April/May 2010

Optimizing Array Voltage for Battery-Based Systems

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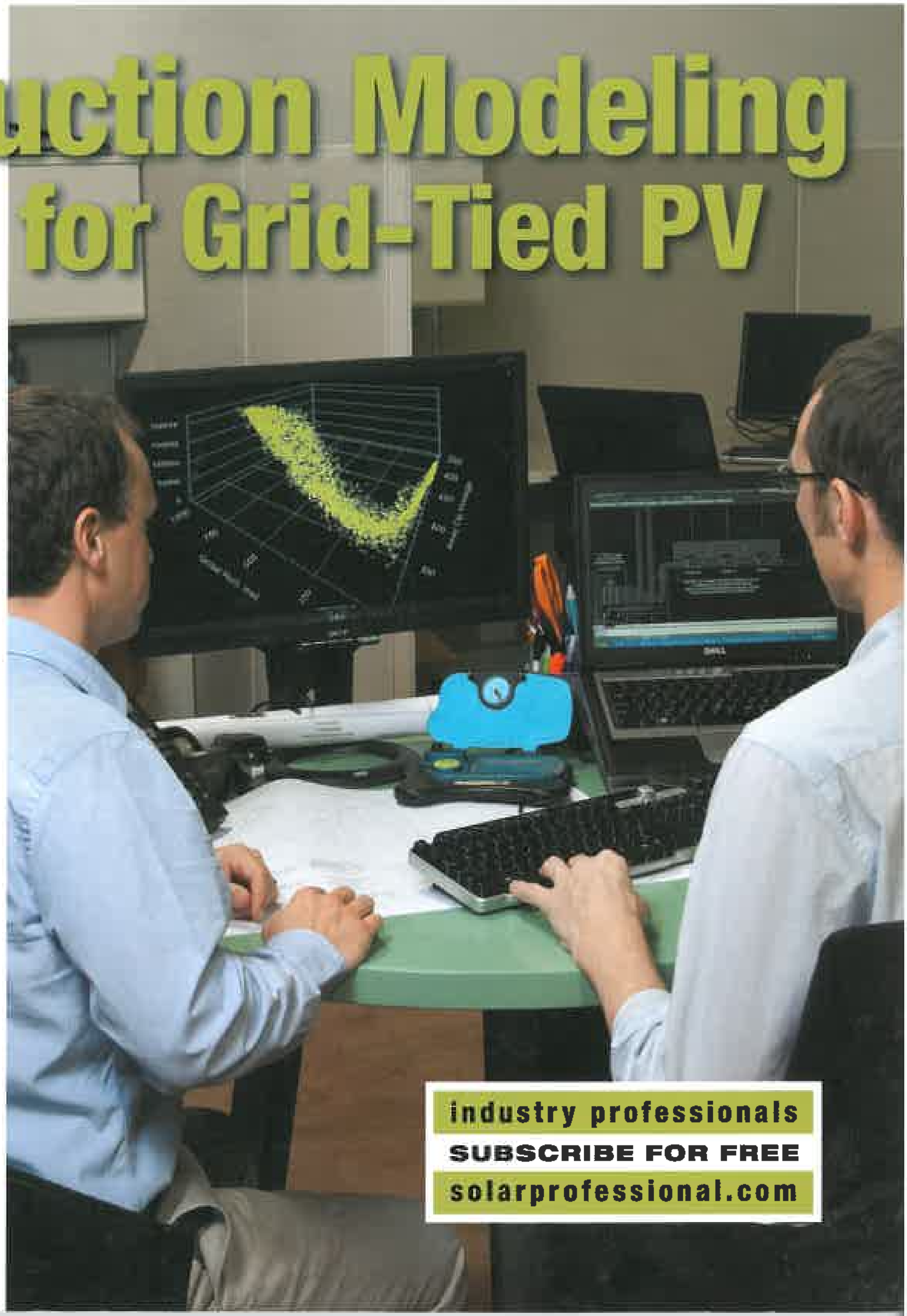
Production Modeling for Grid-Tied PV



Solar Arrays and Inverters

Determining the Optimal Capacity Ratio

Stand-Alone System Design

Loads, Equipment and Lessons Learned

PV Project Permitting

Avoid and Resolve Potential Problems

Solar Thermal Space Heating

Storage Mediums and Temperature Control

Borrego Solar
Berkeley, CA

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April/May 2010 Issue 3.3

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Production Mo

for Grid-Tied PV Systems

Production modeling meets multiple needs. Integrators seek to optimize PV system designs or to provide production guarantees; investors look to verify the right return on investment; operators need performance expectations to compare to measured performance.

All sectors of the maturing solar industry demand accurate production estimates, which require a clear understanding of how the estimates are produced and an ability to interpret the results. In this article we provide an overview of production-modeling theory and review available production-modeling tools. We compare the tools' performance to each other and to real systems, and provide a summary of the key uses of production modeling in PV projects.

At the most basic level, production modeling comes down to two questions:

1. How much sunlight falls on an array?
2. How much power can a system produce with that sunlight?

Answering these questions requires location-specific parameters, such as shading and weather data; educated assumptions about system derating due to soiling, module mismatch, system availability; and complex algorithms to model available radiation as well as module and inverter performance.

HOW MUCH SUN?

A PV system's geographical location, surroundings and configuration determine the amount of sunlight that falls on the modules. Where a system is located geographically determines how much sunlight is available; the surroundings dictate the amount of available sunlight that is blocked before reaching the array; and the array configuration determines how efficient the system is at exposing the modules to sunlight.

Meteorological data. The first factor in determining how much sunlight falls on an array is meteorological data that accurately represent the weather at a system's location. Meteorological data typically include solar radiation (global horizontal, direct beam and horizontal diffuse), temperature, cloud cover, wind speed and direction, along with other meteorological elements. The data are based on ground or satellite measurements and in some instances are modeled rather than measured.

Typically a large amount of analysis is involved in taking raw data and producing a data set suitable for use. Meteorological data are typically measured by government agencies and utilized by a variety of organizations that make the data available in formats suitable for use in production-modeling tools. These organizations include the National Renewable Energy Laboratory (NREL) and NASA, which provide the information free of charge, and also organizations such as Meteonorm and 3Tier, which provide the data for a fee.

The most common sources of data for US solar projects are the Typical Meteorological Year (TMY) files published by NREL and based on analysis of the National Solar Radiation Data Base (NSRDB). TMY data comprise sets of hourly values of solar radiation and meteorological elements representing a single year. Individual months in the data record are examined, and the most "typical" are selected and concatenated to form a year of data. Due to variations in weather patterns, these data are better indicators of long-term performance rather than performance for a given month or year. According to the online document "Cautions for Interpreting the Results" that NREL publishes along with its PVWatts tool (see Resources), these data may vary as much as ±10% on an annual basis and ±30% on a monthly basis.

The first TMY data set was published in 1978 for 248 locations throughout the US. The data set was updated in 1994 from the 1961–1990 NSRDB to create a set of TMY files, called *TMY2*, for 237 US locations. A subsequent 2007 update utilized an expanded NSRDB from 1999–2005 to create TMY3, which covers 1,020 locations across the US. TMY3 data are categorized into three classes that reflect the certainty and completeness of the data, with Class I being the most certain, Class II less certain and Class III being incomplete data. TMY, TMY2 and TMY3 present changes in reference time, format, data content and units from set to set. The data sets are incompatible with each other, but conversion tools are available. The TMY2 and TMY3 data sets are either utilized by or can be imported into all of the major PV performance-modeling tools used in the US.

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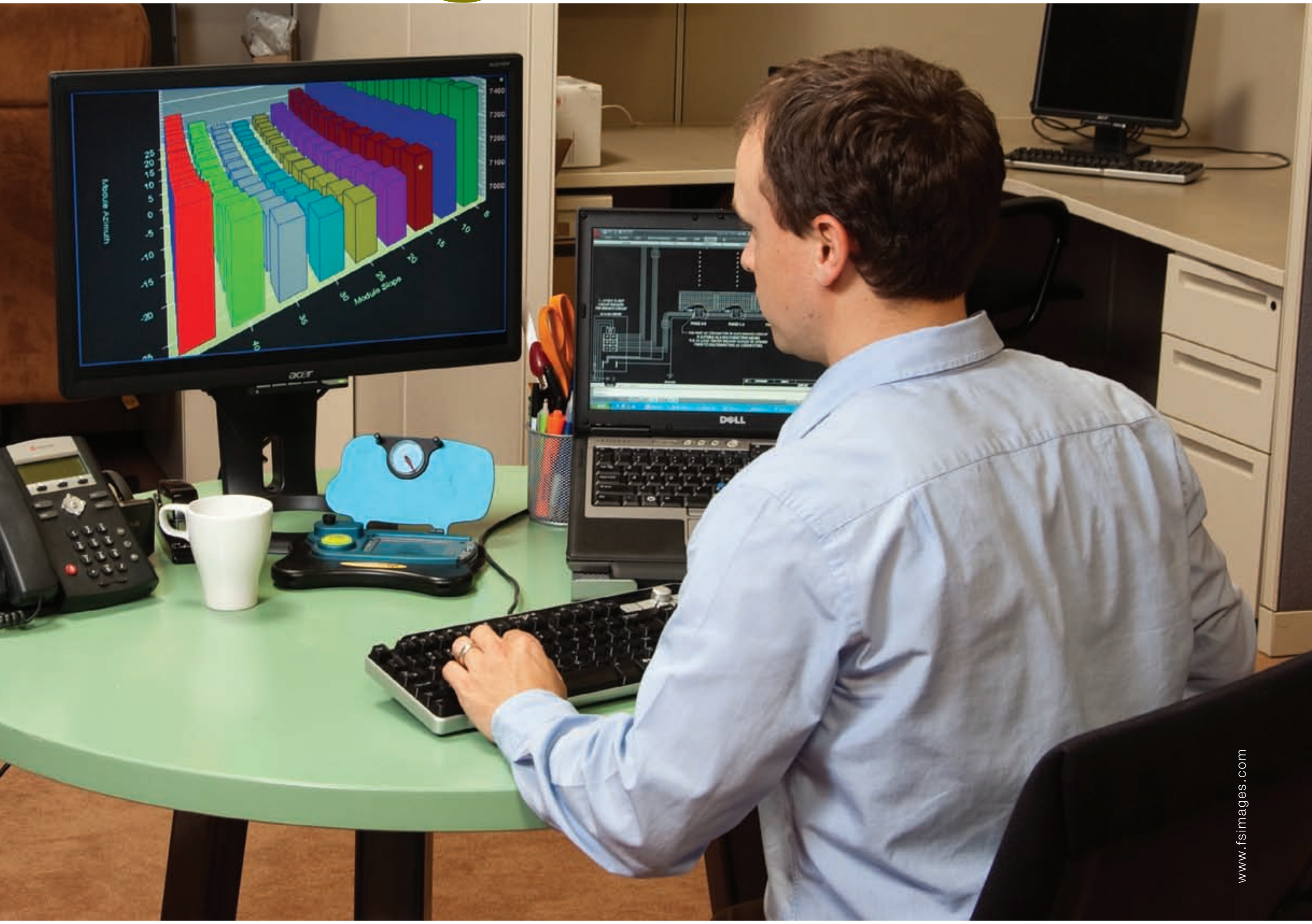
By Tarn Yates and Bradley Hibberd



Radiation models. Typical weather data include three solar radiation values representing radiation incident on a horizontal surface: direct beam, horizontal diffuse and global horizontal radiation. Direct beam radiation is light that travels in a straight line from the sun, whereas diffuse radiation is light that is scattered by the atmosphere or by clouds. In theory, global horizontal radiation is the sum of the direct beam and the horizontal diffuse radiation. However, this is not always the case due to measurement inaccuracies and modeling techniques.

