Foundational Open-Source Solar and Storage Modeling through the System Advisor Model and PVWatts Platforms: FY22-24 Final Technical Report

Janine Keith, Brian Mirletz, Matthew Prilliman, Steven Janzou, Paul Gilman, Nate Blair, Chris Deline, Darice Guittet, and Silvana Ovaitt

National Renewable Energy Laboratory

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Foundational Open-Source Solar and Storage System Modeling through the System Advisor Model and PVWatts Platforms- FY22-24 Final Technical Report

Major Goals & Objectives

This project was a three-year effort leveraging the Department of Energy's (DOE's) past investment in National Renewable Energy Laboratory (NREL) system modeling capabilities and platforms to continue to provide valuable and extensible photovoltaic (PV), battery, and financial modeling resources to the larger solar community. We achieve that by pursuing multiple avenues in parallel: software maintenance and technical support that are foundational to the continued usability of the System Advisor Model (SAM)[1] and PVWatts[2] software suite; platform and PV+battery model improvements and stakeholder engagement activities that are core to the continued relevance of the platforms; and open source activities to foster the continued creation of a vibrant open-source community around the SAM and PVWatts tools, which opens up exciting new avenues for the industry to interact with the tool. As evidenced by broad industry usage—the SAM desktop tool is started once every 1.4 minutes around the world, and the PVWatts application programming interface engine receives 17 million hits per month— improving and maintaining the cutting-edge models in these tools has a far-reaching and compounding impact on solar deployment.

Project Results and Discussion

Task 1: Open Source Synergies and Stakeholder Engagement

1.1: Support open source users, monitor issues submitted to open source repositories, and integrate and validate code contributions across platforms

Throughout the project, the team provided support to open source users by responding to issues opened on our GitHub repositories, integrating user contributions, and validating that code contributions built across all the platforms supported by SAM. The support can be seen on issues and pull requests on our GitHub repositories:

https://github.com/nrel/wex

https://github.com/nrel/lk

https://github.com/nrel/ssc

https://github.com/nrel/sam

1.2: Desktop tool, software development kit (SDK), and PVWatts website user support

Throughout the project, the team provided support through several channels: monitoring issues on the public forum on the SAM website and responding to queries raised there, responding to the SAM Support email address, responding to the PVWatts support email

[1] https://sam.nrel.gov/
[2] https://pvwatts.nrel.gov/

address, providing updated Help documentation showcasing new features, and hosting ”round tables” where users can call in to ask questions live. Updated Help documentation can be seen in each released version of SAM. Evidence of this support can be found on the SAM user forum at https://sam.nrel.gov/forum.html .

The team also gave a variety of live webinars throughout the project, which have been recorded and posted online, accessible from the SAM website. These webinars include:

- ”Modeling Hybrid Power Systems in SAM”, presented August 27, 2024
- ”Modeling Financial Incentives in SAM”, presented August 13, 2024
- ”Modeling PV Uncertainty in SAM”, presented July 30, 2024
- ”Behind-the-meter Battery Dispatch in SAM”, presented Sep 20, 2023
- ”Modeling Utility-scale Photovoltaic Systems in SAM”, presented Aug 23, 2023
- ”Financial Models for Utility-scale Projects in SAM”, presented July 19, 2023

1.3: SAM and PVWatts website maintenance (security and content)

Throughout the project, the team iteratively updated the SAM and PVWatts websites. On the back end, these included cybersecurity and architecture upgrades, and on the front end, these included content updates to address new models and features (e.g., hybrid models).

1.4: Attend and present at industry conferences

Throughout this project, the team attended a variety of relevant industry conferences. These included each of the PV Performance Modeling Collaborative conferences, where the team presented on various topics, gave workshops, and had posters (these products can be found on the PVPMC website at https://pvpmc.sandia.gov/. Additionally, the team attended the IEEE Photovoltaic Specialists Conference (PVSC) each year, and had oral presentations at multiple of those conferences, which are available in the conference proceedings and as preprints online. A list of highlighted conference presentations and publications includes:

- Prilliman et al, ”Side-by-side comparison of Subhourly Clipping Models”. Paper and presentation. IEEE PVSC Seattle. June 2024.

  https://www.nrel.gov/docs/fy24osti/90054.pdf

- Mirletz, “Recent and Planned Improvements to the System Advisor Model”. Presentation. PVPMC Switzerland. Nov 2023.

- Mirletz, “Impacts of Dispatch Strategies and Forecast Errors on the Economics of Behind-the-Meter PV-Battery Systems”. Presentation. IEEE PVSC Puerto Rico. June 12, 2023.

  https://www.nrel.gov/docs/fy23osti/86194.pdf

- Blair, “Recent and Planned Improvements to the System Advisor Model”. Presentation. PVPMC Salt Lake City, UT. May 9, 2023.
- Prilliman, ”Uncertainty quantification of PV annual energy estimates in the System Advisor Model”. Poster. PVPMC Salt Lake City, UT. May 9, 2023.

  https://www.nrel.gov/docs/fy23osti/86169.pdf
- Mirletz, “Successes, Lessons Learned, and Ongoing Challenges from the Open-Source Release of the System Advisor Model”. Presentation. SETO-Funded Open-Source Software Workshop, Albuquerque, NM. Oct 12, 2022.
- Keith, “Recent and Planned Improvements to the System Advisor Model”. Presentation. PVPMC Salt Lake City, UT. Aug 23, 2022.
- Mirletz, “Recent Improvements in PV+Battery Modeling in NREL’s System Advisor Model”. Poster. PVPMC Salt Lake City, UT. Aug 23, 2022.

Task 2: Technoeconomic Analysis Platform Improvements

2.1: Platform maintenance and incremental improvements: energy storage, utility rate models, and financial models

This task supported continuous small updates to the SAM platform energy storage, utility rate, and financial models. Full details of updates made throughout the three year project can be found in the SAM release notes https://nrel.github.io/SAM/doc/releasenotes.html, but a few highlights of improvements are listed specifically below.

