Simplified Method for Modeling the Impact of Arbitrary Partial Shading Conditions on PV Array Performance

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Simplified Method for Modeling the Impact of Arbitrary Partial Shading Conditions on PV Array Performance

Sara MacAlpine and Chris Deline

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***Abstract* — It is often difficult to model the effects of partial shading conditions on PV array performance, as shade losses are nonlinear and depend heavily on a system's particular configuration. This work describes and implements a simple method for modeling shade loss: a database of shade impact results (loss percentages), generated using a validated, detailed simulation tool and encompassing a wide variety of shading scenarios. The database is intended to predict shading losses in crystalline silicon PV arrays and is accessed using basic inputs generally available in any PV simulation tool. Performance predictions using the database are within 1-2% of measured data for several partially shaded PV systems, and within 1% of those predicted by the full, detailed simulation tool on an annual basis. The shade loss database shows potential to considerably improve performance prediction for partially shaded PV systems.**

***Index Terms* — modeling, photovoltaic systems, shading, solar energy.**

I. Introduction

Demand remains strong for residential and small commercial rooftop solar photovoltaic (PV) systems, driven in large part by improved technology and increased affordability. Building geometries and landscapes of PV systems in urban and suburban environments often create situations in which arrays are partially shaded during a portion of their operating hours. Partial shading, while not ideal, does not necessarily preclude the financial viability of a PV installation; the resulting energy losses may be mitigated by use of power electronics (microconverters or microinverters), or they may be insignificant, depending on the location and extent of the shading relative to the array. The impact of partial shading on a proposed PV system's performance must be accurately predicted to determine how it should be configured and installed for maximum value to the customer.

Partial shading conditions, particularly those with irregular shade patterns (i.e. not row-to-row, which is covered in other work [1]), are difficult to model in PV systems with standard, central inverter configurations, as shading effects are nonlinear, dictated by string voltage and current constraints. Some detailed PV simulation tools do include detailed shade modeling capabilities, but these can include long setup and run times, which are not cost effective for smaller projects or for simulating multiple scenarios to optimize system design. Simpler simulation tools, such as NREL's System Advisor Model (SAM) [2] or PVWatts [3], use linear or "best guess" user-input shade loss derates, which enable faster simulations but do not capture the complexity of partial shading's performance impact. There is a need for a solution which allows simpler PV modeling tools to account for the effects of partial shading on a PV array with reasonable accuracy, while adding only minimal simulation time.

The solution proposed in this work is a lookup-table-style database of shade impact results (loss percentages), generated using a validated, detailed simulation tool [4] and encompassing a wide variety of shading scenarios. The shade impact results found in the table are representative of most conventional crystalline silicon PV modules. This shade impact database is intended for use with any annual PV simulation tool; its output is a shade loss derate factor that may be used in hourly or sub-hourly simulations. With its relatively small size and fast access time, the shade impact database adds little overhead and demonstrates potential to drastically improve performance prediction for partially shaded PV systems, particularly when used with software that lacks detailed shade modeling capabilities.

II. Shade Impact Database

A full, detailed shading simulation tool has been developed at CU-Boulder and NREL that is capable of accurate modeling of arbitrary cell-level shading on PV arrays. This tool has been validated and has been used to generate predictions of performance loss from partial shade [4]. While accurate and flexible, this full simulation tool has a lengthy runtime, making it inappropriate for direct use with common PV performance models.

A way around this bottleneck is to run the full simulation tool for a number of scenarios and to store the results in a lookup table database of shading results. This database includes pre-computed solutions for the most common shading scenarios of typical PV systems, with the following guidelines:

- Systems may have up to 8 parallel strings, connected to a single central inverter. Any string length and module orientation is allowed, so long as it is uniform across each system.
- Each string can be shaded in 10% increments, independent of each other string. The database is coded by the fraction of modules/sub-modules shaded in each string.
- The fraction of irradiance available while the module is partially shaded (diffuse fraction) ranges from 10-100% of the total plane-of-array irradiance, again in increments of 10%. At any given time the PV system operates under no more than two light levels, shaded and unshaded.

