Day-Ahead Cumulative Solar Irradiance Prediction Method Using Percent Cloud Cover Forecasts

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Abstract

A method for forecasting solar irradiance has been developed. The goal of this study was to explore the applicability of cloud cover forecasts, typically used to determine visibility for aviation, for solar PV irradiance prediction. Using known equations which define solar position, a theoretical clear-day irradiance profile was calculated specifically for a solar array located near Mesa del Sol in Albuquerque, New Mexico, USA. Percent cloud cover forecasts posted by the National Weather Service (NWS) were then combined with the theoretical data to predict actual irradiance experienced by the array. The cloud cover forecasts do not differentiate cloud types (for example, storm fronts or non-precipitating stratus clouds) which could affect irradiance differently. Nonetheless, a weighting constant was applied to percentages such that, at 100% cloud cover, a minimum irradiance exists. Predictions were calculated for dates with recorded irradiance data, allowing for comparison and optimization of weighting. This comparison was done both for raw data, which for cloudy days was highly variable, and a sliding average of the same data. Comparing predicted versus measured irradiance provided scatter-plots which could be influenced by modifying the weighting constant. Numeric optimization was then performed to minimize either the irradiance or daily energy prediction error. After developing this prediction method, it is apparent there are opportunities for improvement over using only percent cloud cover, such as incorporating precipitation forecasts to characterize the nature of the clouds. This method could be used to estimate energy production of a solar field, which is useful for storage optimization and energy resource scheduling.

I. Introduction

The Prosperity Energy Storage Project near Mesa del Sol in Albuquerque, New Mexico is a DOE-sponsored study into large-scale grid-tied photovoltaic (PV) power generation with battery storage. As with any power distribution, the energy must be supplied reliably and consistently to serve the electricity needs of its customers. One method of ensuring reliable power delivery from a high-variability source such as solar is load shifting by using battery storage to shift peak power production for later peak system distribution or whenever it may be needed. For the Prosperity Project, this is the strategic night-time charging or discharging of battery storage based on an expected next day irradiance availability to most economically maintain and provide electricity when it is needed. This requires a means of predicting next day irradiance for the site of the PV solar array.

The goal of this initial analysis is to compare measured irradiance from the Prosperity Project's solar array to predicted irradiance. Predictions are based on known methods for calculating clear day terrestrial irradiance in combination with National Weather Service (NWS) percent cloud cover forecasts [1].

The direct irradiance on a south-facing surface with 25° tilt was calculated to model the global irradiance for clear-day conditions in Albuquerque, New Mexico.

Data collected from a single pyranometer at the Mesa del Sol site were used to evaluate prediction accuracy and development as the process evolved. The measured data loading and organizing portion of code takes advantage of MATLAB's built-in Excel data loading function. The Excel data were obtained through PI Datalink data extraction. Providing the layout of data is known (i.e. which columns contain what), the data are loaded into the workspace in matrix form.

II. Historical Data

A visual representation of irradiance data recorded for the month of September 2011 is shown in Figure 1. It is apparent that the typical arc of a clear day's irradiance is disrupted by clouds. Clear days maintain a relatively smooth curve and cloudy days cause a jagged profile.

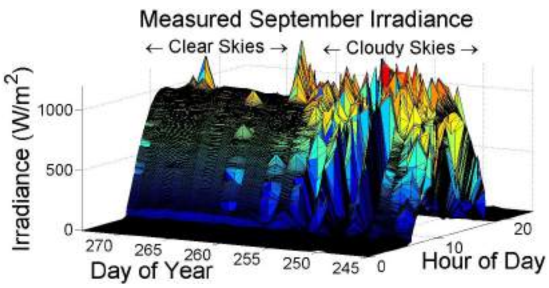

Figure 1: *Measured Irradiance Data (Sept. 2011); displays variability in power due to clouds*

A two-hour cenetered sliding average was taken for these data to provide an alternative best-fit comparison to the prediction method. The same data shown in Figure 1 then appears below in Figure 2.

