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Modeling Photovoltaic and Concentrating Solar Power Trough Performance, Cost, and Financing with the Solar Advisor Model

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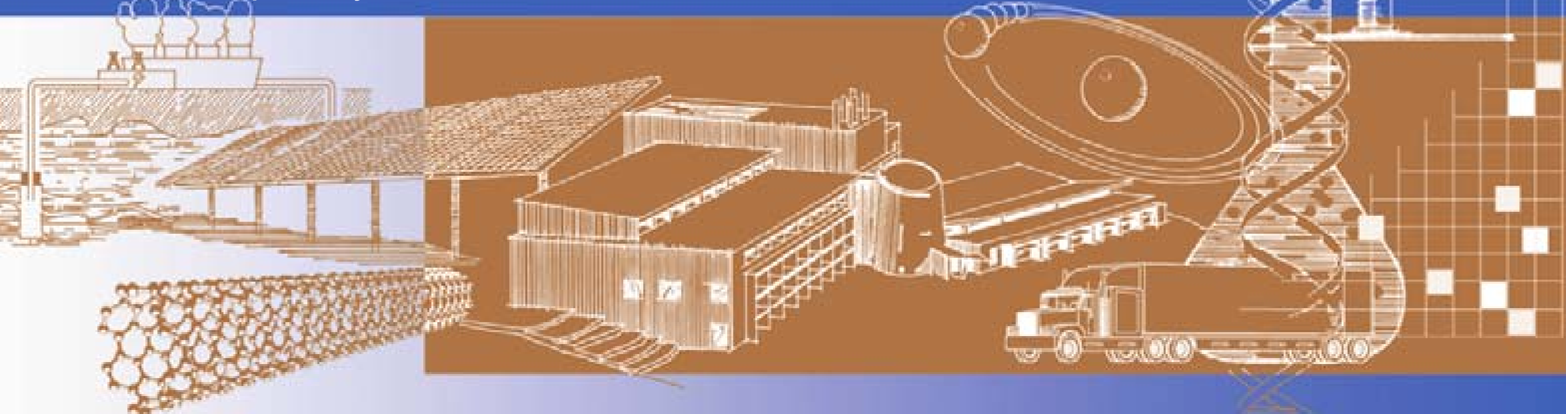

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MODELING PHOTOVOLTAIC AND CONCENTRATING SOLAR POWER TROUGH PERFORMANCE, COST, AND FINANCING WITH SOLAR ADVISOR MODEL

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ABSTRACT

A comprehensive solar technology systems analysis model, the Solar Advisor Model (SAM), has been developed to support the federal R&D community and the solar industry by staff at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratory. This model is able to model the finances, incentives, and performance of flat-plate photovoltaic (PV), concentrating PV, and concentrating solar power (specifically, parabolic troughs).

The primary function of the model is to allow users to investigate the impact of variations in performance, cost, and financial parameters to better understand their impact on key figures of merit. Figures of merit related to the cost and performance of these systems include, but aren't limited to, system output, system efficiencies, levelized cost of energy, return on investment, and system capital and O&M costs.

SAM allows users to do complex system modeling with an intuitive graphical user interface (GUI). In fact, all tables and graphics for this paper are taken directly from the model GUI. This model has the capability to compare different solar technologies within the same interface, making use of similar cost and finance assumptions. Additionally, the ability to do parametric and sensitivity analysis is central to this model.

There are several models within SAM to model the performance of photovoltaic modules and inverters. This paper presents an overview of each PV and inverter model, introduces a new generic model, and briefly discusses the concentrating solar power (CSP) parabolic trough model. A comparison of results using the different PV and inverter models is also presented.

1. INTRODUCTION

Originally, the Solar Advisor Model (SAM) was developed to meet the needs of the systems driven approach (SDA) that was adopted by the U.S. Department of Energy's (DOE) Solar Energy Technologies Program (SETP) (**1**). By clearly establishing the connection between market requirements and R&D efforts (and how specific R&D improvements contribute to the overall system cost and performance), the SDA approach was designed to allow managers to allocate resources more efficiently. The DOE SETP has chosen SAM for its Solar America Initiative (SAI). Some applicants for SAI funding opportunities use SAM to calculate benchmark and projected performance and cost metrics. The SAI Merit Review Committee also uses SAM to both evaluate applications, and to track successful applicants' progress toward meeting their cost and technical goals (**2**).

