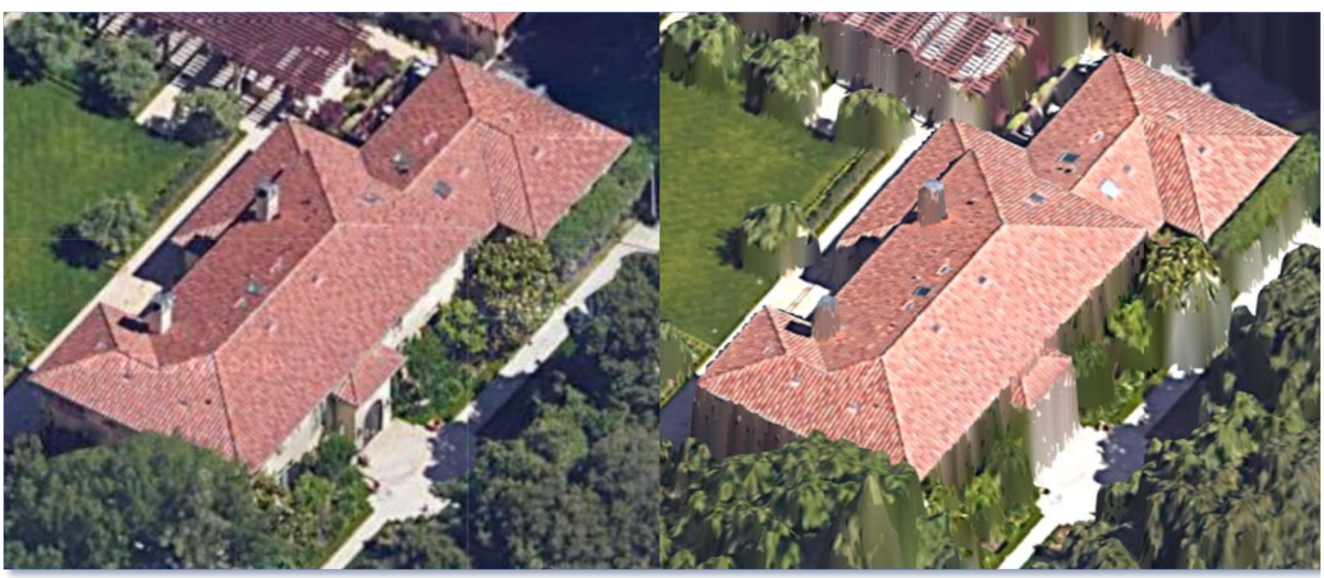
### Software Validation

# OpenSolar Photovoltaic System Design Tool – Bankability Assessment

**Report No.**: R5594B-2

**Date:** 29 October 2021



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| Customer: | OpenSolar USA, Inc. |
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Task and objective:

Complete a bankability assessment and energy production model validation of the OpenSolar web-based design tool.

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| 1 | 10/19/2021 | Initial Release | Owen Westbrook | Max Macpherson | Ryan Desharnais |
| 2 | 10/29/2021 | Revision | Owen Westbrook | Max Macpherson | Ryan Desharnais |

# Table of Contents

# List of abbreviations

| Abbreviation | Meaning |
|---|---|
| 2D | Two-dimensional |
| 3D | Three-dimensional |
| CEC | California Energy Commission |
| c-Si | Crystalline silicon; photovoltaic cell type common in commercially available modules. |
| DHI | Diffuse Horizontal Irradiance ($W/m^2$); diffuse solar energy incident on a horizontal plane. |
| DNI | Direct Normal Irradiance ($W/m^2$); direct beam solar energy perpendicular to the sun's rays. |
| DSM | Digital surface model; 3D data set capturing the location and elevation of surface features including terrain, structures, and vegetation. |
| GHI | Global Horizontal Irradiance ($W/m^2$); total solar energy incident on a horizontal plane facing upward. |
| MPPT | Maximum Power Point Tracking |
| NOCT | Nominal Operating Cell Temperature; the module cell temperature reached under conditions of 800 $W/m^2$ irradiance, 20 °C air temperature, and 1 m/s wind speed. |
| NREL | National Renewable Energy Laboratory |
| POA | Plane of Array |
| PV | Photovoltaic |
| PVEL | PVEL LLC |
| SAM | NREL's System Advisor Model |
| SAPM | Sandia Array Performance Model |
| STC | Standard Test Conditions; 1000 $W/m^2$, 25 °C cell temperature, and 1.5 airmass spectrum |
| TMY | Typical Meteorological Year |

# 1 Executive Summary

OpenSolar USA, Inc. ("OpenSolar") engaged PVEL LLC ("PVEL") to complete a bankability assessment and energy production model validation of the OpenSolar software application (the "Application"). The Application enables users to design and simulate annual energy production for residential and small commercial-scale solar photovoltaic ("PV") systems. While primarily geared towards fixed-tilt rooftop systems, the Application can also design and model both fixed-tilt and tracking ground-mount systems. The Application uses digital surface model ("DSM") data, where available, to determine the pitch, scale, and orientation of rooftop mounting surfaces and to build three-dimensional ("3D") shading models for energy production simulation purposes.

