




# Solar Data Inputs for Integration and Transmission Planning Studies


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*Presented at the 10th International Workshop on Large-Scale Integration of Wind Power into Power Systems*
*Aarhus, Denmark*
*October 25–26, 2011*



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**Conference Paper**
NREL/CP-5500-52749
February 2015

Contract No. DE-AC36-08GO28308

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# Solar Data Inputs for Integration and Transmission Planning Studies

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***Abstract*—Renewable energy integration studies are frequently conducted to evaluate the impacts wind and solar power have on grid operations and planning. In the United States, these studies have historically been focused on wind energy integration. However, with the rapid deployment of large-scale and distributed solar power across the United States. and Hawaii, the interest in solar power variability and its impacts on the grid is increasing. To complete detailed integration studies, modeled power production of existing and future solar power deployments is necessary. This paper discusses some of the methods used to generate photovoltaic (PV) and concentrating solar power (CSP) production profiles for studies undertaken in the United States, evaluates the results, and compares the profiles with measured solar power production characteristics.**

***Index Terms*—numerical weather prediction, PV, solar integration, statistical methods, variability**

## I. Introduction

VARIOUS policy and incentive programs, as well as reduced costs for photovoltaics (PV) are spurring on the manufacturing and deployment of PV systems across the United States. (Fig. 1) [1]. As a result, utilities are increasingly interested in understanding the variability of these systems, and how this could impact their transmission and distribution systems.

Numerous wind integration studies conducted over the last decade address the impacts of high wind energy penetration on grid capacity and reliability [2]-[8]. There are also several significant solar integration studies underway, including: the Hawaii Solar Integration Study (HSIS), the Western Wind and Solar Integration Study Phase 2 (WWSIS2), and the Western Electricity Coordinating Council (WECC) studies. Integration studies generally perform production cost simulations to model the impacts of various penetrations of wind and solar energy on the electrical grid and grid operations. Historically, studies were run on an hourly timeframe, but are increasingly being run at sub-hourly intervals to assess the reserve and regulation requirements in greater detail.

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Ideally, the direct observations of power production would be used, or production would be estimated from observations of wind speed and irradiance measurements. However, to represent high penetration levels, the power produced from existing and potential future wind and solar plants are modeled and used as inputs into the studies. Additionally, hypothetical wind and solar forecasts are often generated to represent how the grid operator would commit and dispatch units if actual forecasts were available for their use. The next sections will discuss the approaches used to model solar production profiles for the Western Wind and Solar Integration Study (WWSIS), WWSIS2, WECC, and HSIS.

First, the nomenclature used in this paper will be similar to that of Lew et al. [9], such that historical measurements of plant production will be called *observations*, modeled production time histories will be referred to as either *modeled* or *actual* profiles, and hypothetical forecasts of plant production will be called *forecasts*.

Lew et al. [9] outline certain characteristics that the wind input data should have to ensure it is representative of observed plant production. Briefly, these characteristics include: appropriate variability at all timescales, intra-plant and plant-to-plant spatial correlation, temporal correlation, and capacity factor. These are all characteristics that should also apply to solar data inputs, for both modeled profiles and forecasts. This paper will focus on the techniques used for and results of the modeled solar production profiles.

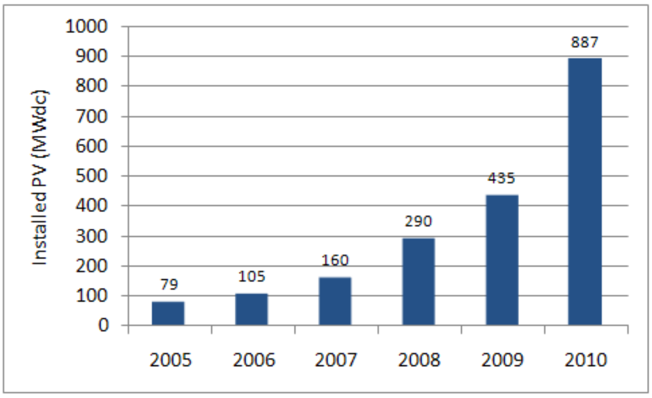



Fig. 1. U.S. PV Installations from 2005-2010. [1]

## II. Methodologies

The aforementioned studies, WWSIS, WWSIS2, WECC, and HSIS, all used different methodologies to generate the solar actuals. The former three studies utilized variations of statistical techniques and gridded satellite-derived data, while the latter employed numerical weather prediction techniques. The satellite-derived data that served as the basis for WWSIS, WWSIS2, and WECC solar profiles was generated by the State University of New York (SUNY)/Clean Power Research (CPR), and will hereafter be referred to as the *SUNY* data. It is available on a 10-km grid at an hourly resolution [10].