Battery model updates included updating the default cell chemistry to lithium ferrophosphate, bug fixes for a new stand alone battery module, corrections and improvements to dispatch algorithms, and maintaining the levelized cost of storage metric.

The utility rate model was upgraded to support 36 time-of-use periods, updating the Utility Rate Database integration to version 8, and bug fixes for rate structures like net billing.

Financial model updates included allowing the investment tax credits to be spread out over multiple years, correcting the interactions between tax credits and the investment based incentives, and correcting the interaction between the battery model and the merchant plant model for charging.

2.2: Maintain a list of user reported bugs and fix according to priority

Over the course of the 3 year project, 314 bug issues were created, and 313 were closed as completed by the end of the project period in the SAM GitHub repository. In the SSC repository, 59 bug issues were created and 59 were closed as completed. No bug issues were reported for the wex and lk repositories.

2.3: SAM releases and patches

Throughout this project, the team released 3 new major versions of SAM, version 2021.12.02, version 2022.11.21, and version 2023.12.17. We also released 7 patches across these three versions of SAM that fixed bugs or improved workflows and user interfaces. We also prepared for a new version of SAM, version 2024.12.12, that was released in December 2024 under different project funding. Full details of all the features included in the SAM releases can be found in the release notes at https://nrel.github.io/SAM/doc/releasenotes.html and each version of SAM, including older versions, can be downloaded from https://sam.nrel.gov/downlo

2.4: PySAM wrapper support and updates

PySAM continues to be a popular way to use SAM models. PySAM updates were released alongside SAM releases such that major versions aligned with SAM new releases, and minor versions with SAM patches. This ensures that users can easily match SAM and PySAM simulations. PySAM user support was provided by the team via the SAM forum and as GitHub Issues. The team corrected several PySAM specific bugs during the project, and designed new capabilities in PySAM to complement new SAM features such as hybrid models. The history of PySAM versions can be found at https://nrel-pysam.readthedocs.io/en/main/versions.html, and public issues addressed by the team are shown on the PySAM GitHub repository at https://github.com/nrel/pysam.

Task 3: Financial Platform Configurability

3.1: Additional integration tests

During the project, the team added financial tests and developed a general way to perform integration tests within SAM cases.

Specifically, 23 integration tests were added to behind-the-meter configurations in ssc pull request 858, https://github.com/NREL/ssc/pull/858.

An additional 138 financial integration tests were added for the remaining financial configurations in ssc pull request 867, https://github.com/NREL/ssc/pull/867.

These 161 added integration tests provided complete test coverage of all the SAM default configurations.

3.2: Introduce further modularity into existing financial models

The team introduced additional modularity in the financial models by separating operations and maintenance calculations from the technology models and setting it up as a standalone proforma line item. This feature was key to the addition of the hybrids compute modules, and was released in SAM version 2023.12.17.

3.3: Make O&M costs available to dispatch models

O&M costs were added to both front of the meter and behind-the-meter dispatch models in ssc pull request 856, https://github.com/NREL/ssc/pull/856.

The dispatch models were updated to include the O&M costs in decision making as described in ssc issue 845, https://github.com/NREL/ssc/issues/845.

Task 4: Interconnection with Annual Technology Baseline

The team developed a script to automatically import data from the Electricity Annual Technology Baseline's "parameter" file and automatically imported PV and wind costs at utility, commercial and residential scales. The script is publicly available on the SAM GitHub at https://github.com/NREL/SAM/blob/develop/samples/.

Task 5: Platform Enhancements for Better Decision-Making and Design

5.1: Improve visualization of PV, battery, load, and utility rate interaction

The team developed new summary plots representing the energy servicing the load from the PV system, battery, and grid as a monthly stacked bar plot. The team also added a summary plot representing the energy charges, demand charges, and fixed monthly charges making up the monthly utility bill for behind-the-meter systems. For behind-the-meter systems with a battery, the 'Time Series' graphing page now shows stacked area plots of the timeseries energy to the load from the PV system, battery, and load. The plot is also superimposed with a line plot showing the battery state of charge (SOC) on a right-hand Y-axis. This time series plot will show up by default on the first simulation run for behind-the-meter battery technologies in the 2024 SAM release.

