Validation of Multiple Tools for Flat Plate Photovoltaic Modeling Against Measured Data

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Abstract—**In this validation study, comprehensive analysis is performed on nine photovoltaic systems for which NREL could obtain detailed performance data and specifications, including three utility-scale systems and six commercial-scale systems. Multiple photovoltaic performance modeling tools were used to model these nine systems, and the error of each tool was analyzed compared to quality-controlled measured performance data. This study shows that, excluding identified outliers, all tools achieve annual errors within ±8% and hourly root mean squared errors less than 7% for all systems. Finally, the acceptability of this range of annual error is discussed with regard to irradiance data uncertainty and the use of default loss assumptions, and two avenues are proposed to reduce photovoltaic modeling error.**

Index Terms—**PV modeling error, PVsyst, PVWatts, PV*SOL, photovoltaic models, System Advisor Model, validation**

I. Introduction and Significance

Building upon the work that started in a previous validation study comparing NREL's System Advisor Model (SAM) results to measured data from operating photovoltaic (PV) systems [1], NREL has performed a new study that expands the comparison to include three other photovoltaic performance modeling tools: PVWatts, PVsyst, and PV*SOL. These tools were chosen due to their popularity; additional modeling tools could be considered in future work. The purpose of validating multiple tools in addition to SAM is to give the industry greater confidence in PV modeling results, and to better characterize the abilities and limitations of PV performance modeling in general. Confidence in PV models helps projects secure competitive financing and more accurately characterize expected performance. To date, validation of these tools has been limited (e.g., [2] and [3]), and much validation work has focused on individual submodels, such as the work by Cameron, et al [4]. This study seeks to characterize the error of multiple tools from end to end to see how the interaction of these submodels affects overall PV modeling tool error.

II. About the Tools

The functionality of the tools used in this study overlap, although each tool contains some unique capabilities. A brief summary of each tool examined follows.

- **SAM Version 2014.1.14** (*sam.nrel.gov*): a detailed performance and financial model allowing users to compare energy production and financial outlooks between multiple renewable energy technologies (not just PV).
- **PVWatts Version 1** (*pvwatts.nrel.gov*): a relatively simple (few inputs) PV performance estimation tool designed to give users a starting point for evaluating the feasibility of a PV system.
- **PVsyst Version 6.1.1** (*pvsyst.com*): a detailed PV performance modeling tool specializing in the "study, sizing, and data analysis of complete PV systems... geared to the needs of architects, engineers, researchers" [5].
- **PV*SOL Expert Version 6.0** (*solardesign.co.uk/pvsol-expert.php*): a "3D software program for PV system design" [6], including full component selection, wiring design, and shading analysis.

We also considered including RETScreen Version 4 in the quantitative analysis, which is another relatively simple energy performance and financial modeling tool that allows users to "quickly and inexpensively determine the technical and financial viability of potential renewable energy, energy efficiency and cogeneration projects" [7]. However, this tool simulates only monthly energy production and only takes monthly weather inputs, making a quantitative comparison to the rest of the tools inconsistent because the others all use hourly data and produce hourly results. It is still included in the qualitative comparison of the tools as a reference.

While the tools implement many of the same internal submodels, the inputs accepted and/or required for these tools differ slightly. The differences between expected inputs may give an indication of the complexity of the tools. An overview of the input options available in each tool is shown in Table I (technical inputs only, financial models are not considered in this study).

As shown in Table I, PVWatts and RETScreen accept the fewest system specifications as inputs.[1] This is indicative of the relative simplicity of these tools, demonstrating that they are intended to perform preliminary estimations of the feasibility of a PV system with rough financial metrics, and not intended to perform in-depth performance modeling. SAM, PVsyst, and PV*SOL take far more inputs, indicating their more in-depth performance modeling capabilities. Additionally, as mentioned above, RETScreen's temporal resolution is monthly, where the rest of the tools accept and simulate hourly data.

Each modeling tool uses a series of internal submodels to translate weather data to PV performance estimates, making certain assumptions along the way. These submodels, however,

[1] SAM includes several PV modeling modes, including a complete implementation of the PVWatts tool. In this table, PVWatts is treated separately and its characteristics are not included in the SAM options list.

