THE VARIABILITY INDEX: A NEW AND NOVEL METRIC FOR QUANTIFYING IRRADIANCE AND PV OUTPUT VARIABILITY

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ABSTRACT

Variability of photovoltaic (PV) power output is a potential concern to utilities because it can lead to voltage changes on the distribution system and have other adverse impacts on power quality unless additional equipment is added or operational practices are changed to mitigate these effects. This paper develops and evaluates a simple yet novel approach for quantifying irradiance variability over various timescales. The approach involves comparison between measured irradiance and a reference, clear sky irradiance, determined from a model. Conceptually, the "Variability Index" is the ratio of the "length" of the measured irradiance plotted against time divided by the "length" of the reference clear sky irradiance signal. Adjustments are proposed that correct for different measurement intervals. By evaluating the variability index at several sites, we show how annual and monthly distributions of this metric can help to classify sites and periods of time when variability is significant.

1. INTRODUCTION

Variability in irradiance over time at a site has important implications for power generation from solar PV plants. Because PV output is highly correlated with the spatial average irradiance over the PV array, irradiance variability characteristics will be directly applicable to PV output variability, if plant size is taken into account.

Irradiance changes cause the power output levels from PV plants to fluctuate, which can have negative implications for management of the electrical grid. Unfortunately there is no single agreed upon method to measure and characterize variability for PV plants and compare variability between different sites and climates. This paper proposes a metric for quantifying irradiance variability over various timescales. It is useful for comparing between different sites and between different periods of time at the same site. We show how annual and monthly distributions of this metric can help to classify sites and periods of time when variability is significant. It is also shown that the proposed variability index is well correlated with the magnitude of irradiance changes, which makes it an especially valuable metric for selecting data for grid integration studies.

Specifically, a good metric for measuring variability will help to (1) classify days or other time periods in which variability effects can be compared, (2) classify sites in terms of the timing, frequency and magnitude of variability, and (3) provide a metric that can be forecasted in the future (e.g., day ahead) to enable utility planners to ensure generation resources are available to balance out variability on the grid.

2. VARIABILITY INDEX

We propose a simple measure of irradiance variability over a period of time, which we call the Variability Index, denoted by VI. For an interval of time, VI is calculated as:

$$VI = \frac{\sum_{k=2}^{n} \sqrt{(GHI_k - GHI_{k-1})^2 + \Delta t^2}}{\sum_{k=2}^{n} \sqrt{(CSI_k - CSI_{k-1})^2 + \Delta t^2}} \qquad (1)$$

where *GHI* is a vector of length *n* of global horizontal irradiance values averaged at some time interval in minutes, Δt, *CSI* is a vector of calculated clear sky irradiance (horizontal) values for the same times as the *GHI* data. We used the clear sky model developed by Ineichen and Perez [1]. A clear sky model should correctly account for the diurnal shape of the irradiance, changing both the length of daylight hours and the magnitude for each day of the year.

Conceptually, variability index can be thought of as the ratio of the "length" of the measured irradiance plotted against time divided by the "length" of the clear sky irradiance plotted against time. For a clear day, assuming the clear sky model is a perfect match to measurements, VI would be equal to 1, since the sum of the absolute values of the irradiance changes would equal the same sum of the clear sky irradiance changes. In reality, clear sky models have uncertainty and radiation measurements experience some amount of natural and random variability or noise, all of which cause clear-sky days to have VI values near 1. Extreme overcast or rainy conditions will also have low VI values. Both of these types of conditions are characterized by low variability.

Lenox and Nelson [2] proposed a related metric they termed the "Inter-Hour Variability Score." This metric represents the summation of the absolute values of 1-min changes in both plane of array (POA) irradiance and AC output power. They presented scores calculated for each hour of the day for a number of sites and demonstrated that this metric correlates quite well with measured ramp rates. The metric presented in this paper differs in that we divide each sum by a reference sum calculated for clear sky conditions. We also use global horizontal irradiance instead of POA irradiance or AC power output. And we present our accounting at the daily level rather than hourly. But there is nothing stopping us from defining our metric for hourly periods or comparing to a clear sky model of power output, however the latter would involve a more detailed analysis and specific input data.