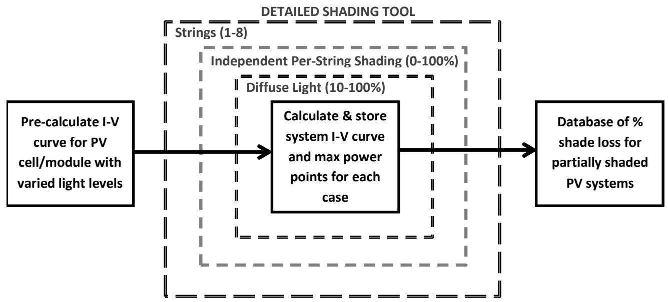

Fig. 1. Flow diagram for generation of the shade impact database. A full-featured simulation tool is queried for several previously determined situations, varying the extent of shade on each string, number of parallel strings in the system, and diffuse fraction of irradiance.

A. Database Structure

The shade impact database is implemented as a structure in MATLAB based on precomputed results of the detailed shading simulation tool. Specifically, DC system performance parameters are stored under various shade scenarios. It is created as shown in Fig. 1, and is stored in the following form:

$$\mathrm{DB}\{\#Strings\}.\mathrm{d}\{Diffuse\}.\mathrm{t}\{[MaxStrShade]\}\begin{bmatrix} maxVs \\ maxIs \\ voltages \\ currents \end{bmatrix}$$

In the database, the variables *#Strings, Diffuse,* and *MaxStrShade* are used to define and index an array's particular partial shading scenario. Variable *#Strings* is the number of parallel strings in the PV system, which can range from 1-8. *Diffuse* is the fraction of the total incident plane-of-array irradiance that is available to the shaded portions of the array, which can range from 1-10, corresponding to 10-100%. *MaxStrShade* is the maximum value in *ShadingFracs,* a user-input vector of length *#Strings*, which indexes the fraction of each string that is shaded, sorted in descending order. These indices may range from 1-11, corresponding to 0-100%.

Each partial shading scenario has four items stored in an array of integers in the database, giving full information about the PV system performance. *maxVs and maxIs* are the system-level local and global maximum power point voltages and currents, respectively, normalized to unshaded conditions. It is possible for these maximum power points to fall outside of the central inverter's maximum power point tracking (MPPT) range, depending on system design, so the database also includes variables *voltages* and *currents*, which are 40 evenly-spaced (in voltage) points on the partially shaded system-level I-V curve, scaled to the unshaded I-V curve. Inclusion of these points allows the database to better track realistic inverter performance. An example of the stored I-V curve data (in power vs. voltage curve form) is seen in Fig. 2.

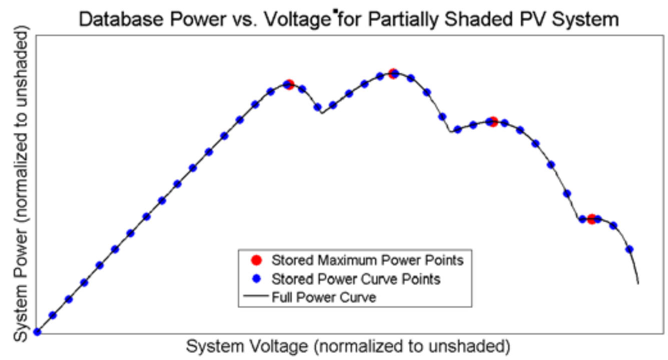

Fig. 2. Example data stored in the partial shading database. A full power vs. voltage curve (blue points) improves simulation accuracy for under-sized PV systems, or other conditions of inverter MPPT mismatch

The database is based on a 250W polycrystalline module, Trina module TSM-PA05, chosen because it has performance characteristics that are typical of crystalline silicon modules used in residential PV arrays. When the database is fully populated from 1-8 strings, its MATLAB-compressed size is 10.5MB. If each partial shading scenario is stored with just the system-level maximum power points (not the 40 points along the power curve), the size decreases by a factor of approximately four. However, this may compromise the accuracy of the performance prediction for some PV systems which are not optimally sized or configured.