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TABLE I: OVERVIEW OF THE INPUTS ACCEPTED BY EACH TOOL

Input Category	**Input**	**SAM**	**PVsyst**	**PV*SOL**	**PVWatts**	**RETScreen**
Irradiance Data	GHI	x	x	x		x
	DNI	x	x		x	
	DHI	x	x		x	
	POA		x		x	
Other Weather Data	Temperature	x	x	x	x	x
	Wind Speed	x	x	x	x	x
	Relative Humidity	x		x	x	x
	Hourly Albedo	x			x	
Module Options	Single Diode Model	x	x	x	x	x
	→ From Database	x	x	x		x
	→ User-Entered	x	x	x		x
	Sandia Array Performance Model (Sandia Database)	x	x			
	Simple Efficiency	x				
Inverter Options	Sandia Inverter Model	x				
	→ From CEC Database	x				
	→ User-Entered	x				
	Grid Inverter Model	x				
	→ From Database		x	x		
	→ User-Entered		x	x		
	Simple Efficiency	x				x
System Design	Nameplate Autosize	x	x	x	x	
	No. Modules	x	x	x		x
	Strings/Parallel	x	x	x		
	No. Inverters	x	x	x		
	Tilt/Azimuth	x	x	x	x	x
	Tracking Type	x	x	x	x	x
Tracking Options	Backtracking	x	x			
	Rotation Limit	x	x			
Temperature Model	De Soto NOCT	x	x			
	Thermal Balance Equation (mounting-specific)	x	x	x		
Shading	Self-shading	x	x			
	Near Shading Geometry	x	x	x	x	
	Far Shading Geometry	x	x	x		

do not account for every phenomenon that may occur in a system. Some known phenomena, such as soiling losses, are not explicitly modeled; rather, an assumption is made about the effect that a phenomenon will have on a given system's performance. Frequently, these assumptions are applied as percentages of predicted power (a loss factor or derate). One important aspect of PV performance modeling is the magnitude of these derates for a given system. Table II lists the default values for these derates. Note that Table II does not list all of the power losses that may occur in a system, only the ones that are accounted for with a loss factor instead of a model. For example, thermal losses may have a relatively large effect on system performance, but those losses are modeled explicitly, and not simply accounted for by a loss factor or derate. Therefore, thermal losses do not appear in Table II.

PVWatts and RETScreen are not included in Table II because they stand out from the other tools in their loss assumptions. Rather than providing detailed loss categories representing many different types of losses, both tools provide only one or two loss categories meant to encompass all of the different types of losses experienced by a PV system. PVWatts defaults to a single overall performance derate of 0.77, lower than the total derate of any other tool. RETScreen features only two losses– miscellaneous photovoltaic losses and miscellaneous inverter losses, which roughly correspond to a total DC and AC derate, respectively. These losses do not have any default values; RETScreen offers the guidance that typical values "range from a few percent to 15%", and in extreme cases "as high as 20%" in the help documentation [8]. This is again an indication that the intent of these two tools is slightly different than the others, providing an initial estimation instead of an in-depth analysis.

Of the remaining tools, the default models used and losses assumed are very similar with one notable exception: the soiling loss. SAM defaults to an annual soiling loss of 5% whereas PVsyst and PV*SOL default to soiling losses of 0%. In its help documentation, PVsyst suggests that in medium-rainy climates, a 0% soiling loss may be appropriate, but re-iterates that soiling is "an uncertainty which strongly depends on the environment of the system, raining conditions, etc." and points to a few sources that may offer guidance to users [5]. PV*SOL provides an input for soiling, but does not mention it in the documentation [9]. This is perhaps an indication of the setup ideology of SAM versus PVsyst and PV*SOL; SAM is designed such that it can be run without changing any inputs whereas this might not be the intent of the other two tools.