Low VI values can result either from clear days or from highly overcast days with low irradiance all day. However, high values for VI can only occur on days with highly variable irradiance. Figure 1 shows an example of 1-min averaged irradiance for a typical day in Lanai, HI. The variability index for this day is 14.3. Figures 2a and 2b show selected irradiance days from Lanai, HI and Las Vegas, NV that yield a range of daily VI values with the clear sky irradiance shown in red for reference.

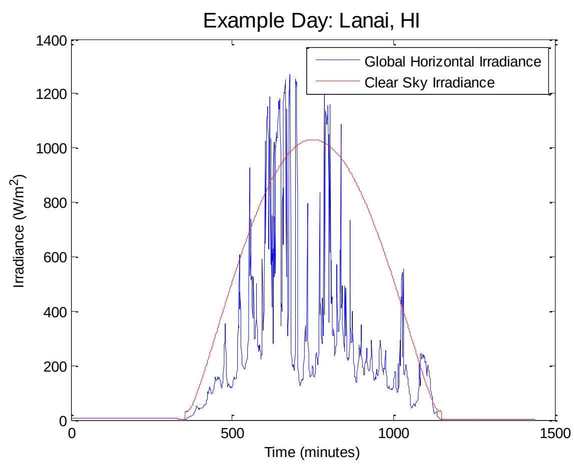

Fig. 1: Example of irradiance measured in Lanai, HI for a day with a relatively high VI (14.3).

Figures 3-5 illustrate some of the differences in the daily VI values between these sites. In each of these figures, the top plot is a histogram of daily VI values for a single year. The bottom plot is the average daily VI for each month of the year. For Lanai (Figure 3) it is evident that most days have relatively high VI values, with only a few days with very low values. The bottom plot of Figure 3 indicates that variability is high throughout the year with slight drops in February and October. In contrast, Las Vegas (Figure 4) has most of its days with very low VI values, indicative of many clear days. Even the days with the highest VI are less variable than in Lanai. In addition, it appears that for the year studied, June and January experienced the lowest amount of variability. Oak Ridge National Laboratory (ORNL), TN (Figure 5) exhibits days with the highest variability compared with the other two sites and has a clear pattern of high variability in the summer and lower variability in the winter.

