Measurement-Supported Soiling Loss Modeling: Incorporating Site-Specific Preconstruction Measurements with Standard and Advanced Soiling Models

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Introduction

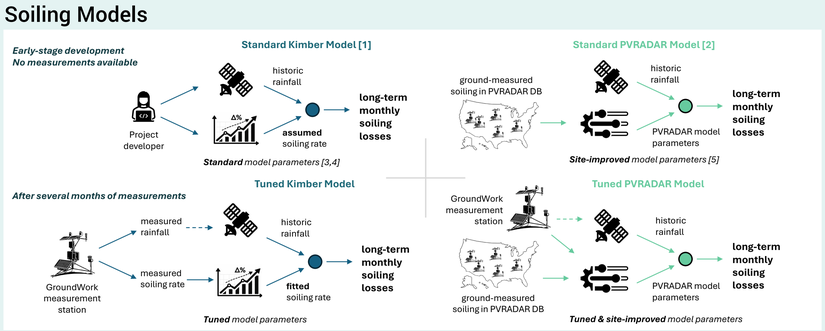
Soiling losses were repeatedly identified at the 2025 PVPMC Workshop in Albuquerque as a primary source of uncertainty in PV energy modeling. Higher uncertainty in development can lead to lower debt service coverage or insufficient budgeting for O&M. While multiple models exist, their reliability depends on the user's ability to adapt model parameters to local conditions. This study uses onsite measurements as "ground truth" to improve soiling model parameterization across two soiling models (Kimber and PVRADAR) and two scenarios: standard assumptions versus site-specific tuning.

Methods

Input Data

- Measurement campaign conducted by GroundWork Renewables for Leeward Renewable Energy
- 18 months of data in Southern Nevada, USA
- Paired (Soiled and Cleaned) 30-W modules at fixed 36-degree south tilt
- Tipping bucket rain gauge
- 20 years of historic rainfall from three sources: MERRA-2, ERA5, NOAA (GHCN-USC00265890)

Soiling Models



Model Tuning and Aggregated Soiling Loss

Tuned models were derived by fitting model parameters to measured soiling and rainfall data over the measurement interval. Each soiling model was run with both standard and tuned model parameters for the designated Leeward measurement campaign, with three 20-year historic rainfall data sources.

Model Tuning

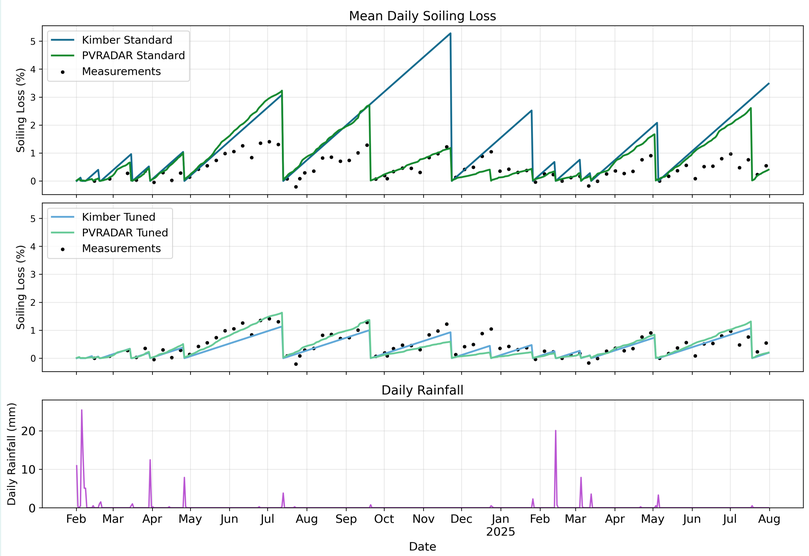


Figure 1. Modeled soiling loss (%) for the measurement period before (top) and after (middle) tuning. Measured rainfall is shown below. Using the measurement data to tune model parameters results, as expected, in modeled values that more closely mirror measured values.

Table 1. Model parameters with and without tuning. For the Kimber model, the rainfall cleaning threshold was cut in half with tuning, and the soiling rate was reduced by more than half. The PVRADAR model varies the cleaning threshold and soiling rate based on several model parameters. Tuning of the PVRADAR model also resulted in a reduced median soiling rate.

