Comparison of Photovoltaic Models in the System Advisor Model

Nate J. Blair
Strategic Energy Analysis Center
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
nate.blair@nrel.gov

Paul Gilman
3164 SE Salmon St
Portland, OR 97214
paulgilman@earthlink.net

Aron P. Dobos
Strategic Energy Analysis Center
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
aron.dobos@nrel.gov

ABSTRACT

The System Advisor Model (SAM) is free software developed by the National Renewable Energy Laboratory (NREL) for predicting the performance of renewable energy systems and analyzing the financial feasibility of residential, commercial, and utility-scale grid-connected projects. SAM offers several options for predicting the performance of photovoltaic systems. The model requires that the analyst choose from three photovoltaic system models, and depending on that choice, possibly choose from three module and two inverter component models. To obtain meaningful results from SAM, the analyst must be aware of the differences between the model options and their applicability to different modeling scenarios. This paper presents an overview the different photovoltaic model options, and presents a comparison of results for a 200 kW system using different model options

1. INTRODUCTION

The System Advisor Model (SAM) is software for renewable energy project analysis that integrates a detailed system performance model with a cost and financial model for a range of applications. It is a package of performance and financial models that can represent different kinds of renewable energy systems for projects with different financial structures. As much as possible, SAM reports the same metrics and uses consistent assumptions for the different models to facilitate comparing technology and financing options for project pre-feasibility studies or for academic research studies. SAM is developed by the National Renewable Energy Laboratory in collaboration with Sandia National Laboratories with funding from the Department of Energy, and is available for download for free. [1]

SAM is among several photovoltaic system models, but is unique in the way it integrates a photovoltaic performance model with a detailed financial model for a given project, and in its ability to compare photovoltaic systems to other renewable energy systems. It also offers additional analysis tools for optimization, parametric, and statistical analysis. Some other photovoltaic systems models are PVsyst, PV Design Pro, PVSol, PVSim, PV F-Chart, and Polysun. [2]

Modeling a photovoltaic system in SAM involves choosing whether to model the system using a model that represents the entire system with just a few inputs, or a more detailed model that uses separate component models for the module and inverter with additional inputs for the and array layout. This paper describes each of the photovoltaic model options, and then compares results from the different models.

2. PHOTOVOLTAIC MODEL OPTIONS

SAM offers three options for modeling a photovoltaic system: The PVWatts System model is an implementation of NREL's online photovoltaic calculator; the Flat Plate PV model combines separate, user-selectable component models for the module and inverter with a set of parameters describing the array layout to represent the system; and the High-X Concentrating PV model is for concentrating PV (CPV) systems.

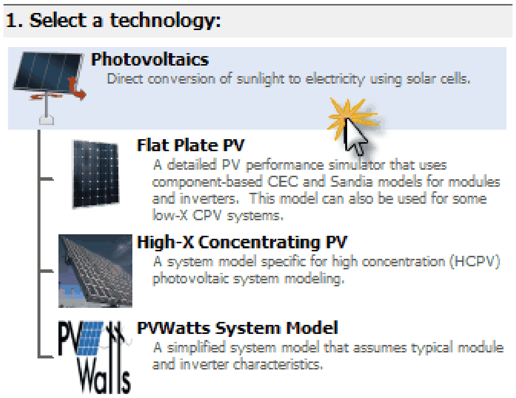

Fig. 1: Screenshot of the SAM user interface showing the three photovoltaic model options.

All three photovoltaic models use an irradiance processor to determine the solar irradiance incident on the array (also called total plane-of-array irradiance) from hourly solar radiation and meteorological data in a TMY2, TMY3, or EPW file. [3,4,5] The solar resource data in the file may be measured, generated by a computer model, or a combination of the two. Depending on the photovoltaic model, the irradiance processor may use one of three different algorithms for calculating the incident irradiance for the array tracking type and location of the system. [6,7,8] The photovoltaic models use wind speed, and ambient temperature data to model the effect of temperature on the array's performance.

The PVWatts System model uses a simple set of inputs that define the system's overall capacity and conversion efficiency, and relies on a fixed set of assumptions about the module and inverter performance characteristics.

The Flat Plate PV and High-X Concentrating PV models multi-step algorithm's use separate models for the module and inverter with a set of parameters describing the array to represent the system's performance. Each model first calculates the array's DC power output using the module model and parameters describing the array. Next it applies a user-specified DC derate factor to account for electrical losses from array tracking errors and module mismatch, differences between nameplate rating and actual performance, and other factors not represented in the algorithm. The inverter model converts the derated DC power value to the inverter's AC output power. SAM then applies an AC derate factor to account for losses on the AC side of the system, and sends the resulting AC power value to the financial model.