PVEL has reviewed the process for creating a system design in the Application and for specifying the system layout, equipment specifications, and energy simulation parameters. PVEL's review evaluated the Application's consistency with its documentation as well as conformance with industry best practices. As part of this review, PVEL has compared the Application's energy simulation results for two example systems against the results from three different external simulation software packages: the National Renewable Energy Laboratory's ("NREL") PVWatts[1] and System Advisor Model ("SAM")[2] tools, as well as the widely used PVsyst[3] software package.

PVEL's major conclusions regarding the Application are as follows:

- The Application allows users to create realistic designs for residential and small commercial PV systems with a high degree of flexibility and customizability;
- The Application's implementation of the SAM modeling engine is accurate and in line with solar industry best practices;
- The Application's 3D ray tracing calculations of beam shading meet or exceed the capabilities of other PV performance modeling software tools with which PVEL is familiar; and
- When the SAM modeling engine is used in conjunction with 3D design mode, the Application is capable of producing high-quality energy generation estimates appropriate for residential and small (<500 $kW_{DC}$) commercial PV systems, provided users design systems in accordance with applicable electrical codes and manufacturer specifications, particularly with regards to string sizing and inverter design compatibility.

PVEL considers it an industry best practice to verify roof orientations and obstructions with an on-site inspection prior to finalizing a PV system generation estimate.

In addition, in a separate report, PVEL has presented a validation of the Application's remote measurement accuracy on-site measurements of the slopes and horizontal dimensions of 20 residential rooftops. That study found that the Application is capable of generally meeting OpenSolar's advertised tolerances of $1^1/_3$ ft for horizontal distance measurements and 4° for slope measurements of roof facets greater than 10 $m^2$ in area, provided the remote measurements are made according to OpenSolar's specified best practices.

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1 https://pvwatts.nrel.gov/
2 https://sam.nrel.gov/
3 https://www.pvsyst.com/

# 2 OpenSolar Application Overview

## 2.1. Documentation

PVEL has reviewed written information provided by OpenSolar about the Application, including the following documentation:

- An OpenSolar manual describing the internal calculations within the Application, in a file titled: "Summary of Calculations v2.0.docx.pdf" and dated July 5, 2021; and
- Web-based support pages for the Application at https://support.opensolar.com.

In preparing this report, PVEL has assumed that this documentation and all other information communicated verbally or in writing to PVEL by OpenSolar personnel are true, complete, and accurate.

## 2.2. Design Process

The OpenSolar Application is a web-based tool accessible to users who sign up for a free login account. OpenSolar has indicated that the Application will run on all modern web browsers, but recommends the use of Google Chrome or Mozilla Firefox. Users create projects tied to a certain location, beginning by specifying a site address and selecting whether the system is residential or commercial. Next, users can enter a design mode to view satellite imagery and 3D DSM modeling of the project site, lay out PV modules, and define inverters and batteries for the system. The Application allows for multiple designs to be associated with each project. Additional designs can be created by copying existing designs and then modifying them.

OpenSolar recommends that users work in 3D design mode, which creates a 3D model of the project site from DSM data provided by Google's Project Sunroof, if available for the project location. This 3D model will determine the linear scale, slope, and azimuthal orientation of surfaces within the project scene and enable automatic placement of PV modules flush to roof, structure, or ground surfaces. The 3D model also integrates with SAM to facilitate detailed energy modeling and automated shading loss calculations. Google has stated that the Project Sunroof DSM data covers approximately 60 million buildings in the U.S.

When using the 3D model, various drawing tools allow users to place solar module groups, outline roof facets, and add roof obstructions or trees of a customizable length, width, and height. Roof facet, tree, and obstruction definitions are carried across all design variants within a project, while module placement is specific to each variant. Users may place module groups anywhere within the project scene, and the Application will automatically align the module group to a single shared orientation parallel to the underlying 3D DSM model surface. Users may manually override the calculated slope and azimuth for a module group. Optionally, users may define roof facets by placing nodes at the facet corners. Users can then manually classify facet boundaries of different types (e.g., roof ridge, roof valley, gutter, etc.), and the Application will refer to a detailed condition set of boundary setbacks and design settings to display visual guidelines for valid module placement locations. Users can create different condition sets of design settings, edit the various setback distances, and associate these custom condition sets with particular projects. The Application does not allow different sets of design settings to be assigned to different design variants within a single project, however. Overall, while fine adjustments in the positioning of modules, facet nodes, and objects may be necessary to achieve desired results, PVEL has found the 3D drawing tools to be reliable in generating reasonable designs.

For locations with or without DSM data, the Application offers a two-dimensional ("2D") design mode displaying flat aerial imagery from Google without any topographic layers, as well as a manual 3D mode, where users may build a 3D model of the project site atop this imagery. In 2D mode, users must place module groups and define their orientations manually. Users may define shading objects for reference in 2D mode, but these objects do not affect energy production, as 2D mode does not include any automated shading calculations. In contrast, manual 3D design mode provides similar array placement and 3D shading calculation functionality as the DSM-based 3D mode.

The Application has a "Racks" parameter that users can activate to create multi-row fixed-tilt and tracking system designs for flat roofs and ground mounts. The user can specify the number of rows, module orientation (landscape vs. portrait), gaps between modules, and clearance from the ground surface. The Application provides options for horizontal and tilted single-axis tracking with and without backtracking, as well as two-axis tracking. For multi-row systems, the ground coverage ratio will be calculated based on the array width and row spacing for eventual input into the energy model.