Model	Cleaning Threshold (mm rainfall/day)	Soiling Rate (% of energy lost/day)
Kimber Standard	1.000	0.0400
Kimber Tuned	0.458	0.0150
PVRADAR Standard	0.254 - 0.508	~0.0270 (median)
PVRADAR Tuned	0.254 - 0.508	~0.0140 (median)

Long-Term Soiling Loss Results

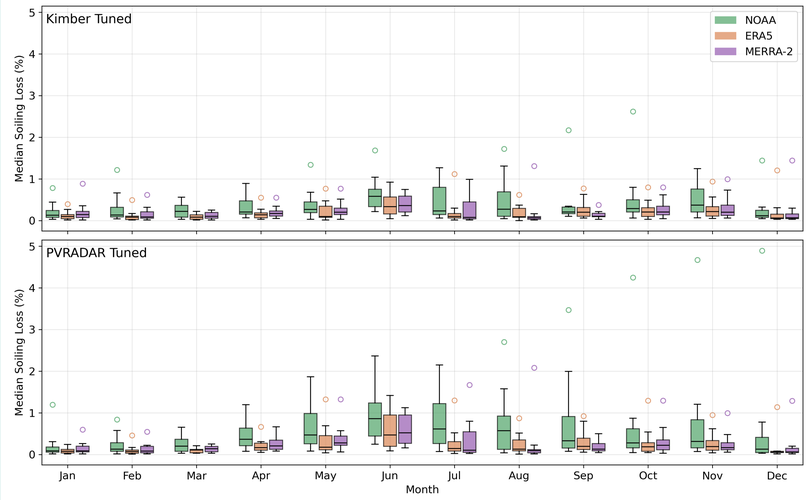


Figure 2. Long-term soiling losses predicted by the two tuned models using three different 20-year rainfall data sets. NOAA measurement data was collected at a site ~15 miles from the soiling measurement site. ERA5 and MERRA-2 are gridded, reanalysis datasets.

Measured Rainfall vs Rainfall from External Sources

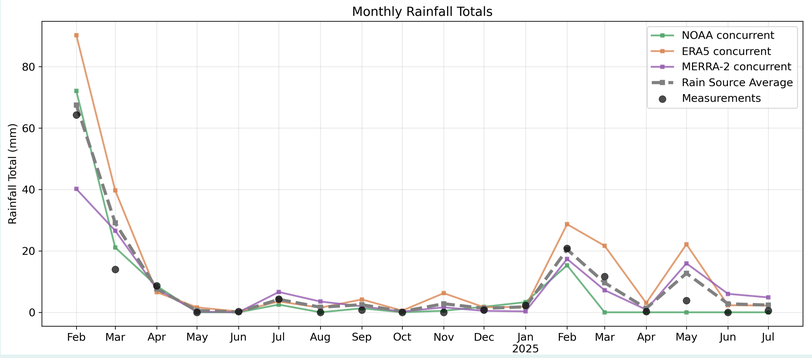


Figure 3. Monthly rainfall measurements compared to historic rain data sources for the measurement period. No single rain data source exactly matched the site-specific measurements. Averaging the results across the three rainfall data sources is expected to best approximate long-term monthly average soiling.

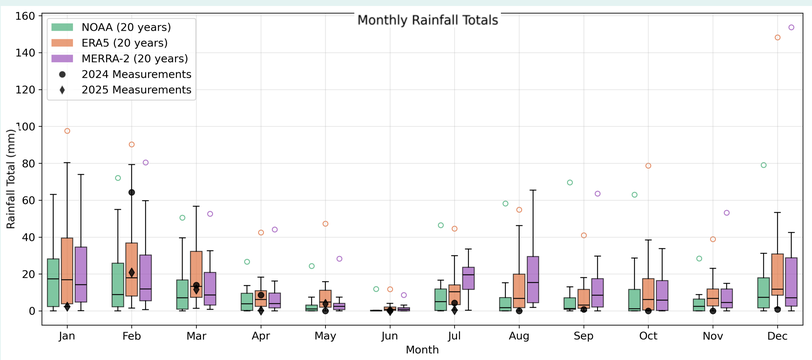


Figure 4. Monthly rainfall measurements (2024, 2025) compared to historic rain data source averages. With the exception of February 2024, measurement period rainfall tracked well with historic averages. Anomalous rainfall years can skew soiling measurements. Measurement campaigns with multiple years of data allow for filtering of anomalous data while retaining a full record of annual seasonality.

References

[1] Kimber, A., Mitchell, L., Nogradi, S., & Wenger, H. (2006). The effect of soiling on large grid-connected photovoltaic systems in California and the Southwest Region of the United States. In Proceedings of the 4th World Conference on Photovoltaic Energy Conversion.

[2] https://pvradar.com/soiling/soiling-model

[3] Croft, N. & Miller, A. (2025). Soiling Inputs for the Kimber dust soiling model derived from soiling measurements (Poster). Presented at the 2025 PV Performance Modeling Collaborative (PVPMC) Workshop, Albuquerque, NM, USA.

[4] Standard values for Kimber model input parameters vary with geographic region and continue to evolve. Standard parameters for the Kimber model were selected by Leeward and based on Croft and Miller, 2025.