Meteorological data indicate how much radiation falls on a horizontal surface, but how much falls on an array? While occasionally installed flat, PV systems usually have a tilt and an azimuth or employ single- or dual-axis trackers. A mathematical model is needed to translate horizontal radiation values into *plane-of-array* (POA) irradiance. The accuracy of a radiation model is affected by the weather at the system location and by the quality of the weather data.

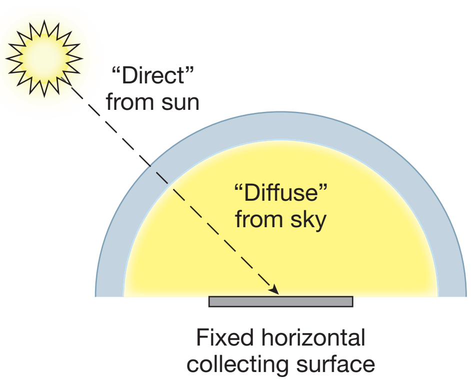
Numerous models are used to make this translation, including the Perez et al., Reindel, Hay and Davies, and Isotropic Sky models. The Perez et al. model is the most complex. A test performed in Albuquerque, New Mexico, by Sandia showed that Perez et al. model predictions are the closest to measured data. This is documented in the Sandia article "Comparison of PV System Performance-Model Predictions with Measured PV System Performance" (see Resources).

In general, radiation models treat the direct beam component the same way. Using the latitude and longitude of the system location as well as the time of day, it is possible to calculate the sun's position in the sky. Once this is known, the translation of direct beam radiation to POA radiation is a relatively simple geometric calculation.

> **"PV production models are really quite simple. Making an accurate model is straightforward. The difficult part is getting the right input assumptions that drive the model—the most critical of these, of course, being insolation."**
>
> *—Joe Song, director of engineering, SunEdison*

Where the models differ is in the treatment of diffuse radiation. The Isotropic Sky model assumes diffuse radiation is emitted equally from every portion of the sky. More advanced models take into account the fact that diffuse radiation is more intense at the horizon and in the circumsolar region, the area directly surrounding the sun. They may also consider variations in intensity based on the altitude angle of a section of sky, the clearness and brightness of the sky, and the air mass. Refer to *Solar Radiation and Daylight Models* for a history and review of radiation models (see Resources).

An additional component of radiation is the radiation reflected by the ground or by the roof or surfaces associated with the ground or roof. The reflected radiation is a function of the *albedo* of the surface, a term that describes the reflective qualities of a surface. The amount of reflected radiation is also a function of the angle of the array; an array at zero degrees will receive no reflected radiation. The amount of radiation received from reflection will increase with increasing tilt angle. Albedo varies with the surface and can change throughout the year with weather conditions such as snow. Modeling programs give you a variety of methods to account for this. For example, both PVsyst and PV*SOL allow you to define monthly values for the albedo, whereas the Solar Advisor Model (SAM) changes the albedo if the weather data indicate snow.



mollyohalloran.com

Global horizontal radiation According to NREL's "Glossary of Solar Radiation Resource Terms," while total solar radiation is the sum of direct, diffuse and ground-reflected radiation, the amount of radiation reflected off of the ground is usually insignificant. As a result, global horizontal radiation is generally referred to as the sum of direct and diffuse radiation.

Shading. Simply translating horizontal radiation into POA radiation does not tell the whole story. Depending on the PV system location and configuration, large distant objects, close obstructions and the system itself may block some of the available sunlight. The complexity of the performance-modeling tool dictates whether these types of shading are treated separately or grouped together. In the latter case, shading is accounted for by a single derate factor.

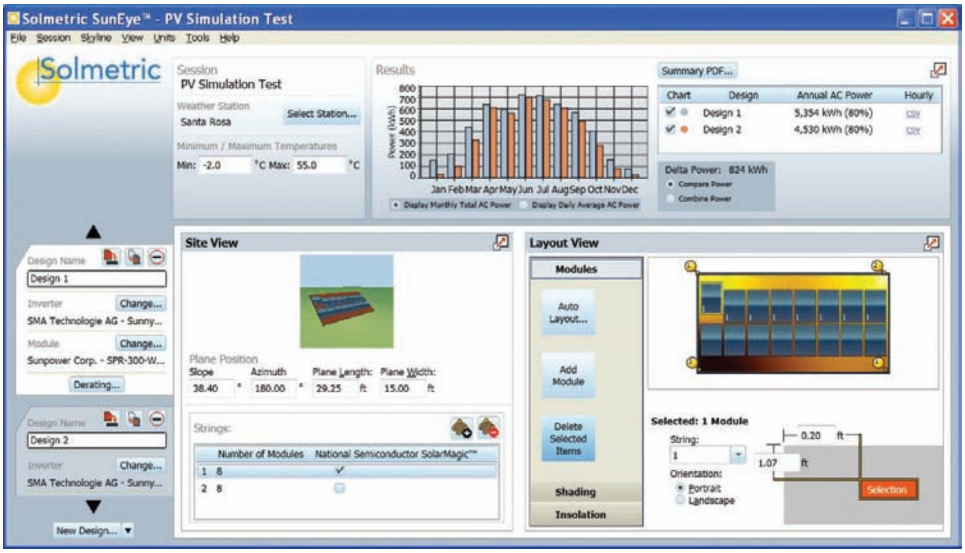
Using a single derate factor for shading assumes that the system experiences the same losses due to shade for every hour of the year. In addition, most production-modeling tools assume that the effects of shade are linear. That is, if 10% of the array is shaded, then you lose 10% of the expected energy production. This is not an accurate model, because shading just one cell in a module can disproportionately impact the whole module, the string or even the entire array.

Accurately defining shading is very difficult. It is not possible to simply go out to a proposed project location, look around and determine a shading derate factor. This is where tools like the Solmetric SunEye and Solar Pathfinder are useful, because these tools quantify shading factors that can be used in many of the production-modeling tools. Both Solmetric and Solar Pathfinder have their own production software that is designed to interact with data collected using their shade survey tools. (For more information on this topic, see "Solar Site Evaluation: Tools and Techniques to Quantify & Optimize Production," December/January 2009, *SolarPro* magazine.)

Soiling. An additional factor that decreases the available sunlight is soiling caused by the accumulation of particulates, such as dust, snow, pollutants and bird droppings. The power lost due to soiling is affected by the tilt of the array, the quantity and seasonal variability of rain and snowfall, the system's cleaning schedule and any site-specific conditions, such as the proximity to a major roadway or a commercial operation that creates dust. Most tools allow you to enter an annual soiling derate factor only. This is not sufficient if the value of power is determined by the period of time in which the power is produced. For example, estimates for the production losses due to soiling in California can be around 1% in winter and at least as high as 10% in late summer for a system that is not washed—a significant loss during a prime production period that an annual soiling factor would not accurately take into account. CONTINUED ON PAGE 34

HOW MUCH POWER?

The second step in production modeling is determining how effective a PV system is at converting the sunlight incident on an array into usable power.



Courtesy solmetric.com

Quantifying shade Solmetric's recently released PV Designer software tool allows you to drag icons representing data collected by its SunEye tool onto a visual representation of a roof surface.

PV PERFORMANCE MODELS

Several models have been created to predict the power output of a solar cell, module or array. Both complex and simple models exist. Here we describe some of the more relevant models.

Sandia performance model. In 2004, Sandia National Laboratories published "Photovoltaic Array Performance Model," which outlines the Sandia array performance model (see Resources). This is one of the more robust production models. The Sandia performance model is based on a series of empirically derived formulas that define five points on the IV curve of a PV cell. These five points can be used to produce an approximation of the actual curve. The model requires approximately 30 coefficients that are measured on a two-axis tracker at the Sandia National Labs in Albuquerque, New Mexico.

The coefficients used in the Sandia model take into consideration module construction and racking technique, solar spectral influences, angle of incidence effects and the irradiance dependence of electrical characteristics such as the temperature coefficients of power, voltage and current. Tests documented in "Comparison of Photovoltaic Module Performance Measurements" show that the model can predict power output to within 1% of measured power (see Resources).

The Sandia performance model is an option in both Solar Advisor Model (SAM) and PV-DesignPro. One of the challenges associated with this model is that the modules must undergo testing at the Sandia labs to be included. Unfortunately, this means that the Sandia database of modules often does not include recently released modules. This issue should soon be alleviated, as Sandia entered an agreement to have commercially available modules tested by TÜV Rheinland Photovoltaic Testing Laboratory at its facilities in Tempe, Arizona.

Single-diode performance model. The single-diode model assumes that the behavior of a PV cell can be simulated by an equivalent circuit consisting of a current source, a diode and two or three resistors, as shown in Figure 1. The current source and diode represent the ideal behavior of a solar cell, and the series and shunt resistors are used to model real-world losses, such as current leaks and resistance between the metallic contacts and the semiconductor.

Using circuit theory, you can define equations that describe the current and voltage characteristics of the equivalent circuit. Unknown variables can be determined by evaluating the equations at conditions such as those specified on the manufacturers' spec sheet for open-circuit voltage and short-circuit current. The single-diode performance model is the basis of both the model used in PVsyst and the CEC model that is an option in SAM.

PVFORM model. The performance model that PVWatts uses is a simplified version of a model developed at Sandia called PVFORM. This model uses the POA irradiance, ambient temperature and wind speed to calculate the operating temperature of a solar cell. It then calculates the power output of the system by adjusting the STC capacity rating of the array based on the POA irradiance and the cell temperature. As implemented in PVWatts, this model assumes that the temperature coefficient of power for a PV module is -0.5%/°C. This is a reasonable approximation for crystalline silicon modules that have temperature coefficients in the -0.55 to -0.40%/°C range. However, it is not appropriate for other technologies, such as thin film, that typically have temperature coefficients in the -0.26 to -0.20%/°C range.

DC DERATE FACTORS

The major factors that determine the amount of dc power produced for a given level of illumination are the efficiency of the technology, the temperature of the module cells and the technology's response to changes in temperature. Other factors that should be considered for accurate production modeling are the accuracy of the nameplate rating of the module, losses due to module mismatch, voltage drop across the diodes and connections in the modules, the resistance of the dc wiring, module degradation, the inverter's accuracy at tracking the maximum power point of the array and the angle of incidence of the sunlight.

Once the theoretical power output of the array has been calculated, a series of derate factors must be applied to arrive at the actual power that will be delivered to the inverter. Following are some of the major factors.

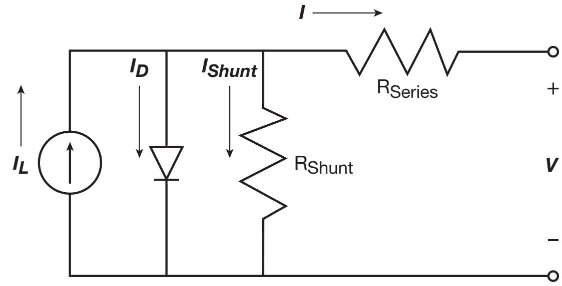


Figure 1 This diagram shows the solar cell equivalent circuit used in the single-diode performance model. The current from the current source, *IL,* is directly proportional to the intensity of the available light and the corresponding photoelectric effect.