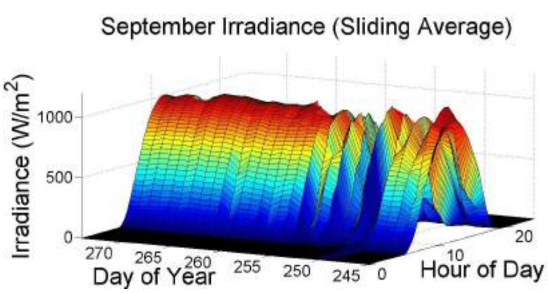

Figure 2: *Sliding Average Sept. 2011 Irradiance Data; used to compare to prediction*

III. Theoretical Irradiance

The predicted clear day irradiance data for a given day and sample rate were obtained using well-known geometric equations coupled with air mass attenuation models [1]. The calculations also provided the angle of incidence necessary for finding the normal component of irradiance impinging on fixed plate collectors. For the solar array's latitude, longitude, altitude and orientation, the theoretical terrestrial clear-day direct-beam irradiance plotted over the year is represented in Figure 3 for the South-facing array tilted at 25°.

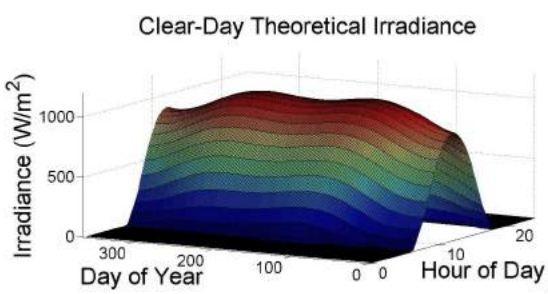

Figure 3: *Clear-Day Theoretical Irradiance for array's location and orientation*

The contributions of secondary effects, such as diffuse irradiance, air mass attenuation and local to solar time adjustments based on location with respect to the local time zone's standard meridian were also considered. More specific to this site, adjustments were made to account for a hill just east of the array which caused a delay in apparent sunrise every morning.

As an example of prediction accuracy for a clear day, consider a single day's irradiance data (September 23, 2011) shown in Figure 4. It is difficult to see the difference between nearly overlapping lines.

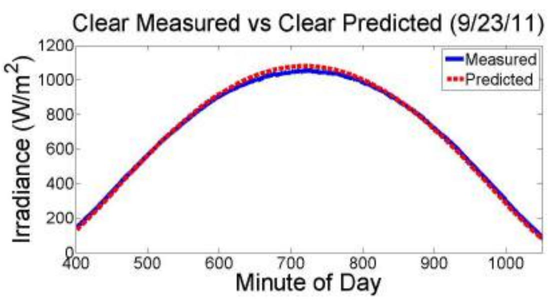

Figure 4: *Clear Day's Irradiance (9/23/2011) vs. Clear Day Prediction*

To show that the method is accurate independently of date, a separate day (October 20th, 2011) is shown directly below in Figure 5.

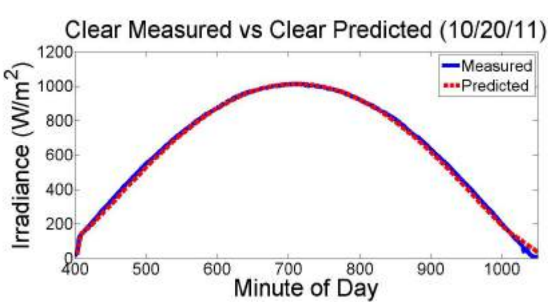

Figure 5: *Clear Day's Irradiance (10/20/2011) vs. Clear Day Prediction*

IV. Cloud Cover Forecasts

Historical day-ahead forecasts of percent cloud cover were made available by the NWS. For these forecasts, the NWS makes a prediction of 0, 20, 50, 80 or 100 percent cloud cover at times 9:00 am, 12:00 pm, 3:00 pm and 6:00 pm, meaning at precisely 9:00 am the NWS will forecast one of five cloud cover percentages. These values were interpolated over the entire day's samples using a cubic spline interpolating function to reflect a gradual change in clouds. In contrast, a linear interpolation can cause sharp changes in cloud cover evolution. One potential problem with cubic spline interpolation is it can create harsh spikes in interpolated data. For this data specifically, an interpolated percent cloud cover could be greater than 100% or less the zero. To address this side-effect, checks were put in place to ensure no percentages exceeded 100% or became negative.

After modifying the clear-day curve in Figure 3 according to Equation 1, the year's irradiance predictions show sharp drops where percent cloud cover predictions are available.

$$I_{Prediction} = I_{ClearDay} * \left(1 - k * \left(\frac{\%CloudCover}{100}\right)\right) \tag{1}$$

Shown in Figure 6 is the resulting prediction plot with cloud cover. Continuously smooth, unaltered curves occur where NWS data were either unavailable or 0% cloud cover and steps down indicate cloud cover.