All three models use a set of user-specified shading factors that adjust the irradiance incident on the array to represent the effect of shading of the array by nearby objects. The Flat Plate PV and High-X Concentrating PV models also have inputs for a set of monthly soiling factors that further reduce the incident irradiance. The soiling and shading factors are optional inputs, so each model can run with or without considering these effects.

SAM applies a set of performance adjustment factors to the system's AC output to determine the AC electricity delivered to the grid. These factors can be used to represent system availability, annual degradation in system output, curtailment, outages, or other operating losses or constraints.

SAM is an hourly simulation model, so the calculations described above occur for each of the 8,760 hours in a typical year. Efforts are underway to develop subhourly versions of the model to allow for simulations based on solar resource data in smaller time steps.

TABLE 1: SUMMARY OF SAM'S PHOTOVOLTAIC MODELS

	Flat Plate	PVWatts	High-X CPV
Array DC output	•	•	•
Inverter AC output	•	•	•
Temperature effects	•	•	•
Array shading	•	•	•
Tracking options	•	•	2-axis only
Row-to-row shading	•		
Backtracking	•		
Mounting options	•		
Multiple subarrays	•		

3. PVWATTS SYSTEM MODEL

PVWatts is a simple but widely used online photovoltaic calculator. [9,10] SAM includes an implementation of the model for analyses that do not require the component-level detail of the Flat Plate PV model, such as for preliminary output predictions and financial modeling before the details of a system's design are known, or for geospatial analysis involving systems in many locations where minimizing simulation is important.

The PVWatts System Model is appropriate for modeling rack-mounted systems with crystalline silicon modules. The PVWatts model calculates cell temperature, array DC output, and system AC output using a single derate factor and internal assumptions about the inverter efficiency.

In PVWatts, the photovoltaic system is characterized by four user-specified inputs: The array's DC power rating, a single DC-to-AC system derate factor, array tilt and azimuth angles, and tracking type, which can be fixed for no tracking, one-axis tracking, or two-axis tracking. The derate factor can be chosen to represent shading, module mismatch, soiling of the array, and other effects not represented in the model calculations. A typical value for PVWatts derate factor is 0.77 [11,12]. The PVWatts model is an adaptation of the Sandia PVFORM algorithms [13,14].

4. HIGH-X CONCENTRATING PV

The High-X Concentrating PV (HCPV) model represents a concentrating photovoltaic module using a table of user-specified cell efficiency values at different plane-of-array direct normal irradiance levels, and a set of factors to account for losses due to optical error, tracker misalignment, and wind flutter. The HCPV model also includes air mass modifier and temperature coefficients that can be adjusted to represent different modules. [15]

The HCPV module model is coupled with the Sandia inverter model (briefly described in Section 5.4) and array layout parameters to represent a complete system. Power for the tracking system is represented as a fraction of the array's DC nameplate capacity, and derate factors represent tracking error, module mismatch, and wiring and connections losses. User-specified limits on tracker rotation angles and a maximum wind speed that triggers tracker stowing further constrain the system's output.

The HCPV model calculates hourly cell efficiency and temperature, module efficiency and backplate temperature, array DC power output, and the inverter AC power output. It reports gross and net power output values to show the effect of the various derate factors. The model also calculates and reports hourly plane-of-array irradiance and air mass values.

NREL developed the HCPV model specifically for SAM to allow for some basic comparisons between HCPV and other renewable energy technologies. The model will be improved as results from ongoing research on characterizing CPV system performance becomes available.

5. FLAT PLATE PV MODEL

The Flat Plate PV model represents a photovoltaic system with separate performance models for the module and inverter, and a set of parameters describing the array layout. It can represent modules with crystalline or thin-film cells.

The Flat Plate PV model offers three options for modeling a photovoltaic module's performance, the Sandia, CEC, and or simple efficiency module model; and two options for modeling inverter, the Sandia or single-point efficiency model. Each option is described in more detail below .

The array layout parameters define the number of modules per string and number strings in parallel in the array, AC derate factors, and options for the sky diffuse irradiance model (Isotropic, HDKR, or Perez). [8]

The array can consist of up to four subarrays, where each subarray can have different orientation, tracking with optional backtracking for 1-axis tracking, shading and soiling factors, and DC derate factors. SAM assumes that each sub-array operates at its maximum power point. It also assumes that the modules in each subarray operate uniformly at the same cell temperature and maximum power point. Similarly, for systems with more than one inverter it assumes that all inverters have the same hourly conversion efficiency.