SAM is able to integrate the financing, costing, and performance of systems, and makes it possible to apply consistent financing and cost assumptions across all solar technologies. This is done by providing a set of financial assumptions that are appropriate for the three typical solar markets: residential, commercial, and utility-scale. For example, the model can show how levelized cost of energy for the same PV technology varies when it is purchased and installed by a homeowner, commercial building developer, or utility-scale power generation company. Finally, because financial incentives are so critical for all solar technologies, a detailed incentives approach has been developed.

Although SAM was originally developed for DOE planning and the SAI, interest in the model from industry stakeholders has resulted in a change of focus. Valuable feedback from users in both the PV and CSP industries is shaping model development, especially in the area of performance modeling described in this paper. As of February 2008, more than 1,000 people have downloaded SAM, which is available for free on the SAM Web site (**3**).

2. Basic Performance Model

To calculate the levelized cost of energy (LCOE) and other system-level metrics, SAM needs to know the annual and hourly energy production from the system. For DOE program planning purposes, researchers need to show how their technology improvements will impact the final system-level metrics. For industry analysts, the output of the specific PV system that they are planning to develop in the particular location is desired. Therefore, the SAM model needs to have an hourly, detailed performance model of the system. Behind the SAM user interface, a series of TRaNsient SYstem Simulation Program TRNSYS **(4)** models are being run. TRNSYS was chosen for its prior validation, extensive library of solar-system simulation models, and execution speed (compiled Fortran executes an annual simulation in a few seconds).

TRNSYS has the capability to use a variety of weather file formats. SAM can handle TMY2 formats **(5)** and EnergyPlus formats **(6).** Additional input data formats will be added in future versions. The necessary hourly weather data variables (including global, direct and diffuse radiation, temperature, wind speed, etc.) are obtained from these weather files and processed to be appropriate for the selected solar technology. The SAM user can select from several standard models for calculating the plane of array irradiance based on the horizontal radiation data including the isotropic sky model, the Hay and Davies Model, the Reindl Model, and the Perez Model (see Fig. 1). Additionally, the SAM user can select one of two different sets of radiation inputs to use from the weather file. Due to inconsistencies between total, beam, and diffuse radiation present in some weather data, using either the total and beam radiation from the file (and calculating the diffuse radiation internally) or starting with the beam and diffuse radiation (and summing them to the total internally) can give statistically different hourly outputs. This is especially important when attempting to match SAM results with other programs or measured output data. Therefore, the settings in SAM allow the user to select either set of inputs to use. For all of the model comparison analysis in this paper, the Perez tilted surface model and the "total and beam" data inputs options, which are the current default values, were selected.

SAM also allows the user to site the PV array (or parabolic trough field) by adjusting the tilt of the array and azimuth orientation, as well as selecting from three tracking modes (fixed, single-axis, or two-axis).

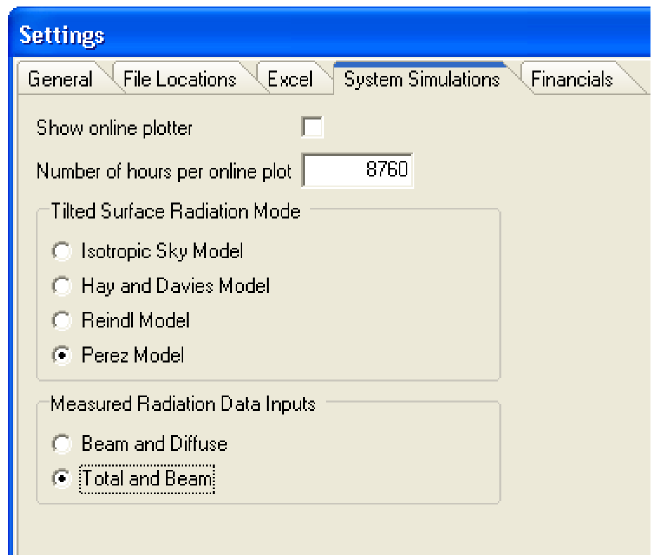

Fig. 1: Radiation processing settings inputs

3. PV Module Models

The SAM model currently includes four different models for representing the performance of a photovoltaic module. These include the Sandia Photovoltaic Array Performance Model, the five-parameter model, and the single-point efficiency model for both flat plate and concentrating systems. All models have different methods and use scenarios.