### *A. WWSIS*

The WWSIS was the first large regional study to investigate significant amounts of solar penetration, up to 5% by energy, and was performed using 2004-2006 as reference years [7]. The majority of the solar modeled was Concentrating Solar Power (CSP) with thermal energy storage (TES). One-hundred MW blocks of rooftop PV were also modeled, but no large-scale PV plants were modeled due to a lack of information at the time of the study. Up to 15 GW of PV and 200 GW of CSP were modeled in the study. The CSP actuals were generated by using hourly SUNY data and the System Advisor Model (SAM) was utilized to convert irradiance to power. The 1-hour CSP power data was then reduced by interpolation to get 10-minute production profiles.

The PV actuals were generated by using the hourly SUNY data combined with temperature and wind speed data from available weather stations in the western U.S. The irradiance to power conversion was performed using PVWatts with 11 different configurations of orientation and tracking capability, and was then aggregated to achieve representative distributed PV power production at the substation level. The hourly profiles were then downscaled using variability characteristics observed from available sub-hourly data and PV output from the Arizona Public Service's Solar Test and Research (STAR) facility, and other small PV systems.

### *B. WECC*

The WECC Transmission Expansion Planning Policy Committee (TEPPC) undergoes a regular process to evaluate the anticipated transmission needs for the region 10 years in the future. As part of the development of their latest Regional Transmission Plan, they investigated how transmission expansion could be affected by large-scale solar deployments within their operating territory, and recently submitted the plan to the WECC board for review. In parallel, the Variable Generation Subcommittee (VGS) is conducting a study to investigate the potential operating cost savings due to balancing area cooperation, impacts of congestion, and the benefits of sub-hourly scheduling for high penetrations of variable generation. For both of these studies, solar actuals were needed as inputs into their models, and used 2006 as the reference year.

Sites were selected based on the Western Renewable Energy Zones [11] collocated with SUNY grid cells. For each selected grid cell, power production was generated for the following technologies: 50-MW PV fixed axis with latitude tilt and 25° tilt, 50-MW PV with single axis tracking and latitude tilt, and CSP with and without 6 hours of TES. This gave WECC flexibility in selecting deployment scenarios that were most appropriate for the respective studies.

Hourly solar actuals were generated for the TEPPC study using the SUNY data and SAM for the power conversion. Sub-hourly (1-minute and 10-minute) profiles were needed for the VGS study. A new statistical model was developed to generate the sub-hourly PV profiles, while the CSP profiles were interpolated from the hourly actuals generated for the TEPPC study.

The sub-hourly PV model consists of the following general process: SUNY data is used for cloud regime classification → 1-minute irradiance ground observations are used to build ramp distributions for each cloud regime → 1-minute irradiance data are synthesized for each selected grid cell → a filter function is used to represent the spatial smoothing of a 50 MW sized plant → irradiance is converted to power using PVWatts.

The cloud regime was determined by examining the clearness index (defined as the actual global horizontal irradiance divided by the expected clear sky global horizontal irradiance) mean and standard deviation at a particular grid cell over a 3-hour period and surrounding grid cells (Fig. 2). This approach was done to preserve the temporal and spatial correlation of the clearness index across a broad geographical area. Hour 9 in the Fig. 2 is a good example of how the surrounding cloud cover can deviate significantly from the site of interest. An exponential decay function was used to weight the contribution of the surrounding sites to the probability that there would be a cloud event at the site of interest within that hour. This probability distribution was then used to inform which algorithms and distributions to use for the 1-minute data synthesis.

