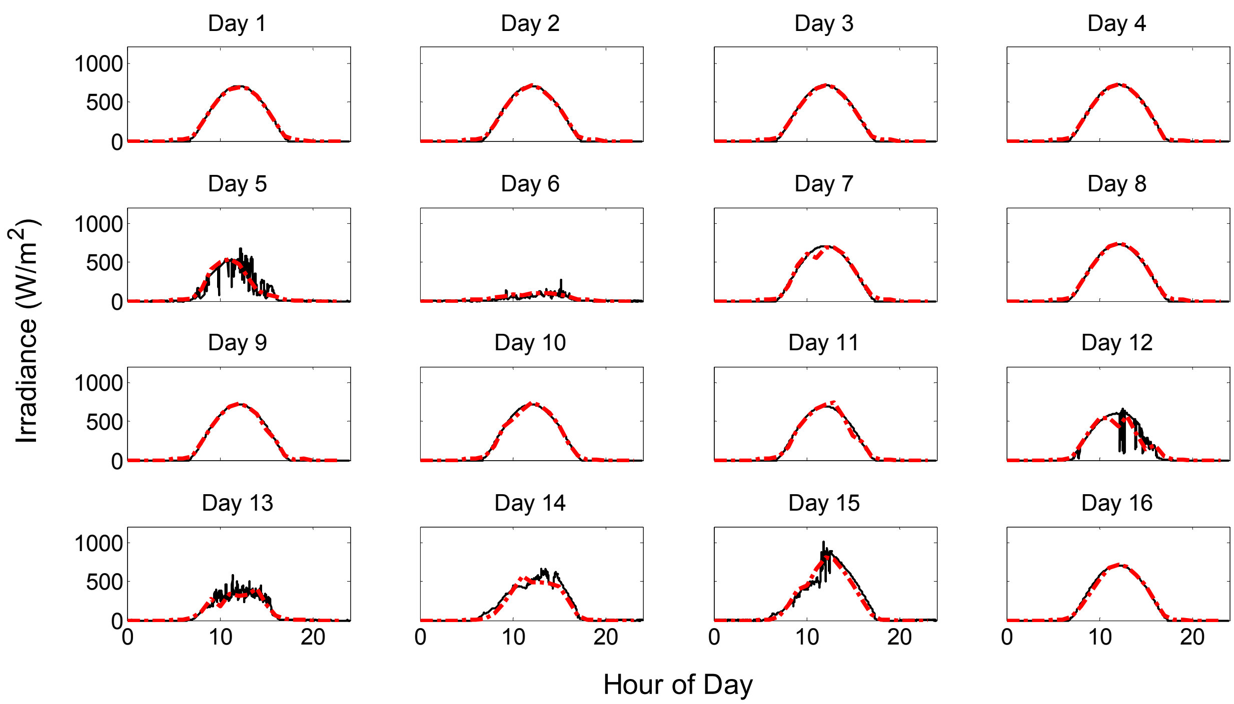

Figure 2. Simulated irradiance using the LVVWD library (black) compared to target hourly average irradiance (red).