After placing modules, users can change the module type and define PV inverters for the system. The Application has an extensive database of PV modules and inverters sourced from both the California Energy Commission ("CEC") database and individual product data sheets. While the vast majority of modules in the pre-populated Application database use crystalline silicon ("c-Si") technology, the Application also includes a selection of thin film modules, including various CdTe and CIS products. Users can also define new modules and inverters based on data sheet parameters. The Application includes a limited number of pre-populated bifacial modules and allows users to define new bifacial modules by specifying a module bifaciality factor and a transparency factor (denoted "transmission" in the Application).

Once inverters are selected, users can select a particular inverter, add one or more maximum power point tracking ("MPPT") inputs, and assign particular modules to one or more strings connected to each MPPT input. The Application will display a warning if strings of different length are assigned to a single MPPT input. The Application does not validate whether the number of MPPT inputs assigned to an inverter exceeds the product specifications. The Application also does not verify whether the chosen string length is expected to exceed the inverter maximum open circuit voltage or operate at a voltage range within the inverter MPPT window. PVEL therefore recommends that system designers using the Application have an understanding of PV string sizing principles and make independent calculations to verify that their designs are technically realistic and compliant with local electrical codes.

Users can also add battery energy storage to their PV system designs. Review of the Application's battery design and modeling features is beyond the scope of this report.

## 2.3. Energy Production Modeling

### 2.3.1. Modeling Engine Selection

Once a user places modules, adds inverters, and assigns modules to specific strings and MPPT inputs, the Application automatically runs an energy production simulation for each design within the project. Simulation results will update without user input as changes are made to the design, or the user can click a "Recalculate" button to force a simulation refresh. When in 2D mode, users can choose between using the PVWatts v6 or SAM v2020.02.29r2 modeling engines to estimate energy output; in 3D mode, OpenSolar has stated that the Application will always use SAM.

OpenSolar encourages users to use SAM rather than PVWatts due to the limitations of PVWatts detailed below.

### 2.3.2. PVWatts Energy Model

PVWatts is a simple PV energy production modeling tool provided by NREL both through its SAM software package and through a standalone website. The Application allows PVWatts to be used for energy production estimates in any design mode. When PVWatts is selected as the modeling engine, only a limited subset of design parameters will affect the simulated energy output:

- Project location
- Array orientation and stringing
- Inverter-specific efficiency
- Module-specific first-year degradation
- Use of microinverters and/or DC optimizers

For all other PVWatts model parameters except the shading loss factor, the Application uses the PVWatts default values. For shading losses, users can set annual, seasonal, or monthly sun access percentages, else PVWatts will use a default 3% shading loss factor. Site-specific shading effects determined from the Application's 3D model cannot be directly passed to PVWatts.

Of particular note, when using PVWatts, the Application runs a default DC/AC ratio of 1.2 and does not incorporate the actual system DC/AC ratio. Therefore, inverter clipping losses will not be accurately calculated with the PVWatts engine.

When running the PVWatts engine, the Application will use the typical year weather file automatically selected by PVWatts based on the project latitude and longitude. PVEL's understanding is that PVWatts will default to the latest version of NREL's Physical Solar Model data set from the National Solar Radiation Database for locations in the U.S.

OpenSolar has stated that for designs with multiple inverters or multiple MPPTs within one or more inverters, the Application will run each MPPT separately in PVWatts before combining the output results. If a single inverter has multiple strings with different module orientations associated with a single MPPT, the performance of the array will be limited in each hour by the worst-performing orientation, unless microinverters or DC optimizer are specified, in which case the performance of each module will be computed individually and summed together without restriction.

In general, PVEL considers the Application's implementation of PVWatts to be appropriate for preliminary energy production modeling of residential PV systems. For reasons elaborated below, PVEL recommends the use of the SAM modeling engine for final production estimates.

### 2.3.3. SAM Energy Model

NREL's SAM software package includes a detailed PV performance model. Past validation studies have shown SAM to exhibit similar accuracy in annual PV energy production estimates as PVsyst, which is the de facto industry standard modeling software for large-scale projects in the U.S.[4] The Application allows far greater control over the energy production modeling parameters with SAM than with PVWatts. The following subsections describe the assumptions and methods OpenSolar uses to run SAM through the Application.

#### 2.3.3.1. Weather Data

Solar insolation and meteorological conditions strongly influence PV system production. By extension, energy simulation estimates depend largely on the selection of accurate weather files. With the SAM modeling engine, OpenSolar has indicated that the Application uses weather data from EnergyPlus. EnergyPlus provides hourly typical meteorological year ("TMY") data sets produced by NREL for weather stations across the U.S. These data sets include NREL's TMY, TMY2, and TMY3 data sets. The original TMY data sets were based on data from 1952-1975 and exhibit significantly higher uncertainty than their immediate successors, the TMY2 data sets. The TMY3 data sets include all stations and data incorporated in the TMY2 data sets, but the TMY3 data sets encompass 1,020 stations and data from 1961-2005, while the TMY2 data sets include only 239 stations with data from 1961-1990. The Application will select the weather station closest to the latitude and longitude of the project site, prioritizing selection of the TMY3 data set whenever multiple data sets are available for a single station. PVEL considers this prioritization of the TMY3 data sets to be appropriate, as NREL intended the TMY3 data sets to supersede the older TMY and TMY2 data sets.