B. Database Access

Database access requires basic information about the PV system to be simulated, including module and inverter characteristics, array configuration, unshaded and shaded plane-of-array irradiance and PV cell temperature, and the shaded fraction of each string of modules. All but the last item of this information are readily available to the user in array design documents, weather files, or datasheets. Per-string shading must be determined using a tool that maps shade patterns onto the plane of the PV array, such as the 3D shade calculator currently implemented in SAM, or other 3rd party CAD design software.

During each database access, the per-string shading and shaded (diffuse) irradiance fractions are rounded to their nearest tenth, and these are used to obtain the most relevant set of DC current and voltage system operation from the database. The maximum power output is calculated, within the PV system's inverter MPPT string voltage range, and this is then used to compute the partial shading losses. Database access time for a year of hourly points is approximately 1 second, which meets the goal of a very fast simulation time.

III. Validation With Detailed Simulation Tool

The shade impact database method is first validated by comparing its annual performance predictions to those of the detailed Matlab simulation tool referenced in Section II. This controls validation to focus exclusively on the database's electrical performance prediction, since both sets of simulations have the same inputs such as weather conditions, system characteristics, and shade patterns.

A. PV System Details

a.

b.

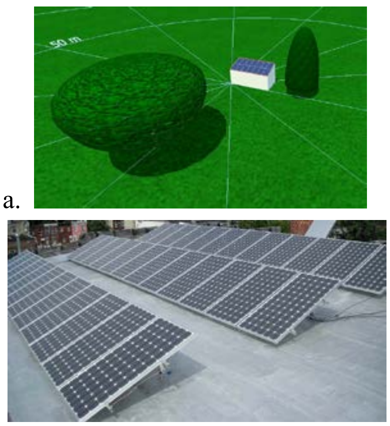

Fig. 3. Representative pictures of the 3kW (3a) and 18kW(3b) PV arrays used to validate the shade impact database.

Two PV systems are chosen for simulation, both located in Denver, Colorado. The first is a small (3kW) array with nearby shading obstacles (two large trees) shown in Fig. 3a; this system is meant to represent a typical residential installation. The second, which is similar to the PV system seen in Fig. 3b, is a larger (18kW) array with row-to-row self-shading; this system is meant to represent a typical commercial installation.

B. Simulation Results

As shown in Table I, the shade impact database predicts an annual shading loss within 0.8% of that predicted by the detailed simulation tool. Both the irregular shading conditions of the 3kW residential system and the regular, row-to-row shading of the commercial system are adequately addressed using the shade database method. Given the rounding of the degree and position of shading in the shade impact database, this is an excellent agreement between the simulation methods.

TABLE I
Comparison of Predicted Shade Loss

	Predicted Annual Shade Loss		
	Detailed Tool	Linear Estimate	Shade Impact Database
3kW System	21.1%	13.8%	20.4%
18kW System	15.8%	14.5%	15.0%

Table 1 also includes a "linear estimate" of the predicted annual shade loss, which assumes that the percent shading losses each hour are equal to the fraction of the incident irradiance blocked by nearby obstacles. This is how shading losses are currently modeled in the NREL SAM tool [2], and is similar to simplifying assumptions used in the SunEye rooftop survey tool [5]. As shown in Table 1, the linear estimate tends to underestimate the shading losses, sometimes by a great deal; use of the shade impact database provides substantially more accurate performance predictions.

IV. Validation With Field Data

Next, the shade impact database is validated by comparing its annual performance predictions to measured field data for several partially shaded PV systems. This adds complexity to the validation, as weather conditions and shade patterns may differ slightly between the simulation and what is actually experienced by the array. However, for the shade impact database to be practical to use, it must predict reasonable outputs even with some variance between user input and actual conditions. The process of validation is as follows:

- Gather system information, including layout and configuration, and at least one year of performance and nearby weather data
- Map site and shade obstacles using SAM 3-D shade calculator
- Use shade calculator to calculate hourly fraction of sub-modules shaded per string
- Access shade database using system and shading information, to calculate hourly shade loss
- Apply hourly shade loss to unshaded SAM simulation results for whole year
- Compare these shaded simulation results to measured data, adjusting for snow days and system downtime, as applicable

A. PV System Details

Three PV systems are chosen for validation, all newer installations (<5 years old) located in Colorado. In all cases they are deemed close enough geographically to NREL that the MIDC/SRRL hourly weather measurements [6] are used to find operating conditions. Each of the three arrays has at least one year of measured, daily performance data, as well as imagery available to determine shading obstacles. A summary of the three systems is found in Table II.