Module mismatch losses in each subarray can be represented using a DC derate factor. For an array with more than one subarray used in combination with the CEC module model, SAM can calculate subarray mismatch losses caused by subarrays with different maximum power point voltages.

The Flat Plate PV model calculates the hourly cell temperature, DC output, and module conversion efficiency for each subarray, and the inverter DC input voltage and inverter AC output. The subarray mismatch option also calculates subarray DC voltages. Gross and net AC and DC power output values to show the effect of the AC and DC derate factors.

The array's hourly DC output depends on the results of the module performance model (described below), electrical configuration of modules and subarrays, and tracking type and soiling and pre-inverter derate factors for each subarray. The array's DC output is the input to the inverter model, which determines the system's AC output.

5.1 Sandia Module Model

The Sandia PV Array Performance Model with Module Database calculates hourly module efficiency values using a set of equations and coefficients developed from data measured from modules (and, in some cases, arrays) in realistic outdoor operating conditions. This empirical model requires 40 coefficients calculated from measurements taken over multiple days of module testing at a certified test facility. [16]

SAM stores a database of module coefficients for commercially available modules in a library, which NREL updates as coefficients from new test results become available from Sandia. The Sandia module library includes modules with thin-film cells, including amorphous silicon, copper indium diselenide (CIS), cadmium telluride (CdTe), and heterojunction with intrinsic thin layer (HIT). Because the Sandia model coefficients are based on measured data, the Sandia model may more accurately represent the performance of thin-film modules at low light levels than the CEC and simple efficiency models. This is an area that requires further study. [17]

5.2 CEC Module Model

The California Energy Commission (CEC) Performance Model predicts module performance based on a database of module characteristics for commercially-available modules determined from manufacturer's module ratings. Like the Sandia model, the CEC model calculates hourly module efficiency values.

The CEC module model is an implementation of the five-parameter model developed at the University of Wisconsin-Madison, with an additional temperature correction adjustment coefficient. It is a single diode model whose physical parameters can be calculated for a particular PV module from the specifications provided on a typical manufacturer datasheet. [9]

SAM offers two versions of the CEC module model, one that uses parameters stored in a library, and one that allows the user to specify parameters by hand from a manufacturer's datasheet. The library stores parameters from the database of modules maintained by the California Energy Commission, which regularly updates the database with data for modules currently available in the market. Over 10,000 modules are in the database as of this writing. [18] For the user-specified parameter option, SAM uses an internal algorithm to calculate the model coefficients from the module parameters (Vmp, Imp, Voc, Isc, temperature coefficients, and number of cells in series). [19]

The CEC module model offers a choice of two temperature correction algorithms that calculate the cell temperature for different module mounting configurations, including on a rack that allows air to flow over the module back, flush with no airflow over the module back, or building-integrated. The NOCT cell temperature algorithm is from the original five-parameter model [9], and the Mounting-specific Cell Temperature Model is a first-principles heat transfer algorithm. [20,21]

5.3 Simple Efficiency Model

The Simple Efficiency Module Model represents module performance using a set of parameters for the module area, irradiance-to-DC-output conversion efficiency values for a range of irradiance levels. [22] It also uses a set of coefficients for the Sandia temperature correction algorithm [16].

NREL developed the simple efficiency module specifically for SAM to allow for analyses that require specifying the module efficiency as an input, such as for parametric studies on module efficiency. The simple efficiency model is the least accurate of the three models for predicting the performance of specific modules.

We have excluded the simple efficiency model from this comparison because its results are strongly dependent on the user-specified module efficiency and temperature coefficients, which can be chosen to match the results of the other models. For the other photovoltaic module models, those parameters are determined by values stored in libraries that the analyst cannot easily change.

5.4 Inverter Models

SAM's two inverter models use the DC output from one of the module models to calculate the system's AC output.

The Sandia Model for Grid-connected Inverters calculates the inverter's hourly efficiency using coefficients from a library of hundreds of inverters developed from manufacturer specifications and field test data. [23,24]

The Single Point Efficiency Model uses two user-specified inputs, the rated AC power in Watts, and rated DC-to-AC conversion efficiency. It assumes that the inverter's efficiency is constant from hour to hour. [25]

The PVWatts model represents the inverter using an internal algorithm without separate inputs for the module and inverter algorithms. [10]

This comparison uses the Sandia inverter model with coefficients for the SMA America 36 kW inverter from the default inputs for the Flat Plate PV model with commercial financing. Because we used the same inverter with both module models, the comparison does not provide insight into SAM's inverter models.

