COMPARISON OF SOLAR IRRADIANCE SMOOTHING USING A 45-SENSOR NETWORK AND THE WAVELET VARIABILITY MODEL

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ABSTRACT

With increasing penetrations of solar photovoltaic (PV) power in the electricity grid, the variability of the irradiance, and therefore power, is important to understand because variable resources can challenge grid operations. Predicting PV variability using one irradiance sensor, as is commonly done, does not account for the smoothing of irradiance over the extent of the power plant. This smoothing is examined using two methods: averaging measurements from many irradiance sensors, and using a model developed by Lave, Kleissl, and Stein [1] called the Wavelet Variability Model. The results show the similarities and differences between two irradiance smoothing models. These two models both show that the smoothing effect is significant for large PV power plants, which means the power plant output has less variability and is easier to integrate into the electricity grid than might have been expected using a single point sensor measurement to predict variability.

1.0 INTRODUCTION

Solar PV power plants are variable generation sources because of the entirely predictable motion of the sun through the sky, which causes increasing power in the morning hours and decreasing in the afternoon. A second source of variability is the less predictable, shorter timescale effects of clouds. The less predictable component of variability is of interest to grid operators and is the focus of this work. Cloud motion over a single irradiance sensor can show large changes in irradiance on a second-to-second basis. If this represented the variability of a large PV power plant, and if many of such generators existed on the grid, it would negatively affect the stability of the grid. In reality, though, as clouds move over a PV plant, each PV module is impacted at a different time, depending on the location of the module and cloud characteristics. This is referred to as spatial smoothing and it results in less variability of the true power plant output than of the single point irradiance measurement. The irradiance averaged over the area of the power plant footprint will have smaller fluctuations than the irradiance point sensor. Since power is approximately proportional to aggregate irradiance [2], the plant's power fluctuations are expected to be proportional to the smaller, spatially smoothed fluctuations, not the fluctuations from a single point sensor. The goal of this project was to determine what the spatial smoothing is over the area of large PV power plants.

This work utilizes data from a network of 45 solar irradiance sensors which was deployed north of Flagstaff, Arizona as part of a Wind and Solar Variability Study completed by Northern Arizona University, NextEra Energy Resources, and WindLogics. The 45 LI-COR brand irradiance sensors were deployed over a one-square mile grid. Figure 1 shows the sensor layout. The sensors are on a 590 ft grid in the center part of the network and on a grid of up to 1,770 ft in the less dense outer parts of the network. Using this network of sensors, two different size power plants are considered in this study. A transmission scale power plant, which would be connected at the high-voltage, transmission level of the electricity grid, is a 30 MW plant represented using the inner 25 stations. A distribution scale power plant, connected at the lower-voltage, distribution feeder level of the electricity grid, is a 10 MW plant represented by using the inner nine stations. The plant footprints were selected using a density of 0.125 MW PV capacity per acre (i.e. 8 acres per MW). Figure 1 shows the plant footprints. Using irradiance measurements from this sensor network, the spatially smoothed irradiance was modeled with the Wavelet Variability Model (WVM) as well as a simple average of the point-measured irradiances.

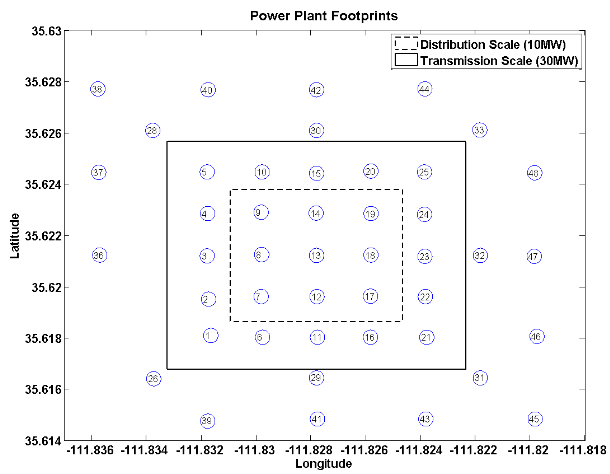


Fig. 1: The 45 irradiance sensors used in the study were located over a one square mile grid. Two power plant sizes within that grid were examined in detail for this study.