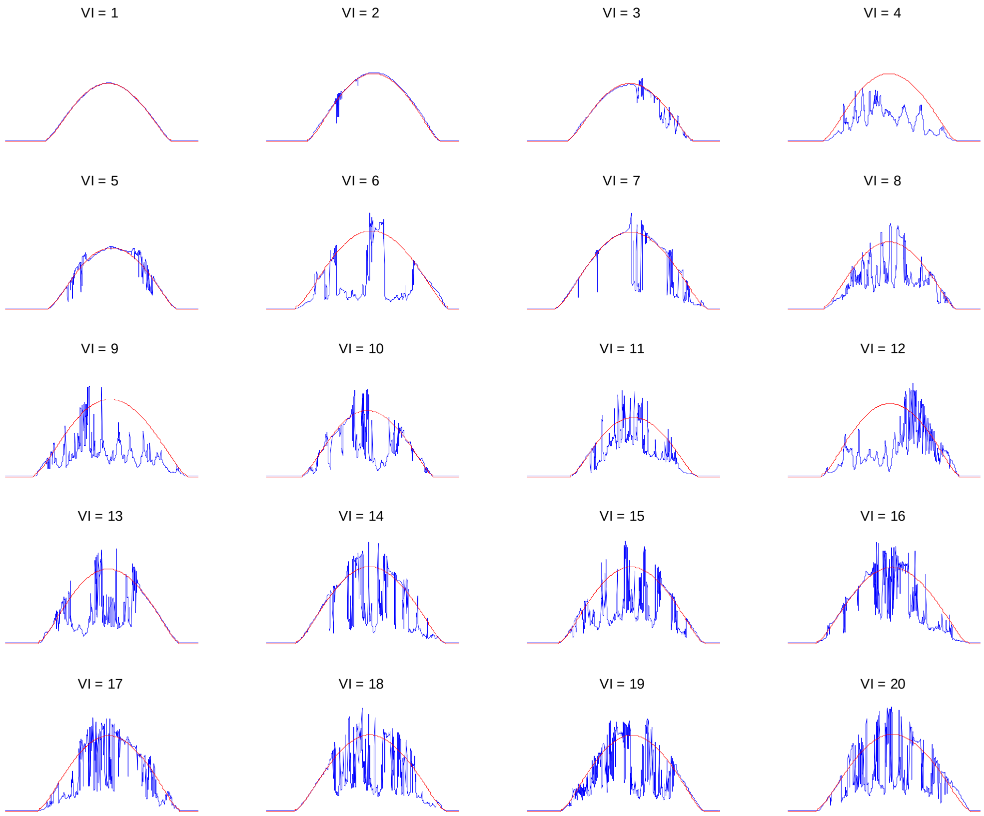

Fig. 2a: Example of days with increasing VI values from Lanai, HI showing how apparent variability increases with VI. Clear sky irradiance is shown in red.

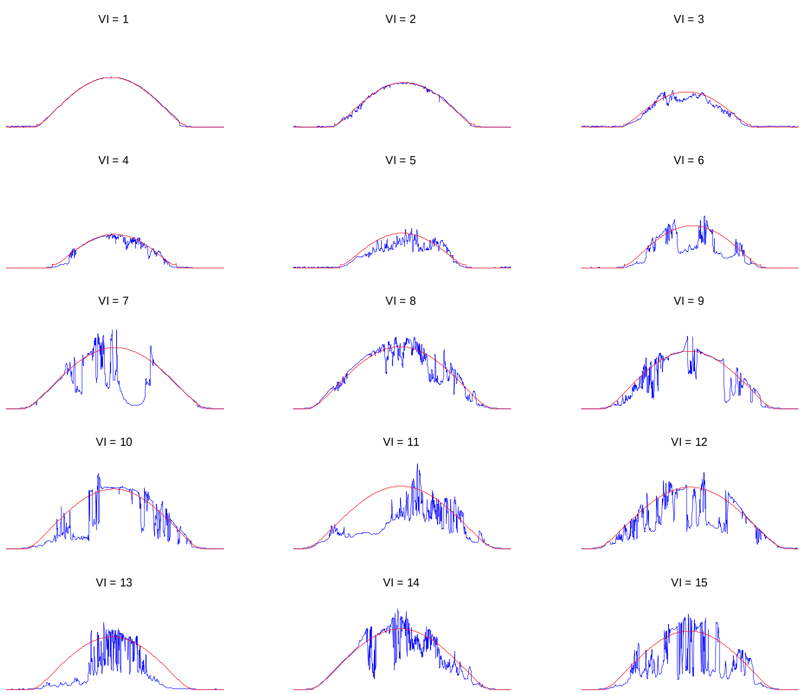

Fig. 2b: Example of days with increasing VI values from Las Vegas, NV showing how apparent variability increase with VI. Clear sky irradiance is shown in red.

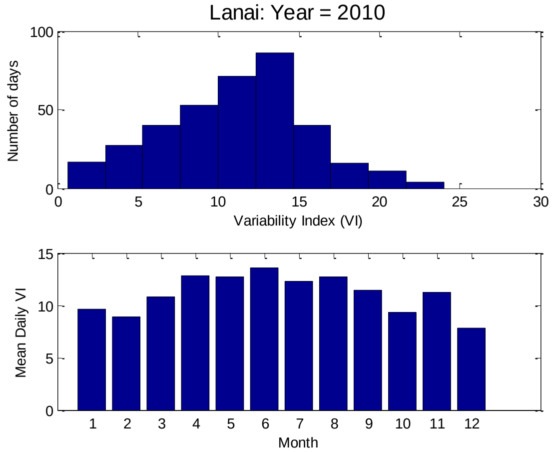

Fig. 3: Annual distribution of daily VI values (top) and mean daily VI values by month for Lanai, HI.