3.1 Sandia Photovoltaic Array Performance Model

The Sandia Photovoltaic Array Performance model was developed by Sandia National Laboratories-Albuquerque (**7**). The model is empirically based and includes electrical, thermal, solar spectral, and optical effects. The model consists of 10 different inter-related empirical equations that take a variety of inputs including the ambient temperature, direct and diffuse radiation, module characteristics (for calculating the cell temperature), and array layout. The model has been extensively tested and compared to measured data on a large variety of different module technologies. SAM uses the empirical equations to calculate the maximum-power-point (MPP) power at each hour of the simulation, but the model can also be used to calculate power levels at other voltage levels.

Within the SAM GUI, a user need only select an actual module type, and the proper set of roughly 30 inputs to the model are selected from a database. This data comes from extensive outdoor performance tests on commercially available modules. The database is available at the Sandia PV Web site at no charge (**8**). Several other simulation tools also make use of this database.

The extensive testing of a new, commercially available PV module before entering it into the database takes time and resources to do objectively and independently. Therefore, the primary drawback to using the Sandia PV Array Performance model in SAM is that the Sandia database may not contain the recently released module that the user desires to model, especially with the accelerating pace of products being released into the marketplace. However, for commercial modules present in the database, this is the recommended model to use in SAM – primarily because of the independent nature of the testing and the detailed responsiveness of the model.

3.2 The CEC Performance Model

A second PV module model has recently been added to SAM called the "CEC Performance Model" (CEC stands for California Energy Commission). This model is also known as the "five parameter" model, originally developed at the University of Wisconsin-Madison Solar Energy Laboratory (**9**). This model was developed specifically to allow for the use of standard manufacturers' data, which are the primary parameters to the model. This requirement allows any manufacturer's module to be modeled within this model. The model is called the "CEC Performance Model" because the CEC uses this model for their free tool titled "CECPV Calculator" as part of their New Solar Homes Partnership program (**10**). The CEC provides the five parameters for all modules approved for the program.

The CEC model is based on a theoretical circuit that represents the PV module (Fig. 2 from Ref. 9). The five parameters are shown in the circuit including:

IL	the light current
Io	the diode reverse saturation current
Rs	the series resistance
Rsh	the shunt resistance
A	a modified ideality factor

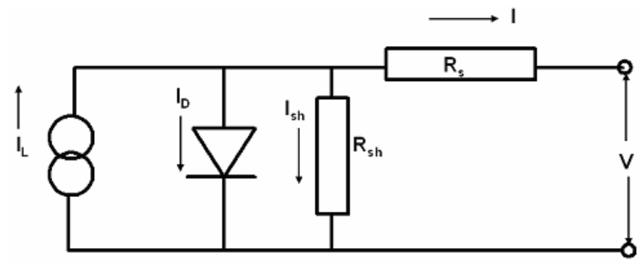

Fig. 2: Theoretical circuit showing the five parameters

These five parameters to represent the circuit can be derived from several typical items of manufacturer's data at standard test conditions (STC) including:

- the short-circuit current
- the open-circuit voltage
- the current and voltage at the maximum power point
- the temperature coefficient of the open-circuit voltage
- the temperature coefficient of the short-circuit current

As manufacturers provide more standard information, efforts will be made to incorporate that data into the model to improve the accuracy – especially at conditions away from the STC.

The advantage of using this model is that the CEC and individual users can quickly create the necessary parameters for the model based on a limited set of manufacturers' data. The drawback to using this model is the lack of independent validation of the manufacturer's performance claims over a wide range of conditions.

Within SAM, this model should be used when the desired commercial module is in the SAM library. The database of existing parameters from the CEC is up-to-date and includes most commercial modules available in the marketplace.

3.3 The Single-Point Efficiency Performance Model

As its name suggests, the single-point efficiency model requires only the overall module efficiency and the array size as inputs to calculate the hourly module power output. The equation is:

Power = efficiency * module area * incident radiation

In addition, the model includes a temperature correction algorithm based on that used in the Sandia Photovoltaic Array Performance Model.