Module nameplate rating. Module manufacturers assign a range of accuracy to the nameplate rating of their modules, such as +/-5%. This means that a module rated at 200 W may have a power output of only 190 W. Unless the tolerance is -0%, many modules do not have an STC rating as high as that specified. A conservative value to use for this factor is one that assumes that all of the modules have a rating at the low end of the tolerance.

DC wiring losses. Most integrators have standards for acceptable voltage drop that provide a good starting point for determining this number. It is common for a wiring loss factor to be calculated using the current and voltage at the maximum power point at STC conditions, as specified on the manufacturer's data sheet. Less rigorous tools take this single factor and apply it over all operating conditions. This practice neglects the fact that the current and voltage are rarely equal to the values specified on the spec sheet. More advanced programs (such as PVsyst, PV*SOL and PV-DesignPro) ask you to specify the size of conductors and length of the wire run, or specifically ask for the losses at STC. They then calculate the wiring losses at other operating conditions.

Module mismatch. This derate factor accounts for the fact that the current and voltage characteristics of every module are not identical. Although the MPPT in the inverter keeps the array at its maximum power point, each individual module does not operate at its maximum power point. A loss of 2% is a typical estimate for module mismatch. (Note that this factor is not relevant when using microinverters.)

MPPT efficiency. According to "Performance Model for Grid-Connected Photovoltaic Inverters" (see Resources), most grid-tied PV inverters are between 98% and 100% efficient at capturing the maximum available power from a PV array.

Degradation. If you are modeling future production, the degradation of power over time must be considered. A standard value for module degradation is 1% per year. Recent warranties for crystalline modules, such as the 85% power guarantee after 25 years offered with Suntech's Reliathon module, indicate that manufacturers expect the value to be less. Additionally, "Comparison of Degradation Rates of Individual Modules Held at Maximum Power" (see Resources) suggests that 0.5% per year is a better rule of thumb for crystalline modules, but notes that it should be higher than 1% for many thin-film modules.

AC DERATE FACTORS

Unfortunately, the conversion of dc power delivered to the inverter into ac power at the point of interconnection is not a lossless process. The inverter is the major factor in this stage, but it is also important to consider losses due to wiring, transformers and system downtime.

AC wiring losses. As with dc wiring, the losses due to resistance in ac wiring vary with the amount of current. In the case of ac current, loss factor calculations typically assume full power output from the inverter. This occurs for only a portion of the inverter's operating time.

Transformer losses. When a transformer that is not included as part of the inverter is required, it is necessary to account for its losses. While many transformers are more than 98% efficient, it is worth verifying the transformer's efficiency.

System downtime. Every PV system experiences downtime at some point. This can be due to the failure of an inverter or a short in a single string. The severity and duration of the downtime can be mitigated by diligent maintenance, monitoring and rapid response.

INVERTER PERFORMANCE MODELS

According to the authors of Sandia's "Performance Model for Grid-Connected Photovoltaic Inverters" (see Resources), "Frequently in modeling PV system energy production, inverter efficiency is assumed to be a constant value, which is the same as assuming that inverter efficiency is linear over its operating range, which is clearly not the case." In reality, the inverter efficiency depends on both the loading of the inverter and on the input voltage of the array. This is illustrated in Figure 2 (p. 36), which shows a typical inverter efficiency graph available through the CEC. A similar graph is available for every inverter that is approved for incentives in California. An accurate inverter model should account for any power shaving that may occur due to overloading or inverter shutdown due to the dc voltage being out of range. The power consumption of the inverter under standby and operating conditions is also a factor in total power production.

Sandia performance model for grid-connected PV inverters. The Sandia inverter model is similar to the Sandia module model in that it is based on empirically derived equations. It considers the ac power output of an inverter to be a function of the dc input power and voltage. Several coefficients are used to define this relationship. It is possible to approximate a version of the inverter model with parameters usually available on a manufacturer's spec sheet. Field and laboratory testing enable more refined versions of the inverter model. A benefit of this model is that it is compatible with the parameters recorded as part of the CEC testing process, and therefore the associated database is kept up-to-date. A Sandia study showed this model to be accurate to within 0.2% when compared to measured results. The Sandia inverter model is available in the system production-modeling tool SAM.

Other inverter models. The single-point efficiency model is utilized in PVWatts and is also an option in SAM. This model specifies a conversion efficiency that is used for all operating conditions. In PVsyst and PV*SOL, inverters are defined by the manufacturers' spec sheet values, such as the maximum power rating, the MPPT voltage range, the threshold power and the inverter's efficiency at various levels of loading. These programs use the efficiency inputs to define a curve that is used in simulations. Although not a perfect correlation, input values for defining inverter efficiency curves can be pulled from the online results of the CEC inverter tests at Go Solar California, as illustrated in Figure 2.

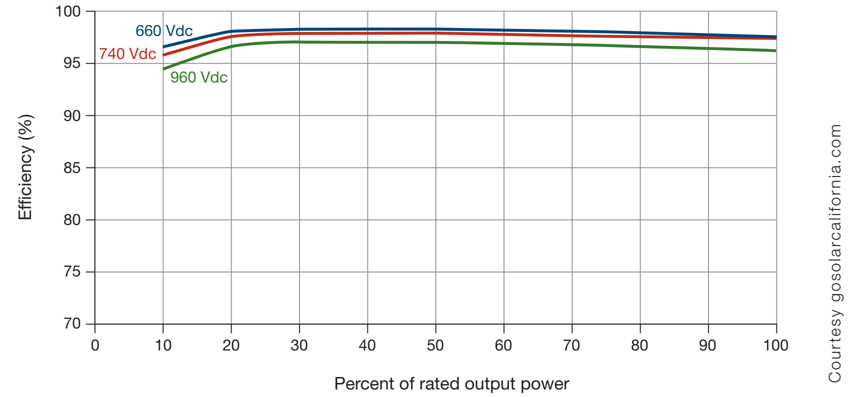


Figure 2 This graph is typical of the performance test results available for all CEC-eligible inverters, showing, in this case, how the efficiency of an AE Solaron 333 is a function of inverter loading and dc input voltage.

PHOTOVOLTAIC PRODUCTION-MODELING TOOLS

While it is beyond the scope of this article to compare all of the available production-modeling tools, we review the major software packages currently utilized by researchers, integrators and project developers in North America: PVWatts, Solar Advisor Model, PV-DesignPro, PV*SOL and PVsyst.

These production-modeling tools, along with five others, are surveyed in the companion table, "2010 Production-Modeling Tools," on pages 40–43. This table does not include estimators used by various incentive or rebate programs and tools that are primarily intended to generate sales quotes and proposals. Some of the entries in this table are adopted from a table developed by Geoffrey Klise and Joshua Stein for their article "Models Used to Assess the Performance of Photovoltaic Systems" (see Resources.)

PVWATTS

PVWatts was developed by NREL and has long been the default production-modeling tool of the US PV industry. Its strength lies in its simplicity. You can make a reasonable estimate of a system's production by selecting the location from a US map, entering the system size in dc watts and specifying the array tilt and azimuth. You can also select single- or dual-axis tracking options. By default the program uses a single conservative derate factor. This value is based on assumptions for variables such as the inverter efficiency, ac and dc wiring loses, and soiling. You can easily revise these assumptions to recalculate the derate factor.

PVWatts provides estimates of the monthly and annual values for the ac energy production and average solar radiation per day, plus a rough calculation of the value of the energy produced based on local energy rates. These values are often reasonable estimates, but PVWatts lacks the level of control and specificity of results that can be found in other tools.

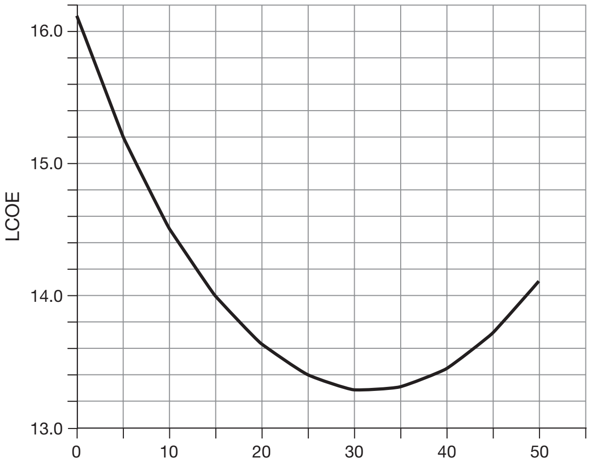
Version 1. PVWatts v. 1 presents a simple map of the US from which to choose the state where the project is located. You then chose the TMY2 data location that is closest to the project site (in some instances the closest data location may not be in the same state). A feature specific to v. 1 is that it outputs an 8,760 report—an hour-by-hour report of energy production for the entire year—in text format.

Version 2. PVWatts v. 2 provides a map of the US that is divided into 40-by-40 km grid areas. The program then combines data from the closest TMY2 data location with monthly weather data that are specific to the grid area that you select. This more accurately reflects local weather conditions and accounts for distances from the TMY2 data locations. The v. 2 map is searchable by zip code or by latitude and longitude. A beta version of a new PVWatts v. 2 map viewer was recently released. This new interface allows you to quickly see the annual and monthly irradiance specific to each grid cell. It is also easier to navigate and more attractive.

SOLAR ADVISOR MODEL (SAM)

SAM was produced by NREL in conjunction with Sandia through the US Department of Energy's Solar Energy Technologies Program. It is a step up from PVWatts in the level of control available. SAM provides a wide range of options for estimating PV module production, including the Sandia PV array performance model, the CEC performance model and the PVWatts performance model. The Sandia inverter performance model is used to simulate inverter performance. You can select modules and inverters from databases so that the specific characteristics of the system components can be used in the simulations. In cases where components are not in the databases, simple efficiency models can represent their performance. SAM uses two composite derate factors, pre-inverter and post-inverter, to account for system losses. A 12-month-by-24-hour matrix is used to define the percent of shading for every hour of every month of the year.