The Application does not allow the user to determine which weather file has been selected, nor does it show the annual global horizontal irradiance associated with the annual energy production estimate. Making this information visible to Application users would improve modeling transparency and facilitate comparisons with other software tools. The Application does not allow users to import their own custom weather files. PVEL notes that multiple commercially available data sets have demonstrated reduced uncertainty in comparison to the TMY3 data sets.

#### 2.3.3.2. Module and Inverter Performance Models

To characterize PV module performance, the Application defaults to SAM's six-parameter CEC performance model, except that the Sandia Array Performance Model ("SAPM") is used if SAPM coefficients are available for that module. Module specifications are inputted from the Application into SAM using the "CEC Performance Model with User Entered Specifications" method.

For inverters, the Application uses the SAM's "Inverter Datasheet" method, which incorporates a single point efficiency number and datasheet values for maximum output power, input voltage ranges, and temperature derating.

#### 2.3.3.3. Irradiance Transposition Model

The Application runs the Perez et al. (1990)[5] model in SAM to estimate sky diffuse irradiance in the plane-of-array ("POA"). The Perez model is widely accepted as the standard diffuse transposition model in the PV industry.

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[4] J. Freeman, J. Whitmore, L. Kaffine, N. Blair, A. Dobos (2014): "Validation of Multiple Tools for Flat Plate Photovoltaic Modeling Against Measured Data." National Renewable Energy Laboratory, NREL/TP-6A20-61497. http://www.nrel.gov/docs/fy14osti/61497.pdf

[5] R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart (1990): "Modeling Daylight Availability and Irradiance Components from Direct and Global Irradiance." Solar Energy, Vol. 44, pp. 271-289.

#### 2.3.3.4. Shading Model

When 3D mode is activated, the Application automatically calculates beam and sky diffuse shading losses according to the site DSM model and placement of PV modules and objects. Beam shading is calculated using a ray tracing model run hourly for one representative day per month. For modules manufactured by Solaria, the Application uses sixteen ray-traced points per module, with shading calculated for eight distinct substrings. For all other modules, the Application uses nine ray-traced points per module to represent three bypass diode substrings. Beam shading impacting any of these points will cause 100% shading loss for the entire associated substring. PVEL considers this approach to be conservative and generally consistent with typical engineering practice. However, PVEL notes that the Application's beam shading calculations will overestimate shading losses for newer half-cell crystalline silicon module designs with six bypass diode strings as well as for thin film modules with linear shading loss characteristics.

The Application also estimates sky diffuse shading according to the percentage of the sky dome that is shaded. This calculation assumes that diffuse shading impacts each module uniformly and that the sky diffuse distribution is isotropic. This diffuse shading approach is consistent with standard industry practice used in other modeling tools with which PVEL is familiar.

Finally, when in 3D mode, the Application permits users to input custom horizon shading profiles specified in terms of azimuth by horizon elevation angle. Users may also import horizon profiles from PVGIS[6] with a single button click. The horizon profile is then incorporated into the beam shading ray tracing calculations.

The 3D shading model can only be used in conjunction with the SAM modeling engine. The Application converts the month by hour shading table to 8760 hourly loss values, which are passed to SAM. The Application will also select the SAM optional setting to "enable partial shading model (c-Si modules only)," which will incorporate electrical shading effects on the array DC output. As noted previously, this approach will overestimate shading losses for half-cell c-Si and thin film module designs but is generally appropriate for most commercially available module types.

The Application does not utilize ray-traced shading for bifacial or tracking systems. OpenSolar has stated that the Application would defer to SAM's calculation of row-to-row shading effects for these system types. The Application would also use SAM's row-to-row shading calculation for multi-row monofacial systems. PVEL has not validated this functionality.

In general, PVEL considers the Application's 3D beam shading calculation capabilities to exceed those of most other commercially available PV modeling tools. Unlike most other software tools, the Application will calculate shading from vegetation and structures automatically, with no need in most cases to manually create and position shading objects. The Application's implementation of those shading calculations in the SAM energy model follows standard industry practice.

OpenSolar has stated that a separate validation study of the Application's shading calculations is currently underway with NREL.

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[6] See https://ec.europa.eu/jrc/en/PVGIS/tools/horizon

#### 2.3.3.5. Module Temperature Model

The Application uses SAM's built-in cell temperature model, which is based on the nominal operating cell temperature ("NOCT") value specified in the module definition. SAM's cell temperature model has a mounting standoff parameter to adjust the NOCT for flush mounted systems with minimal airflow. The Application assumes the system is rooftop mounted when the array slope is non-zero but the "racks" parameter is left blank. For rooftop systems, the Application uses a racking standoff of >3.5 inches, which does not result in a modification to the NOCT for SAM's temperature calculations.

The SAM cell temperature model uses wind speed as an input, with higher wind speeds resulting in cooler operating temperatures. SAM scales the wind speed downward according to system mounting height, using one scaling factor for systems mounted at one-story building height or lower and another scaling factor for systems two-story height or higher. The Application allows the user to select the installation roof height in terms of number of stories.

PVEL considers the Application's module temperature modeling approach to be satisfactory for most rooftop and ground-mount installations. However, the Application may tend to underestimate temperature-related losses for building-integrated PV or for flush-mounted racking designs that do not allow for rear-side airflow.

#### 2.3.3.6. Loss Parameters

For each project, users may apply a set of simulation settings that the Application then passes to the SAM modeling engine. These settings include:

- DC and AC wiring loss
- Diodes and connections loss
- Module nameplate adjustment
- Annual soiling
- Mismatch
- DC and AC system availability

In addition to these parameters, first-year module degradation is defined in the module specification and incorporated as a DC loss in the SAM engine.