This model is best used in situations when the true behavior of the PV array is unknown, but sensitivities to module efficiency are desired. This is typical for analysis being done on potential future module improvements. For the most accurate results, the single-point efficiency model should be used only when the desired module is not available in the module libraries of either of the other two models.

3.4 Concentrating Photovoltaics Module Model

SAM includes an extension of the single-point efficiency model for use in concentrating PV systems. This model extends the single-point efficiency model by allowing only two-axis tracking (removing the options for fixed or one-axis tracking), and using only the direct normal component of solar radiation data to calculate the incident radiation on the module. The user then decides which costs and efficiencies to enter. Future plans include developing parameters for concentrating PV systems to be included in the Sandia model database.

3.5 Comparison of Results between PV Models

The analysis described below compares the results of modeling a residential PV system using the three PV module models: Sandia PV Array model, CEC Performance model, and the single-point efficiency model. A module was chosen that is available in both the Sandia model and the CEC model. For the single-point efficiency model, the average module efficiency value from the Sandia model was used. For all three module models, the single-point efficiency inverter model was used with 90% efficiency. The same values were used for all of the other assumptions in SAM for each of the three cases. These assumptions were based on the values in the residential case included in the PV sample file distributed with SAM.

Output Metrics	Sandia	CEC 5-Par.	1-Pt Eff.
LCOE (real)(¢/kWh)	22.4	21.6	22.0
kWh / kW - Year 1(h)	1,554	1,616	1,580
Capacity Factor(%)	17.7	18.4	18.0
Annual Output - Year 1(kWh)	6,467	6,723	6,575

Table 1: Comparison of different PV module models

Table 1 shows a 4% difference in the total annual output in kWh between the same module as modeled by the Sandia model and the CEC model. This results in a difference of 0.9 ¢/kWh in the LCOE. The hourly results in Figure 3 show that the CEC model (shown in the lower graph) produces slightly higher output during the day.

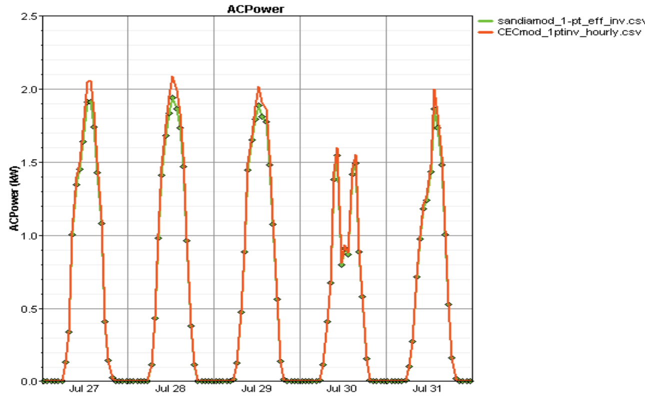

Fig. 3: Comparison of hourly results from the Sandia model (green-symbols) and CEC model (red-no symbols)

One can also compare the Sandia PV Array model and the single-point efficiency model (Fig. 4).

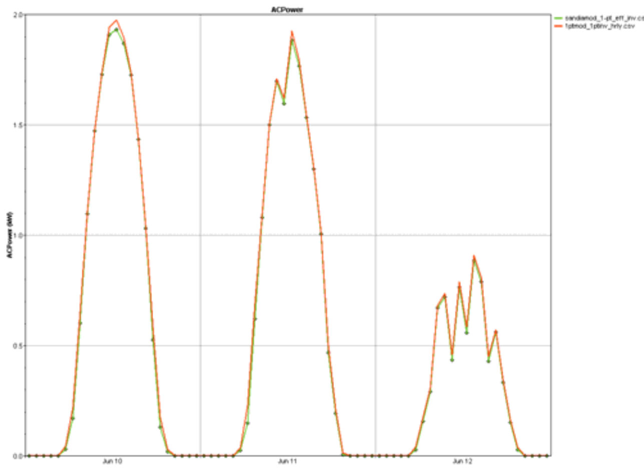

Fig. 4: Hourly comparison of Sandia (green-symbols) and single-point efficiency model (red-no symbols)

4. PV Inverter Models

There are two PV inverter models available within SAM. The primary model is the Sandia Empirical Inverter Performance Model and a single-point efficiency model.