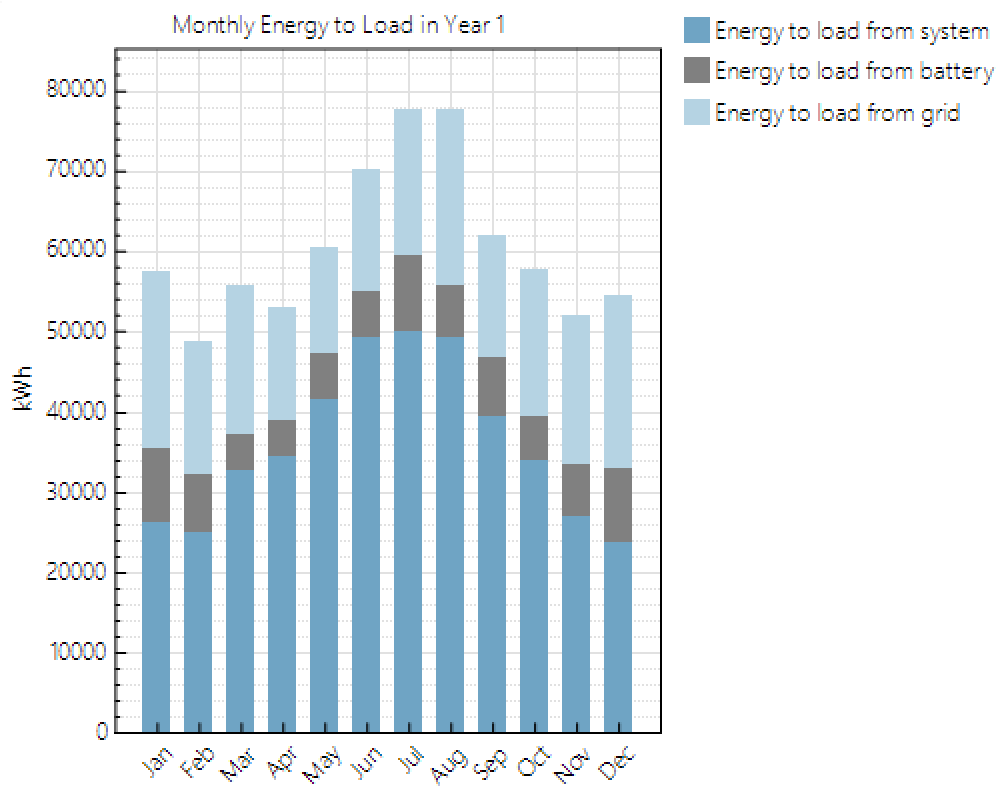


Figure 1: Monthly energy to load graph in SAM development version

5.2: Create a method to easily compare cases

The SAM team has developed macros to compare up to 4 individual cases based on key performance and financial metrics and graphical displays of energy and project cashflows. There is also a version of the macro for battery technologies that has plots specifying the

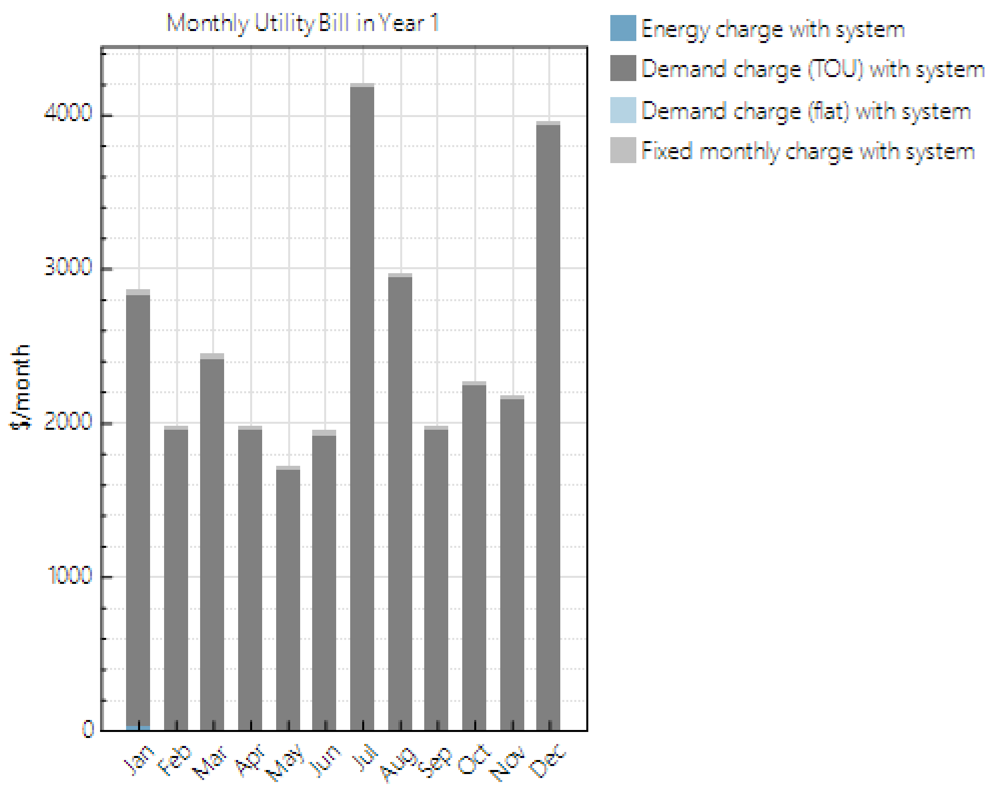


Figure 2: Monthly utility bill graph in SAM development version

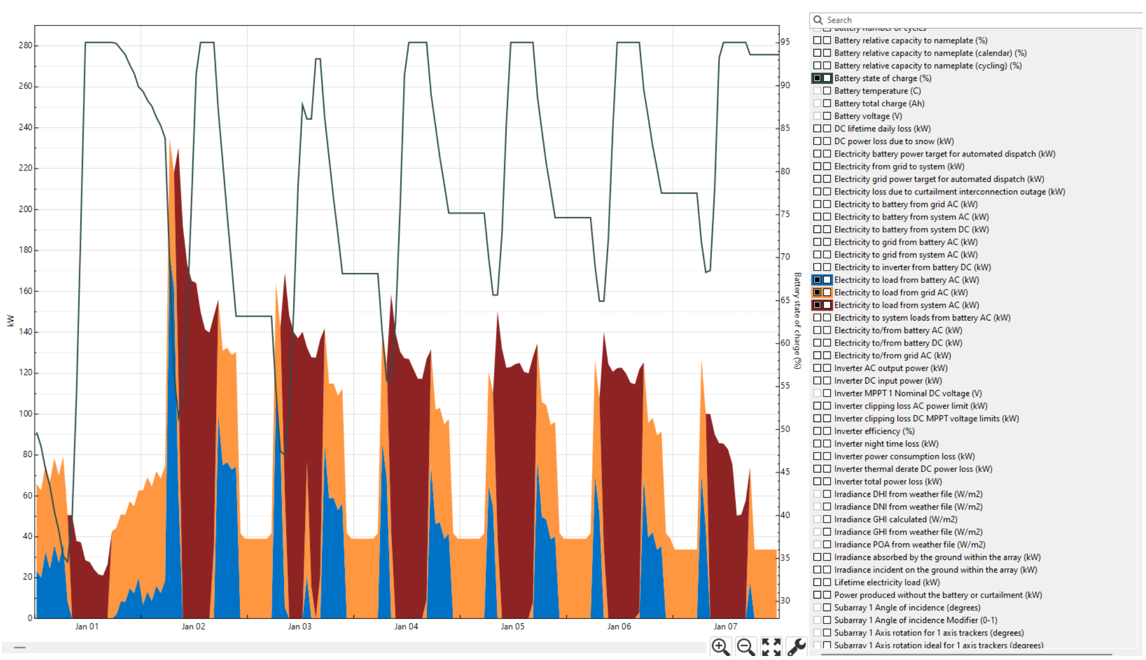


Figure 3: Screenshot of time energy to load stacked area plot with battery state of charge line plot in SAM development version

battery discharge from the systems and a waterfall chart showing the difference in annual energy charged between two battery configurations. These comaprison reports are made using interactive html and are displayed in a web browser. The reports only compare cases modeled from the same financial perspective, and can compare across the range of SAM performance models. These macros will be available in the next SAM release.