In addition to its production-modeling capabilities, SAM puts an emphasis on analyzing the financials involved in PV project development. The analysis focuses on the US market



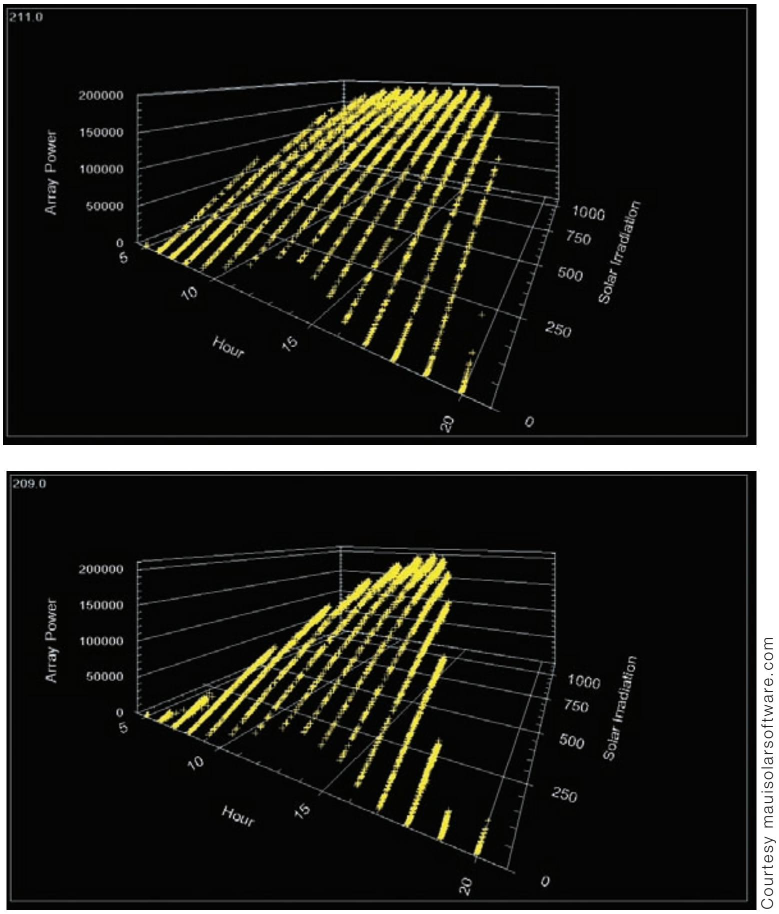
Courtesy nrel.gov/analysis/sam

Parametric analysis The results from the parametric analysis optimization tool in SAM show that the tilt resulting in the minimum levelized cost of energy (LCOE) is 32.5° with an LCOE of 19.15 ¢/kWh. This graph assumes a cash purchase, using the default system cost and financial information provided in SAM. The system modeled consists of 1,190 Sharp ND-216U1F modules with a due south azimuth connected to a SMA Sunny Central 250U inverter in San Francisco, CA.

and includes tax credits, depreciation, and capacity- and production-based incentives. Detailed cash flow models are available for residential, commercial and utility-scale projects that can be used to calculate parameters such as the levelized cost of energy (LCOE). SAM provides a method for entering utility rate schedules, including time of use (TOU) schedules, to accurately represent the varying value of electricity.

SAM contains a suite of analysis tools that includes parametric, optimization, sensitivity and statistical tools. These tools give you insight into how changes in system variables (including tilt, azimuth, system capacity or component cost) impact output metrics such as annual production or LCOE. The parametric and optimization tools run numerous iterations of the production simulation, stepping through a range of values that you can define for one or more system variables. The optimization tool maximizes or minimizes a specified output metric, whereas the parametric tool provides a broader view of the relationship between system variables and output metrics.

Two interesting new features were added to the program with the release of the latest version in October 2009. A scripting language called SAMUL has been developed for SAM that is similar to the VBA language available in Microsoft Excel. This allows you to control many of the program functions through code, and it facilitates the automation of repetitive tasks. In addition, the program now generates source code in Excel/VBA, C and MATLAB formats so that the core simulation engine can be accessed separately from the user interface.



Courtesy mauisolarsoftware.com

PV-DesignPro scatter plots These plots, with the hour of the day and the solar irradiance on the horizontal plane and the array power in dc watts on the vertical axis, show the difference in production for a horizontal single-axis (north-south) tracker and a fixed system with a tilt of 37° and an azimuth of 0° (true south) in San Francisco, CA. Each figure shows 8,760 data points, one for every hour of the year. (System specifications: 1,376 Mitsubishi PV-UD185MF5 modules; one Xantrex PV225 inverter.)

PV-DESIGNPRO

PV-DesignPro was developed by Maui Solar Energy Software. The program is similar to SAM in that you define system configuration and derate factors. PV-DesignPro utilizes the Sandia PV array performance model and provides module and inverter databases from which to choose system components. The program accounts for shading by means of a horizon profile that you define by specifying the azimuth and altitude angle as well as the opacity of the obstruction. You also have the ability to define the size and length of wire runs, as well as the efficiency of the inverter's MPPT. All other system losses are accounted for in overall current and voltage derate factors.

One of PV-DesignPro's strengths is the wealth of information that it supplies. At every step in the process the program attempts to provide as much insight as possible into the variables that affect energy production. Once you select a system location, for example, the program produces charts showing detailed irradiance, temperature and wind data for every day of the year. When defining system capacity, graphs show typical IV curves and the max power of the array at cell temperatures from 25°C to 50°C. Once you have run a simulation, you can create scatter plots containing data on system variables for every hour of the year. These scatter plots can be used to visualize and learn about system behavior or to inform design decisions.

PV-DesignPro also performs parametric analyses and produces graphs that illustrate how changes in system variables influence production and financial parameters. This function can help you minimize or maximize important variables such as kWh production or the cost of a utility bill. The software also includes tools to produce detailed load and TOU profiles. These can be used to CONTINUED ON PAGE 44

2010 Production Modeling Tools [1]

Software Program	Basics: Developer	Basics: Cost	Basics: Web-Based or Application	Weather Data Source	Irradiance Model
HOMER	HOMER ENERGY, originally developed by NREL	free	application	user provides hourly average global solar radiation on the horizontal surface (kW/m^2), monthly average global solar radiation on the horizontal surface (kWh/m^2/day), or monthly average clearness index	Hay and Davies model
Polysun	Vela Solaris	Light $159 Pro $489	application	Meteotest	unknown
PV Designer	Solmetric	$400/yr	application	various weather sources including TMY2 and TMY3 data; outside the US, the same weather sources as Energy Plus	Perez et al. model
PV-DesignPro	Maui Solar Energy Software with Sandia	$259	application	TMY2, TMY3 , Meteonorm, Global Solar Irradiation Database	Perez et al. model (default), HDKR model (option)
PV F-Chart	F-Chart Software with University of Wisconsin	$400	application	TMY2, TMY3, weather data can be added	Isotropic Sky model
PV*SOL	Valentin Software	$698 [2]	application	MeteoSyn, Meteonorm, SWERA, PVGIS, NASA SSE	Hay and Davies model
PVsyst	University of Geneva	1st license $984, additional $197	application	TMY2, TMY3, Meteonorm, ISM-EMPA, Helioclim-1 and -3, NASA-SSE, WRDC, PVGIS-ESRA and RETScreen; user can import custom data in a CSV file	Hay and Davies model (default), Perez et al. model (option)
PVWatts v. 1	NREL	free	Web	in the US—TMY2 data; 239 options outside the US—TMY data from the Solar and Wind Energy Resource Assessment Programme, the International Weather for Energy Calculations (V1.1), and the Canadian Weather for Energy Calculations	Perez et al. model
PVWatts v. 2	NREL	free	Web	combination of TMY2 data with monthly weather data from Real-Time Nephanalysis (RTNEPH) database (cloud cover), Canadian Center for Remote Sensing (albedo), National Climatic Data Center (daily maximum dry bulb temperatures) and RDI/FT Energy (1999 residential electric rates)	Perez et al. model
RetScreen	Natural Resources Canada	free	application	combination of weather data collected from 4,720 sites from 20 different sources with data from 1961–1990 & NASA-SSE	Isotropic Sky model
Solar Advisor Model (SAM)	NREL	free	application	TMY2, TMY3, EPW, Meteronorm	Perez et al. model (default); Isotropic Sky Model, Hay and Davies model, Reindl model (options); total and beam (default), beam and diffuse (option)

Notes:

[1] Some entries in this table adopted from Klise and Stein (2009). [2] Does not include expert version to be released in 2010.

[3] Shading derate is from SunEye readings. Inverter efficiency derate is from an equipment database.

[4] User enters array operating temperature, reference efficiency, temperature coefficient and array area.

Modeling					
Production-Estimating Model: Module	**Production-Estimating Model: Inverter**	**Simulation Frequency**	**Tilt**	**Orientation**	**Derate Factors**
linear irradiance model with temperature correction	single efficiency derate factor	hourly	manual input	manual input	derate factors not categorized, all losses except for single percentage for inverter efficiency are covered by "miscellaneous losses"
empirical model of module performance, dependent on three MPPT power ratings at different irradiance values and the module temperature coefficient	unknown	hourly	manual input	manual input	soiling, degradation, mismatch, wiring
proprietary model based on nominal power and operating temperature	single-weighted efficiency derate factor	hourly	manual input	manual input	PV module nameplate dc rating, inverter and transformer, mismatch, diodes and connections, dc wiring, ac wiring, soiling, system availability, shading, sun tracking, age [3]
Sandia model	Sandia model	hourly	manual input	manual input	wiring, MPPT efficiency, array current derate factor, array voltage derate factor
function of efficiency and temperature	power tracking and power conversion efficiency factors	hourly	manual input	manual input	inverter conversion efficiency and power tracking efficiency
modeled using V and irradiance at STC, module efficiency curve and an incident angle modifier; linear or dynamic temperature model options	inverter profile and efficiency curve generated from measured data	hourly	manual input	manual input	mismatch, diodes, module quality, soiling, wiring, deviation from standard spectrum, module height above ground
Shockley's one-diode model for crystalline silicon; modified one-diode model for thin film	inverter profile and efficiency curve generated from measured data	hourly	manual input	manual input	field thermal loss, standard NOCT factor, Ohmic losses, module quality, mismatch, soiling (annual or monthly), IAM losses
simplified PVFORM	single efficiency derate factor	hourly	manual input	manual input	PV module nameplate dc rating, inverter and transformer, mismatch, diodes and connections, dc wiring, ac wiring, soiling, system availability, shading, sun tracking, age
simplified PVFORM	single efficiency derate factor	monthly	manual input	manual input	PV module nameplate dc rating, inverter and transformer, mismatch, diodes and connections, dc wiring, ac wiring, soiling, system availability, shading, sun tracking, age
Evan's average efficiency model	single efficiency derate factor	monthly	manual input	manual input	inverter efficiency, miscellaneous losses
Sandia model, CEC model, PVWatts model	single efficiency derate factor, Sandia Model for grid-connected inverters	hourly	manual input	manual input	mismatch, diodes and connections, dc wiring, soiling, sun tracking, ac wiring, transformer