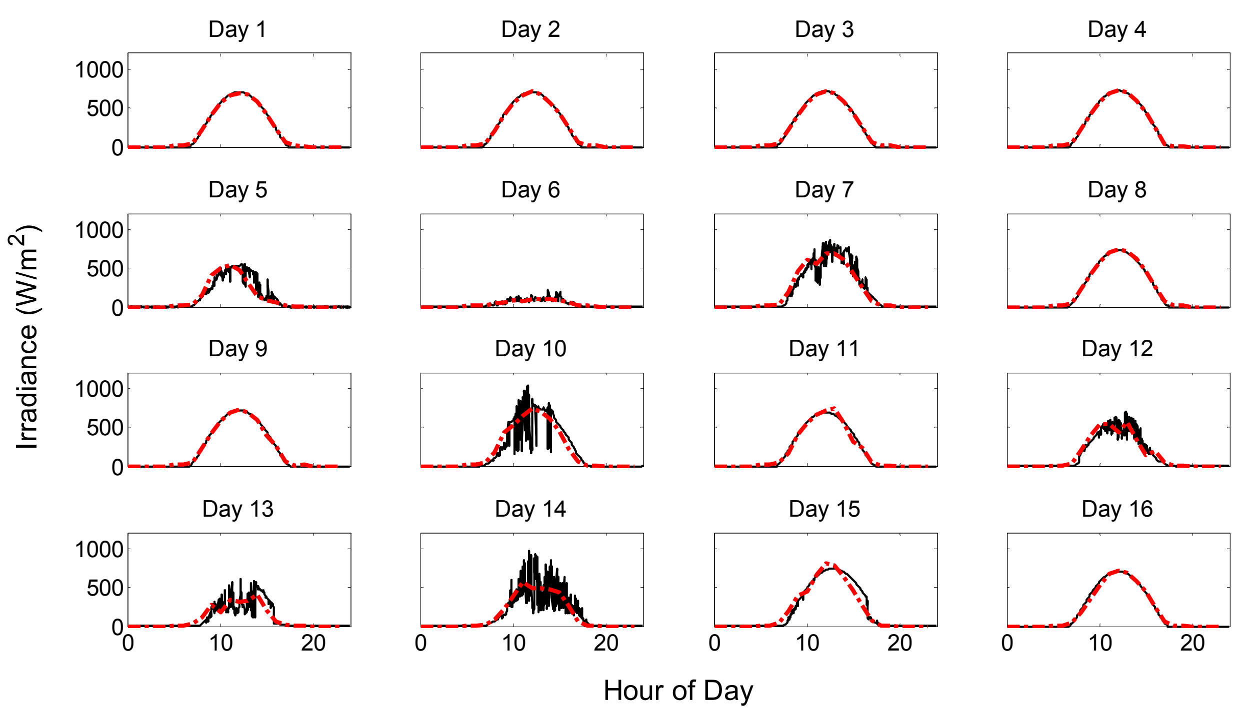

Figure 3. Simulated irradiance using the ORNL library (black) compared to target hourly average irradiance (red).

Figures 2 and 3 illustrate 16 of 24 days of simulated one-minute irradiance from the LVVWD and ORNL sites, respectively, with the target hourly averages from the Florida measurements in Figure 1 (red) overlaid on the simulated one-minute time series (black). Each library contains irradiance days estimated using a clear-sky model; consequently the simulated irradiance agrees well with the hourly averages when the hourly averages result from clear or mostly clear days (e.g, days 3 and 4, judged to be clear from the data shown in Fig. 1). The hourly averages are insufficient to distinguish completely clear days from days with brief variations in irradiance (e.g., Fig. 1, days 1 and 2); in these cases the method selects clear days from the library (Figs. 2 and 3, days 1 and 2). Consequently, the simulation does not reproduce irradiance time series for partly cloudy days, where the hourly averages of irradiance are similar to those for clear sky conditions, likely because of cloud enhancement effects (compare one-minute data for day 2 between Fig. 1 (measured) and Figs. 2 and 3 (simulated)). Both libraries contain an overcast day adequate to simulate the observed overcast day (day 6).

For partly cloudy days (e.g., days 13, 14 and 15 on Fig. 1), days selected from the LVVWD library (Fig. 2) are generally less variable than the measured irradiance. The ORNL library (Fig. 3) performs somewhat better on partly cloudy days (e.g., days 13 and 14) but not always (e.g., day 15).

Because the simulation method assigns one-minute irradiance values measured elsewhere based on matching hourly averages of irradiance, we do not expect that simulated one-minute irradiance values will compare favorably with measured values. However, application of this method to southern Nevada demonstrated that the statistical properties of simulated irradiance compared favorably with those of measured irradiance; we examined these statistics for the Florida results.

Figures 4 and 5 compare cumulative distribution functions (CDFs) for simulated and measured one-minute irradiance over the full 24 day simulation period, i.e., the distributions associated with the values of irradiance appearing in each time series. These CDFs indicate the frequencies at which different values of irradiance are observed. Except at very high or low values, irradiance simulated using the LVVWD library is generally overestimated. In contrast, irradiance simulated using the ORNL library is generally underestimated. These results indicate that, even after selecting daily, one-minute time series of irradiance from the two libraries that are the closest matches to the observed hourly averages, the selected daily time series contain irradiance values that occur with frequencies different from those observed at the location in Florida.

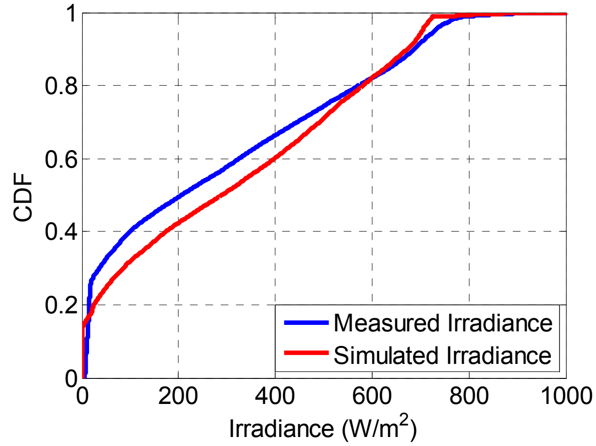

Figure 4. Comparison of CDFs for measured and simulated irradiance (LVVWD library).