Advanced users with access to historical performance data might be able to calibrate the loss assumptions in any of the five tools (including PVWatts and RETScreen) for higher accuracy. The main difference is that the more detailed tools (SAM, PVsyst, PV*SOL) allow for more granular adjustment of these loss assumptions and more control over where they

TABLE II: DEFAULT LOSS ASSUMPTIONS OF EACH TOOL

Default System Derates	SAM	PVsyst	PV*SOL
Dev. from wavelength spectrum	N/A	N/A	1%
Annual soiling loss	5%	0%	0%
Total Environmental Derate	0.95	0.99	0.99
Mismatch	2%	1%	2%
Diodes and connections	0.5%	0%	0.5%
DC wiring	2%	Modeled	Modeled
Tracking error	0%	0%	N/A
Nameplate	0%	Module-dependent	0%
Total DC Derate	0.96	0.95	0.98
AC wiring/Cabling losses	1%	0%	N/A
Step-up/External transformer	0%	0%	N/A
Total Interconnection/AC Derate	0.99	1.00	1.00

are applied in the overall modeling process.

III. Methodology

In general, system specifications and performance data were collected for each of the nine systems. The available weather and performance data were subjected to quality control procedures to remove sensor errors and system or component downtime. Because none of the tools utilized account for the effects of snow on PV performance, and because snow was previously shown to have a large effect on model performance [1], hours affected by snow cover were removed from the analysis. Finally, nighttime hours were removed from the analysis in order to avoid misleadingly skewing the hourly error. After these data cleaning procedures, the nine systems were modeled using each of the tools studied. Finally, modeled AC power production predicted by each tool was compared to measured AC power production for each system on an hourly, monthly, and annual basis. Additional details of methodology are given in [1].

The major input choices selected to provide consistency between tools include:

- Total and Beam (GHI and DNI) weather file inputs were used in each tool.
- Each tool's implementation of the single diode module model was used.
- Default loss assumptions/derates were used, with the exception of availability losses. These losses were set to zero because we were comparing to quality-controlled data with downtime removed. The only non-zero default availability loss was in PVWatts.
- The appropriate thermal model configuration for the system was chosen in each tool:
  - SAM: the "Mounting Standoff" chosen on the "Module" page was:
    - "Ground or rack mounted" for free-standing systems
    - "Greater than 3.5 inches" for rooftop systems (information about the actual standoff distances was not available)
  - PVsyst: the "Constant loss factor Uc"[2] chosen in the "Field Thermal Loss Factor" section of the detailed loss parameters page was:
    - 29 W/m^{2}K for free-standing systems
    - 20 W/m^{2}K for rooftop systems
  - PV*SOL: the "Installation Type" chosen was:
    - "Free-Standing" for free-standing systems
    - "With Ventilation" for rooftop systems
  - PVWatts: No mounting structure input option is available in PVWatts Version 1.

It is important to acknowledge that many of the results presented here do not match the results presented in the previous validation study [1]. There are a variety of reasons for these differences, including some of the model choices outlined above. These differences will be enumerated in a forthcoming report [10].

IV. Quantitative Results

A. Annual Results

Annual error is computed as the total predicted annual AC energy production minus the total measured annual AC energy production, normalized by the total measured annual AC energy production. The annual error is presented in Figures 1 and 2 for all nine systems using the default loss assumptions of the available tools. Note that we were unable to model the two largest systems, DeSoto and FirstSolar1, with PV*SOL because the "Expert" version limits the number of modules that can be used in a simulation to six subarrays of 65535 modules each, which is not enough modules to model a larger utility-scale system.

PV*SOL shows significantly higher error for the Mesa Top System than any of the other examined systems. This is expected since PV*SOL does not take row-to-row spacing or backtracking limits as inputs, meaning that it inherently cannot correctly model a one-axis tracking system. Therefore, this result is considered an outlier and removed from overall results. Note that we were unable to model the other one-axis

[2]Per guidance from PVsyst.