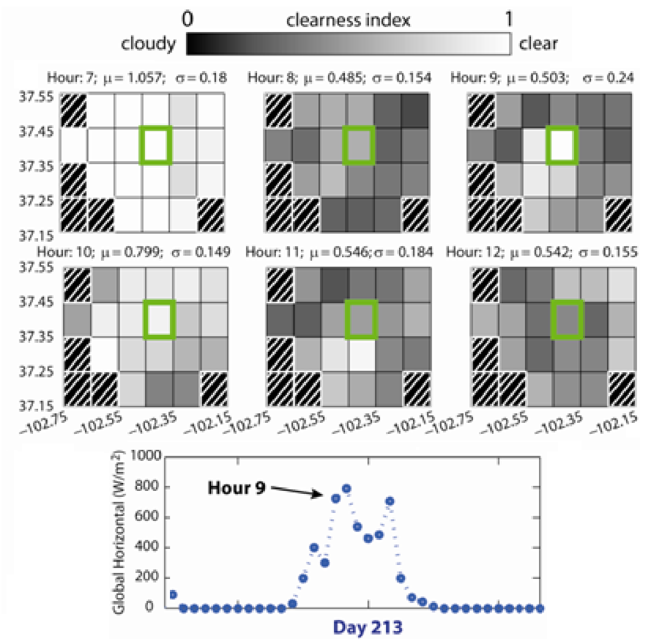



Fig. 2. Clearness index of SUNY data for hours 7-12. The green box is the grid cell of interest with associated mean (μ) and standard deviation (σ) for each hour.

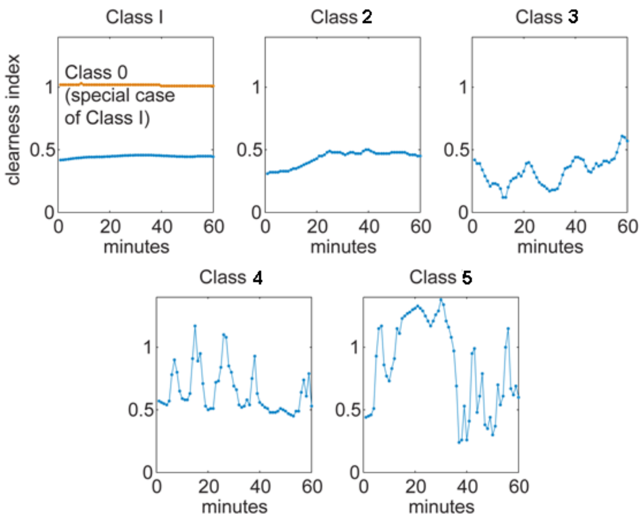
The filter function was derived empirically by analyzing the measured 1-second irradiance from a network of 18 sensors spaced over a 0.75 km$^2$ area on the island of Oahu.

A 50-MW plant would span an area of roughly 1 $km^2$ assuming an array density of 50 $W/m^2$. It was determined that a 3-minute moving average would correspond with an appropriate level of spatial smoothing for a 50-MW PV plant with the aforementioned array density. This filter function was applied to the 1-minute synthesized irradiance, and then the data was converted to power using PVWatts. The 10-minute data was sampled directly from the 1-minute actual.

## C. *WWSIS2*

WWSIS2 is the second phase of WWSIS, and is focusing on the impacts of solar penetrations up to 30% by energy on grid operation and reliability. In this second phase, large-scale PV systems are included, and the solar generation mix is more balanced between CSP and PV.

The method used in WWSIS2 builds upon that developed for the WECC studies. The cloud classification criteria, cloud regime algorithms, and filter function were all improved based on additional analyses and feedback from the WECC studies. The new cloud classification criteria are outlined in Fig. 3.




standard deviation of ci

| mean ci | 0-0.02 | 0.02-0.05 | 0.05-0.1 | 0.1-0.2 | 0.2-0.4 |
|---|---|---|---|---|---|
| 0-0.1 | 1 | 1 | 2 | 3 | 3 |
| 0.1-0.2 | 1 | 1 | 2 | 3 | 5 |
| 0.2-0.3 | 1 | 1 | 2 | 3 | 5 |
| 0.3-0.4 | 1 | 1 | 2 | 3 | 5 |
| 0.4-0.5 | 1 | 2 | 2 | 4 | 5 |
| 0.5-0.6 | 1 | 2 | 2 | 4 | 5 |
| 0.6-0.7 | 1 | 2 | 3 | 4 | 5 |
| 0.7-0.8 | 1 | 2 | 3 | 4 | 5 |
| 0.8-0.9 | 1 | 2 | 3 | 4 | 5 |
| 0.9-1.0 | 0 | 2 | 3 | 5 | 5 |
| 1.0-1.1 | 0 | 0 | 3 | 5 | 5 |
| 1.1-1.2 | 0 | 0 | 3 | 4 | 5 |
| 1.2-1.3 | 0 | 0 | 3 | 4 | 5 |
| 1.3-1.4 | 0 | 0 | 3 | 4 | 5 |
| 1.4-1.5 | 0 | 0 | 3 | 4 | 5 |
| 1.5-1.6 | 0 | 0 | 3 | 4 | 5 |

Fig. 3. Cloud classification criteria used for WWSIS2. Example time histories of each class are also included.