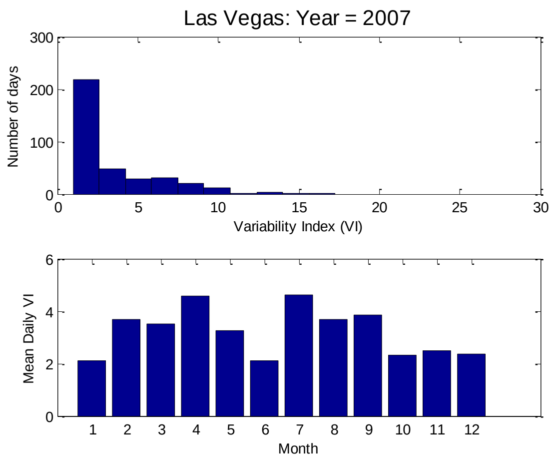

Fig. 4: Annual distribution of daily VI values (top) and mean daily VI values by month for Las Vegas, NV.

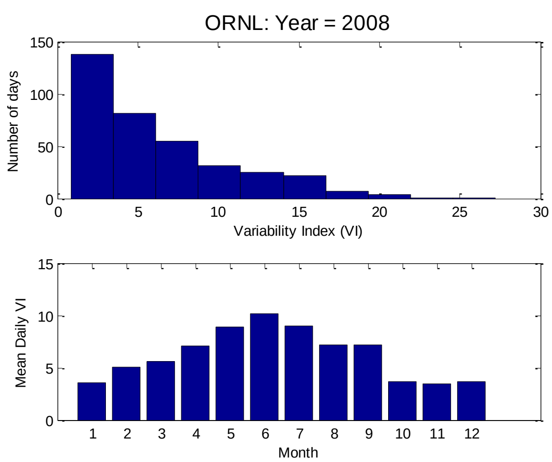

Fig. 5: Annual distribution of daily VI values (top) and mean daily VI values by month for Oak Ridge National Laboratory, TN.

4. EFFECT OF TIME INCREMENT

The time increment or resolution of the irradiance data affects the magnitude of VI. Irradiance measurements are typically reported as the average over an interval (e.g., 1, 2, 5, 10, 15, 60 minutes). We examined how VI changes as the averaging time increment varies from 1 min to 10 minutes at each of the sites. Shorter time increments result in higher values of VI as is shown with the solid lines on Fig. 6. This figure plots mean annual VI as a function of averaging time increment. The decrease in mean annual VI with increasing time increment is likely due to several reasons. First, any random error in the irradiance measurements will add to the “length” of the measured irradiance signal with a magnitude directly related to the sum of the absolute values of each random error. Because higher time resolution data have more time increments, these sums are larger for shorter time increments. Also, random errors tend to be reduced when averaged over longer time intervals. In addition, irradiance variations can happen quickly and longer averaging time increments will hide short term variability.

The observed patterns at each site suggest a possible model for mean annual VI at longer averaging time increments that takes the form of:

$$\overline{VI}_{\Delta t} = \frac{\overline{VI}_{t=1}}{\sqrt{\Delta t}} \qquad (2)$$

where $\overline{VI}_{t=1}$ is the mean annual VI at an averaging time increment of 1 minute. Dashed lines in Figure 6 show this model result. Note that the shape of the model matches the observations but that the modeled rate of decrease is not quite fast enough for Lanai and ORNL. Examination of more sites and time increments is necessary to develop a more general and accurate model for the relationship between mean annual VI and averaging time increment. Nevertheless, this model could be used to compare variability indices from different sites with different averaging intervals.

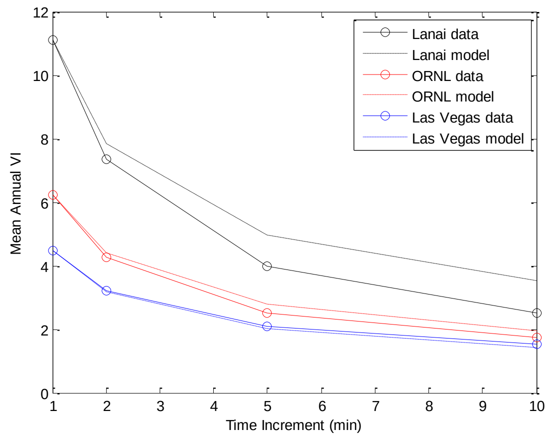

Fig. 6: Effect of time increment on mean annual VI. Dashed lines show simple model of this reduction.