2.0 METHODS

This section describes the two methods which were used to estimate smoothed irradiance, the metrics chosen to quantify variability, and the selection of representative time periods for the analysis.

2.1 Smoothing Methods

The irradiance determined from a single point sensor, the WVM, and an aggregate irradiance from the network of sensors are compared for both a distribution scale and transmission scale power plant.

The WVM developed by Lave, et al. uses a wavelet transform to quantify the smoothing effect over a PV power plant or distributed network of small PV systems. A wavelet transform is a method of transforming a signal into sub-signals which are fit to a chosen waveform at different timescales. The WVM uses a single irradiance sensor, a correlation scaling coefficient, and the size of the power plant to model the smoothed irradiance over the area of a power plant. The correlation scaling coefficient, which depends on the site location and the weather conditions, is calculated for each day using data from the 45-sensor network. This correlation scaling coefficient (‘A value’) determines the extent of the spatial smoothing effect. It represents how well correlated the irradiance changes are between stations, and has also been shown to be proportional to cloud speed [3]. The WVM was chosen for this work because it has been shown to accurately predict spatial smoothing [4] and because of its potential for modeling smoothed irradiance using only one single irradiance measurement (although 45 irradiance measurements are used in this project, if cloud speeds are available, they could supplant the need for anything more than one irradiance measurement in future studies.)

The aggregated irradiance was determined from a simple average of the sensor irradiance. For a 10 MW plant, this was a simple average of the 1-second data from the nine inner stations. For the 30 MW plant, this was a simple average from the 25 inner stations. These sensor layouts are shown in Figure 1.

2.2 Variability Metrics

In order to compare the variabilities, the raw irradiance, Variability Index, and ramps detected in the irradiance signals are compared.

The Variability Index (VI) is an irradiance variability metric developed by Stein, Hansen, and Reno [5] that was used in this study to categorize the daily variability conditions as well as to compare the variability of single station irradiance to that of spatially smoothed irradiance. The VI is the ratio of length of the measured irradiance line (plotted in W/m^2 vs time) divided by the length of the clear sky irradiance line, where the clear sky irradiance is the modeled irradiance on a cloudless day determined from a clear sky model. Thus, a VI of one indicates a perfectly clear day, while a high VI (for example 25) indicates that many rapid fluctuations in irradiance exist. For the purpose of this work, the daily VI was determined based on one-minute averaged irradiance.

Grid operators and system planners are interested in the ramps that the system must respond to in order to maintain balance of frequency and/or voltage. In a solar PV variability study such as this one, it is of interest to identify the irradiance ramps and provide some quantification of their size and frequency of occurrence. These irradiance ramps are then useful in understanding the possible power ramps of a PV plant and they are another way of looking at the variability of the resource. The specific metrics of interest are the ramp magnitude (size in W/m^2 of the change in the irradiance), the ramp duration (the length of time required for the change to occur), and the ramp rate (the rate of change of the increase or decrease in power in $\frac{W}{m^2 time}$).

Since there is no single definition of a ramp event, variable generation studies use different ramp definitions. For the purpose of this work, a ramp detection algorithm is implemented using the deadband method which detects ramps of different durations per Willy [6] and Flood et al. [7]. The sensitivity of the algorithm is set by choosing a deadband size, which will determine the size of the event that is considered a ramp. The deadband was chosen as 25 W/m^2 for this work.

2.3 Selection of Representative Periods

Four periods were selected which represent the variety of variability conditions which can occur throughout the year at this location. The Very Low Variability category was a clear seven day period during the summer with an average daily VI of 1.2. The Low Variability category was a fall period with an average daily one-minute VI value of 8.17. The Medium Variability category was a spring period (VI 11.8), and the High Variability category is a monsoon-like period (VI 15.4). The 28 individual days included a range of different daily VI values as well as A values, as shown in Figure 2. The days with highest variability, which are of most concern from a grid interconnection and integration point of view, can have a range of A values from low to high. This indicates that the smoothing of the high variability on those days could range from strong to weak.