The filter function was adapted from that suggested in Marcos et al. [12], such that:

$$f_c = 0.0204\sqrt{A} \quad (1)$$

where $A$ is the plant area in hectacres, and $f_c$ is the cut off frequency where the spectra will begin to be affected by the spatial smoothing. A bilinear transform was then used to generate a digital filter, which was then applied to the time series data.

## D. *HSIS*

The HSIS is investigating the impacts large penetrations of distributed and centralized PV will have on the Oahu and Maui grids. These systems do not have the advantage of using balancing area cooperation or geographic diversity to manage generation variability, so understanding the extent of the variability is critical to maintaining system reliability.

The data for this study was generated by AWS Truepower using the Mesoscale Atmospheric Simulations System (MASS) model [reference?]. MASS is a 3D, full-physics numerical weather prediction model that simulates and predicts the atmosphere as it evolves over time and space. For this study, it was run at a 1-km, 10-minute resolution in a nested grid over the islands of Oahu and Maui for 2007 and 2008. A model output statistics (MOS) technique is then used to correct any biases to better represent measured data. A power conversion is then applied to obtain the modeled PV production profiles.

# III. Results

The results described here will focus on the WWSIS2 and HSIS, since these studies are still underway, the modeled solar profiles have yet to be documented, and the forecasts are not yet available.

## A. *Ramp Distributions*

One of the most effective ways to evaluate the variability of the solar profiles is to characterize the ramp distributions. To do this, the point-to-point deltas were determined for various time intervals. These intervals include 10, 20, 30, 40, 50, and 60 minutes. Please note that the datasets are not averages, but rather they represent instantaneous snapshots. Therefore, for a 10-minute dataset, the 30-minute deltas are determined by finding the difference between every third data point. The data was normalized to show the relative ramps.

Fig. 4 shows the ramp distributions for a subset of the modeled PV plants on Oahu for HSIS. Additionally, data measured at a large PV plant in the southwest United States is included for comparison. The modeled and observed ramp distributions match very well for shorter ramp intervals, but not as well for longer intervals. This result may be due in part to the shorter period of observed data used (only one month) and therefore the smaller sample size of ramps for longer intervals.

The WWSIS2 data was also examined, and the results were similar to that found for HSIS. Fig. 5 shows an example of the production from a modeled plant located near an existing PV plant.