Within a Project, users may define different values for soiling, DC wiring, and mismatch depending on whether string inverters, microinverters, or DC optimizers are selected. Otherwise, each design variant within a project will use the same set of simulation parameters.

In general, the Application's customizability of simulation loss parameters is in line with industry standards for residential and small commercial and industrial systems. PVEL notes that an annual soiling loss value may be overly simplistic for modeling systems in locations with seasonally dependent soiling or snowfall trends.

#### 2.3.3.7. Designs with Multiple Inverters, Microinverters, and DC Optimizers

OpenSolar has indicated that for designs with multiple inverters or multiple MPPTs within one or more inverters, the Application will run each MPPT separately in SAM before combining the output results.

If a single inverter has multiple strings with different orientations associated with a single MPPT, the performance of the array will be limited in each hour by the worst-performing orientation, unless microinverters or DC optimizer are specified, in which case the performance of each module will be computed individually and summed together without restriction.

When a user defines a system with microinverters, the Application assumes the one microinverter per module is used. With DC optimizers, the Application divides the optimizer power rating by the PV module nameplate rating to determine the number of optimizers.

All external shadings will result in a linear impact to the output of modules equipped with either microinverters or DC optimizers.

# 3 Energy Model Validation

## 3.1. Methodology

### 3.1.1. Overview

PVEL has performed comparative modeling to validate the implementation of the SAM energy modeling tool within the Application. PVEL created two 6.8 $kW_{DC}$, 5 $kW_{AC}$ rooftop PV systems in the Application, one in the Phoenix, Arizona, area (the “SW System”) and the other in the Boston, Massachusetts, area (the “NE System”). Table 3-1 details the system designs, and Figures 3-1 and 3-2 show the Application’s 3D model renderings of the respective systems. PVEL compared the Application’s energy production estimates for these systems, as generated with the SAM modeling engine, with production estimates developed with three external software tools: SAM, PVWatts, and PVsyst.

To ensure a fair comparison, PVEL made efforts to match the input data, modeling algorithms, and loss factors across all four simulation tools. In several instances, the various simulation tools use different parameter nomenclature or modeling approaches. Appendix A details the input parameters for each simulation tool, along with a description of major differences. The following sections highlight notable assumptions PVEL made in the study.

**Table 3-1: PV systems in the energy model validation study**

| System Designation | Location | DC Capacity (kW) | AC Capacity (kW) | Module Model | Inverter Model | # Modules | # Strings | # Independent MPPTs |
|---|---|---|---|---|---|---|---|---|
| **SW System** | Tempe, AZ | 6.84 | 5.0 | Hanwha Q Cells Q.Peak Duo ML-G9+ 380 | SMA SB5000US [208V] | 18 | 2 | 2 |
| **NE System** | Cambridge, MA | 6.84 | 5.0 | Hanwha Q Cells Q.Peak Duo ML-G9+ 380 | SMA SB5000US [208V] | 18 | 2 | 2 |