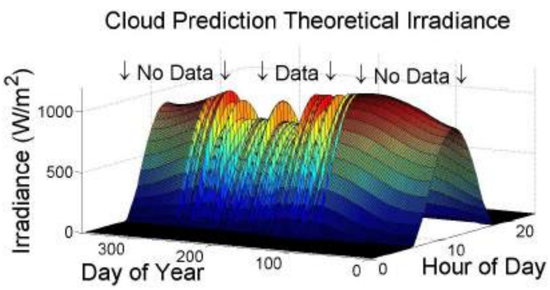

Figure 6: *Prediction including cloud cover; original curve unchanged where data unavailable*

For a closer look, September's predicted irradiance curve appears as the plot below. Comparing to Figure 1, high percent cloud cover was predicted early in the month, corresponding to measured irradiance. Later in the month, when there were clear skies, the NWS predicted light cloud cover, suggesting conservative forecasting meaning the NWS tends to over-estimate cloud cover. This tendency to over-predict has been observed in other studies which use cloud forecasting to determine next-day irradiance [3].

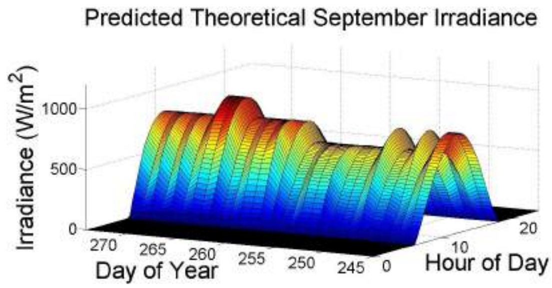

Figure 7: *September's Prediction; compare lower curves to spikes in Figure 1*

Conservative forecasting is appropriate considering the percent cloud cover forecasts are typically meant for use in aviation. They provide pilots with a general idea of expected visibility.

V. Method Validation

Smooth behavior, similar to a clear day bell curve irradiance profile, on a cloudy day is not realistic and should not be used for real-time control, but may be inevitable for day-ahead planning. Consider, for example, September 10, 2011 which was a cloudy day with NWS predictions to match (80%, 80%, 80%, and 50%). The following comparison (zoomed in for detail) shows actual irradiance and predicted irradiance. The prediction shows a relatively good best-fit curve for both raw data and sliding average.

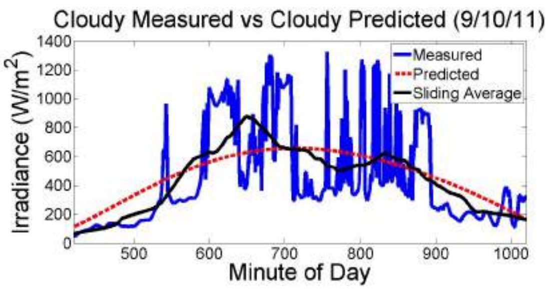

Figure 8: *Cloudy Day's Irradiance (9/10/2011) and Sliding Average vs. Prediction*

As an overall comparison of the measured and predicted irradiance values, a one-to-one scatter plot was generated. Here, for every measurement time, the predicted irradiance is plotted against measured irradiance. If compared to a perfect prediction method, all data points would be located on a line at 45° from the origin (i.e. $y = x$).

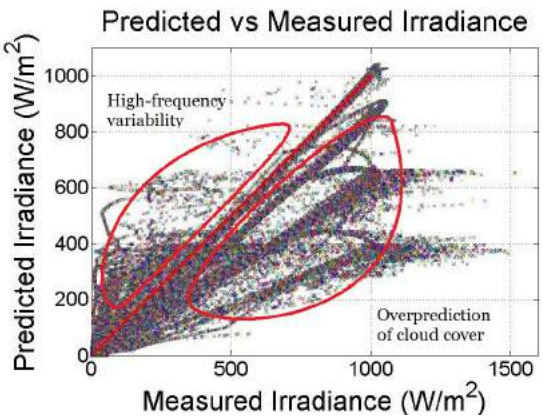

Figure 9: *Initial Predicted vs. Measured Irradiance Plot; note patterns to right of red line*

This plot shows 1440 data points per day for 60 days from September 2, 2011 to October 31, 2011. The three line patterns, shown flowing low and right of the $y = x$ line, are days where a forecast greater than zero percent cover was made, but the array experienced clear day irradiance. Moving away from $y = x$, the lines correspond to 20%, 50% and 80% cloud cover forecasts. For the dates represented, no 100 % cloud cover forecasts were made.