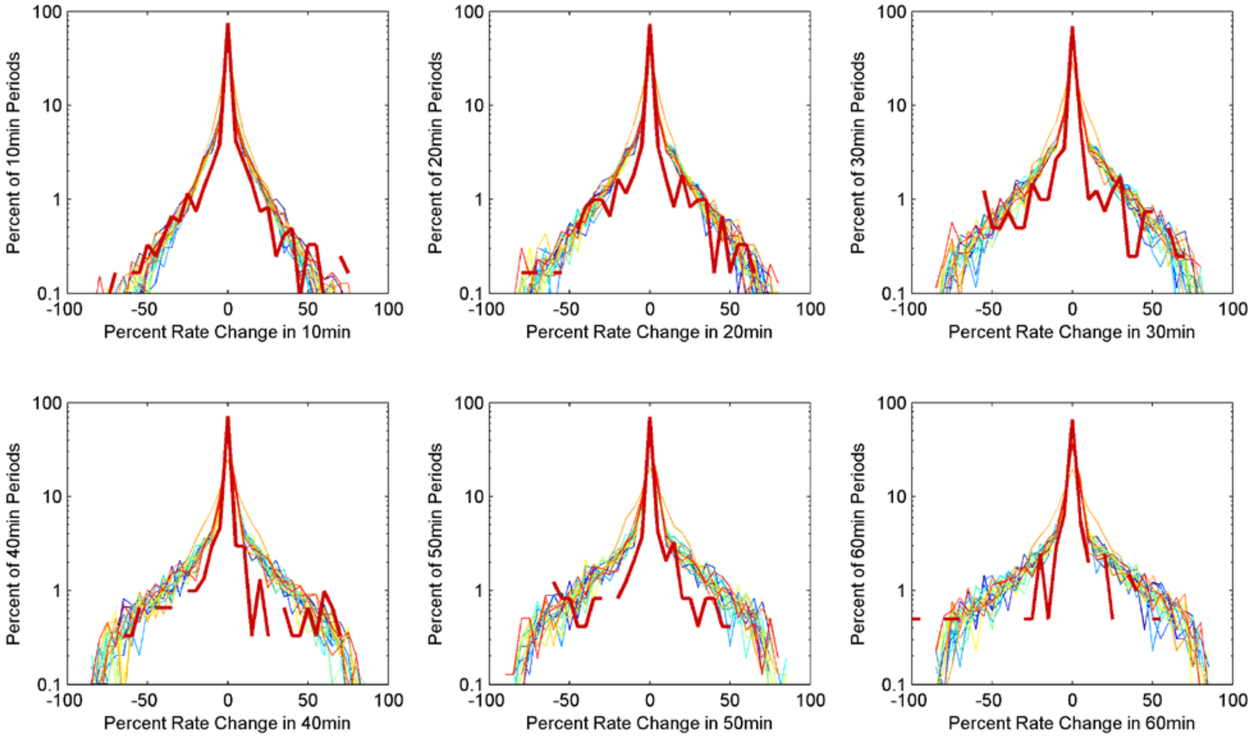



Fig.4. Ramp distributions for 18 modeled PV plants on Oahu (thin lines) and observed power production from a large PV plant (bold line) in the southwestern United States.