TABLE II
PV SYSTEMS FOR SHADE DATABASE VALIDATION

	Modules	Size	# Strings
NREL Garage	Sunpower, mono-si	156kW	62
Denver,CO Residence	Sharp, mono-si	2.8kW	1
Boulder, CO Residence	BP Solar, mono-si	2.8kW	2

The first of these systems, located on the NREL parking garage facade (Fig. 4), is a south-facing array with rows of modules that cast inter-row shade on the rows below them, predominately during the summer time (Fig. 5). Though this array is quite large, it can be simplified to a smaller, 7-string array with a fraction of unshaded (top row) and shaded (middle and bottom rows) strings, due to its regular string and shading patterns. This allows it to be simulated using the shade impact database, which is limited in size to 8 parallel strings.

Fig. 4. NREL parking garage PV array

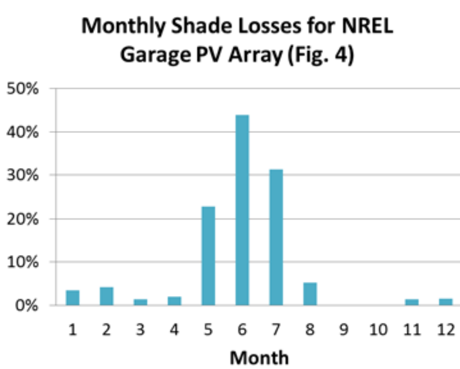

Fig. 5. Estimated monthly % shade loss for the NREL parking garage PV array (measured performance compared to annual unshaded simulation in the NREL SAM tool)

Next is a smaller rooftop array in Denver, Colorado (Fig. 6). This south-facing array is shaded by a chimney, as well as a very large deciduous tree located to the south west of the roof. It receives most of its shading in the winter and surrounding months (Fig. 7).

Fig. 6. Partially shaded PV array at a Denver residence. (Google Street View, 2014)

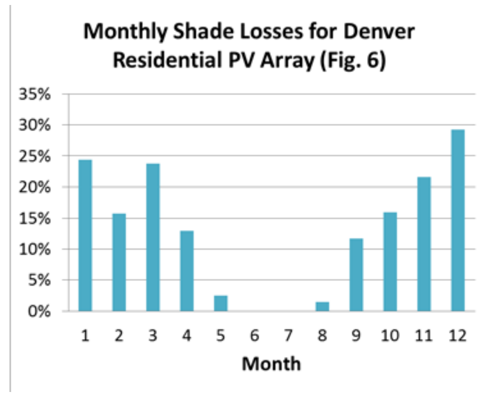

Fig. 7. Estimated monthly % shade loss for the Denver residential PV array (measured performance compared to annual unshaded simulation in the NREL SAM tool)

The final validation case is another small rooftop PV array, located in Boulder, Colorado. This array faces southeast, and is shaded in the mornings by several nearby trees, as well as sometimes in the afternoon by a large, deciduous tree to the south of the house (Fig. 8).

Fig. 8. Partially shaded PV array at a Boulder residence. (Google Street View, 2012). The PV system is barely visible behind the trees.