5.3: Identify and integrate high-impact user interface (UI) enhancements

Over the course of the three-year project, the team conducted several extensive user interface (UI) updates based on user feedback and a desire to emphasize key input variables in the model setup. These UI enhancements include, but are not limited to:

- Redesigned the battery dispatch UI pages to only show the input options relevant to the currently selected dispatch model.
- Reorganized battery design pages to separate battery cell configuration, degradation modeling and replacement, and battery dispatch to reduce the number of inputs on each individual page.
- Moved module dimension inputs to the Module pages rather than the Shading and Layout pages to clarify the impact of those module dimensions on shading, land area, and module temperature.
- Updated Merchant Plant revenue pages to allow for easier editing of different ancillary service markets, streamlined downloading of NREL's Cambium hourly price data.
- Added Spatial tab in simulation results to show heatmap graphs for bifacial albedo, ground irradiance analysis.
- Added a page for specifying the modeling timestep for standalone battery systems, alleviating potential confusion for users.
- Renamed the Generic System model to Custom Generation profile, including in hybrid configurations with PV and batteries, to clarify the intended use of this model as a input data stream of performance data, simple generation model, or combined generation profile from other SAM technologies.

The exact release of each of these updates is listed in the SAM release notes at

https://nrel.github.io/SAM/doc/releasenotes.html

and can be downloaded in the associated publicly available versions of SAM at

https://sam.nrel.gov/download.html.

5.4: Migrate UI equations to software development kit

Several models now have UI equations available to the software development kit (SDK), instead of being isolated in the SAM GUI. These models include marine energy, detailed PV, PVWatts, battery, geothermal, single owner, merchant plant and utility rate calculator. Some other models such as CSP have moved their UI equations entirely within the

SDK. This means that these equations are now more easily accessible to the language wrappers, including the popular PySAM Python package.

Task 6: Bifacial Model Improvement

6.1: Reduce model and validation uncertainty

In this project, a comparison of the ground-irradiance obtained with view factor method versus with raytrace was performed, finding good agreement within 1-2% of mean bias deviation, exploring different clearance heights and pitch. Data from NSRDB for most of the US locations were analyzed for various setups for comparison presented in the table below, considering most common variations in PV and AgriPV including higher ground-clearances, more spacing between modules, tracked and fixed systems. The ground-irradiance validation and method for this wide-scale dataset generation were presented at an oral presentation on the 2023 IEEE PVSC Conference, in Puerto Rico, Viewfactor and Raytracing for AgriPV Modeling.

Scenario	System Type	Racking	Panel Tilt	Hub Height (m)	Row Spacing (m)	Panel Spacing (m)
1	Conventional utility-scale	1-axis tracking	-50° to 50°	1.5	5	0
2	Elevated panels	1-axis tracking	-50° to 50°	2.4	5	0
3	Elevated & intra-row spaced panels	1-axis tracking	-50° to 50°	2.4	5	1
4	Utility-scale with 2x edge-to-edge spacing	1-axis tracking	-50° to 50°	1.5	8	0
5	Conventional utility-scale	Fixed tilt	Latitude (max 40)	1.5	Location dependent*	0
6	Elevated panels	Fixed tilt	Latitude*	2.4	Location dependent*	0
7	Elevated & intra-row spaced panels	Fixed tilt	Latitude*	2.4	Location dependent*	1
10	Vertical bifacial	Fixed vertical	90°	2	8.6	0

Figure 4: Scenarios compared for raytracing and view factor results on ground-irradiance.

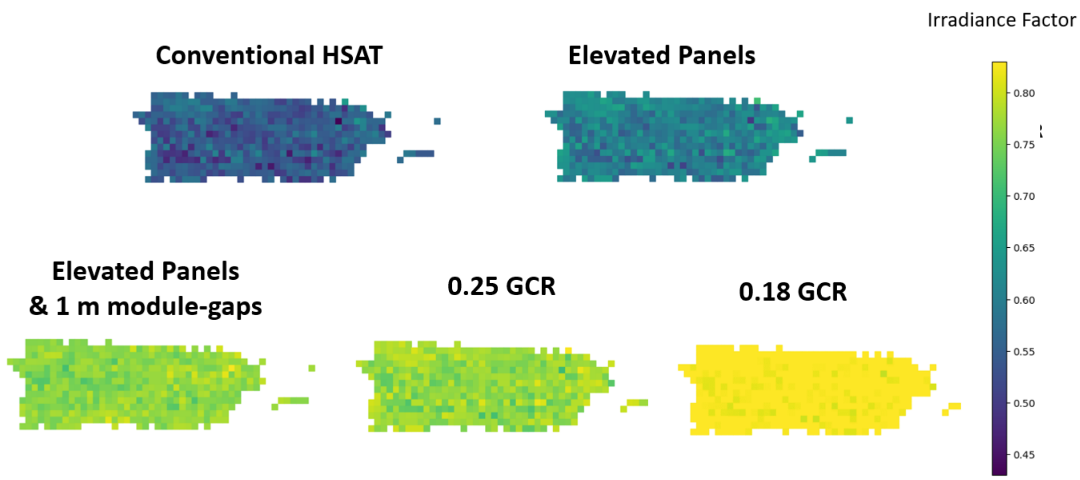


Figure 5: The different scenarios, close-up of irradiance factor results for Puerto Rico for the day and location of the PVSC confernece