One of the user determined characteristics in this analysis was the effect of cloud cover resulting from the constant k in Equation 1. Considering this, secondary lines were added at 34° and 60° out from the origin to help center the data cloud equidistantly from x-coordinate of the $y = x$ line. This means for a predicted irradiance (e.g. 600 W/m^2) there is an equal range of irradiance above and below the predicted value. The resulting horizontal centering generated the plot in Figure 10.

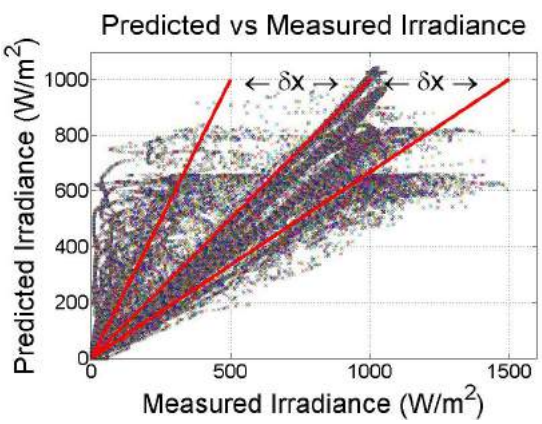

Figure 10: *Centered Predicted vs. Measured Irradiance; average distribution of scatter*

In Figure 10 the scatter can make it difficult to see the behavior of individual days. The sliding average of the measured data helps filter noisy data by removing many of the large spikes seen in measured data. This also yields clear path lines for specific days' sliding average irradiance curves.

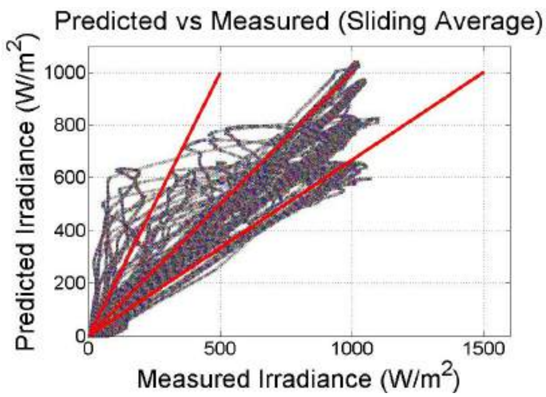

Figure 11: *Predicted vs. Sliding Average of Measured Irradiance*

To show the correlation of cloudy days versus clear days, Figure 12 compares two days' irradiance. The line nearly coincident with the $y = x$ line is a clear day and the scattering black path and green looped paths are a cloudy day's measured and sliding average irradiance, respectively.

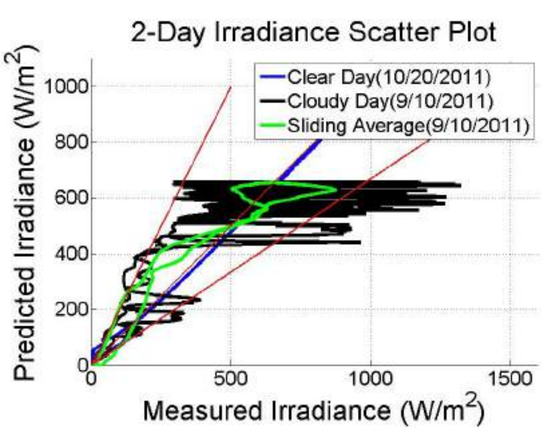

Figure 12: *Clear and Cloudy Day Comparison*

One test of this algorithm includes adjusting the data cloud or cloud cover weighting based on total energy for the day. A preliminary energy comparison was done by calculating the area under both theoretical and measured irradiance curves, producing Figure 13 below. The scatter low and right of the red line suggests that the prediction is too low. However, this is largely due to over-predicted cloud cover by the NWS.

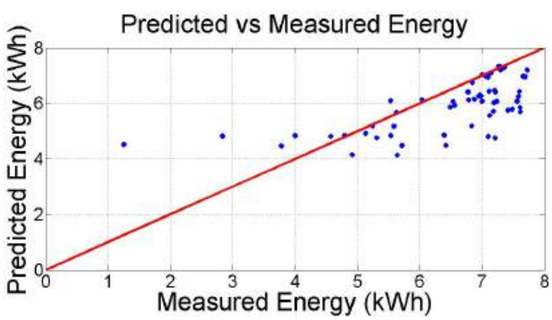

Figure 13: *Measured vs. Predicted Energy per day; over-predicted cloud cover evident*