5. VARIABILITY CLASSIFICATION

In Fig 2a the top row shows days with low VI values and demonstrate one limitation of the Variability Index: it does not do well distinguishing between clear and overcast days (the 4th day shown is overcast). In this section we suggest pairing VI with an additional quantity, the daily clearness index, to better classify days. Daily clearness index is the ratio of the daily insolation and the daily clear sky insolation. Figure 7 plots daily values of the clearness index against VI. Data from this figure display a characteristic arrow shape pointing to high values of VI.

We have selected four days with different irradiance conditions to show how classification using both VI and daily clearness index performs in distinguishing different types of irradiance variability conditions. Figure 8 displays the daily irradiance for each of these selected type days. Note that the days differ in their variability characteristics and the position on the "Arrow Head" plot appears to indicate general categories of (1) clear, (2) overcast, (3) mixed (clear and variable), and (4) highly variable all of the day. The longer length of day in Figure 8 for the "Highly Variable" day reflects the monthly pattern seen in the lower plot of Fig. 5, which demonstrates that the summer has higher variability conditions at this site.

Figure 9 presents a conceptual interpretation of the position of days in the "Arrow Head" shown in Fig. 7. To test this interpretation, we examine "Arrow Head" plots for the Lanai data and see if we see similar patterns.

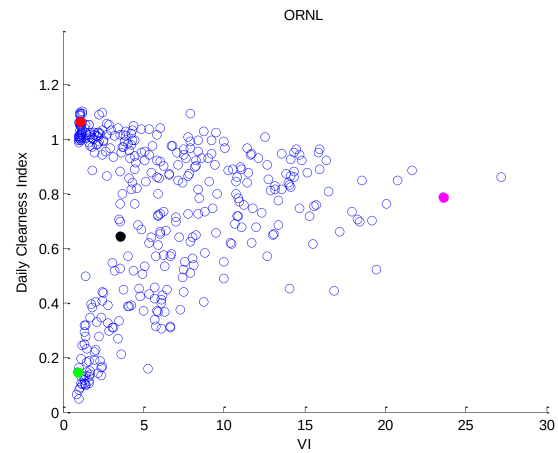

Fig. 7: Scatter ("Arrow Head") plot of daily clearness index and corresponding VI for each day of the test year at ORNL. The four colored solid circles are days shown in Fig 8.

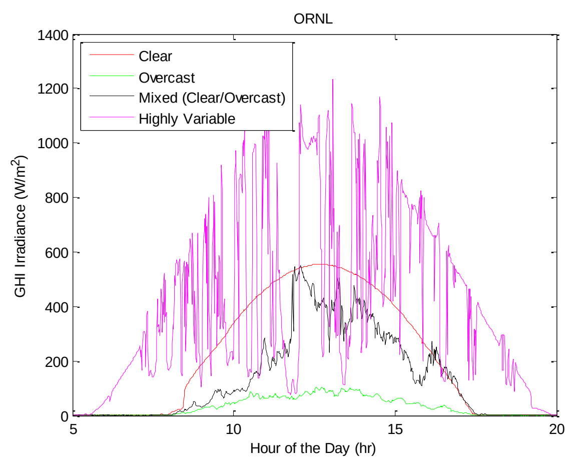

Fig. 8: Example irradiance patterns from four selected type days (shown on Fig. 7) from ORNL.

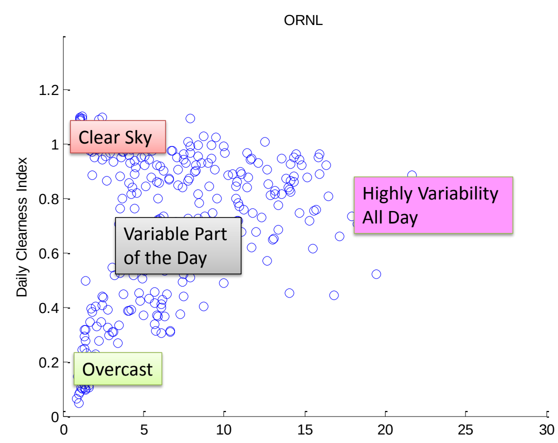

Fig. 9: Possible classification scheme for the "Arrow Head" plot shown in Fig. 7.