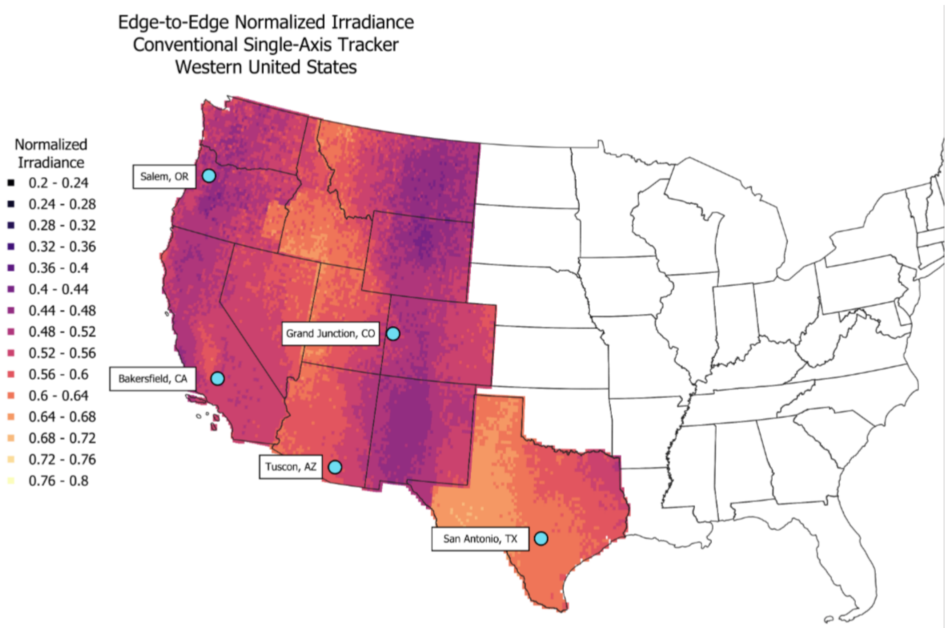


Figure 6: Raytrace results of average ground irradiance, normalized by location, underneath a conventional utility-scale tracker field (hub height 1.5m, GCR 0.4). NSRDB data as input.

Additional work on this task also included updates to three chapters in the textbook from IET Publishers: "Bifacial Photovoltaics (Subtitle: Technology, Applications and Economics), 2024". These are Chapter 4: Modeling, Chapter 8: Global optimization and a new Chapter 6: Emerging Bifacial Applications. The anticipated publication date is Q12025.

6.2: SAM bifacial model

A variety of bifacial PV modeling additions and improvements were completed through this project. The new features include:

1. Irradiance loss factor differentiation
2. Rack shading loss
3. Intra-module electrical mismatch
4. Multi-albedo ground
5. Temporospatial ground and rear irradiance output
6. Bifacial loss diagram additions

The single value for average annual rear irradiance loss due to soiling, mismatch, or external shading on bifacial modules has been split into a rear soiling loss, a rack shading loss and a bifacial electrical mismatch loss. These losses are applied only for bifacial modules and all can be specified as constant percentages. The electrical mismatch loss can optionally be calculated by selecting a checkbox in the UI. An optional calculation for the rack shading was added, utilizing pre-calculated look-up tables of ray-traced torque-tube and rack geometries [3].

Intra-module electrical mismatch was also added to the bifacial performance model that accounts for non-uniform rear irradiance distributions. The loss is calculated according to Deline, et al. 2020 [4], and considers the modules' fill-factor, average front-side irradiance, rear irradiance distribution and the module bifaciality.

Temporospatial ground albedos have been added to SAM as another option to the existing constant uniform and uniform monthly albedos. This allows the simulation of monthly and spatially varying ground covers and vegetation. A UI widget, as shown in Fig. 7, has been developed for easy specification of these albedos. The representational drawings of the arrays automatically change for either single-axis tracking or fixed mount arrays, including their reference position to the ground albedo sections. The underlying front and rear-side irradiance and shading models, which are based on view factor calculations, have all been modified to utilize these new spatial albedos.

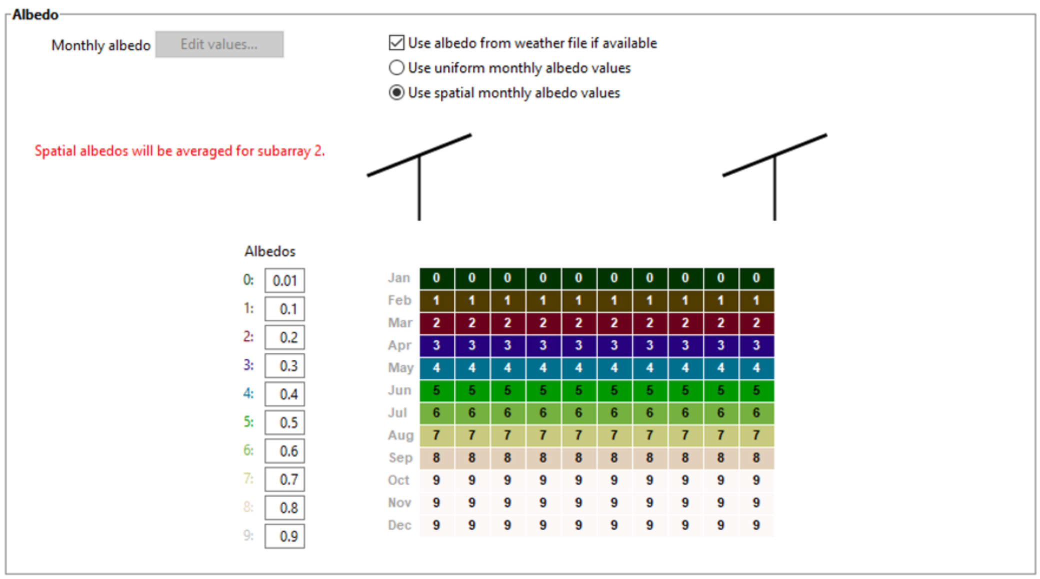


Figure 7: New widget for specifying the monthly spatial ground albedo

The bifacial model was also modified to output calculated spatial irradiance on the ground between PV rows along with the spatial irradiance on the rear of the PV modules. This feature may be useful for owners, developers, and researchers interested in exploring the gains of combined bifacial and agricultural sites. These spatial irradiance timeseries are

[3]Peláez, Silvana Ayala, Chris Deline, Joshua S. Stein, Bill Marion, Kevin Anderson, and Matthew Muller. "Effect of torque-tube parameters on rear-irradiance and rear-shading loss for bifacial PV performance on single-axis tracking systems." In 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), vol. 2, pp. 1-6. IEEE, 2019.