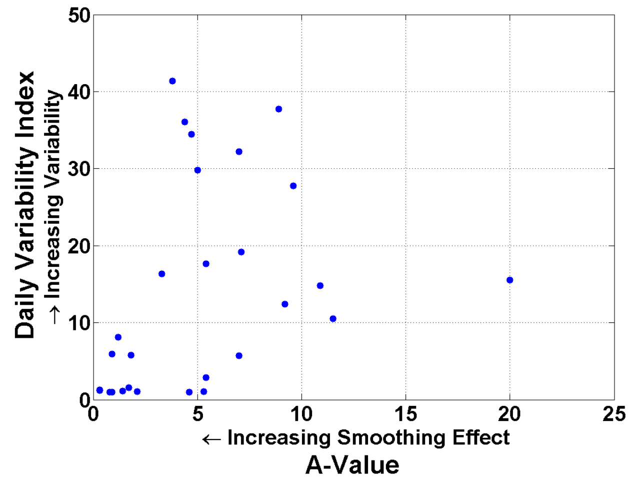


Fig. 2: The 28 days selected for detailed analysis had a range of different daily VI values as well as A values.

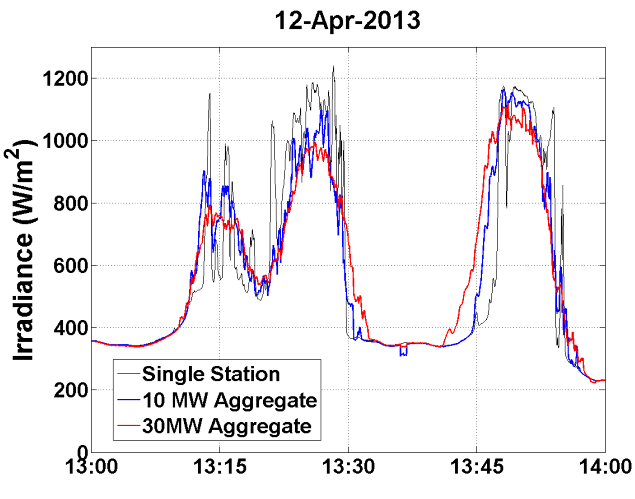
3.0 RESULTS

The spatially smoothed irradiances estimated are compared in three ways; first by simply examining the irradiance signals, then by considering how much the daily VI changes due to smoothing, and finally by analyzing the irradiance ramp events detected.

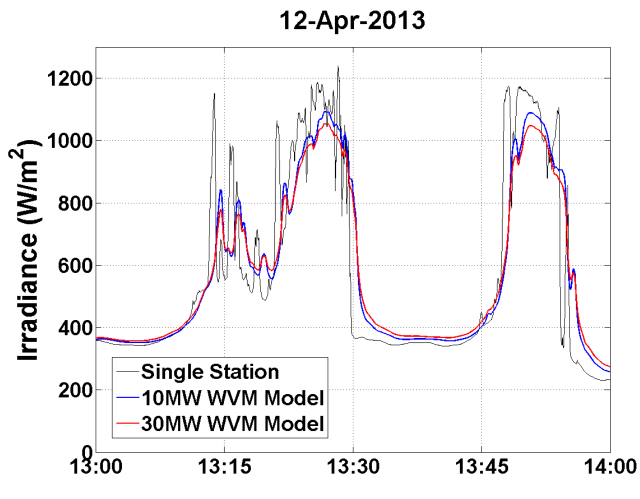
3.1 Irradiance results

The irradiance results are provided here for two example days in the Medium Variability period during April 2013. April 12th has a VI of 12.7, and an A value of 3.3. The raw irradiance is compared to smoothed irradiance modeled by the aggregate in Figure 3a for one hour of this day. The raw irradiance is compared to WVM smoothed irradiance in Figure 3b. Whether using the aggregate model or WVM, the 30 MW power plant appears more smooth than the 10 MW plant due to plant size. Using the WVM model, however, appears to provide more smoothing than the aggregate model. This 'appearance' of smoother irradiance is later confirmed by using ramp analysis to quantify variability.