Plots for data from Lanai, HI are shown in Figures 10 and 11. These plots confirm that the Arrow Head shape is not specific to the ORNL data and that the interpretation from Fig. 9 appears to hold. Figure 12 shows the Arrow Head plot for Las Vegas, NV. Note the preponderance of clear days (i.e., high VI and high daily clearness index) at this site, which do not appear for Lanai, HI (Fig. 10). The contrast between Fig. 10 and Fig. 12 indicates that the combination of VI and daily clearness index is sufficient to distinguish between sites with substantially different climate conditions.

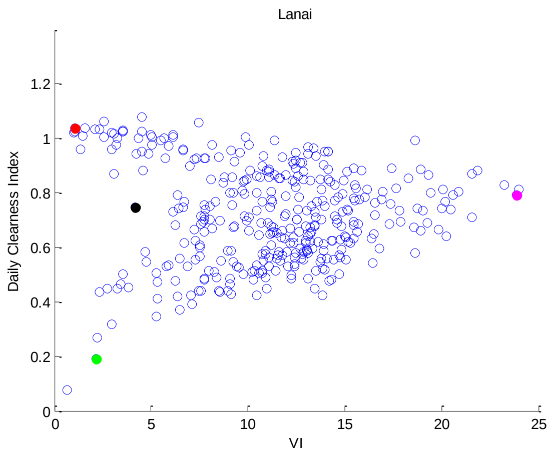

Fig. 10: Scatter ("Arrow Head") plot of daily clearness index and corresponding VI for each day of the test year at Lanai, HI. The four colored solid circles are days shown in Fig. 11.

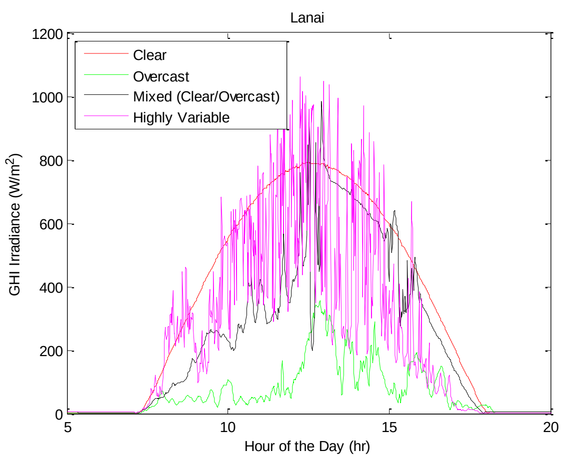

Fig. 11: Example irradiance patterns from four selected type days (shown on Fig. 10) from Lanai, HI.

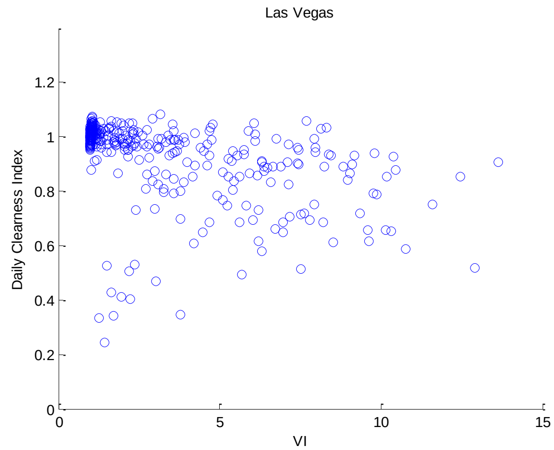

Fig. 12: "Arrow Head" plot for Las Vegas, NV.

6. CORRELATION OF VARIABILITY INDEX TO IRRADIANCE RAMPS

A simple metric like VI is only useful if it allows one to predict other quantities of interest. One such quantity that is particularly important for integrating solar PV systems into the grid is the frequency and magnitude of irradiance changes, which lead to power fluctuations. To illustrate how the magnitude of irradiance changes is related to the daily VI value, Fig. 13, Fig. 14 and Fig. 15 display scatter plots for the three sites. The plots show three different statistics (mean, 95th, and 99th percentiles) of the 1-min irradiance changes scaled by the maximum irradiance observed on each day. The normalization was done to correct for seasonal differences in the upper range of GHI. What is encouraging about these plots is that both the mean and the 95th percentile of 1-min irradiance changes are very well correlated with VI. The scatter increases as we approach the largest changes, but the correlation is still strong. This pattern indicates that an understanding of VI patterns at a site may be a good predictor of ramp rate distributions and demonstrates the potential value of the Variability Index.