**Figure 3-1: 3D model of the SW System created by PVEL in the Application.**

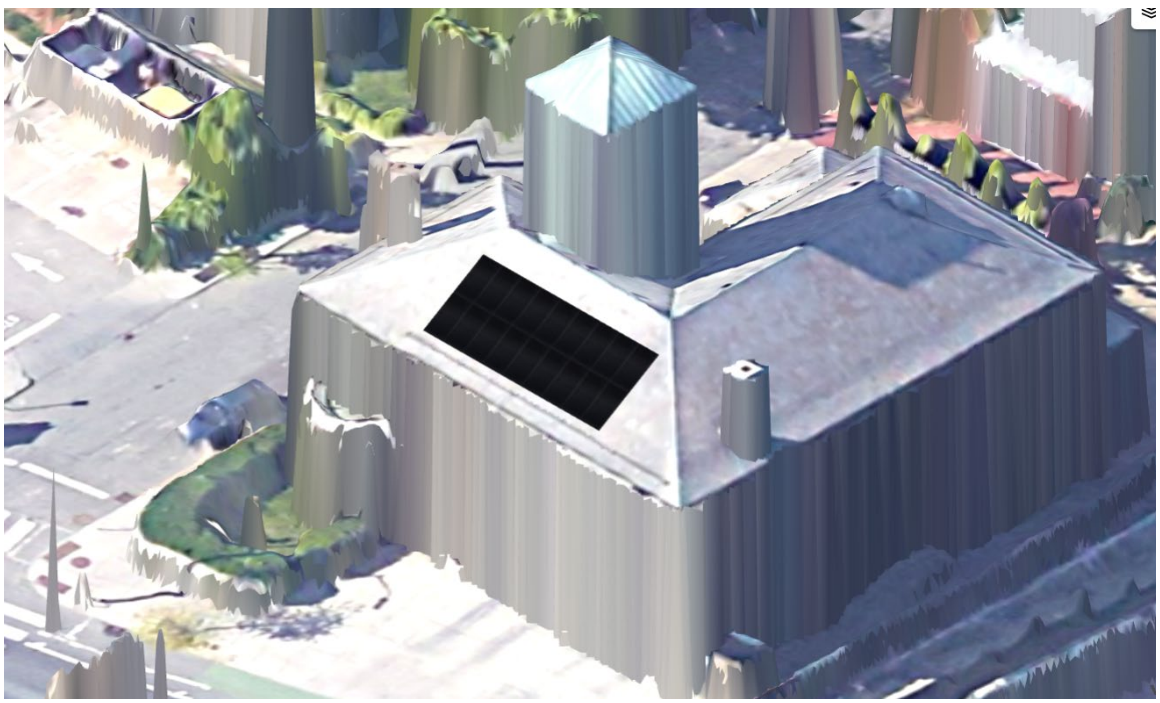

**Figure 3-2: 3D model of the NE System created by PVEL in the Application.**

### 3.1.2. Simulation Tool Versions

For the validation exercise, PVEL used SAM v2020.2.29 to match the version of SAM currently implemented within the Application. While NREL has released v2020.11.29, an update to v2020.2.29, the more recent version uses a different solar position algorithm and thus returns slightly different plane-of-array irradiance values. OpenSolar has stated that their software development roadmap includes plans to update the Application to the SAM v2020.11.29 modeling engine.

PVEL ran PVWatts v7 within NREL's SAM desktop application to allow for specification of the same TMY weather files used in the other simulations. Because NREL's online PVWatts calculator[7] utilizes v6, results presented in this study may differ from those obtained with the online calculator using identical inputs.

PVEL used PVsyst v7.2.6 for the validation study.

### 3.1.3. Meteorological Data

After PVEL built 3D system models for the SW System and NE System in the Application, OpenSolar provided PVEL with the corresponding weather files that the Application automatically selected according to the site coordinates. For the SW System, the Application selected the TMY3 data set for Phoenix Sky Harbor International Airport (USA_AZ_Phoenix-Sky.Harbor.Intl.AP.722780_TMY3.epw), while for the NE System, the Application selected the TMY3 data set for Boston Logan International Airport (USA_MA_Boston-Logan.Intl.AP.725090_TMY3.epw). These files were used for the comparative simulations in all four modeling tools.

### 3.1.4. PV Module Specifications

For both PV systems, PVEL designed around the Hanwha Q Cells Q.Peak Duo ML-G9+ 380 module built into the Application. PVEL re-created this module in SAM using the "CEC Performance Model with User Entered Specifications" method. In PVWatts, which does not allow for detailed module specifications, PVEL simply used the "Standard" module type. In PVsyst, PVEL used the built-in module .PAN file for the same module model, which had slight parameter differences compared to the Application version.

### 3.1.5. Inverter Specifications

Both validation PV systems used the SMA SB5000US [208V] string inverter built into the Application. PVEL duplicated this model in SAM with the "Inverter Datasheet" method. PVWatts allows definition only of the inverter efficiency and capacity (through the DC/AC ratio setting); PVEL set these to match the Application's specified values. PVEL used PVsyst's built-in inverter .OND file for the chosen inverter, which had slight parameter differences relative to the Application version.

### 3.1.6. Shading Losses

Because the Application's shading loss calculations are the subject of a separate validation study, the SW System and NE System were sited and designed to minimize shading from external objects. However, the Application's 3D ray-tracing model did predict beam shading at certain hours of the year, resulting in <0.5% beam shading losses for the SW System and ~1% beam shading loss for the NE System. To capture these shading effects and

[7] https://pvwatts.nrel.gov/

maintain consistent shading losses across all simulations, PVEL made various adjustments to the external software models, as described in Table 3-2.

**Table 3-2: Beam shading model approach for comparative model validation**

| Simulation Tool | SW System | NE System |
|---|---|---|
| **OpenSolar (SAM engine)** | Application's 3D ray-tracing model | Application's 3D ray-tracing model |
| **PVWatts** | 0.0% annual shading loss specified based on Application's beam shading estimate | 1.3% annual shading loss specified based on Application's beam shading estimate |
| **SAM** | Incorporated Application's month-by-hour beam shading loss table | Converted Application's month-by-hour beam shading loss table to an 8760 hourly loss table, with separate losses calculated for each string. Partial shading model option enabled. |
| **PVsyst** | 3D shading scene with no external shade objects. | 3D shading scene with simplified renderings of key shade objects. |

### 3.1.7. Module Temperature Model

One modeling assumption that could not be perfectly aligned across all simulation tools was the module temperature model. As discussed previously, with the SAM modeling engine enabled, the Application uses SAM's NOCT-based module temperature model and corrects module output according to a specified module NOCT and temperature coefficient of maximum power. PVWatts uses a slightly different NOCT-based temperature model with a single NOCT and maximum power temperature coefficient for all "standard" type modules. PVsyst uses a heat balance equation with constant and wind-linked thermal loss parameters, respectively denoted Uc and Uv. PVEL set the Uc and Uv values to 24.0 $W/m^2/K$ and 0.0 $W/m^2/K/(m/s)$, which it considers appropriate for roof-mounted modules with some rear airflow.

## 3.2. Results and Discussion

Tables 3-3 and 3-4 summarize PVEL's comparative modeling results.