4.1 Sandia Empirical Inverter Model

As with the Sandia PV Array Performance Model, the Sandia Empirical Inverter Model was developed by Sandia National Laboratories-Albuquerque **(11).**

The model uses four equations that give the AC power out of the inverter as a function of several empirical coefficients, the DC power input, and the electric self-consumption. The model is capable of handling several levels of input data. The minimal amount of information is the manufacturer's specifications of the inverter. Detailed field test data and laboratory test data add to the detail and accuracy of the model. The CEC has, in conjunction with Sandia, created a database of current, commercially available inverters that is available at no charge; this database is available within the SAM interface. The input sheet for the Sandia inverter model is shown in Figure 5, which only involves the user selecting an inverter from the drop-down menu. It displays the selected parameters and plots the inverter part-load efficiency.

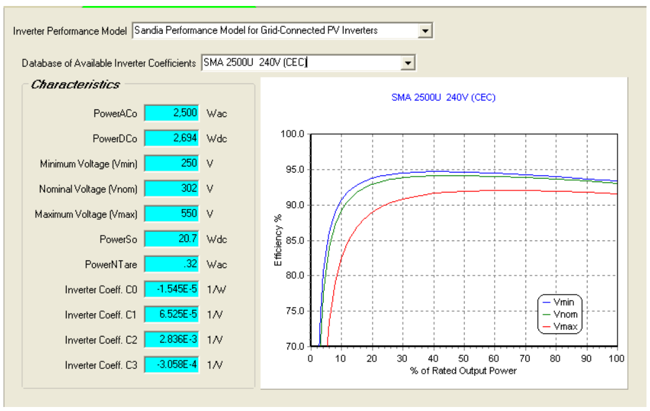

Fig. 5: Sandia Empirical Inverter data within SAM GUI

The Sandia model has been extensively evaluated and validated at Sandia. As long as the inverter, or a similar inverter, is available in the database for the system that the user wants to model, then this is the best model to use within SAM. It works with any of the PV module models described above and provides accurate hourly results even in conditions far from the standard operating conditions.

The number of inverters combined with the number of array strings impact the results. In the model, the array strings are divided evenly across one or more inverters.

4.2 Single-Point Efficiency Inverter Model

The single-point efficiency inverter model works similarly to the single-point efficiency module model in that a single annual average efficiency number is provided. In addition to this, an inverter cutoff and minimum power levels are also provided. Only the inverter size and efficiency are inputs for this model. This model should be used to do sensitivity analysis for the system to the inverter efficiency. If a suitable inverter is not available for the Sandia Empirical model described above, this model also can be used. This model is also usable with any of the PV module models as shown in Section 3.4.

4.3 Comparison of Results between Inverter Models

To compare the impact of using the Sandia Empirical Inverter model or the single-point efficiency model, two cases were constructed that each used the Sandia PV Array Performance model but a different inverter model. The value of inverter efficiency used for the single-point efficiency was taken from the plotted Sandia model part-load efficiency at 100% part load for Vnom shown in Fig. 5. The other assumptions were based on the default values in the residential PV case from the PV sample file. The inverter capacity was chosen to be larger than the PV array (4,161 kW array output with a 5 kW inverter bank). Table 2 shows the impact on the standard output metrics. The annual energy production by both systems is just less than 1% different resulting in an LCOE difference of 0.2 cents/Kwh or roughly 1%. These differences are within the larger uncertainty of the model and the expected uncertainty of the associated weather data. These differences are a function of the entire set of input assumptions and would vary with sets of inputs other than this typical system.

Output Measure	Sandia Inverter	1-pt eff. Inverter
LCOE (real)(¢/kWh)	23.1	23.3
kWh / kW - Year 1(h)	1,622	1,606
Capacity Factor(%)	18.5	18.3
Annual Output - Year 1(kWh)	6,747	6,683

Table 2: Comparison of standard outputs for inverter models

Although the total annual output is similar for the two models, the hourly data looks very different. Figure 6 shows how the two models represent the inverter's efficiency. The single-point efficiency model assumes a constant efficiency, while the Sandia model represents the efficiency's response to inverter throughput.