6. COMPARISON OF PV MODEL RESULTS

This section describes a comparison of SAM performance model results for a 200 kW (rated DC kilowatts of array capacity) photovoltaic system with a fixed array (no tracking) using the Sandia module model, CEC module model, and PVWatts system model. The Sandia and CEC models use coefficients from their respective libraries for the SunPower SPR-210-WHT-U module.

The remaining model input values are the SAM default values for a commercial photovoltaic system. For each case in the comparison, only the module model was varied. For the PVWatts cases, a 200 kW system was modeled with two DC-to-AC derate factors, 0.77 and 0.86.

The graph of total monthly system AC output in Figure 2 shows that the simulation results for the Sandia and CEC module models are in close agreement with monthly values within 2%. The graph also shows that the PVWatts derate factor of 0.86 more closely matches the other model results than the default value of 0.77.

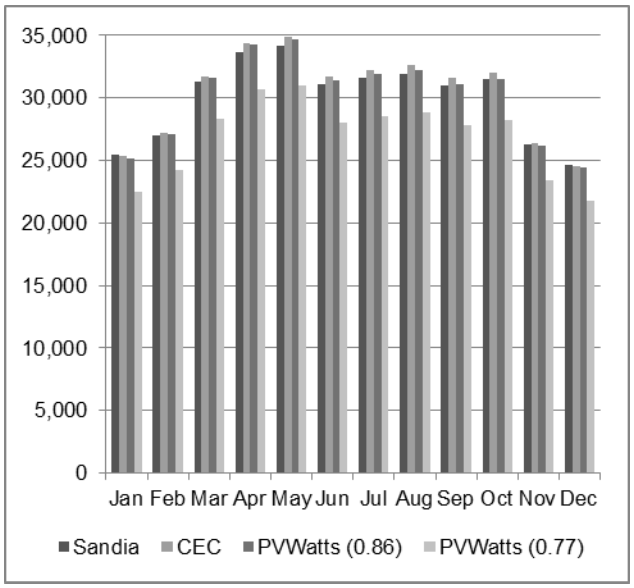

Fig. 1: Graph of system monthly output in kWh/month for the same 200 DC kW system modeled using the Sandia and CEC module models, and with the PVWatts model with two different DC-to-AC derate factors.

The monthly results also show that the difference between the CEC and Sandia module models is greater in the summer months than in the winter months. This difference is caused by the different temperature correction algorithms used by each model: The Sandia model predicts lower cell temperatures under the same ambient temperature and wind speed conditions than the CEC model with the NOCT cell temperature model.

Table 2 shows the system total annual AC output for each case along with the levelized cost of energy (LCOE) based on the SAM default cost and financing assumptions for a commercial photovoltaic project. The Sandia, CEC, and PVWatts with 0.86 derate factor models are in close agreement, while the PVWatts with 0.77 predicts a lower annual output and higher LCOE.

For the TMY2 weather data used for this comparison, the differences between photovoltaic model results is within the uncertainty of the weather data. [26] The differences in LCOE are also within the uncertainty of the various cost and financial assumptions. This suggests that any of the three model options are suitable for estimates of a PV system's output or cost.

TABLE 2: ANNUAL OUTPUT AND LCOE FOR THE SIMULATIONS SHOWN IN FIGURE 1

	Annual Output (kWh/yr)	LCOE (¢/kWh)
Sandia Module	360,000	11.8
CEC Module	365,000	11.7
PVWatts (.86)	361,000	11.8
PVWatts (.77)	323,000	13.2

7. CONCLUSIONS

SAM's implements several different photovoltaic models, which each use different algorithms and databases to represent a photovoltaic system and predict its performance. For a system with crystalline silicon modules, the Flat Plate PV CEC and Sandia module models and the PVWatts System Model predict total monthly AC output values within 2.0% of each other, and for a financial analysis using SAM's commercial financing model with default values, an LCOE within 0.1 cent per kilowatt hour.

For the PVWatts model, the default derate factor of 0.86 results in monthly AC output values much closer to the Flat Plate PV model than the default value of 0.77.

NREL has developed case studies comparing SAM results to data measured from installed systems [27] and is involved in ongoing efforts to validate model results against measured data.

8. ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

9. REFERENCES

(1) System Advisor Model website. https://sam.nrel.gov/

(2) Yates, T., Hibberd, B., Production Modeling for Grid-Tied PV Systems, Solar Pro Magazine, Issue 3.3, April/May 2010

(3) Marion, W., Urban, K., User’s Manual for TMY2s,. National Renewable Energy Laboratory, 1995 http://rredc.nrel.gov/solar/pubs/tmy2/titlepg.html

(4) Wilcox, S., Marion, W., Users Manual for TMY3 Data Sets, National Renewable Energy Laboratory, NREL/TP-581-43156, 2008

(5) Crawley, D., Hand, J., Lawrie, L., Energy Plus Weather File Documentation, 1999 http://apps1.eere.energy.gov/buildings/energyplus/pdfs/weatherdatainformation.pdf

(6) Liu, B. Y. H., Jordan, R. C., Daily insolation on surfaces tilted toward the equator, ASHRAE Journal 3(10), pp. 53-59, 1961

(7) Perez, R., Ineichen, P., Seals, R., Michalsky, J., Stewart, R., Modeling Daylight Availability and Irradiance Components for Direct and Global Irradiance, Solar Energy, 44(5), pp. 271-289, 1990

(8) Duffie, J., and Beckman, W., Solar Engineering of Thermal Processes, John Wiley & Sons, Hoboken, NJ, 3rd Edition, 2006

(9) De Soto, W., Klein, S. A., and Beckman, W. A., Improvement and Validation of a Model for Photovoltaic Array Performance, Solar Energy, 80(1), pp. 78-88, 2006

(10) Marion, W., Anderberg, M. PVWATTS - An Online Performance Calculator for Grid-Connected PV Systems, Proceedings of the ASES Solar Conference, June 15-21, Madison WI, 2000

(11) PVWatts Version 1 Online Derate Calculator. 2012 http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/derate.cgi

(12) PVWatts Version 1 Online Parameter Reference. 2012 http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/change.html

(13) Fuentes, M. K, A Simplified Thermal Model for Flat-Plate Photovoltaic Arrays, Sandia National Laboratories, SAND85-0330, 1987

(14) Menicucci, D. F., Fernandez, J. P., User's Manual for PVFORM: A Photovoltaic System Simulation Program For Stand-Alone and Grid-Interactive Applications, Sandia National Laboratories, SAND85-0376, 1988

(15) Gilman, P., High-X Concentrating PV (HCPV), System Advisor Model Help System, 2013 https://www.nrel.gov/analysis/sam/help/html-php/index.html?pvhcpv_high-x_concentrating_pv_hcpv.htm

(16) King, D., Boyson, W., Kratochvil, J., Photovoltaic Array Performance Model, Sandia National Laboratories, SAND2004-3535, 2004

(17) Cameron, C., Boyson, W., Riley, D., Comparison of PV System Performance-Model Predictions with Measured PV System Performance. 33rd IEE PVSC, San Diego, CA 2008

(18) California Energy Commission CEC PV Calculator http://gosolarcalifornia.org/tools/nshp calculator/index.php

(19) Dobos, A. P. An Improved Coefficient Calculator for the CEC Photovoltaic Module Model, ASME Journal of Solar Energy Engineering, 2012

(20) Gilman, P.., Flat Plate PV Module Model: Simple Efficiency Module Model, System Advisor Model Help System, 2013 https://www.nrel.gov/analysis/sam/help/html-php/index.html?pvfp_module.htm

(21) Neises, T. Development and Validation of a Model to Predict the Temperature of a Photovoltaic Cell. University of Wisconsin-Madison, Master's Thesis, 2011

(22) Neises, T., Klein, S., Reindl, D., Development of a Thermal Model for Photovoltaic Modules and Analysis of NOCT Guidelines, Journal of Solar Energy Engineering, 134(011009), 2012

(23) Bower, W., Whitaker, C., Erdman, W., Fitzgerald, M., Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems. California Energy Commission, 2004 http://www.gosolarcalifornia.org/equipment/documents/2004- 11-22 Test Protocol.pdf

(24) King, D., Gonzalez, S., Galbraith, G., Boyson, W., Performance Model for Grid-Connected Photovoltaic Inverters, Sandia National Laboratories, SAND2007- 5036, 2007

(25) Gilman, P., Inverter: Single Point Efficiency Inverter Model, System Advisor Model Help System, 2013 https://www.nrel.gov/analysis/sam/help/html-php/index.html?pvfp_inverter.htm

(26) Stoffel, T., Renne, D., Myers, D., Wilcox, S., Sengupta, M., George, R., Turchi, C., Concentrating Solar Power: Best Practices and Use of Solar Resource Data, National Renewable Energy Laboratory, NREL/TP-550-47465, 2010

(27) SAM case studies. https://sam.nrel.gov/content/case-studies