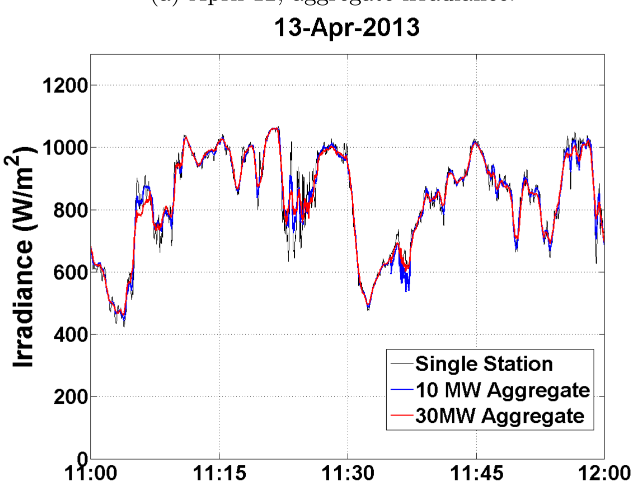
Another example day is considered on April 13, which has similar variability to April 12 (VI=12.7 for the 12th and VI=11.4 for the 13th). Although the two days have similiar variability, the 13th has much less smoothing based on the higher A value (A=20 compared to 3.3 for April 12). Figures 3c and 3d can be compared directly to Figures 3a and 3b to see that the smoothing is much less significant on April 13th than on April 12th. The smoothed irradiance from the aggregate model and WVM model appear similar on April 13th, and both are similar to the single station irradiance when considering the irradiance over a one hour period.



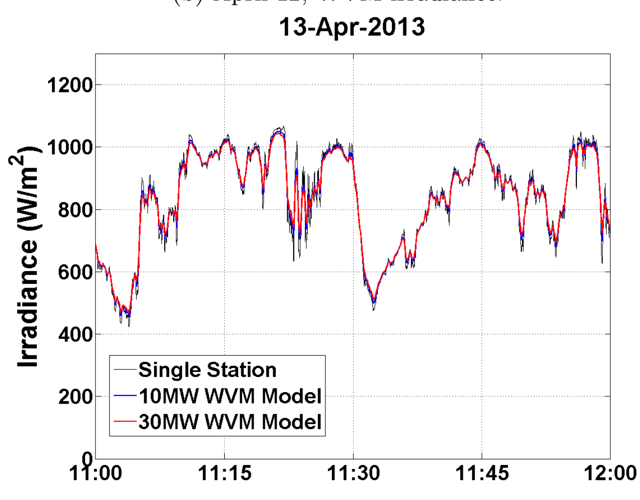
(a) April 12, aggregate irradiance.



(b) April 12, WVM irradiance.



(c) April 13, aggregate irradiance.



(d) April 13, WVM irradiance.

Fig. 3: Irradiance results for two days with similar variability but different correlation scaling coefficients. Smoothed irradiance over one hour on April 12, 2013 (VI=12.7, A=3.3) and April 13, 2013 (VI=11.4, A=20.0). Smoothed irradiance over one hour for April 12, 2013, is very different on a sub-hour timescale between the aggregate model and WVM. Smoothed irradiance over one hour using WVM and aggregate model for April 13, 2013 appears to be the same regardless of the model used or the size of the power plant on a sub-hourly timescale because the day has a high A value (20.0).

3.2 VI results

The change in daily VI from the single point sensor to the smoothed irradiance is one way to quantify the smoothing effect. Table 1 shows what the average of the weekly VI values are for each period and smoothing model. During the low variability period, the smoothing effect is not significant. During the other periods, the WVM typically, but not always, has a lower average VI than the aggregate model, indicating a stronger smoothing effect. Considering each of the 28 days individually allows for some observations of the difference between the two models. Figure 4 shows how the A value dictates the extent of smoothing - days with high A values exhibiting only a 10% decrease in VI while days with low A value exhibit up to a 60% decrease in VI. Figure 4 also shows how the two models compare. Generally the WVM has a greater smoothing effect. Note that Figure 4 does not include days with a single station VI of less than five, as these are mostly clear days where the variability and smoothing are not of much concern.