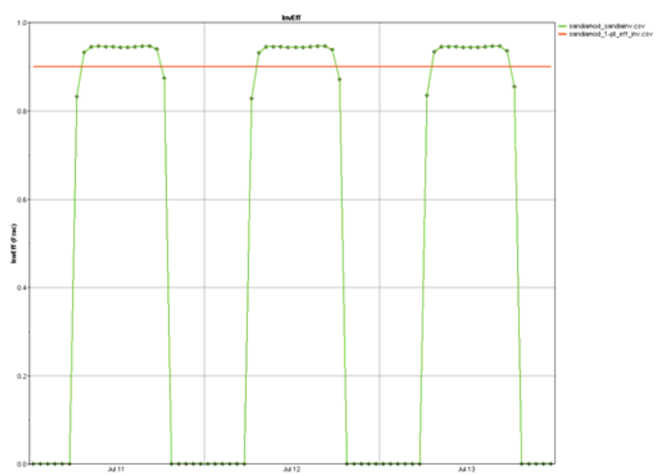

Fig. 6: Hourly comparison of inverter efficiency for Sandia model (green-symbols) and single-point efficiency (red-no symbols)

5. CSP Model and "Generic" Model

SAM currently contains two other solar models that are not photovoltaic models. The first is the parabolic trough model used for utility-scale concentrating solar power (CSP) trough plants (**12)**. This model has a detailed solar field model including optical efficiencies of the receiver and empirical heat losses from the receiver. The model allows for thermal storage with the plant before using an empirical power plant curve-fit model to calculate the hourly generated electricity. The model also allows the user to determine the appropriate hourly dispatch strategy for the system. Additional CSP system models are being developed for future implementation into SAM.

Another non-PV model within SAM is the "generic" model, which allows the user to enter basic information about an electric generation plant, including anything from a dish Stirling engine-based CSP system to a coal power plant. Figure 7 shows the necessary inputs for the "generic" model. Only the nameplate capacity, efficiency, availability, derate, degradation, and heat rate are system inputs. The cost of fuel is included on the cost page. This simple model calculates a first-year average annual output based on the assumptions; and, unlike the PV and CSP system models, does not perform an hourly simulation.

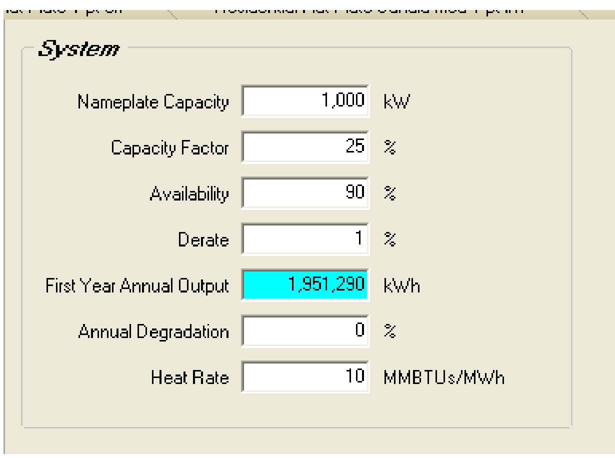

Fig. 7: "Generic" model input values and calculated annual output

A SAM user would choose the "generic" model primarily when the user does not have a lot of detail about the system, is not concerned with the hourly performance of the system, or to model a system that is not represented in more detail within SAM. The model makes it possible to take advantage of SAM's financing, incentive, and cost capabilities to determine the levelized cost or other output metrics when detailed performance assumptions are not available. The model also provides a way to compare utility-scale solar systems to conventional fossil fuel-based power plants. This model was developed in response to solar industry analysts requests for a capability to compare their PV or CSP technologies with fossil technologies with the same financial parameters.

6. CONCLUSIONS

The Solar Advisor Model allows for a variety of detailed simulations of photovoltaic and other solar (and non-solar) energy systems using several models developed by the national laboratories, which are being used by several organizations. There are four PV module models and two PV inverter models within SAM. Using the best option for each particular user and use scenario will achieve the most accurate results – but all models produce "reasonable" results. The existing database of modules within SAM continues to grow and includes the most current commercial modules available. The ability to compare PV systems across markets with CSP and non-solar technologies within the same tool is unique.

SAM is a tool that serves a multitude of users for a variety of analysis needs in different technologies and markets.

7. ACKNOWLEDGMENTS

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

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15. SUBJECT TERMS

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