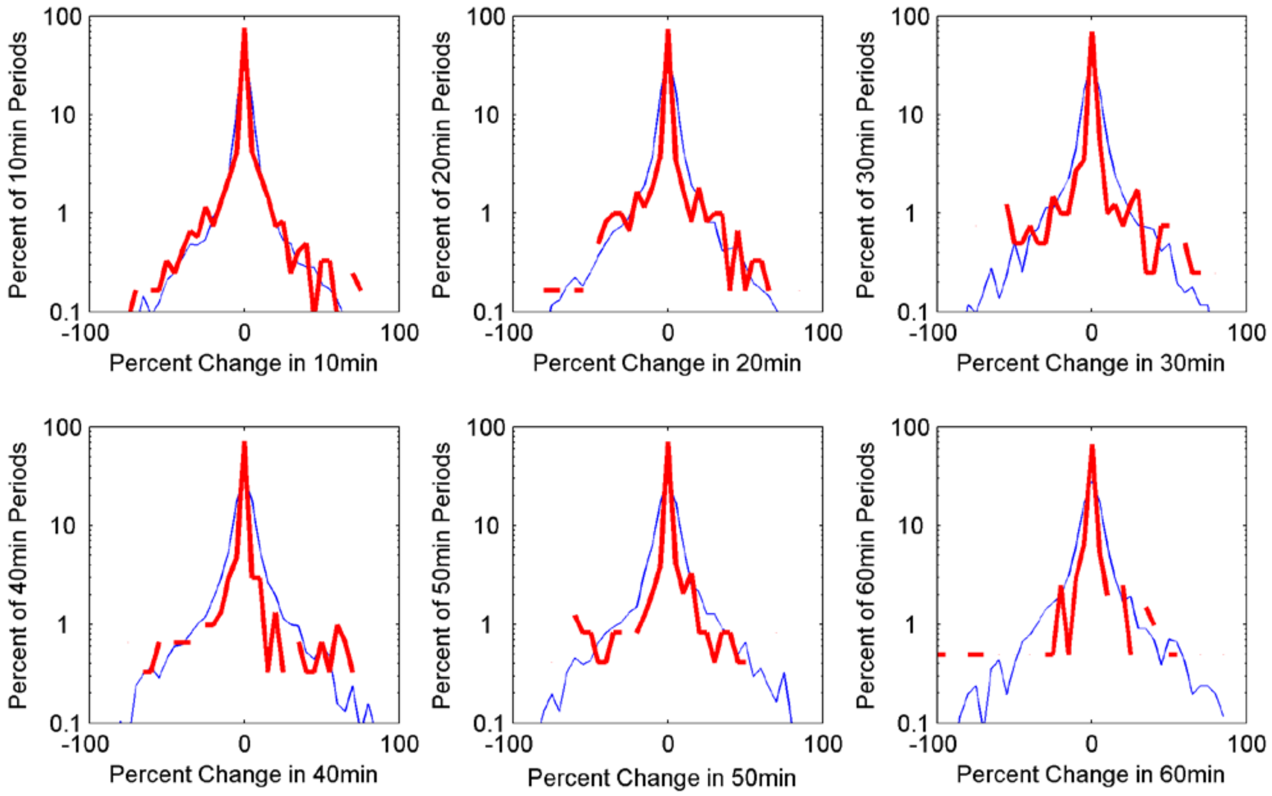



Fig.5. Ramp distributions for a modeled PV plant from WWSIS2 (thin line) that was located near an existing large PV plant (bold line) in the southwestern United States.

## B. Correlations

As clouds or weather systems pass over an area, one or more plants could be affected. Cross correlations between plants provide an indication of the geographic diversity and independence of the plant production, particularly for the coincidence of ramp events. The ramps generated for the analysis in the previous section were also used here for the cross correlations.

The correlation coefficients for 25 randomly selected PV plants from the WWSIS2 dataset reveals little to no correlation between adjacent plants (Fig. 6). Note that 25 plants are much less than a recommended sample size of 291, and are used for clarity in the plot. However, the sample sites selected do represent the characteristics of the total population. The lack of correlation between adjacent plants is especially true for plants >50 km apart. These results compare well with the observations of clearness indices documented by Mills et al. [13], who showed correlation coefficients of <0.2 for measurement sites >100 km apart. There also appears to be little differentiation in correlation coefficient between ramp interval lengths, particularly for distances >400 km.

The 10-min solar actuals generated for HSIS reveal the variability characteristics over a smaller region. Fig. 7 shows the cross correlation coefficients of ramps for a subset of the PV plants modeled on Oahu. Overall, the ramps are somewhat more correlated here regardless of the ramp interval due to the relatively close proximity of the plants, the majority of which are within 15 km of one another. There is also greater differentiation in correlation between ramp intervals, with greater correlations for longer ramps. This differentiation does, however, decrease with increasing distance.

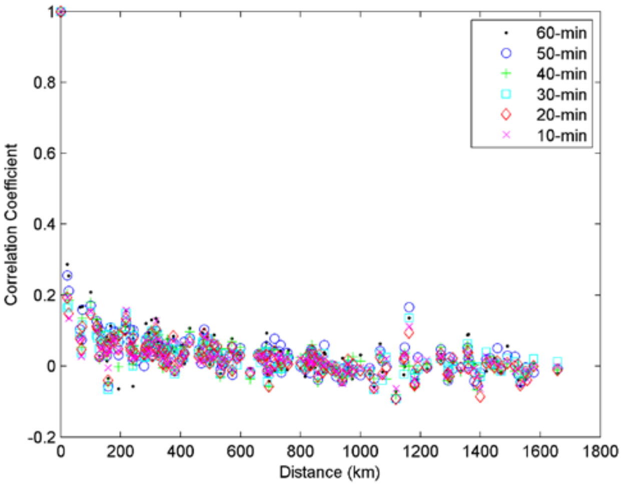



Fig. 6. Cross correlation coefficients for 25 randomly selected modeled PV plants in WWSIS2.

## C. Power Spectral Density

The power spectral density (PSD) provides a mechanism to look at the variability of signal in the frequency domain. The PSD is estimated using Welch's method [14]. The time series is segmented into 8 equal length segments, a Hamming window is applied without overlapping segments, and then the resulting 8 spectra are averaged to obtain an estimated PSD.

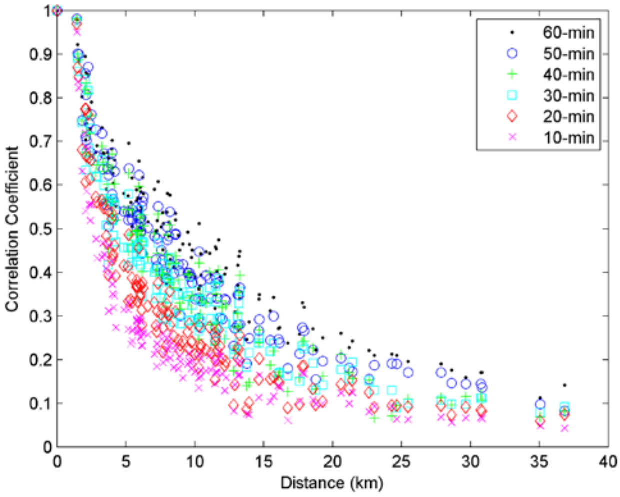



Fig. 7. Cross correlation coefficients for 18 modeled PV plants in HSIS.