TABLE 1: The average VI over the week-long periods was reduced compared to the single station VI using either smoothing model, except for the very low variability period.

Variability Period	Single Station	10MW Agg	30MW Agg	10MW WVM	30MW WVM
Very Low	1.1	1.1	1.2	1.0	1.0
Low	11.9	10.3	9.0	9.1	8.1
Medium	16.8	15.2	13.0	12.7	11.2
High	25.2	21.2	17.6	20.2	17.8

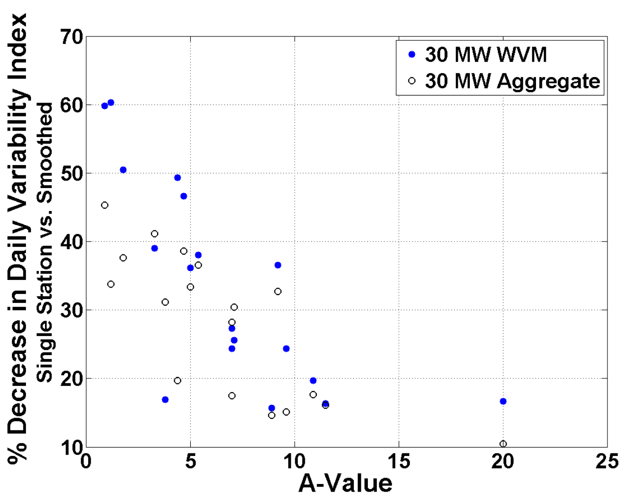


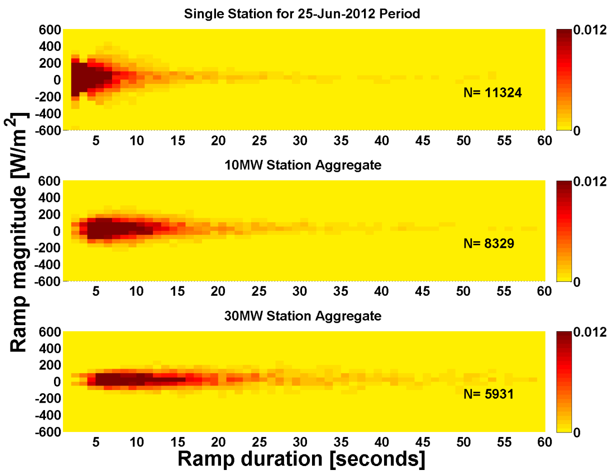
Fig. 4: The percent decrease in VI between the single point sensor irradiance and smoothed irradiance is up to 60% for low A values but decreases to 10% for high A values. The WVM smoothed irradiance generally has a higher percent decrease in VI than the aggregate model. Days with VI of less than five for the single station irradiance are not included.