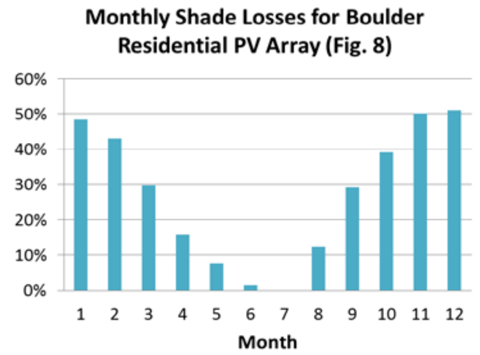

Fig. 9. Estimated monthly % shade loss for the Boulder residential PV array (measured performance compared to annual unshaded simulation in the NREL SAM tool)

B. Validation Results

Results of the annual simulations for each of the three validation systems are found in Tables III and IV. As in Table I, these tables compare results of simulations using the shade impact database method and the current SAM linear shading model. They also include results of simulations using PVsyst version 6.38 [7]; version 6 of this tool enables the user to perform very detailed partial shading simulations, similar in intent to the shade impact database. In addition, the Denver PV array results are compared to those obtained using monthly shade derates from a Solmetric SunEye rooftop shading survey.

Table III shows the results of each shade modeling method, relative to the measured data, with each case using 3D shading geometry based on aerial and site imagery. While obstacle size and placement are known and easy to map for the NREL array, the exact locations and sizes of the trees for the two residential arrays are more difficult to determine from pictures. This is reflected in the results; though performance predictions are good for the NREL array, both of the detailed tools (shade database and PVsyst) mispredict performance by several percent for the Boulder array, and the shade database also does so for the Denver array. As expected, the linear shade estimation method implemented in SAM significantly overpredicts performance in all of the test cases. The SunEye monthly derates' prediction is similar to the shade database.

TABLE III
ANNUAL VALIDATION RESULTS – FIRST PASS

	Predicted Performance Rel. to Measured Data			
	SAM Linear	SAM Shade DB	PVSyst	Solmetric SunEye
NREL Garage	+4.1 %	-2.0 %	-1.5 %	-----
Denver, CO Residence	+6.3 %	-2.1 %	-0.6 %	-2.2 %
Boulder, CO Residence	+22.2 %	+4.9 %	+3.1 %	-----

Further examination of the predicted vs. measured performance data indicated that there were some assumptions that needed to be adjusted for each of the test cases. As Sunpower modules (NREL array) are more tolerant to mild partial shading, shade database access was adjusted to reflect this, by requiring that any sub-module be obstructed by at least four cells to be considered "shaded". The two residential arrays had their trees moved slightly farther from the house (Denver) or closer (Boulder), by 10% or less. These minor adjustments are reflected in the results found in Table IV.

TABLE IV
ANNUAL VALIDATION RESULTS – ADJUSTED

	Predicted Performance Rel. to Measured Data			
	SAM Linear	SAM Shade DB	PVSyst	Solmetric SunEye
NREL Garage	+4.1 %	-0.1 %	-1.5 %	-----
Denver, CO Residence	+6.6 %	-1.3 %	+0.2 %	-2.2 %
Boulder, CO Residence	+ 20.2 %	-1.1 %	-3.1 %	-----

With these slightly adjusted results, the predictions from the detailed tools are improved. Use of the shade impact database significantly improves performance prediction as compared to the linear model. The shade database shows performance prediction that is in line with the PVSyst and SunEye tools when they all have accurate shading inputs; given the uncertainty introduced by use of weather data from a distance away from the arrays, as well as mapping shade obstacles from aerial and other images, the difference between the methods is not necessarily significant.

Examination of the adjusted predictions on an annual and monthly (Fig. 10) level for the NREL array shows excellent agreement using the shade database method. Sources of external uncertainty are reduced for this array as the weather data are from the same site, and the regular module-to-module shading lends itself to accurate shadow mapping. One can see in this case that PVsyst tends to underpredict in the months of April, May, and August, when there is minimal shading on the array; it is not clear whether this comes from shadow mapping onto the array or possibly neglecting to account for the added shade tolerance of Sunpower modules.

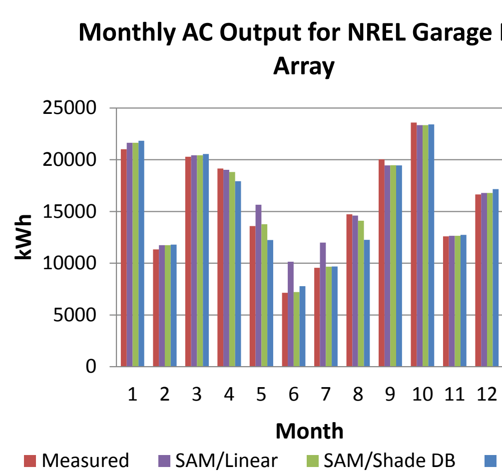

Fig. 10. Monthly comparison of partial shade modeling tools for the NREL garage PV array.