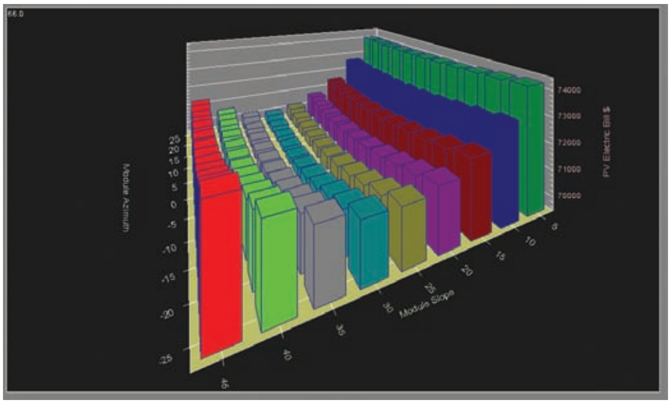
2010 Production Modeling Tools

Software Program	Modeling			
	Technologies	Tracking	Shading	Output Data
HOMER	not technology specific[4]	single axis (horizontal, daily adjustment), single axis (horizontal, weekly adjustment), single axis (horizontal monthly adjustment), single axis (horizontal, continuous adjustment), single axis (vertical, continuous adjustment), dual axis	not considered independently, could be incorporated into single derate factor	hourly ac production data
Polysun	cSi, aSi, CdTe, CIS, CIGS, HIT, µc-Si, Ribbon (EFG)	single axis, dual axis	horizon profile may be defined or imported	unknown
PV Designer	cSi, aSi, CdTe, CIS	n/a	sub-module level shading, computed based on distance-weighted interpolation of readings taken from Solmetric SunEye	hourly ac energy production; daily and monthly ac energy production displayed graphically on screen
PV-DesignPro	cSi, aSi, CdTe, CIS, CPV, mj-CPV	single axis (horizontal axis EW), single axis (horizontal axis NS), single axis (vertical axis), single axis (NS axis parallel to Earth's axis), dual axis	horizon profile user-defined	hourly data available for meteorological data, PV array behavior (cell temp, module efficiency), energy production and more
PV F-Chart	not technology specific [4]	flat-plate array, single-axis tracking (adjustable tilt/azimuth), dual-axis tracking, concentrating parabolic collector	not considered, could be incorporated into other derate factors	monthly average hourly values of ac energy
PV*SOL	cSi, aSi, CdTe, CIS, HIT, µc-Si, Ribbon	single axis (vertical), dual axis	horizon profile user-defined or imported from shade survey tool, 3D modeling environment in Expert version	hourly energy production in one-week segments
PVsyst	cSi, HIT, CdTe, aSi, CIS, µc-Si	single axis (horizontal axis EW), single axis (vertical axis), single axis (tilted axis), dual axis, dual axis (frame NS), dual axis (frame EW), tracking sun shields; ability to define parameters such as collector width, shade spacing and rotation limits	horizon profile can be user-defined or imported from a shade survey tool, 3D modeling environment, based on array configuration	hourly data available for meteorological data, PV array behavior (cell temp, wiring losses, etc.), energy production
PVWatts v. 1	cSi	single axis, dual axis	single derate factor	hourly ac energy production
PVWatts v. 2	cSi	single axis, dual axis	single derate factor	n/a
RetScreen	cSi, aSi, CdTe, CIS, spherical-Si	single axis, dual axis, azimuth	n/a	n/a
Solar Advisor Model (SAM)	cSi, aSi, CdTe, CIS, CPV, HIT	single axis (tilted NS axis), dual axis	12-month by 24-hour shade profile can be imported	hourly data available for meteorological data, PV array behavior (cell temp, wiring losses, etc.), energy production

Notes:

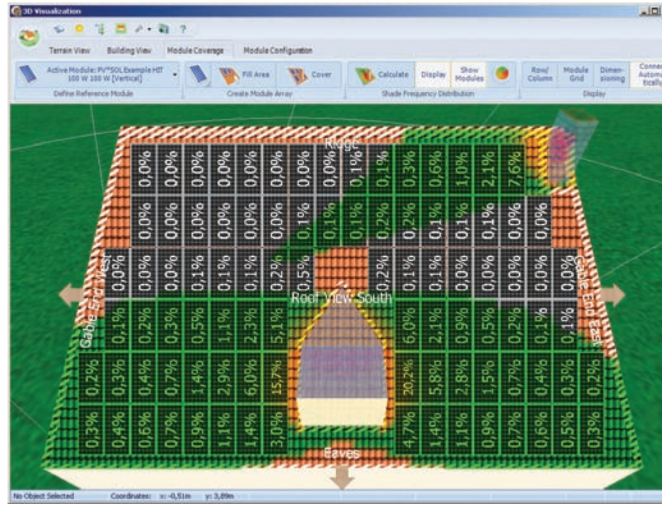
[4] User enters array operating temperature, reference efficiency, temperature coefficient and array area.   n/a = not available

Details			Component Database			
Financial Analyses	**Ability to Export Data to Excel**	**Optimization**	**Module**	**Inverter**	**Update Method and Frequency**	**User Support & Documentation**
cash-flow analysis considering energy costs, operating costs and calculation of LCOE	exported as a text file	sensitivity analysis and optimization capability	n/a	n/a	n/a	user manual provided with software
financial analysis including O&M costs, incentives, projected electricity costs, inflation and interest rates	yes	n/a	yes	yes	automatically checks for updates	user manual provided with software
n/a	yes	n/a	yes	yes	component data complied from PVXchange database, updated approximately monthly	user manual provided with software
basic cash-flow analysis	yes	parametric analysis	yes	yes	updates supplied periodically on the Maui Solar Software site; you can add modules and inverters	online help file, training videos
lifecycle cost calculations including electricity purchased from utility, electricity sold to utility, O&M costs, rebates, tax credits, depreciation; cash-flow analysis	can be copied and pasted into Excel	parametric analysis	n/a	n/a	n/a	user manual provided with software
economic efficiency and cash-flow analysis	yes	tilt, inter-row spacing, inverter loading	yes	yes	updates to the database are supplied by manufacturers; the program can be set to check for updates at start up	limited help file available with program; training available
considers energy costs, feed-in tariffs and system financing	yes	tilt, orientation, inter-row spacing, inverter loading	yes	yes	updated approximately once a year, usually with the release of a software update; you can define additional components or import individual component files received from other sources	detailed help file available with program, FAQ on Web site, no user manual
basic calculation of energy value	8,760 report is output as text that can be pasted into an Excel file	n/a	n/a	n/a	n/a	online documentation and support available
basic calculation of energy value	n/a	n/a	n/a	n/a	n/a	limited help file provided available with program, additional online documentation and support available
detailed cash-flow analysis, sensitivity and risk analysis	program is Excel based	n/a	yes	n/a	manufacturer must contact RetScreen	online manual, detailed help file, online training courses
detailed cash-flow analysis for residential, commercial and utility scale projects; focused on the US market; sensitivity and statistical analysis tools	yes	numerous production and financial optimization tools, parametric analysis	yes	yes	CEC module model (NREL maintains a library of CEC-approved modules), SAM can sync with the most recent library, additional modules can be added by contacting NREL; library of inverter coefficients is updated regularly as the CEC inverter database is updated	extensive user manual, detailed help file, online user group, email support



Courtesy mauisolarsoftware.com

PV-DesignPro parametric analysis This chart was created using the default load profile available in PV-DesignPro and the PG&E A-6 rate schedule that is preloaded in the program. The lowest electric bill for a customer in San Francisco, CA, is achieved at a module tilt of 30° and an azimuth of 10°. (System specifications: 1,376 Mitsubishi PV-UD185MF5 modules; one Xantrex PV225 inverter.)



Courtesy valentin-software.com

PV*SOL shading simulation This PV*SOL screen capture is color-coded to indicate the amount of shading across the roof. The numbers on the modules indicate the shading loss for each. A US version of PV*SOL will be available in 2010.

compare the financial benefits that may result from switching rate schedules when installing a PV system.

PV*SOL

PV*SOL is produced by Valentin Software, based in Germany. The program is widely used in the European market, and Valentin has begun efforts to increase market share in the US. These efforts include a 2010 release of an Americanized version of both PV*SOL and its most advanced tool, PV*SOL Expert, that use American numbering conventions and a North American product database. PV*SOL contains an extensive database of modules and inverters that is frequently updated. The program can be set to automatically check for updates to the database on startup. You can account for shading by creating or importing a horizon profile. Derate factors, such as mismatch, soiling, dc voltage drop, module tolerance, and losses across diodes and connections, are all considered.

At the start of each session you are given the option to use a Quick Design tool. After you select a specific type of module, the number of modules that are to be installed and an inverter brand, the program calculates all of the possible stringing combinations. The options are ranked based on how efficient they are at using inverter capacity. This is useful when trying to determine the best way to use numerous string inverters on a project.

PV*SOL stands out in its ability to model multiple arrays and multiple inverters in the same simulation, something not possible with most tools. Each array can be specified independently of the others, including module type, array tilt and azimuth, and single or multiple inverters. Derate factors and horizon profiles can also be specified independently for each array. On complex projects with multiple buildings, this can significantly reduce the simulation time.

PV*SOL Expert contains a 3D shade modeling environment in which a building can be defined that includes typical features such as gables and chimneys. Other objects that may shade an array, such as trees and additional structures, can be added to the model. You can then run a simulation that color-codes the roof according to the amount of shade an area receives. This simulation also lets you arrange modules on the roof and see the shading loss for each one, as shown in the screen capture above.

Although many of the advanced tools available in both versions of PV*SOL are geared toward the simulation of roof-mounted systems, the program also contains options for vertical single-axis tracking as well as dual-axis tracking. The program does not have an option for horizontal single-axis tracking.

PVSYST

PVsyst, developed at the University of Geneva, Switzerland, is currently the hot name in production modeling. It is the primary tool used by independent engineers who are brought in to verify production numbers for investors. The program contains a large database of modules and inverters for component selection. PVsyst considers many of the system losses as the other modeling tools do. Where it stands out is its treatment of shading and soiling.

You have the ability to enter a different soiling factor for each month in PVsyst, which more accurately reflects real-world conditions. The program can quickly model the effects of inter-row shading through CONTINUED ON PAGE 46

an option called *unlimited sheds* that calculates when the system experiences inter-row shading based on the array parameters and on the location and orientation of the array. PVsyst also provides you with a 3D CAD-like environment in which a more complex model of a PV system and the nearby surroundings can be created. Once an array is defined, it can be broken into strings, and the effect that shading has on a string can be specified.

"PVsyst provides more conservative results and is more powerful at covering complex issues such as shading."

—Manfred Bächler, chief technical officer, Phoenix Solar

PVsyst provides numerous array configuration options. To simulate tracking, you can define the important characteristics such as single or dual axis, maximum and minimum tilts, the spacing between rows or arrays, and whether or not the tracker employs backtracking. (*Backtracking* is a tracking strategy controlled by a microprocessor that adjusts the array tilt to constantly avoid inter-array shading, especially early and late in the day.) PVsyst can simultaneously model systems that comprise more than one size or type of inverter, as well as arrays with two different tilts and azimuths connected to a single inverter.

What makes PVsyst such a valuable tool is not that it has a more accurate model for PV or solar cell production than the other production-modeling systems available, but rather its unique ability to control and accurately define many of the other factors that are involved in production modeling. The report that PVsyst produces, and in particular the diagram showing system losses, is especially valuable. A new version of the program, PVsyst 5.0, was released in June 2009 and updates to the program are released regularly on the PVsyst Web site (see Resources).

COMPARISON OF PV PRODUCTION MODELS

We use the production-modeling tools just discussed to simulate the annual energy yield for different system designs. In this section we compare the tools' production estimates for theoretical systems of different technologies and perform two case studies to compare the modeling tools' production estimates to measured production. These tools are evaluated in the following model-to-model comparisons:

- PVWatts, v. 1
- PVWatts, v. 2
- PVsyst v. 4.37
- SAM, Sandia PV performance model and Sandia inverter performance model
- SAM, CEC PV performance model and Sandia inverter performance model
- PV*SOL 3.0, release 7
- PV-DesignPro, v. 6.0

In order to provide an understanding of the relative performance of each tool in different scenarios, we compare the performance-modeling tools' production estimates for crystalline silicon PV modules on a fixed-tilt array, a single-axis tracking array and a dual-axis tracking array, as well as thin-film modules on a fixed-tilt array.