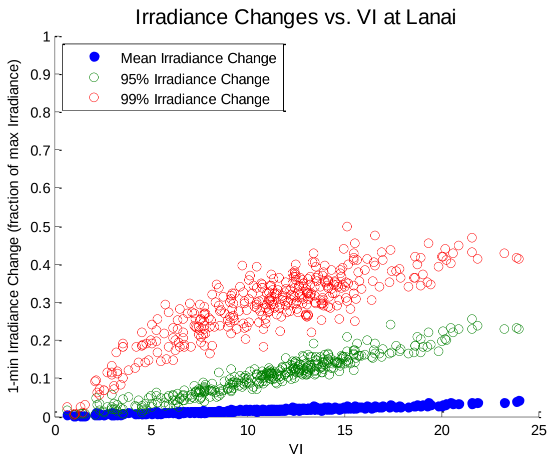

Fig. 13: Correlation between VI and Ramp Rates for Lanai.

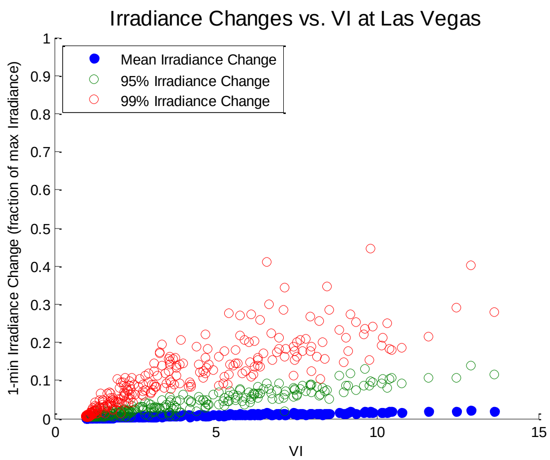

Fig. 14: Correlation between VI and Ramp Rates for Las Vegas, NV.

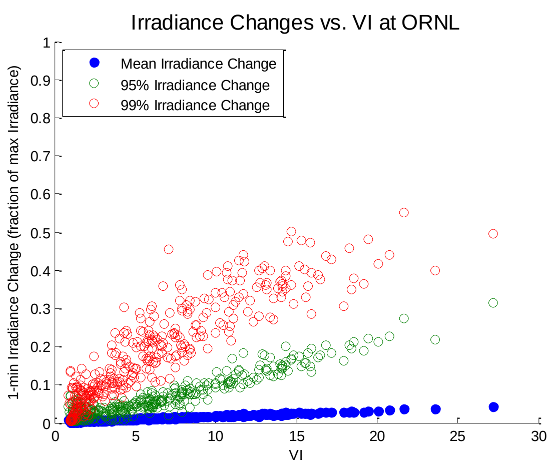

Fig. 15: Correlation between VI and Ramp Rates for ORNL.

7. SUMMARY AND CONCLUSIONS

We have introduced and described a new type of metric to measure variability in irradiance at potential solar PV sites. The metric measures the amount of variability in irradiance relative to variability of a clear sky reference. We calculate the variability index for three sites with different weather conditions and show how this metric can be used to distinguish between sites, both in aggregate and as a measure of variability patterns by month. We show how the time increment used for averaging and reporting irradiance affects the variability index and present a simple model to account for these effects. We then present a classification scheme using the variability index along with a daily clearness index to distinguish four types of irradiance days. Finally, we show that the variability index is well correlated to various ramp rate statistics.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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(2) Lenox, C., Nelson, L., "Variability Comparison of Large-Scale Photovoltaic Systems Across Diverse Geographic Climates," Proceedings of the 25th European Photovoltaic Solar Energy Conference, Valencia, Spain, 2010.