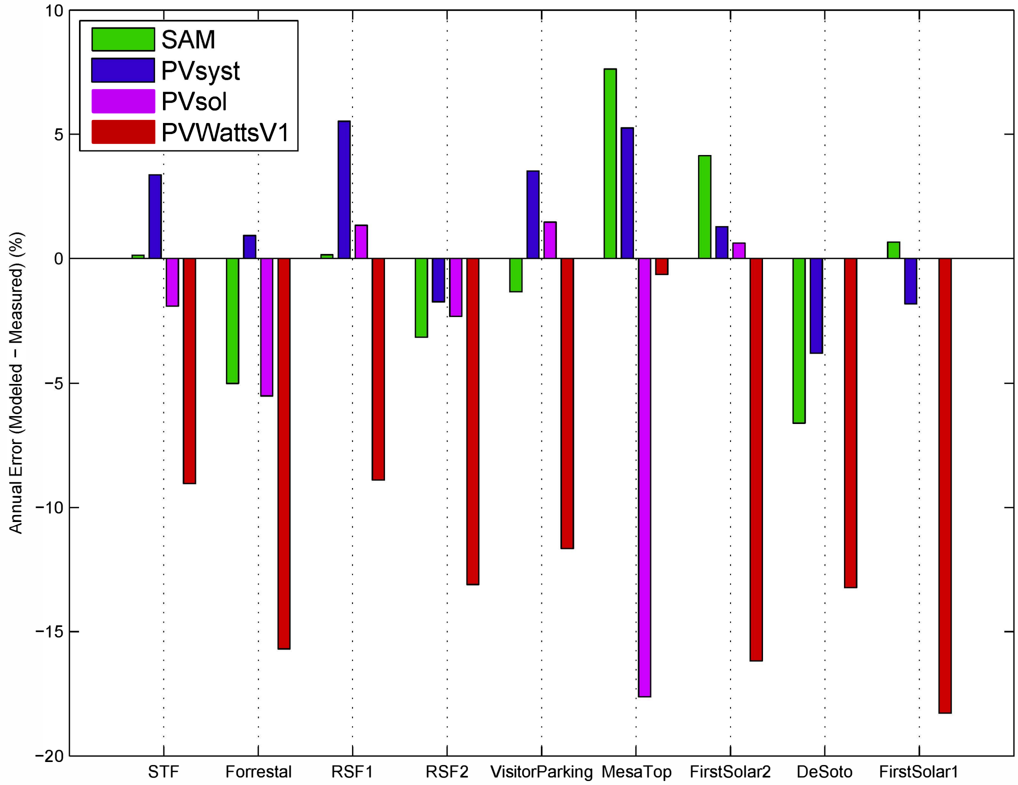

Fig. 1: Annual error (modeled-measured) using each tool, sorted in order of system size

tracking system in PV*SOL since it is one of the two largest systems.

Among the various tools, PVWatts Version 1 quickly emerges as an outlier due to its greater underprediction of every system compared to the other tools. This underprediction ranges from -0.6% to -18.3%, averaging -11.9%. The underprediction is much lower for the Mesa Top system than the other systems due to the fact that PVWatts Version 1 assumes that one-axis tracking systems are unshaded, which is not an accurate assumption for this system. This trend of underprediction is an indication that the default PVWatts Version 1 derate[3] is too low for many real systems compared to measured operation. NREL is working to update the PVWatts derate to a more appropriate value.

Apart from these two outliers, there were no apparent correlations between system characteristics (size, location, technology type, etc.) and the magnitude of model error for that system. Future work should further investigate correlations in order to identify possible sources of error.

Table III shows the range of errors seen with each tool for a subset of six systems (S&TF, Forrestal, RSF1, RSF2, Visitor Parking, and FirstSolar2). This subset was chosen because these systems can be appropriately modeled by all of the tools. All errors shown in the table were calculated using the model choices listed in Section III.

TABLE III: RANGE OF ANNUAL ERRORS FOR A SUBSET OF SIX SYSTEMS

Tool	Error Range
SAM	-5.0% $\rightarrow$ 4.1%
PVsyst	-1.7% $\rightarrow$ 5.5%
PV*SOL	-5.5% $\rightarrow$ 1.4%
PVWatts	-16.2% $\rightarrow$ -8.9%

B. Hourly Results

The root mean square error is a commonly used metric to evaluate the accuracy of a PV performance modeling tool on an hourly basis. The RMSE was computed comparing predicted hourly energy production to measured hourly energy production, then normalized by the maximum measured hourly production of that system. The RMSE for all tools for all systems is shown in Figure 3. Again, the RMSE is not presented for PV*SOL for the two largest systems because we were unable to model them in PV*SOL Expert.