**Table 3-3: Comparative modeling results summary for the SW System**

| Simulation Tool | POA Irradiance [$kWh/m^2/yr$] | DC Energy at Inverter [kWh/yr] | AC Energy [kWh/ year] | Specific Yield [kWh/ kWp/year] | Deviation from OpenSolar POA Irradiance [%] | Deviation from OpenSolar DC Energy [%] | Deviation from OpenSolar AC Energy [%] |
|---|---|---|---|---|---|---|---|
| **OpenSolar (SAM engine)** | 2,228 | 12,360 | 11,603 | 1,696 | --- | --- | --- |
| **PVWatts** | 2,228 | 12,177 | 11,565 | 1,691 | 0.0% | -1.5% | -0.3% |
| **SAM** | 2,228 | 12,359 | 11,602 | 1,696 | 0.0% | 0.0% | 0.0% |
| **PVsyst** | 2,251 | 12,240 | 11,594 | 1,695 | 1.0% | -1.0% | -0.1% |

**Table 3-4: Comparative modeling results summary for the NE System**

| Simulation Tool | POA Irradiance [kWh/m²/yr] | DC Energy at Inverter [kWh/yr] | AC Energy [kWh/ year] | Specific Yield [kWh/ kWp/year] | Deviation from OpenSolar POA Irradiance [%] | Deviation from OpenSolar DC Energy [%] | Deviation from OpenSolar AC Energy [%] |
|---|---|---|---|---|---|---|---|
| **OpenSolar (SAM engine)** | 1,481 | 8,710 | 8,205 | 1,200 | --- | --- | --- |
| **PVWatts** | 1,481 | 8,716 | 8,259 | 1,207 | 0.0% | 0.1% | 0.7% |
| **SAM** | 1,481 | 8,733 | 8,225 | 1,202 | 0.0% | 0.3% | 0.2% |
| **PVsyst** | 1,547 | 8,850 | 8,364 | 1,223 | 4.5% | 1.6% | 1.9% |

### 3.2.1. SAM Results

For both demonstration systems, the annual POA irradiance, DC energy, and AC energy agreed closely between the external SAM model and the Application's SAM results. AC energy results aligned almost exactly for the SW System, while the NE System matched to within 0.2%.

Overall, PVEL considers the validation results to demonstrate accurate implementation of the SAM engine within the Application. With OpenSolar's assistance, PVEL was able to trace the likeliest cause of the residual difference in AC energy for the NE System to subtleties in the translation of shading factors from the Application to SAM (slight differences in the module temperature calculation might also contribute). For all other loss factors besides "Shading" and "Module Deviation from STC," PVEL was able to perform a side-by-side comparison of the loss trees in SAM and the Application and verify agreement.

Running SAM through the Application instead of as a standalone model should result in equivalent modeling accuracy with numerous workflow efficiency advantages, including real-time model updates in response to design changes and rapid automatic shading calculations for complex scenes. The primary downsides of using the Application's SAM engine are the inability to input custom weather files or specify monthly soiling losses and the inaccessibility of detailed hourly and monthly model outputs. For many residential and small commercial systems, these features offered by the standalone SAM tool will not be necessary.

### 3.2.2. PVWatts Results

The PVWatts prediction of POA irradiance matched the Application's exactly for both the SW System and the NE System. This result met expectations, as both SAM and PVWatts use the Perez model for sky diffuse transposition.

PVEL's PVWatts AC energy results agreed with the Application's to within 1% for both demonstration systems. This result represents very close agreement considering that PVWatts is a much less sophisticated model than SAM or PVsyst. Compared to SAM and PVsyst, PVWatts runs a highly simplified module performance model and allows less customizability of loss factors. For example, PVWatts does not allow DC and AC wiring losses to be defined separately. PVEL considers PVWatts to be a lower accuracy tool for estimating PV system energy production than the SAM or PVsyst. The Application offers clear advantages over PVWatts in modeling accuracy for comparable ease of use, though creating system designs in the Application requires basic knowledge of DC system design and module stringing not required for PVWatts.

### 3.2.3. PVsyst Results

For the SW System, the PVsyst AC energy yield agreed within 0.1%. However, the AC energy yield for the NE System was 1.9% higher in PVsyst. The largest source of difference for both systems stemmed from the POA irradiance, which was 1.0% higher annually in PVsyst for the SW System and 4.5% higher for the NE System. While PVsyst, SAM, and PVWatts all use the Perez transposition model, the Perez model implementation differs between PVsyst and SAM/PVWatts. PVsyst calculates POA irradiance based on global horizontal irradiance ("GHI") and diffuse horizontal irradiance ("DHI") in the input weather file; SAM instead uses direct normal irradiance ("DNI") and DHI. In addition, PVsyst v7.2.6 by default separates the Perez circumsolar diffuse component from the remainder of its diffuse calculations, while SAM does not. Finally, SAM and PVsyst employ different sun position algorithms. PVEL expects these differences to have a greater impact for the NE System, which has a cloudier climate and an array orientation off-axis from due south, than for the SW System, which has a predominantly sunnier climate and shallow, due south tilt.

In general, PVEL expects wider deviation between the Application and PVsyst for other reasons. Compared to the SAM engine, PVsyst uses different module and inverter performance models, as well as different approaches to shading, module reflective losses, and module temperature. The Application estimated over 1% higher reflective losses than PVsyst, while PVsyst calculated over 2.5% greater module temperature losses than the Application. PVsyst also does not allow users to import 12x24 or hourly shading factors, meaning that PVEL had to create a 3D shading scene approximating the NE System in a process that could have introduced further deviations.

PVEL typically estimates base PV performance model uncertainties to be ±4% at a 95% confidence interval, excluding solar resource uncertainty and variability. The model results from the Application and PVsyst therefore agree to within the expected margin of uncertainty.