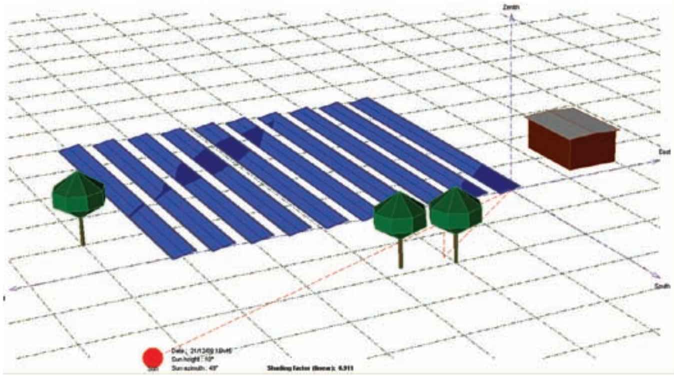
To perform the simulations in each modeling tool across the three mounting systems and the two module technologies, we input specifications for four generic systems, as follows:

CRYSTALLINE SYSTEMS

Modules: Sharp ND-216U2 (216 W STC, 187.3 W PTC)
Inverter: Xantrex GT250 (250 kW, 96% CEC efficiency)
Array: 1,400 modules (302.4 kW STC), 100 strings of 14 modules each
Installation #1: Fixed-tilt ground mount, 0° azimuth (true south), 30° tilt
Installation #2: Single-axis tracking (north-south), 0° azimuth (true south)
Installation #3: Dual-axis tracking

THIN-FILM SYSTEM

Module: First Solar FS255 (55 W STC, 51.8 W PTC)
Inverter: Xantrex GT250 (250 kW, 96% CEC efficiency)
Array: 5,028 modules (276.5 kW STC), 838 strings of 6 modules each
Installation: Fixed-tilt ground mount, 0° azimuth (true south), 30° tilt CONTINUED ON PAGE 48



Courtesy pvsyst.com

PVsyst 3D model The near shading scene function in PVsyst is used to calculate the impact of obstructions like adjacent trees or structures on system performance. In this case, the effects of shading are modeled on a vertical east-west single-axis tracking system.

The systems are sized by starting with a chosen inverter, dividing the ac power rating by the CEC-rated efficiency, then dividing by the module's PTC rating. The resulting number of modules is rounded up to a whole number of strings.

MODELING-TOOL PARAMETERS

We use the default derate parameters for each modeling tool—with the exception of SAM, for which we match the derate factors to those from PVWatts for consistency. Table 1 lists the derate parameters used in the various modeling tools.

Each PV system is located in San Francisco, California. NREL TMY2 data for that location are used in the modeling. For the purposes of modeling with PVWatts v. 2, the 94124 zip code is used to identify the 40-by-40 km grid.

Each tool's default POA radiation model is used. This means that simulations performed with PVWatts v. 1 and v. 2, SAM and PV-DesignPro use the Perez et al. model; PVsyst and PV*SOL use the Hay and Davies model.

To maintain consistency between tools when modeling tracking, we did not use PVsyst's capability to model the back-tracking or shade avoidance. In addition, the horizontal single-axis tracking design was not modeled in PV*SOL, as that tool can model only a vertical single-axis tracking design.

RESULTS OF MODEL-TO-MODEL COMPARISONS

The results of the modeling comparisons are presented in terms of *specific yield* in Graph 1. Specific yield is the production in kWh with respect to the STC system size in kW. In other words, it is energy divided by nameplate power. This allows for a more direct comparison between different technologies.

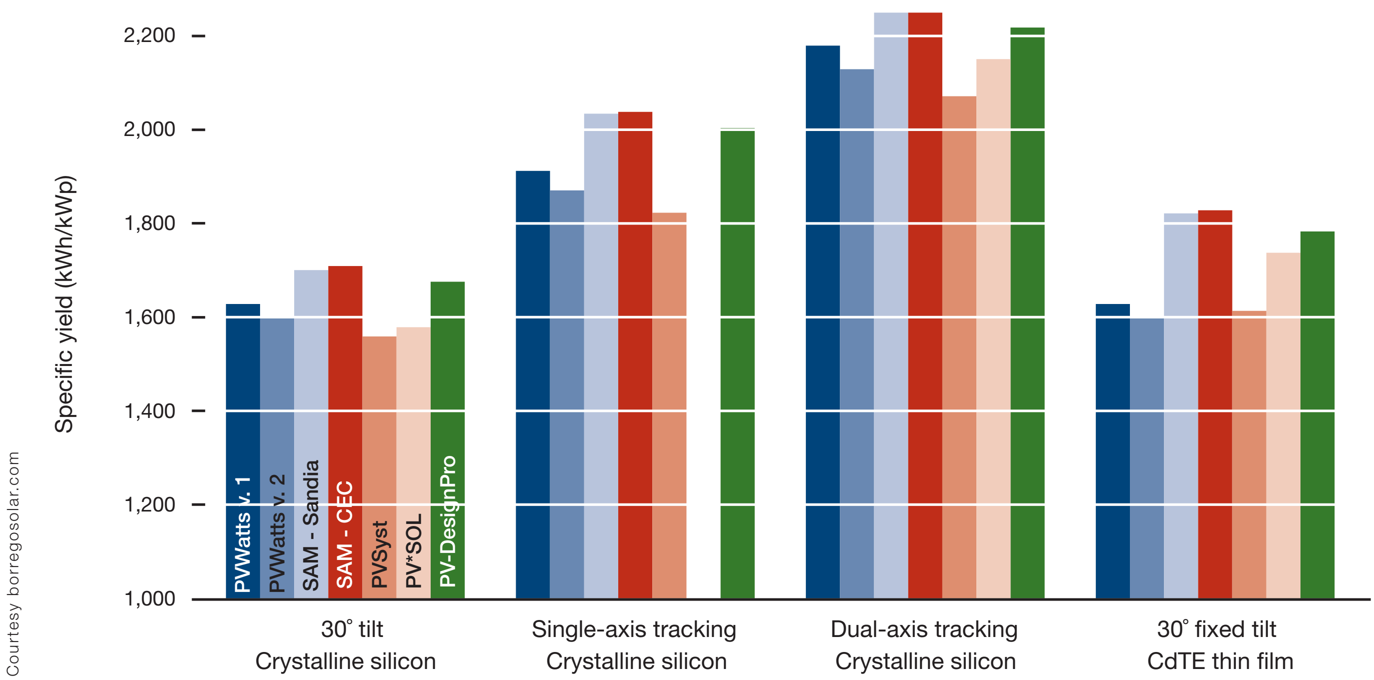
In reviewing the results presented in Graph 1 and the source data, we make the following observations about the estimates that each of the tools generated:

- For any single scenario, the discrepancy between the maximum and minimum production estimate ranged from 9% to 14%; the average difference was 11.5%.
- The largest discrepancy between production estimates was 14% for the thin-film scenario. This reflects the greater level of uncertainty associated with modeling the performance of thin-film modules.
- With the exception of the thin-film scenario, PV*SOL and PVWatts (v. 1 and v. 2) consistently produce estimates that fall between those for SAM and PV-DesignPro at the high end and PVsyst at the low end.
- In the thin-film scenario, the relatively lower estimates for PVWatts v. 1 and v. 2 are expected due to the inability of the tool to accurately model thin-film performance. What is unexpected is that the PVsyst estimate is similar to those from PVWatts v. 1 and v. 2.
- The estimates of the two SAM models were consistently the largest or most aggressive estimates. Using the CEC PV performance model, SAM generally estimated a 1% higher annual production than it did when using the Sandia PV array performance model. The small percentage suggests that the difference in module performance models is small, in the context of a full-system simulation.
- PV-DesignPro consistently estimates between 1.5% and 2% below the SAM models, but still significantly higher than most other tools' estimates. By default, PV-DesignPro considers MPPT efficiency and dc wire loss only. We expect that its production estimates would be lower if consistent derate factors were applied.
- PVsyst consistently produced the smallest or most conservative production estimates. Comparing the PVsyst loss diagram that the software generates with the simple derate factors for other modeling tools leads us to believe that this result is largely due to the module performance model within PVsyst. Differences in module and inverter characteristics within the tool's databases may also contribute to this result.
- PVWatts v. 1 estimates an average of 2% more annual production than v. 2. We believe the difference is attributable

Derate Factors Model-to-Model Comparisons

	PVWATTS v. 1 & v. 2	SAM (CEC & Sandia models)	PVsyst	PV*SOL	PV-DesignPro
PV module nameplate	0.95	-	0.97	1	1
Inverter & transformer	0.96	MOD	MOD	MOD	MOD
Mismatch	0.98	0.98	0.98	0.98	1
Diodes & connections	0.995	0.995	MOD	0.995	1
dc wire loss	0.98	0.98	MOD	MOD	.99
ac wire loss	0.99	0.99	1	1	-
Soiling	1	1	1	1	1
Shading	1	MOD	1	1	1
Sun tracking	1	1	MOD	1	1
MPPT efficiency	-	-	-	-	0.95

Table 1 Derate factors for each program are translated to a decimal value for comparison, matching the convention used in PVWatts. "MOD" denotes that the parameter is modeled within the tool, rather than reduced to a single derate factor.



Graph 1 This graph shows the annual specific yield estimated by the different PV production models for the four comparison PV systems. Absent data in the single-axis tracking example is due to the fact that PV*SOL does not model vertical (north-south) tracking.

to the modification of weather data in PVWatts v. 2 to improve geographic resolution; as such, other sites may produce dissimilar results.

CASE STUDIES: COMPARING MODELING TOOL OUTPUT TO PRODUCTION DATA

To compare predicted performance with the measured performance of actual systems, we perform two case studies of PV systems in operation. Case Study #1 is a fixed-tilt hybrid monocrystalline /amorphous silicon installation on a rooftop in Escondido, California. Case Study #2 is a fixed-tilt carport installation with amorphous silicon thin-film modules in Santee, California. Both projects have monitoring equipment that includes measurement of insolation; as such, both the energy produced by the systems and the insolation available to the systems can be compared to simulations.

For the case studies, we reduced the number of tools used. This is due to the similarity in results observed in the comparisons between two pairs of PVWatts and SAM models. For PVWatts, only v. 2 was used in the case studies. For the two SAM models, we used the Sandia PV array performance model for Case Study #1 and the CEC performance model for Case Study #2; this is due to the availability of modules in the respective databases.

MODELING PARAMETERS

Weather data. The meteorological data for all simulations are NREL TMY2 data for San Diego, California, with the exception of the PVWatts v. 2 simulation, which uses modified data based on the zip code for each system.

Shading. Each modeling tool addressed inter-row shading as follows:

- In PVsyst, by utilizing the “unlimited sheds” modeling technique;
- in SAM by using the 12-by-24 shading matrix;
- in PVWatts by entering the shading loss resulting from the PVsyst simulation; and
- in PV*SOL and PV-DesignPro by creating a horizon profile.

No additional shading is considered, because the arrays are largely shade-free.

Soiling. This is modeled in PVsyst at 1.5% per month, accumulating from month to month when the average rainfall in that month was not significant. When rainfall was significant or the system was cleaned, the soiling factor was reduced to 1.5% for that month. Case Study #1 was not cleaned and the resulting annual soiling loss was 4%. Case Study #2 was cleaned at the end of June, and the resulting annual soiling loss was 3.1%. These annual soiling losses are used in all modeling tools.