Fig. 8 shows the estimated normalized PSDs for one modeled PV plant each from HSIS and WWSIS2, along with that of an existing PV plant. The PSDs are very similar, with spikes at expected diurnal and sub-diurnal periods. Observe that that there is some smoothing of the spectra for frequencies greater than ~$10^{-3}$ Hz. This smoothing is due to the spatial smoothing that occurs from the areal coverage of the plant and resultant reduction in high frequency variability. At lower frequencies, the spectra follow a slope of $f^{-1.5}$, where $f$ is the frequency in (Hz). This slope is similar to the $f^{-1.3}$ observed in Curtright and Apt [15], but is somewhat different than the $f^{-0.7}$ observed by Marcos et al. [12].

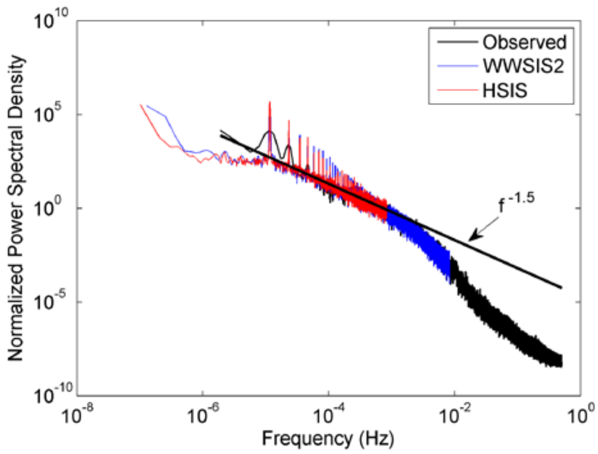



Fig. 8. The normalized PSD of modeled and observed PV plant power production. The sampling rate of the observed data is 1-second, WWSIS2 is 1-minute, and HSIS data is 10-minute.

## IV. Conclusion

Renewable energy integration studies are useful to help inform grid operators about the potential system impacts and benefits of large penetrations of variable energy resources. Accurately modeling the power production is critical to the success of the studies. Two studies in progress, the WWSIS2 and the HSIS, are both evaluating significant penetrations of solar power. There are several methods that can be used to model solar power production, a few of which have been described here, including satellite-derived statistical approaches and numerical weather prediction techniques.

Preliminary results reveal that the ramp distributions of modeled solar data profiles for the WWSIS2 and HSIS studies compare reasonably well with those of measured ramps. Ramp events produced by the HSIS modeled PV plants were much more correlated than the WWSIS2 plants due to the closer proximity of plants in an island setting; therefore, suggesting that grid operators on Oahu and Maui will not be able to take advantage of geographic diversity, as operators in the WECC region have the benefit of doing.

The PSDs of the modeled and observed PV power production were estimated, and they were very similar. The WWSIS2 and observed data exhibited some smoothing (reduction in variability) at higher frequencies, while the HSIS did not due to the 10-minute sampling frequency. The curves also exhibited a slope ($f^{-1.5}$) similar that observed by one study [15], but dissimilar to that of another [12].

Further analysis and validation of these input datasets are planned over the coming months. Additionally, the forecast data will soon become available, and will be examined.

## V. Acknowledgment

The authors gratefully acknowledge the contributions of the United States Department of Energy Solar Program, Dr. Jan Kleissel with the University of California San Diego, and Michael Brower and Jaclyn Frank of AWS Truepower.

## VI. References

[1] Solar Energy Industries Association, GTM Research, “U.S. Solar Market Insight, 2010 Year-In-Review,” Greentech Media, Inc., 2010.

[2] EnerNex, "Xcel Energy and the Minnesota Department of Commerce Wind Integration Study - Final Report," September 28, 2004.

[3] CAISO, "Integration of Renewable Resources: Operational Requirements and Generation Fleet Capability at 20% RPS," August 31, 2010.

[4] GE, "Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements," March 28, 2008.

[5] EnerNex, "Wind Integration Study for Public Service of Colorado Addendum Detailed Analysis of 20% Wind Penetration," December 1, 2008.