# 4 Conclusions

Based on PVEL's review of the Application and validation of the implementation of the SAM energy production model engine, PVEL has made the following conclusions:

- The Application allows users to create realistic designs for residential and small commercial PV systems with a high degree of flexibility and customizability;
- The Application's implementation of the SAM modeling engine is accurate and in line with solar industry best practices;
- The Application's 3D ray tracing calculations of beam shading meet or exceed the capabilities of other PV performance modeling software tools with which PVEL is familiar; and
- When the SAM modeling engine is used in conjunction with 3D design mode, the Application is capable of producing high-quality energy generation estimates appropriate for residential and small (<500 $kW_{DC}$) commercial PV systems, provided users design systems in accordance with applicable electrical codes and manufacturer specifications, particularly with regards to string sizing and inverter design compatibility.

# Appendix A – Energy Production Model Assumptions

Tables A-1, A-2, A-3, and A-4 outline the assumptions used in the OpenSolar energy production modeling validation study described in Section 3. Notable differences in loss nomenclature among models include:

- Deviation from module nameplate (set to 2.0% total in all models):
  - The Application provides two loss categories: “Nameplate Loss” and “Module First Year Degradation.”
  - SAM provides a single input for “Nameplate Loss.”
  - PVWatts provides inputs for “Light-Induced Degradation” and “Nameplate.”
  - PVsyst provides inputs for “Module Quality” and “Light-Induced Degradation.”
- DC and AC wiring losses:
  - The Application and SAM allow the user to specify annual DC and AC wiring losses, with DC wiring losses broken out into “DC Wiring” and a DC “Diodes and Connections” loss. PVEL used loss factors of 2.0% for DC Wiring, 0.25% for Diodes and Connections, and 0.5% for AC Wiring.
  - PVEL used a 0.25% “Connections” loss factor and a 2.5% “Wiring” loss factor to capture an equivalent loss in PVWatts.
  - PVsyst allows the user to specify DC and AC wiring losses at Standard Test Conditions[8]; PVEL adjusted these losses to match the annual losses of the other models. For the SW System, DC and AC wiring losses at STC were 2.95% and 0.88% to yield 2.25% and 0.5% annually, respectively. For the NE System, DC and AC wiring losses at STC of 3.86% and 1.00%, respectively, yielded the desired annual losses.

**Table A-1: OpenSolar Modeling Assumptions**

| Modeling Assumption | Value |
|---|---|
| **Sky Diffuse Transposition Model** | Perez |
| **Soiling Loss** | 4.0% |
| **Module Mismatch** | 2.0% |
| **Diodes & Connections** | 0.25% |
| **DC Wiring** | 2.0% |
| **Nameplate Loss** | 0.0% |
| **Module First Year Degradation** | 2.0% |
| **AC Wiring** | 0.5% |
| **Transformer Losses** | 0.0% |
| **Availability Loss** | 0.0% |
| **Total Above Losses (Excluding Shading)** | 10.32% |

[8] Standard Test Conditions, or “STC,” refers to incident irradiance of 1000 W/m$^2$, module cell temperature of 25 °C, and a 1.5 airmass spectrum.

**Table A-2: SAM Modeling Assumptions**

| Modeling Assumption | Value |
|---|---|
| **Sky Diffuse Transposition Model** | Perez |
| **Soiling Loss** | 4.0% |
| **Module Mismatch** | 2.0% |
| **Diodes & Connections** | 0.25% |
| **DC Wiring** | 2.0% |
| **Nameplate Loss** | 2.0% |
| **AC Wiring** | 0.5% |
| **Transformer Losses** | 0.0% |
| **Availability Loss** | 0.0% |
| **Total Above Losses (Excluding Shading)** | 10.32% |

**Table A-3: PVWatts Modeling Assumptions**

| Modeling Assumption | Value |
|---|---|
| **Sky Diffuse Transposition Model** | Perez |
| **Soiling** | 4.0% |
| **Connections** | 0.25% |
| **Light-Induced Degradation** | 0.0% |
| **Mismatch** | 2.0% |
| **Wiring** | 2.5% |
| **Nameplate** | 2.0% |
| **Age** | 0.0% |
| **Availability** | 0.0% |
| **Total Above Losses (Excluding Shading)** | 10.33% |

**Table A-4: PVsyst Modeling Assumptions**

| Modeling Assumption | Value |
|---|---|
| **Sky Diffuse Transposition Model** | Perez |
| **Soiling** | 4.0% |
| **Module Quality** | 0.5% |
| **Module Mismatch** | 2.0% |
| **Light-Induced Degradation** | 1.5% |
| **DC Wiring (annual)** | 2.25% |
| **AC Wiring (annual)** | 0.5% |
| **Transformer Losses** | 0.0% |
| **Availability Loss** | 0.0% |
| **Total Above Losses (Excluding Shading)** | 10.32% |

## About PVEL

PVEL is the leading reliability and performance testing lab for downstream solar project developers, financiers, and asset owners and operators around the world. With nearly ten years of experience and accumulated data, PVEL conducts testing that demonstrates solar technology bankability. Its trusted, independent reports replace assumptions about solar equipment performance with quantifiable metrics that enable efficient solar project financing and development. The PVEL network connects all major PV and storage manufacturers with 300+ global downstream partners representing 30+ gigawatts of buying power. PVEL's mission is to support the worldwide PV downstream buyer community by generating data that accelerates adoption of solar technology.