Other. Except as noted below, all other derate factors are as per Table 1:

- In PV*SOL a module tolerance of -3% is specified.
- In PV-DesignPro MPPT efficiency is modeled as 98%; an array voltage derate factor of 0.975 is used to account for module mismatch and losses in diodes and connections; wiring losses are set at 3%.

As these systems are both in their first 12–18 months of operation, no module degradation is considered. System availability is also not considered, because each system had no significant downtime.

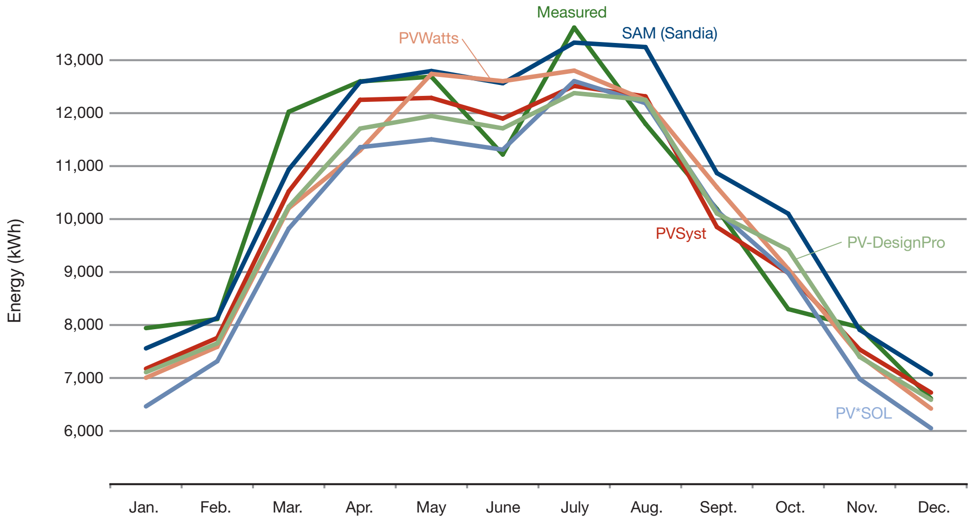
CASE STUDY #1

The first case study is a 78.4 kW roof-mounted array in Escondido, California, consisting of Sanyo HIP-200BA3 hybrid monocrystalline/amorphous silicon modules that are tilted at 10° and oriented directly south (0°). The array is wired with seven modules per source circuit, and the resulting 56 source circuits are connected to a PV Powered PVP75KW-480 inverter. The system has been in operation for just over 18 months with no significant downtime since being commissioned. The site is relatively new construction and is located in an area where further construction is occurring. As a result, soiling is expected to have a significant impact on the system's performance. In addition, there is a local wastewater ordinance restricting the owners' ability to clean the system. Therefore, it has not been cleaned since it was commissioned.

Results. The modeling results for Case Study #1 are presented in Table 2. They show that measured insolation is approximately 10% greater than modeled. This is consistent across the different tools, indicating that they perform comparably in modeling weather data. The estimated production, however, is close to the measured production, with the exception of the PV*SOL modeling tool. The combination of the modeled insolation being lower than measured, but modeled production approximately matching what was measured, indicates that the modeling tools will significantly overestimate system production if an average or typical weather year were to occur. Our interpretation is that the system is underperforming with respect to the modeling tools' predictions. This underperformance is consistent with reports from the project site indicating that significant soiling is reducing production.

Graph 2 shows that the monthly production estimates and measured production values are within the same range and follow the same trend over the course of the year, with some exceptions. The most significant exception is the drop in measured production in June. When reviewing the insolation data, we observe an equivalent drop. Therefore the system is performing as expected. (This drop in June is also observed in Case Study #2.)

With the exception of June, the modeling tools appear to have produced estimates in reasonable CONTINUED ON PAGE 52



Courtesy borregosolar.com

Graph 2 This graph shows the monthly energy production in kWh for the measured and modeled system in Case Study #1.

Case Study #1: Measured-to-Modeled Comparison

	Measured	PVsyst	SAM (Sandia)	PVWatts	PV*SOL	PV-DesignPro
Insolation (kWh/m2/year)	2,178.6	1,977.3	1,981.2	2,004.8	1,911.8	1,984.6
Delta to measured (%)	0.0%	-9.2%	-9.1%	-8.0%	-12.2%	-8.9%
Production (kWh)	123,058	119,816	127,107	119,986	114,736	118,502
Delta to measured (%)	0.0%	-2.6%	3.3%	-2.5%	-6.8%	-3.7%

Table 2 This table presents the measured and estimated annual insolation and production values for Case Study #1 as well as the percent difference of measured-to-modeled values.

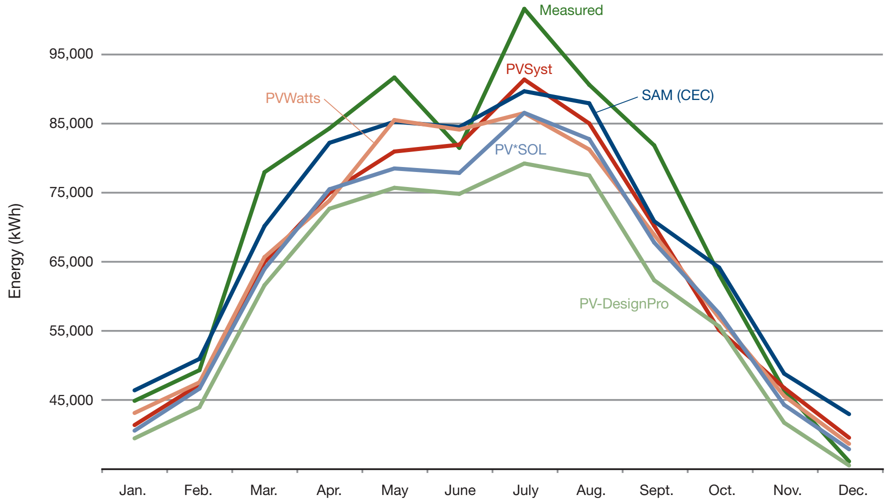
agreement with the measured data. However, when you examine Graph 2 closely, you can see that—with the exception of June—the measured data either exceed or are equal to the estimated data from January to July. It is reasonable to suppose that if insolation in June had not been relatively low, the production that month would also have exceeded the predictions. From August through October, however, the measured data fall below nearly all of the modeled estimates. Only one modeled data point—that for PVsyst in September—is lower than the measured data. This indicates the impact of soiling on production through the dry summer season in San Diego County. The PVsyst capability to model soiling on a monthly basis captures the behavior. The estimated production values in November and December are similar to the measured values.

CASE STUDY #2

The second case study is a 481.5 kW carport-mounted array in Santee, California, consisting of Kaneka G-SA60 single-junction amorphous silicon thin-film modules, tilted at 5° and oriented 27° west of true south. The array is wired with five modules per source circuit, and the resulting 1,605 circuits are connected to two Xantrex GT250-480 inverters. The carport is actually an RV parking shelter and has a roof deck immediately below the modules, which reduces airflow and increases module temperature. The system has been in operation for just over 12 months with no significant downtime since being commissioned.

Results. The modeling results for Case Study #2 are presented in Table 3. They show that measured insolation is approximately 5% lower than modeled. This is consistent across the different tools, indicating that they model weather data comparably. The estimated production, however, varies widely, ranging from 3% below the measured value for SAM to 15.2% below for PV-DesignPro. The wide variation is an indicator that modeling the performance of thin-film modules is more complex and presently less accurate than modeling performance for crystalline silicon modules.

PVWatts is limited in its ability to model modules other than crystalline silicon. Given that amorphous silicon modules are used in this case study, we account for this limitation in PVWatts by applying a correction factor to the STC system size specified in the PVWatts model. The correction factor is determined by comparing the PTC to STC ratio for the Kaneka G-SA60 module to that for a reference crystalline module, in this instance the Sharp ND-216U2. The PTC to STC ratio is 10% higher for the Kaneka module; as a result, the system size modeled in PVWatts is increased by 10%. The results shown in Table 3 indicate that the adjusted PVWatts v. 2 results are similar to those for the other tools. This approach is similar to the one used by the Los Angeles Department of Water and Power in its incentive program. While this appears to produce reasonable results, more effective tools are available for modeling thin-film module performance.



Courtesy borregosolar.com

Graph 3 This graphs shows the monthly energy production in kWh for the measured and modeled system in Case Study #2.

Case Study #2: Measured-to-Modeled Comparison

	Measured	PVsyst	SAM (CEC)	PVWatts	PV*SOL	PV-DesignPro
Insolation (kWh/m2/year)	2,037.6	1,944.1	1,922.7	1,956.4	1,855.7	1,918.3
Delta to measured (%)	0.0%	-4.6%	-5.6%	-4.0%	-8.9%	-5.9%
Production (kWh)	849,136	779,192	823,635	777,359	759,531	719,869
Delta to measured (%)	0.0%	-8.2%	-3.0%	-8.5%	-10.6%	-15.2%

Table 3 This table presents the measured and estimated annual insolation and production values for Case Study #2 as well as the percent difference of measured to modeled values.

Graph 3 shows that the monthly estimates for production and the measured production follow the same broad trend, in terms of an increase in production during the summer. As in Case Study #1, the one instance where measured and modeled production do not track one another is the drop in measured production in June. Again, the insolation data reveal a similar reduction, and thus the behavior is as expected.

While generally predicting near the average of the other modeling tools, PVsyst has the highest production estimate in July. This is due to PVsyst's ability to model month-by-month soiling factors. The soiling factor was reduced from 6% for June to 1.5% for July when scheduled cleaning was carried out, and the resulting production increase is reflected in the production graph. Other tools also show a similar trend, but this is simply in proportion to the increased insolation available in July.

THE VALUE OF PRODUCTION MODELING

Production modeling impacts many aspects of PV project development. During the sales cycle, performance estimates are necessary for determining project capacity and lining up financing. These estimates are also used during the design and engineering phase to make informed design decisions that optimize PV system performance. During operations, production modeling is used to evaluate system performance to ensure appropriate production. Production modeling also has a key role in the evaluation of new products and technologies.

System sizing. Production estimates of varying complexity are essential in determining the appropriate size system to build. In simple situations where customers are trying to offset a portion of their annual energy bill, a back-of-the-envelope production estimate may suffice. However, if customers are trying to zero out their electric bill or if TOU rate schedules are in play, the method used to estimate production needs to be more precise, more sophisticated. You can have more confidence in design decisions by modeling with tools that use location-specific weather data and produce hourly estimates of production.

Financials. Revenue from energy production is a major force, if not *the* driving force in PV project development. In an environment where the majority of PV projects, particularly larger projects, are not purchased outright but financed through complex deals, the value of each kWh generated cannot be understated. Incentives based on kWh rather than kW—such as the California Solar Initiative Performance Based Incentive program or one of many solar renewable energy credit programs—can double or triple the simple value of a kWh, exceeding $0.30/kWh.

Given the potential value of each kWh, system production has a huge impact on the revenue a project generates. If production is significantly under- or overestimated, the effects can be serious on the project at hand, on future deals and on the industry as a whole.

Underestimated production can cause any number of development issues, perhaps misrepresenting project viability or resulting in an oversized system. Underestimated production may prevent a project from being developed that might otherwise have been attractive. Or it could push a customer toward a deal with a developer whose production estimate is higher. If an oversized system results, the excess electricity generated may have to be given away to the utility without compensation.