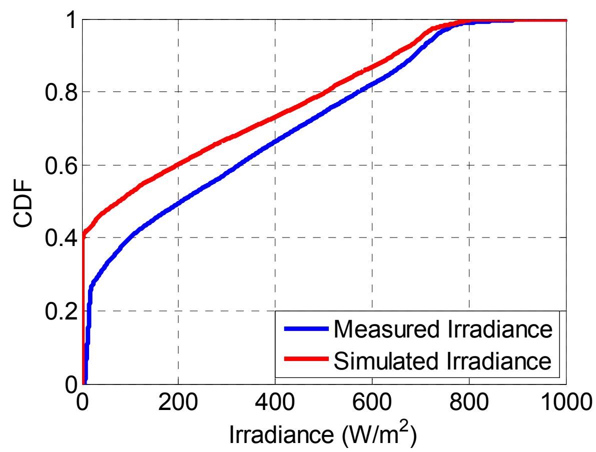

Figure 5. Comparison of CDFs for measured and simulated irradiance (ORNL library).

Figures 6 and 7 compare CDFs for the one-minute changes in irradiance, i.e., the distributions associated with the values in the time series obtained by differencing consecutive values of irradiance. These CDFs illustrate the frequencies at which different ramps in irradiance occur, and are informative regarding the relative likelihood of gradual or rapid changes in irradiance. Using either library, the simulation results significantly understate the occurrence of large ramps in irradiance. The measured values indicate that relatively large one-minute changes (e.g., 200 W/m^2 per minute or greater) occur at approximately 10% of the time steps, whereas such changes are rare in the simulation results (occurring at less than 0.3% of time steps).

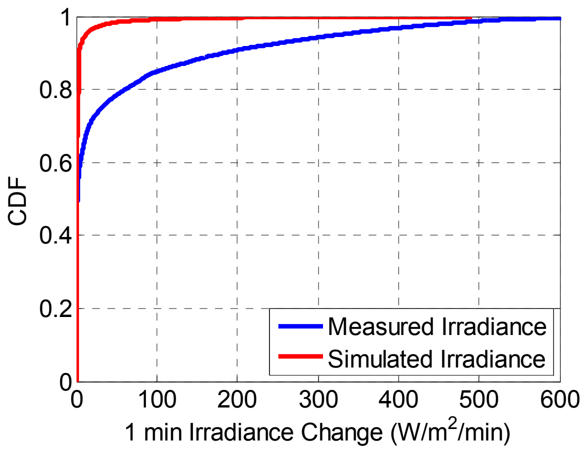

Figure 6. Comparison of CDFs for one-minute changes in measured and simulated time series of irradiance (LVVWD library).

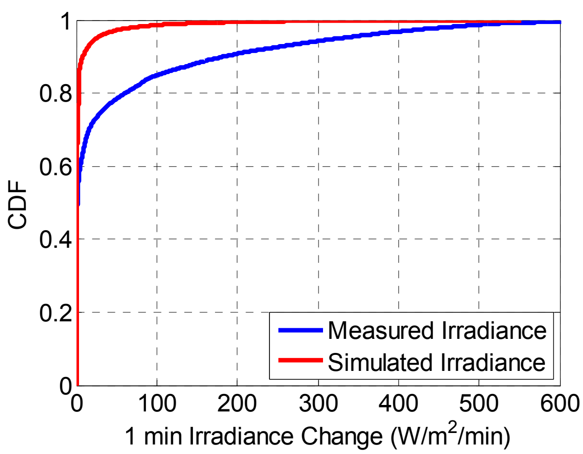

Figure 7. Comparison of CDFs for one-minute changes in measured and simulated time series of irradiance (ORNL library).

CONCLUSIONS

We employed a method for simulating one-minute time series of irradiance using one-hour values of irradiance estimated from satellite data for the location of interest, and one-minute time series of irradiance measured in other regions. Prior analyses showed that the method, when used with ground measurements of irradiance within the region of interest, produced time series of one-minute irradiance with statistics that compared favorably to measurements within the region. However, when out-of-region ground measurements are combined with in-region satellite-derived irradiance, the resulting simulated time-series compare poorly with ground measurements. We conclude that the simulation method, documented in [1], is sensitive to the region from which the library of one-minute irradiance days is obtained. The daily time series at one-minute convey information about the frequency at which different irradiance values, and changes in irradiance, occur; these statistics vary sufficiently between regions that one-minute time series of irradiance from one region may be a poor surrogate for time series in a climatically different region.

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