[4]Deline, Chris, Silvana Ayala Pelaez, Sara MacAlpine, and Carlos Olalla. "Estimating and parameterizing mismatch power loss in bifacial photovoltaic systems." Progress in Photovoltaics: Research and Applications 28, no. 7 (2020): 691-703.

plotted in heat maps that are displayed on the Summary page of the results, as shown in Fig. 8.

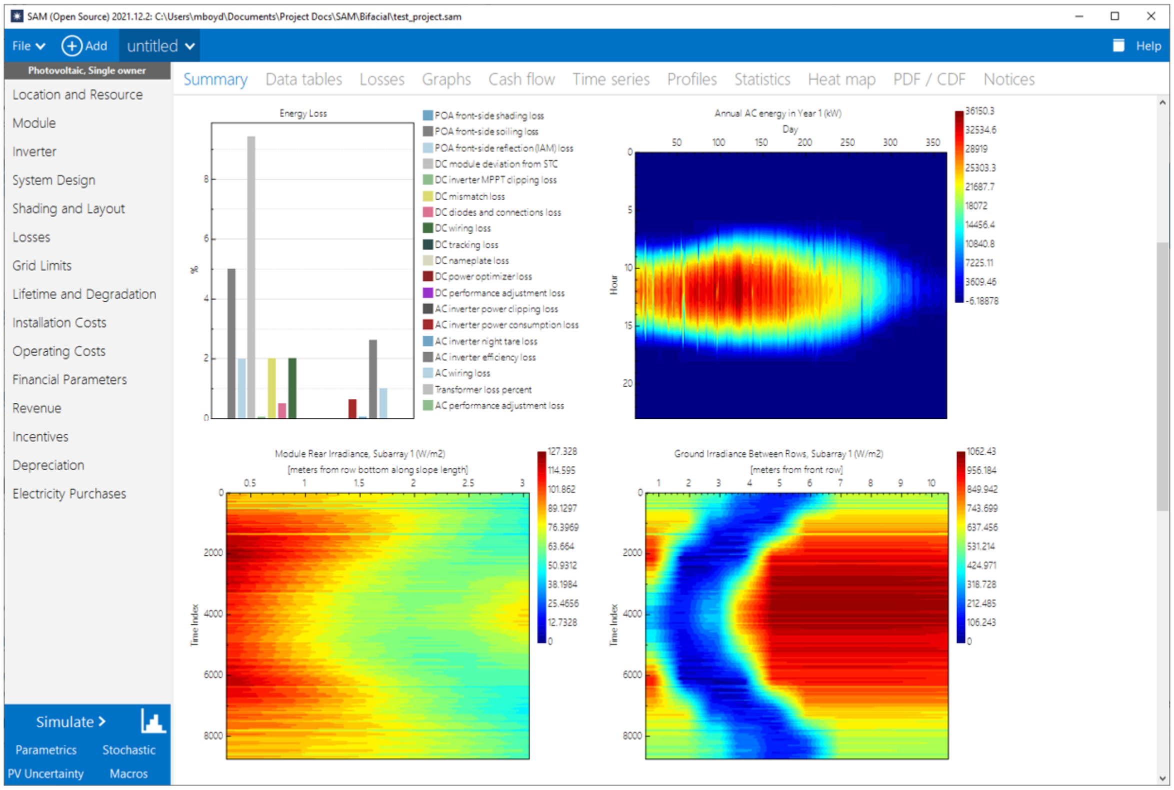


Figure 8: New heat maps of the module rear irradiance and ground irradiance between rows, versus position and time

The loss diagrams have also been updated to include the differentiated bifacial irradiance losses when the bifacial model is enabled. The new diagram replaces the single bifacial irradiance addition with a ground reflected to rear irradiance addition, a rear rack shading loss, a rear soiling loss and a bifacial electrical mismatch loss.

These bifacial model updates were first released as a part of SAM version 2022.11.21, and are present in all subsequent versions.

Task 7: Hybrid User Interface and Analysis Capabilities in SAM

7.1: Create hybrid user interface in SAM

For this project, the SAM team created a new ”Hybrid” category for hybrid systems that combines photovoltaic and wind power generation with optional battery storage and/or fuel cells. The option to use SAM’s ”Generic System” model makes it possible to model a hybrid system with a fuel-based generator or any type of power generation system using data from an external performance model. The user-interface approach allowed the team to add hybrid systems to SAM without developing new performance models – the user interface runs the appropriate combination of existing Detailed PV, PVWatts, Wind Power, Generic System, and Fuel Cell performance model to calculate the hybrid system’s generation profile and uses that as input to the Battery Storage model that determines how to operate the battery.