The same two outliers as in the annual error are present in the hourly RMSE– PVWatts and the Mesa Top system in PV*SOL. Apart from these two outliers, all RMSEs are less than 7% for all tools and all systems. The RMSE also seems to vary similarly between systems for all tools (e.g., all tools have a higher RMSE for the RSF1 system than the Forrestal system), indicating that the RMSE is likely more dependent

[3] 0.77 is the default derate found in PVWatts; however, since the availability loss was zeroed for the simulations in this study, the total derate used in this study was 0.79.

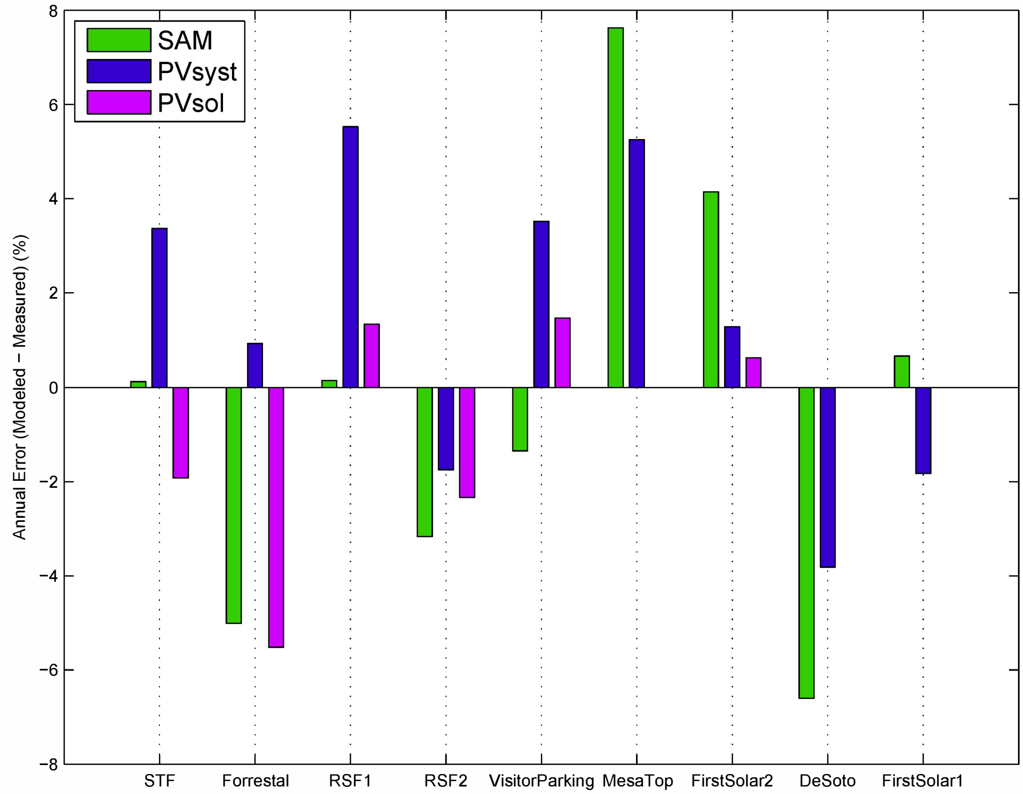

Fig. 2: Close-up of annual error with outliers excluded, sorted in order of system size

on the data quality and specifications of the system analyzed than the tool used. No tool consistently has higher or lower RMSE compared to other tools, excepting the two outliers. For the same subset of six systems (shown in Table III) that SAM, PVsyst, and PV*SOL could all model appropriately, the average normalized hourly RMSE was approximately 4% for each of the three tools.

V. Conclusions

This work highlights the distinction between the three detailed performance modeling tools examined (SAM, PVsyst, and PV*SOL), and the simpler tool, PVWatts. PVWatts underestimates all systems due to its much higher default loss assumptions compared to the detailed tools. If adjusted, PVWatts could do a much better job predicting annual performance. This default loss value is being updated in an upcoming release of PVWatts in order to make it more representative of modern systems.

Of the three detailed performance modeling tools (excluding one-axis tracking systems in PV*SOL, which the makers of PV*SOL confirm that this tool does not accurately model), all annual errors were within 8% and all hourly RMSEs were less than 7% for all systems.