3.3 Irradiance ramp results

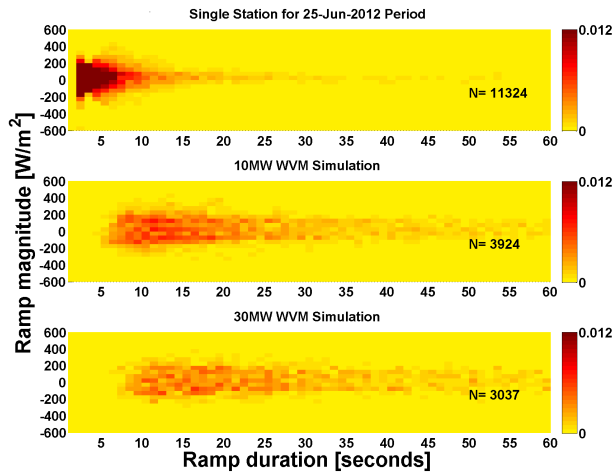
The distribution of irradiance ramps detected varied significantly from single station irradiance to aggregated irradiance to WVM smoothed irradiance. Figure 5a shows the irradiance ramps detected during the High Variability periods using a single station and the aggregate model. The number of ramps detected in any one week is indicated on the heatmaps by 'N'. The aggregate models show that, as expected, the distribution of irradiance ramps changes, having fewer, short (less than five second) ramps when the irradiance is smoothed using a 10 MW aggregate or 30 MW aggregate model. In addition the number of ramps (N) detected during the seven day period decreases. Figure 5b shows a different distribution of ramps when the irradiance is instead smoothed using the WVM. The irradiance ramps less than five seconds in duration are not only fewer, they are essentially eliminated. The number of ramps detected is significantly fewer (3,037 for 30MW WVM model versus 5,931 for 30MW aggregate model). The ramp distribution predicted by the WVM are 'spread out' such that ramps are no longer concentrated as they are in aggregate model, but are spread over a larger range of ramp magnitudes.

While the Medium and Low Variability periods (not shown here) had similar results as the High Variability period, the Very Low Variability period provided different results. Figure 6a and 6b show the aggregate and WVM ramp distributions for the Very Low Variability period. The aggregation smoothing curiously shows more ramps for the 10 MW and 30 MW plant sizes than for the single station. This was examined in more detail and it was found that the additional ramps are due to single stations seeing a short drop in irradiance during a clear period. Although it is possible that a single station could see a drop in irradiance due to a very small cloud which is only measured at one station, some examination of the data showed that it was often due to intermittent data logger operation. These effects are seen more often when more than one station is used because there is a higher likelihood that one of the dataloggers will malfunction. The WVM model only uses one station as a direct irradiance input, so the effects are less likely. The increase in ramps in the aggregated models over the single point sensor model is a case for the WVM model because the WVM model is less subject to these singularities.

The WVM's predication of a 'spread out' distribution which includes some larger magnitude ramps is also evident when considering the most extreme ramp events. The extreme values of the ramps are of interest and are examined by considering 97.5/2.5th percentiles of ramp magnitudes by ramp duration bins, corresponding to the ramp magnitudes that fall within two standard deviations of the mean for normally distributed ramp magnitudes. Figure 7a shows the extreme (97.5th/2.5th percentile) ramps for the single station and the aggregate models. These aggregate models predict extreme ramps for ramp durations of up to ten seconds of about 50 W/m^2 for the 30 MW aggregated model. Figure 7b shows that the WVM, in contrast, predicts no ramps ramps at all below four seconds, but predicts extreme ramp values of up to 200 W/m^2 for ramps about 10 seconds long for the 30 MW models. In summary, the WVM eliminates ramps of under a few seconds and predicts