[6] E. A. DeMeo, *et al.*, "Accomodating Wind's Natural Behavior," IEEE power and energy magazine, vol. 5, No. 6, Nov/Dec. 2007.

[7] GE, "Western Wind and Solar Integration Study," NREL/SR-550-47434, 2010.

[8] EnerNex, "Eastern Wind Integration and Transmission Study," National Renewable Energy Laboratory, NREL Report No. NREL/SR-5500-47078, February 2011.

[9] D. Lew, K. Orwig, Y. Wan, C. Alonge, M. Brower, J. Frank, L. Freeman, C. Potter, “Wind Data Inputs for Regional Wind Integration Studies,” in *Proc. 2011 Power & Energy Society Annual Meeting.* [Online]. Available: http://www.nrel.gov/docs/fy11osti/50636.pdf

[10] Wilcox, S.; Anderberg, M.; George, R.; Marion, W.; Myers, D.; Renne, D.; Lott, N.; Whitehurst, T.; Beckman, W.; Gueymard, C.; Perez, R.; Stackhouse, P.; Vignola, F. “Completing Production of the Updated National Solar Radiation Database for the United States,” NREL Report No. CP-581-41511, July 2007.

[11] Western Governors’ Association and the U.S. Department of Energy, “Western Renewable Energy Zones Phase 1 Report,” June 2009. [Online]. Available: http://www.westgov.org/component/joomdoc/doc_download/5-western-renewable-energy-zones--phase-1-report

[12] J. Marcos, L. Marroyo, E. Lorenzo, D. Alvira, E. Izco, “From Irradiance to Output Power Fluctuations: The PV Plant as a Low Pass Filter,” *Prog. Photovolt. Res. Appl.*, Vol. 19, No. 5, Aug 2011.

[13] A. Mills, M. Ahlstrom, M. Brower, A. Ellis, R. George, T. Hoff, B. Kroposki, C. Lenox, N. Miller, J. Stein, and Y-H. Wan, “Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System,” Ernest Orlando Lawrence Berkley National Laboratory, LBNL Report No. LBNL-2855E, December 2009.

[14] J.S. Bendat and A.G. Piersol, *Random Data Analysis and Measurement Procedures*, 3rd ed., New York: John Wiley & Sons, 2000, pp. 401-456.

[15] A.E. Curtright and J. Apt, “The Character of Power Output from Utility-Scale Photovoltaic Systems,” *Prog. Photovolt: Res. Appl.*, Vol. 16, No. 3, Sept 2008.

## VII. Biographies

**Kirsten Orwig** graduated with a Ph.D. in Wind Science and Engineering and an M.S. in Atmospheric Science from Texas Tech University. Her B.S. is in Chemistry and Physical Science from Wayland Baptist University. She is a Systems Integration Analyst and Project Leader for the Transmission Grid Integration Group at the National Renewable Energy Laboratory. She has ten years of experience analyzing measured and modeled atmospheric data using traditional and non-traditional statistical methods. She is also heavily involved the solar power profile development and validation for the HSIS study.

**Marissa Hummon** received the B.A. degree in physics from Colorado College, Colorado Springs, CO and the Ph.D. degree from the Harvard University, Cambridge, MA in applied physics. She joined the NREL Strategic Energy Analysis Center to work on energy forecasting models. Her work focuses on spatial statistical analysis of multi-point time-series data including irradiance, PV power plant production, and advanced grid measurements (smart grid components). She also developed the solar power production model used for the WECC and WWSIS2 studies. Her fields of interest include large-scale grid modeling, sub-hourly variable renewable modeling, and applied mathematics.

**Bri-Mathias Hodge** received the B.S. degree in chemical engineering from Carnegie Mellon University. He received a M.S. from Åbo Akademi, and completed the Ph.D. in chemical engineering at Purdue University. He is currently a research engineer in the Transmission and Grid Integration Group at NREL. His research interests include energy systems modeling, simulation and optimization.

**Debra Lew** graduated with a M.S. and Ph.D. in Applied Physics from Stanford University, California, US, and with B.S. degrees in Physics and Electrical Engineering from the Massachusetts Institute of Technology. She presently works as a Senior Engineer in the Transmission and Grid Integration Group at the National Renewable Energy Laboratory (NREL). She leads the Western Wind and Solar Integration Study and works generally in grid integration and transmission for wind and solar power.