Overestimated production may result in changes to the financial structure of the project. This is true when the commissioned system cannot meet the performance requirements established through production modeling. Production guarantees that are based upon an overestimated production model can lead to financial penalties for the party guaranteeing the system performance. An underperforming asset may not have the market value that an owner had planned on when committing to the project terms.

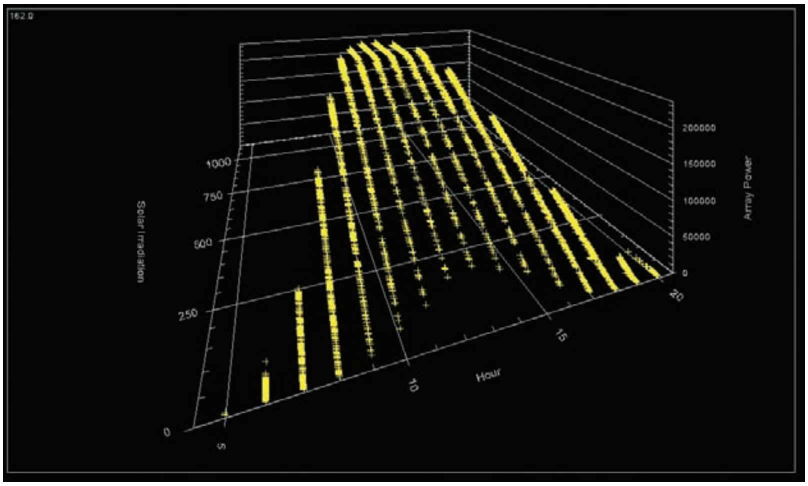
Whether used by investors examining revenue streams, integrators looking to guarantee that revenue, or end customers looking to offset their utility bills, accurate energy production estimates are crucial to all parties in the successful deployment of a solar energy project. Given this importance, investors rarely evaluate production estimates themselves. Instead, independent engineering firms with extensive production-modeling experience are generally relied upon. Typically, the independent engineering firm also verifies system performance following commissioning.

System design. Production-modeling tools play an essential role in maximizing the production or financial return of a PV system. The first step is making a decision about what technology to deploy based on a given location or a set of financial considerations. Different climates and locations affect the output of various technologies, such as crystalline silicon versus thin-film PV or single- versus dual-axis trackers. The times of the day and seasons of the year when these technologies produce power also vary. A technology that has the best financial return in one location or under a given rate schedule may not be the best choice in other circumstances.

> **"Currently, all the models lack the seriousness that can be provided only by having skin in the game. Once there is a tool out there that people put money behind, the entire solar industry will get far more serious and real."**
>
> *—Fred Unger, president, Heartwood Group*

Once a technology choice has been made, modeling tools allow you to optimize the array layout. A general rule of thumb holds that the optimal configuration to maximize annual production is a tilt angle equal to the site's latitude with a due south azimuth. While this rule would be true for a single-plane array under ideal circumstances, inter-row shading and local weather variations can skew the optimum configuration. Modeling tools can be used both to find the optimal configurations and to look at what effect a nonoptimal configuration would have. For fixed-tilt systems, modeling tools can be used to determine the effects of inter-row shading. They also help to determine the balance between the increased capacity allowed by smaller shade setback distances and the decreased production. For tracking systems, modeling tools can help you make decisions about the spacing of arrays or whether backtracking is a valuable option. The 3D shade simulations can be used to place arrays in areas where they are least impacted by shading from trees or roof obstructions.

Performance-modeling tools also allow you to make informed decisions about inverter sizing. For example, if a building can accommodate an array rated at 500 kW STC, should you use a 500 kW inverter or a 350 kW inverter? Using a modeling tool that accounts for power loss due to clipping allows you to compare the value of the lost power



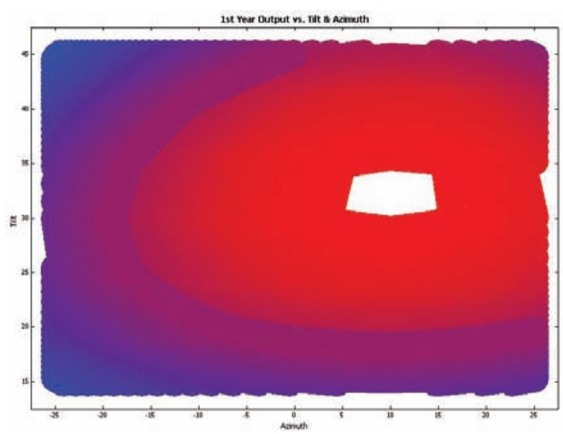
Courtesy mauisolarsoftware.com

Inverter clipping This PV-DesignPro scatter plot has one data point for each hour of the year. It illustrates how much power clipping results from overloading a Xantrex PV225 inverter with a 384.8 kW array (2,080 Mitsubishi PV-UD185MF5 modules) for a system in San Francisco, CA, with a 25° tilt and a 0° (true south) azimuth.

The Dollars Are in the Details

The following production-modeling examples, which seek to correlate annual production to system tilt and azimuth, show the importance of using modeling tools that account for detailed system variables.

Example 1: SAM. An optimization run using SAM for a 250 kW system in San Francisco, California, at a latitude of 37.6°, shows that annual production is maximized with a tilt of 32.5° and an azimuth of 8°, where true south is 0° and positive values indicate an azimuth that is west of south. See Graph 4 for a representation of this result. The SAM optimization assumes no shade. However, most large systems are composed of numerous rows spaced at a calculated distance, and are often designed to have inter-row shading before 9am and after 3pm on December 21. Unfortunately, SAM does not provide an easy method for defining inter-row shading.

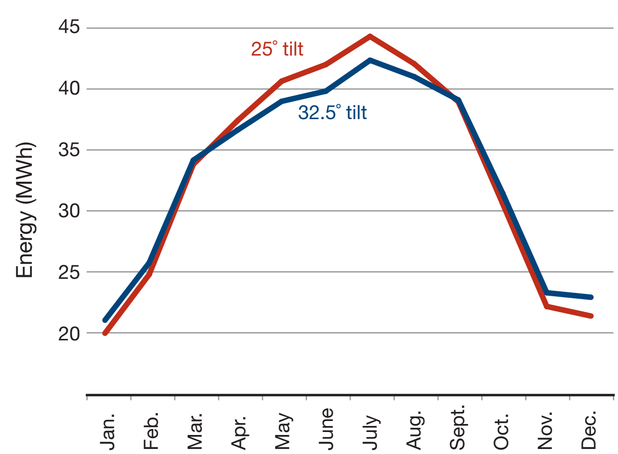


Data courtesy nrel.gov/analysis/sam

Graph 4 This contour graph was created by SAM and shows the relationship of energy production to tilt and azimuth for a modeled PV system in San Francisco, CA.

Example 2: PVsyst. Production numbers run in PVsyst, which provides an inter-row shading option, show that for systems with an 8° azimuth and inter-row spacing that keeps the array shade free between 9am and 3pm on December 21, a tilt angle of 25° actually produces slightly more annual power than one tilted at 32.5°. This is illustrated in Graph 5, which shows the monthly kWh production for 25° and 32.5° tilt angles, as modeled by PVsyst. Tilting the array at 25° has additional benefits: Production is weighted toward the summer months when power is generally more valuable; the system covers a smaller area; and less racking material is required.

In this case, using the data from SAM would appear to result in a less productive, more expensive system. You could run additional comparisons to optimize the system for total production, TOU weighted production or other system metrics. ●



Data courtesy pvsyst.com

Graph 5 This graph was produced using monthly energy production numbers generated by PVsyst. It indicates that for a system with an 8° azimuth in San Francisco, CA, a 25° tilt generates more energy than a 32.5° tilt, especially in the summer.

over the life of the system when using the 350 kW inverter to the increased upfront cost of installing the 500 kW inverter. You can run the same type of analysis to make the decision between a single inverter or multiple inverters for arrays with different orientations.

Operations. Production-modeling tools can also be used to evaluate a PV system's long-term performance. Accurate production modeling establishes a relationship between the irradiance available to the system and the electricity produced by the system. This ratio is applied to the measured irradiance and used to determine the expected production. This result can be compared to the measured production to determine whether the system is performing as expected. This can be done in real time, typically using Web-based analysis tools for viewing the data from the system, or retrospectively over a given time, typically monthly or annually. Accurate modeling of all of the system parameters is critical to the effectiveness of this technique, as are accurate measurements of the irradiance and production values.

CONCLUSIONS

Based on our evaluations, the radiation model components of the evaluated tools perform consistently, predicting similar POA irradiance from the same weather data. In terms of production estimates, SAM is the most aggressive modeling tool and PVsyst the most conservative. There is an average of 9% difference between their estimates.

> **"New technologies and applications create new challenges for modelers. There is a continuing need for development and validation of models for diverse technologies, applications and climates to ensure model accuracy and to quantify uncertainty."**
> *—Chris Cameron, project lead for systems modeling, Sandia National Laboratories*

Given the importance of accurate energy production estimates, the sophistication and capabilities of modeling tools *must* continue to evolve along with the solar industry. At this stage, an ideal tool might combine the following features: the Sandia PV array performance model; a component database updated as frequently, or more often, than the CEC database; PVsyst's control over system and location variables; and SAM's ability to perform financial, parametric and statistical analyses. Throw in the ability to define 3D layouts in a CAD-like environment—as in PVsyst—and to load shade readings taken in the field—as with Solmetric's PV Designer software and its SunEye tool—and you would have it all.

In the end, production-modeling tools are only as good as the person who uses them. The choice of derate factors can easily shift a production estimate by 5% or more. That said, for accurate simulations, it is important to have a tool that gives you as much control as possible over the factors that affect production. Currently, PVsyst is the tool that stands out, due to its ability to account for shading from a variety of sources and to vary soiling definitions over the course of the year as well as its flexibility to model a large number of different configurations.

The authors wish to thank Geoffrey T. Klise and Christopher P. Cameron of Sandia National Laboratories for their expert input during preparation of this article as well as for sharing a prepublication draft of the report "Models Used to Assess the Performance of PV Systems."

CONTACT

Tarn Yates / Borrego Solar / Berkeley, CA / tyates@borregosolar.com / borregosolar.com

Bradley Hibberd / Borrego Solar / Berkeley, CA / bradley@borregosolar.com / borregosolar.com

RESOURCES

Production-modeling software

HOMER / 720.565.4046 / homerenergy.com

Polysun / 415.671.6292 / velasolaris.com

PV Designer / 707.823.4600 / solmetric.com

PV-DesignPro / mauisolarsoftware.com

PV F-Chart / 608.255.0842 / fchart.com

PV*SOL / 888.786.9455 / valentin-software.com

PVsyst / +41.22.379.0650 / pvsyst.com

PVWatts v. 1 / 303.275.3000 / rredc.nrel.gov/solar/codes_algs/PVWATTS/version1/

PVWatts v. 2 / 303.275.3000 / rredc.nrel.gov/solar/codes_algs/PVWATTS/version2/

RetScreen / 613.995.0947 / retscreen.net

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Go Solar California / gosolarcalifornia.ca.gov/equipment (Inverter performance test summaries located here.)

Glossary of Solar Radiation Resource Terms / rredc.nrel.gov/solar/glossary