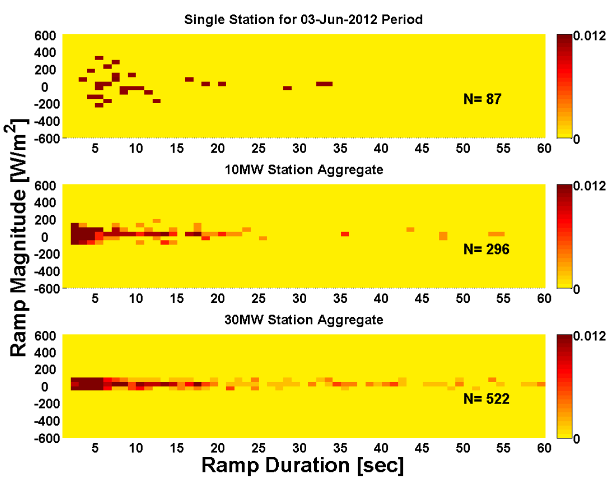


(a) Aggregate, High Variability Week

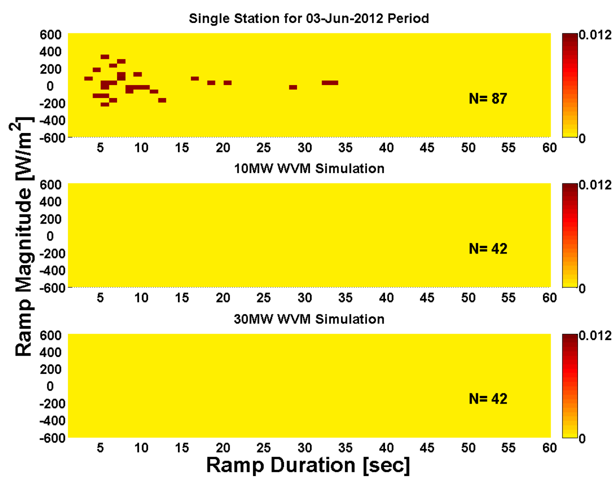


(b) WVM, High Variability Week

Fig. 5: Irradiance ramps distributions for the aggregate model and WVM in the high variability week show the smoothing of irradiance results in fewer ramps over the one week period. The aggregate model and WVM result in different distributions of ramps, with the WVM having fewer ramps, and longer duration ramps.



(a) Aggregate, Very Low Variability Week



(b) WVM, Very Low Variability Week

Fig. 6: Irradiance ramp distributions for the Very Low Variability period shows that the aggregate model has an 'anti-smoothing' effect.

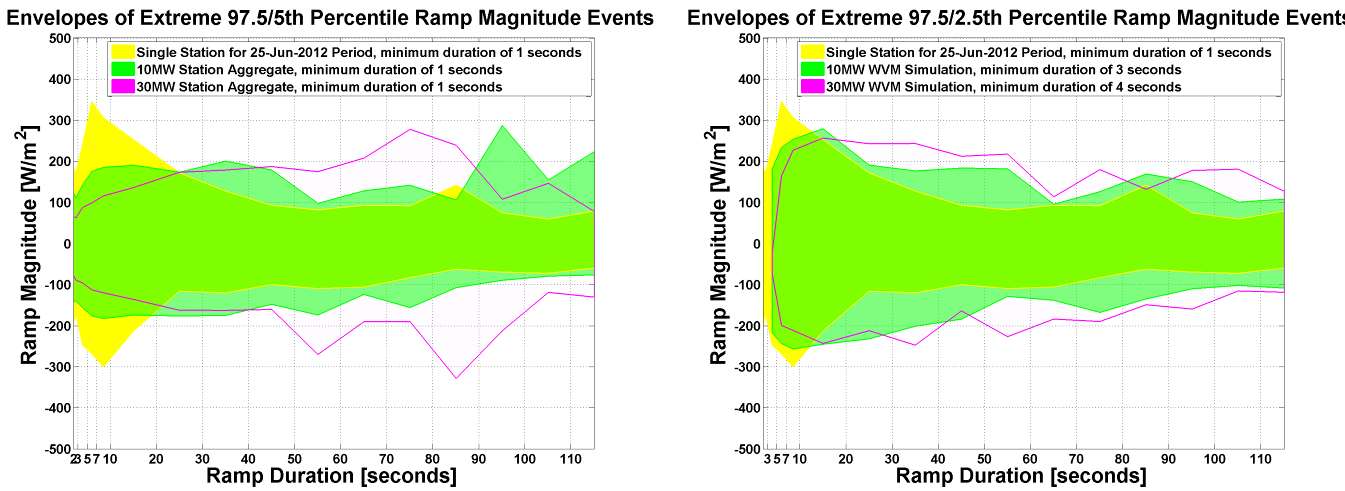
fewer, but larger ramps of longer durations. Notably the duration transition from no ramps at all to higher ramps is about five seconds in this case, but will be a higher or lower duration depending on the size of the power plant as well as the correlation scaling coefficient A.

Summary statistics of the ramps detected in the high variability period are provided in Table 2.

4.0 CONCLUSION

This project used the Wavelet Variability Model and a simple average of point-measured irradiance to predict the spatial smoothing of irradiance over the area of large-scale PV power plants. The two models predicted smoothing differently, with the WVM in general predicting more smoothing (lower smoothed VI values, fewer ramp events).