VI. Optimization

After adjusting the percent cloud cover weighting visually, numerical optimization was performed to minimize the error between predicted and measured data. Because both irradiance and energy prediction accuracies are valuable, constants were optimized to minimize average irradiance percent error and average daily energy percent error during typical PV power production hours. A second adjustable parameter was added to Equation 1, resulting in:

$$I_{Prediction} = I_{ClearDay} * \left(1 - \left(a - b * \left(\frac{\%CC}{100}\right)\right)\right) \quad (2)$$

The variable a was added to simultaneously optimize the visually calibrated clear day irradiance. The variable b represents the cloud cover weight previously denoted by k in Equation 1. Irradiance predictions calculated using a range of a and b values were then compared to historical data. We see the minimum average percent error of 16% when $a = 0$ and $b = 0.39$ in Figure 14.

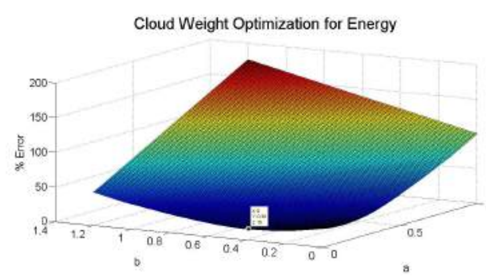

Figure 14: *Error versus Varying Constant Values*

From this new cloud weighting, the fraction of predicted irradiance to clear-day irradiance versus percent cloud cover is shown Figure 15. At 100% cloud cover there exists an irradiance fraction just over 0.61.

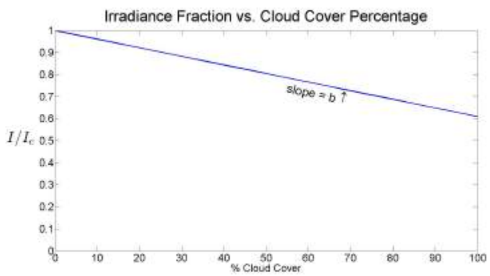

Figure 15: *Irradiance Fraction vs. % Cloud Cover*

This correlates to an irradiance scatter plot shown in Figure 16. While bearing sharp resemblance to Figure 10, there is noticeable change.

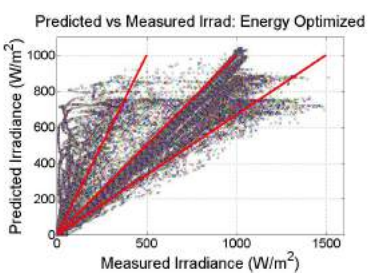

Figure 16: *Error versus Varying Constant Values*

Likewise, the cumulative energy scatter in Figure 17 shows the grouping more centered on the $y = x$ line, pushing the outlying low-energy days away.

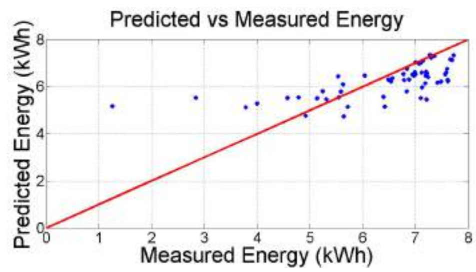

Figure 17: *Error versus Varying Constant Values*

Though separate optimizations were performed for irradiance and energy, the irradiance optimization values resulted in unrealistic irradiance profile predictions and cumulative energy predictions with large error. This is due to the high degree of variability for irradiance. Also, as a tool for load shifting, the constants are best optimized to energy prediction accuracy.

VII. Conclusion

Testing and development are ongoing for this irradiance prediction method. Because the Prosperity Project was relatively new at the time that this study was started, limited quantities of data were available. As the project continues gather performance data, further correlation and maturation of this prediction method can take place.

Clearly there are opportunities for improvement over using only percent cloud cover forecasts when predicting irradiance or energy. It is possible that incorporating other weather forecasts such as precipitation or wind may provide added resolution to the nature of the clouds which will shade the PV array.

Other considerations include the number of data sources for irradiance in the system. This method was developed using irradiance data from a single horizontal PV sensor. Many studies have concluded that an average of multiple spread-out sensors is a better measure of irradiance experienced by the array [4]. Moreover, there is also a PV Meter showing the total power output of the array. Both of these data sources could be explored to obtain more accurate results.

There are many ways to improve this prediction method. Once it is validated to within an acceptable accuracy, it can be used for load shifting to more economically and reliably meet grid power demands.

References

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