[5] PVRADAR uses measurements from nearby or similar locations in a global soiling database to find the set of model parameters that best represents the expected conditions at the target site.

Model Errors

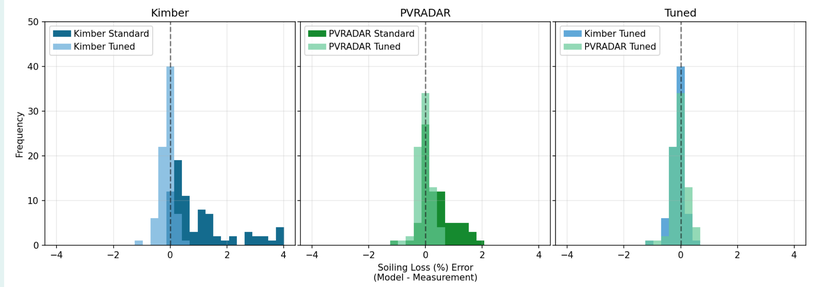


Figure 5. Error Distribution. Prior to tuning, the PVRADAR model predicted the measurement data significantly better than the Kimber model, as reflected by consistently lower error metrics across all indicators. Both models were biased high, predicting higher soiling losses than measured when standard parameters were used. Tuning significantly reduced the error in both models.

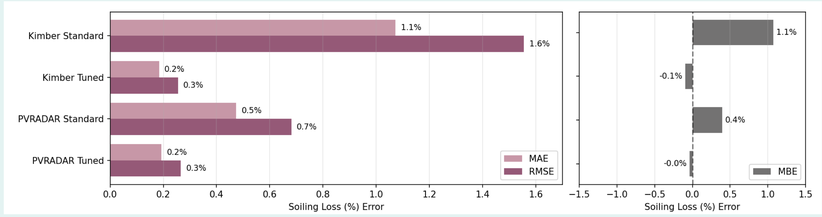


Figure 6. Error Metrics. Visualization of MAE and RMSE shows the dramatic error reduction achieved through tuning, especially with the Kimber model. Prior to tuning, both models predicted higher soiling losses than what was measured (positive MBE). After tuning, After including site measurements Kimber and PVRADAR showed the same (improved) performance and MBE for both models was negligible.

Statistics Refresher for Non-Statheads:

- **RMSE** describes the 'goodness of fit' of the model to measured values. RMSE is expected to decrease when the model is tuned to the measurement data.
- **MAE** is a measure of the average magnitude of errors between the model and the measurements. MAE provides a direct measure of average error magnitude.
- **MBE** is used to measure the average bias (systematic error) of a model, calculated as the average difference between predicted and actual values.

Sensitivity of Results to Measurement Duration

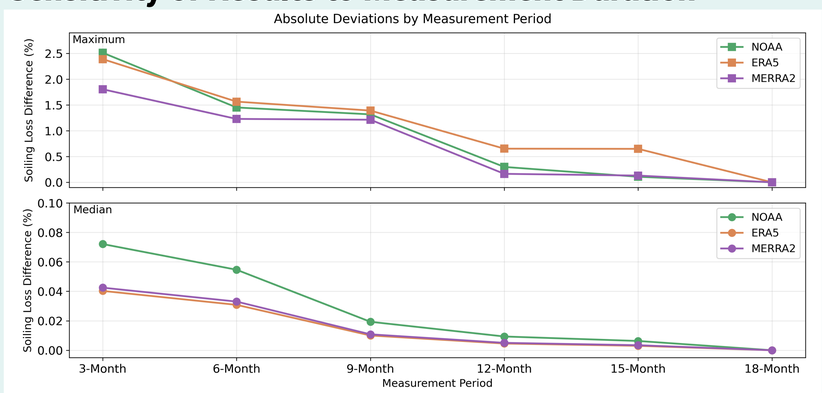


Figure 7. Long-term modeling was performed using shorter durations of measurement data. Kimber model parameters were tuned using moving window combinations of 3-, 6-, 9-, and 12-month measurement periods within the full 18-month measurement campaign. Variability in results diminishes with longer measurement periods.

Recommendations for Project Developers

- Before a ground-based measurement campaign is completed, the PVRADAR model can greatly improve soiling modeling accuracy relative to the traditional Kimber model.
- Tuning soiling assumptions using ground-based measurements of daily rainfall and daily soiling rate can significantly improve model bias and precision, whether the Kimber or PVRADAR model is used.
- A soiling rate of ~0.015 percent per day and a rainfall cleaning threshold of ~0.5 mm best describes the soiling behavior for this location.
- Models rely heavily on rainfall information, so selecting one or more historical data sets that are representative of the project location is key.
- Measurement campaigns of 12 months or longer are preferred for model tuning.
- Soiling rates determined in preconstruction can be used to predict O&M spend and cleaning schedules.

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