Annual performance predictions made with the shade impact database are also within 1.5% of the measured data for the two residential PV systems, which appears to show similarly excellent agreement. However, closer examination at the monthly level (Figs. 11 and 12) indicates that both the shade database method and the PVsyst simulations overpredict for some months and underpredict for others, on the order of up to 10% per month; the annual performance agreement is in part the result of fortuitous error cancellation.

This underscores one of the great challenges of performance prediction for partially shaded PV systems: modeling of the shade obstacles. Because the effects of partial shading are nonlinear, small differences in size or placement of a tree or other shading obstacle can affect the predicted annual array output by several percent, which may be a greater uncertainty than the differences between performance models. This effect may be compounded as trees grow or are removed during a PV system's lifetime. While this work demonstrates an excellent model for the electrical behavior of PV systems under partially shaded conditions, there is certainly more work to do regarding shade mapping onto an array.

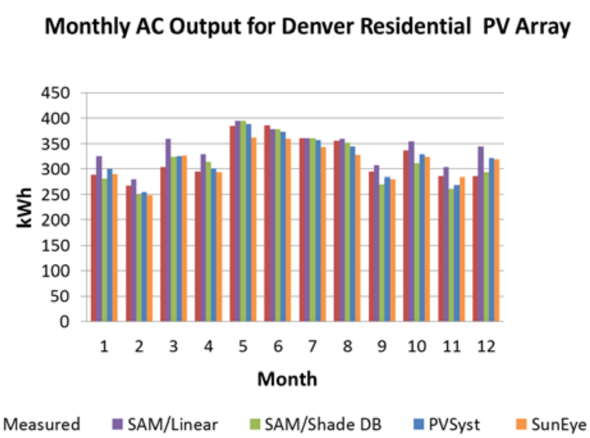

Fig. 11. Monthly comparison of partial shade modeling tools for the Denver residential PV array.

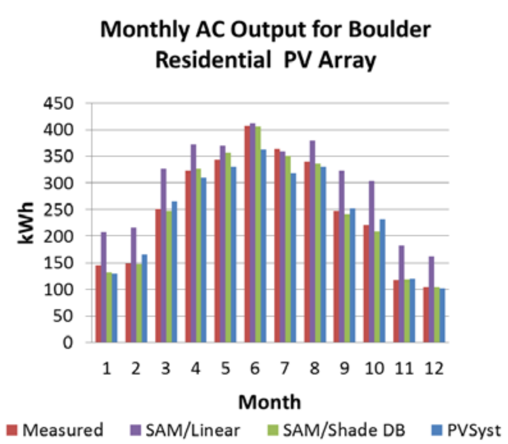

Fig. 12. Monthly comparison of partial shade modeling tools for the Boulder residential PV array

V. Summary

To address the need for a simple way to predict the performance of partially shaded PV systems, this work proposes a lookup table style database of shade impact results (loss percentages), generated using a validated, detailed simulation tool, and encompassing a wide variety of shading scenarios. This shade impact database could be used with any annual PV simulation tool; its small size and fast access time make it suitable for a variety of applications including NREL's SAM and PVWatts modeling tools.

Performance data from several partially shaded PV systems were used to validate use of the shade database with NREL's SAM tool. In each case, the shade database showed improved accuracy compared to SAM's present shade modeling capability, with performance predictions in line with those made using SunEye rooftop shading site survey data, and the detailed shade modeling in PVsyst. However, shade mapping onto the array remains a large source of uncertainty, as slight mistakes in obstacle sizing or placement may have a large impact on annual performance prediction; this is an area for future study. The shade impact database will be made available within NREL's SAM and PVWatts simulation tools, as well as to other software developers by contacting the authors.

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