For a transmission scale power plant (30MW was the selected size here) the WVM model decreased the aver-



(a) Aggregate, High Variability Week

(b) WVM, High Variability Week

Fig. 7: The 97.5/2.5th percentile extreme ramp magnitudes by duration show the smoothing effect: extreme ramp magnitudes for the 0-10 second durations are reduced from the single sensor irradiance to the aggregated irradiance. For the WVM, the extreme ramp magnitudes can be larger than those predicted by the aggregate model at some durations. However, the WVM eliminates ramps of under about four seconds during this High Variability period.

TABLE 2: A statistical summary of the ramps detected during the high variability period shows how smoothing results in fewer ramps, and longer duration ramps with either the aggregate or WVM, but that the smoothing effect is stronger with the WVM.

	Number of Ramps		Standard Deviation of Absolute Value	Mean of Absolute Value	Minimum	Maximum	95th Percentile of Absolute Values
Single Station	11,324	Duration [sec]	188.5	25.8	1	8,155	70
		Magnitude [W/m^2]	80.3	94.6	(1,154)	1,139	237
		Ramp Rate [W/m^2 per sec.]	62.2	44.1	(1,154)	1,139	156
10 MW Agg	8,329	Duration	234.7	35.1	1	15,289	97
		Magnitude	52.6	64.8	(417)	441	169
		Ramp Rate	13.8	10.7	(156)	166	36
30 MW Agg	5,931	Duration	271.9	49.3	1	15,280	153
		Magnitude	46.0	53.6	(506)	315	140
		Ramp Rate	6.2	4.9	(55)	75	16
10 MW WVM	3,924	Duration	330.8	74.5	3	11,372	236
		Magnitude	69.9	93.5	(452)	414	235
		Ramp Rate	8.2	6.8	(56)	49	24
30 MW WVM	3,037	Duration	375.8	96.3	4	11,353	307
		Magnitude	67.2	92.0	(386)	373	224
		Ramp Rate	5.5	4.6	(34)	30	17

age daily VI over the highly variable period from 25.2 to 17.8, and the aggregate model resulted in an average VI of 17.6. The irradiance ramps detected over this period decreased from 11,324 ramps with a single point sensor to 3,037 ramps with the WVM and 5,931 with the aggregate model. For the 30 MW plant, for this High Variability period, while the single point sensor irradiance detected many one second ramps, the 30MW WVM simulation had no ramps shorter than four seconds. The mean ramp duration was 26 seconds for a single sensor, 96 seconds for the 30 MW WVM model, and 50 seconds for the 30MW aggregate model. The ramp distributions of the 10 MW models were generally consistent with the 30 MW models but showing less smoothing as expected over the smaller area. These smoothing effects mean the power plant output would have less variability and would be easier to integrate into the electricity grid than would have been expected using a single point sensor measurement to predict variability. Although validation against actual power plant output was not possible at this site, the WVM's prediction of fewer, longer ramps would be more favorable from a grid integration perspective and so is a promising result.

The WVM uses the correlation scaling coefficient (A) to model the smoothing of irradiance over the power plant. The magnitude of the A value indicates the extent of the smoothing. For the 28 days examined in detail in this study, it was found that for clear days (daily one-minute VI approximately one), the smoothing over the area of the plant for either a transmission scale or distribution scale plant is negligible due to the negligible variations in the irradiance on a clear day. However for more variable days, the A value dictates the smoothing extent. Using the percent decrease in daily one-minute VI as a measure of the smoothing, it was found that for low A values (less correlated stations/lower cloud speeds), the smoothing results in an up to to 60% decrease in VI. For days with higher A values (more correlated stations), the smoothing would only result in a 10 to 20% decrease in VI. Although this result is not surprising, it is important to understand the effect that A value has if the model is adopted for solar variability studies which cover longer periods of time. It is key to understand that high variability days, which are of most concern to system planners, could be characterized by either high A values (little smoothing will occur) or low A values (smoothing will be significant), or anything in between.

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