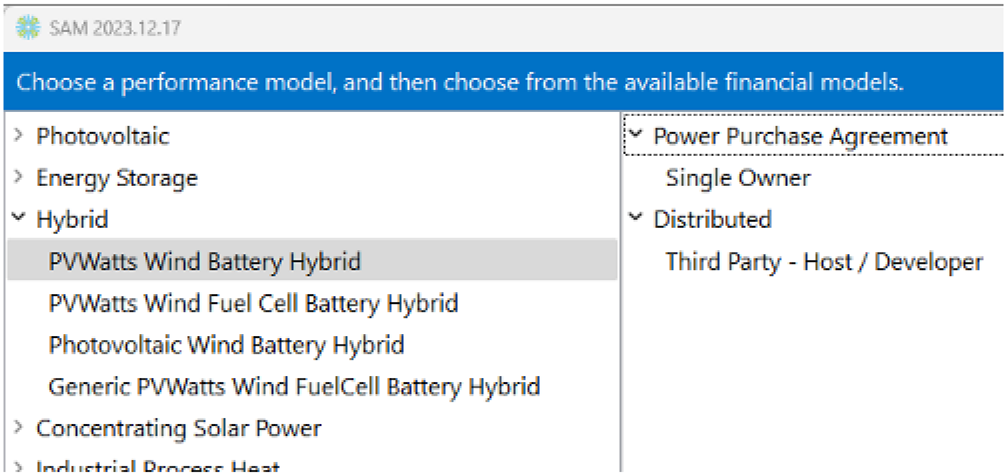


Figure 9: Screenshot of hybrid configuration options in SAM 2023.12.17

For each hybrid configuration, SAM reports performance metrics for each subsystem and calculates financial metrics for the hybrid system as a whole.

Hybrid simulations were first released in SAM version 2023.12.17, and are available in all subsequent versions.

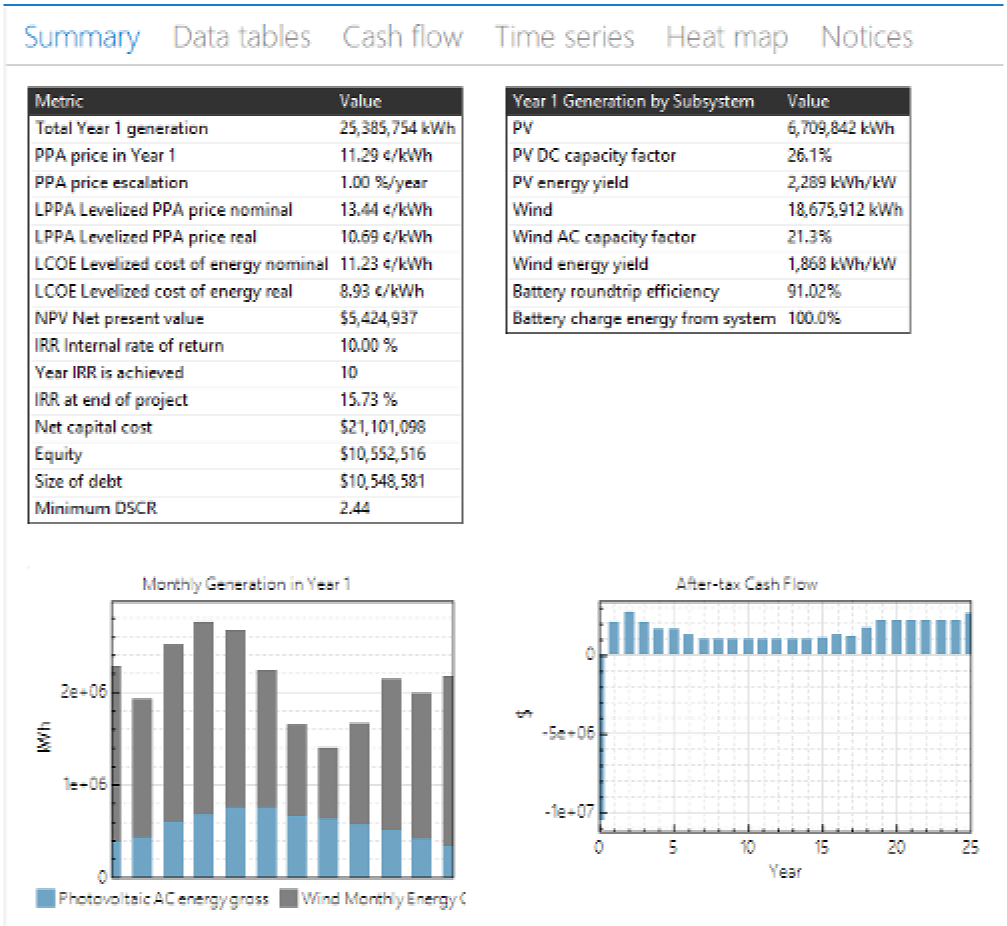
7.2: Instantaneous net-zero dispatch

The instantaneous net-zero dispatch option for behind-the-meter systems with battery storage dispatches the battery to eliminate or minimize the use of grid power to either charge the battery or meet the building or facility's electric load. This option is available in SAM as the "self-consumption" dispatch option.

The self-consumption battery dispatch option works by effectively setting the grid interconnection limit to zero. It requires the user to run iterative simulations to determine the battery size that completely eliminates the use of grid power. Figure 12 compares SAM's peak shaving battery dispatch option to the self-consumption option, showing that the latter meets the building's electricity load without using grid power. This feature was first released in SAM version 2023.12.17, and are available in all subsequent versions.

Conclusion

This three-year project continued to provide valuable and extensible PV, battery, and financial modeling resources to the larger solar community through model development and the SAM and PVWatts platforms. Software maintenance and technical support tasks enabled continued usability of the platforms and releases of new features, including the popular PySAM Python package; relevant financial, utility rate, and battery modeling updates allowed these models to continue to provide up-to-date and relevant information to users; and open source activities allowed for external contributions, full transparency, extended usability, and collaboration opportunities throughout the project. Additionally,



Metric	Value
Total Year 1 generation	25,385,754 kWh
PPA price in Year 1	11.29 ¢/kWh
PPA price escalation	1.00 %/year
LPPA Levelized PPA price nominal	13.44 ¢/kWh
LPPA Levelized PPA price real	10.69 ¢/kWh
LCOE Levelized cost of energy nominal	11.23 ¢/kWh
LCOE Levelized cost of energy real	8.93 ¢/kWh
NPV Net present value	$5,424,937
IRR Internal rate of return	10.00 %
Year IRR is achieved	10
IRR at end of project	15.73 %
Net capital cost	$21,101,098
Equity	$10,552,516
Size of debt	$10,548,581
Minimum DSCR	2.44