One important consideration in the evaluation of these results is that the error includes the measurement uncertainty of the irradiance data being input into the models. The minimum uncertainty of high-quality measured irradiance data ranges from approximately 2-8% depending on the instrument used and how well it is maintained. Therefore, the model errors seen in this study could be within the uncertainty of the irradiance data used for these systems. However, it is difficult to disaggregate irradiance measurement error from model error. This makes sensitivity analysis an important part of PV modeling. Running multiple weather sets through a PV modeling tool can help a user to hone in on the best possible estimate of energy production.

Another opportunity to reduce model error lies in the derate or loss assumptions used in PV modeling. In this study, the default derates were used in all tools, with the exception of the availability loss. As with any other model, all PV models (including PVWatts) can be "tuned" to get the correct annual number for a given system by adjusting the derates. Expert PV modelers may have the data and experience to make more accurate loss assumptions for a given system; however, the data to make informed PV modeling derate assumptions is lacking in the industry as a whole. Because derates can have such a large effect on the accuracy of energy predictions, improving derate assumptions is a prime opportunity for the industry to reduce PV modeling error. Two avenues to enable all modelers to make more informed decisions about system losses include (1) developing models to replace some of the derates in PV modeling today, which would enable a better prediction of the effect of certain factors on energy production,

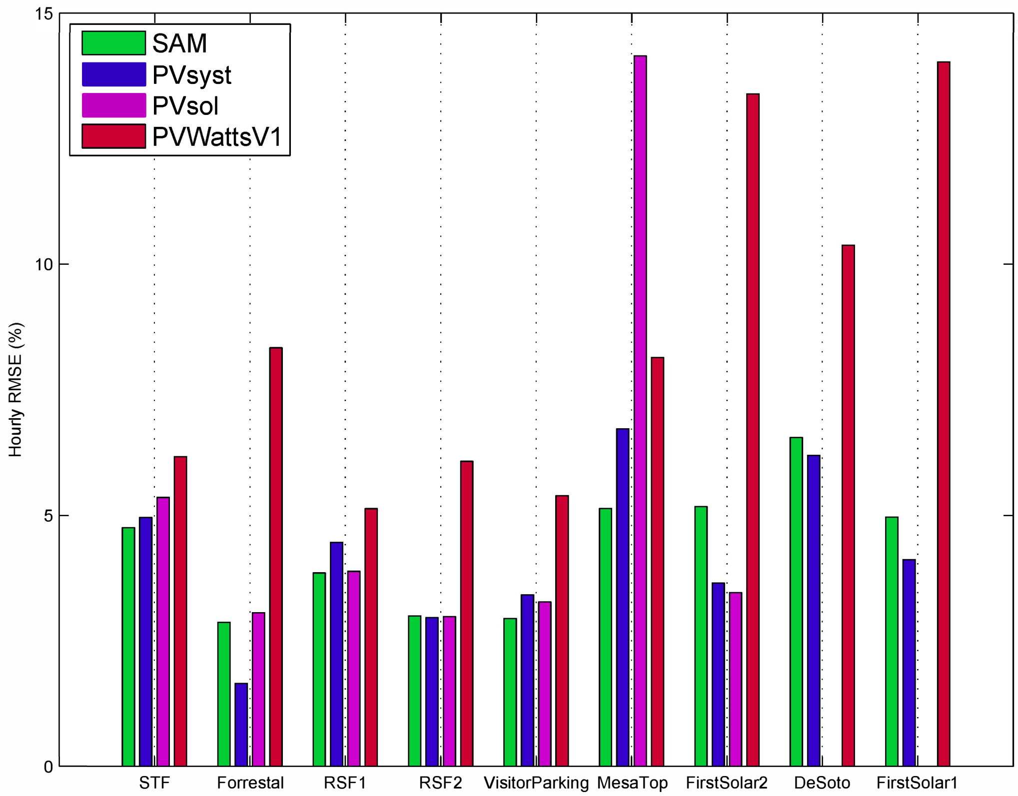

Fig. 3: Normalized RMSE using each tool in order of system size

and (2) providing better guidance on what values to use for certain derates by performing studies to determine more representative values for a given system characteristic (e.g., average soiling derates by location).

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