Year 1 Generation by Subsystem	Value
PV	6,709,842 kWh
PV DC capacity factor	26.1%
PV energy yield	2,289 kWh/kW
Wind	18,675,912 kWh
Wind AC capacity factor	21.3%
Wind energy yield	1,868 kWh/kW
Battery roundtrip efficiency	91.02%
Battery charge energy from system	100.0%

Figure 10: Screenshot of results summary for a front-of-meter PV-wind-battery hybrid project

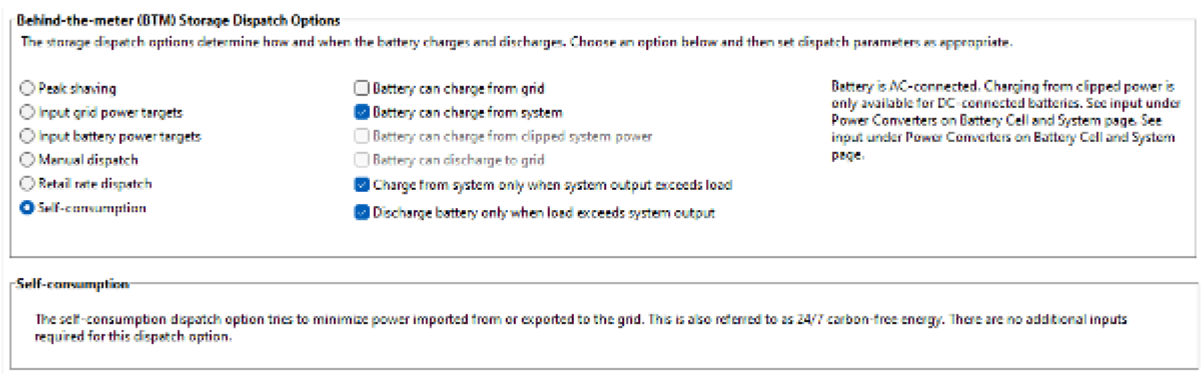


Figure 11: Battery Dispatch input page showing self-consumption dispatch option and description.

this project supported the validation of and concrete improvements to the bifacial models, the addition of hybrid modeling features that have been popular since their release, the addition of a new battery dispatch algorithm to maximize self-consumption in support

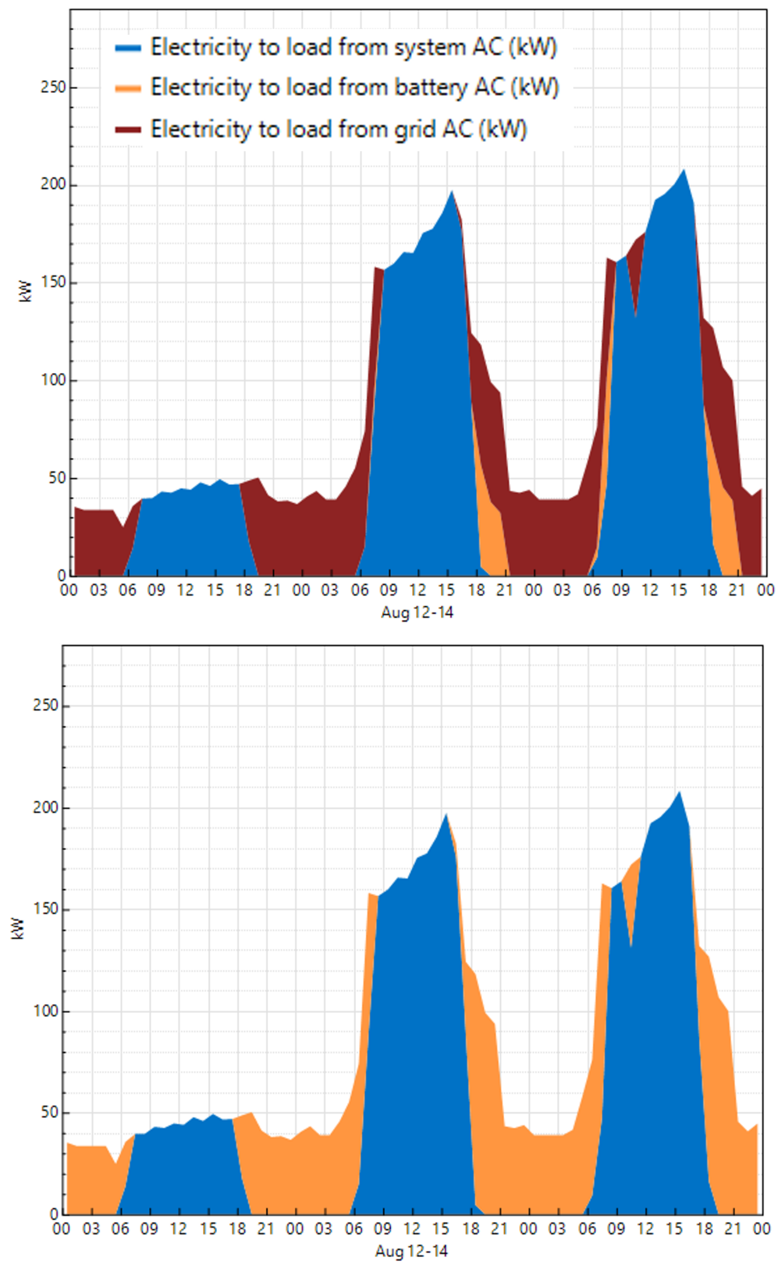


Figure 12: Comparison of peak-shaving (top) and self-consumption (bottom) battery dispatch options.

of 24/7 carbon-free energy goals, specific and high-priority user interface improvements, and automated connection to the NREL Annual Technology Baseline for easier future maintenance. The SAM and PVWatts usage statistics over this three-year project indicate that the software suite continued to enable and support PV and battery evaluation and deployment across a broad spectrum of academia and industry.