FY19-FY21 Final Technical Report: Foundational Open Source Solar System Modeling Through Improvement and Validation of the System Advisor Model and PVWatts

Janine M. F. Keith, Brian Mirletz, Matt Prilliman, Nate Blair, Darice Guittet, Steven Janzou, and Paul Gilman

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Final Technical Report

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Principal Investigator	Janine Freeman Keith Senior Engineer janine.keith@nrel.gov 303.275.4694
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Executive Summary

Accelerating intelligent deployment of solar energy technologies demands accurate system modeling every step of the way. From project development to policy research, grid integration studies to development of novel technologies, industry and researchers alike need validated, transparent, easy-to-use, extensible, cutting-edge, and accurate models of both the performance and financing of solar systems. The System Advisor Model (SAM) and PVWatts tools provide a platform to fill that need. The overarching goal of this set of software tools is to enable accurate PV system modeling across the industry, and our usage metrics indicate that we continue to succeed in that endeavor, with a user starting SAM **every 2 minutes** globally, and over **17 million PVWatts hits per month**.

NREL is in a unique position to provide these capabilities to the broader industry as a trusted, validated, and independent third-party. In addition to the many grid integration, cost modeling, and policy analysis EERE studies that depend on SAM (including the SunShot Vision Studies, ERGIS, and NARIS), we reduce the barrier of entry for researchers and new entrants to the market, thereby supporting innovation and growth. When we make improvements or add new features in SAM, it drives other tools (that focus on more specific market sectors) to add new features as well. And because we are not profit-driven, we can support emerging technologies that have the potential to drastically reduce the price of solar, that don't yet have a modeling solution provided by private industry because their market share isn't high enough. SAM also seamlessly integrates with other DOE sponsored high-quality open data products, such as the National Solar Radiation Database (NSRDB) and the Utility Rate Database (URDB), and provides a vehicle for impactful research to be communicated to the broader industry. The NREL team can also easily leverage in-house expertise in multiple areas across the laboratory to deliver informed models in several areas.

This project leveraged DOEs past investment in the SAM and PVWatts platforms to continue to provide valuable and extensible PV, battery, and financial modeling resources to the larger solar community. We pursued multiple avenues in parallel: software maintenance and technical support that are foundational to the continued usability of the SAM and PVWatts platforms; platform and PV 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 opportunities for industry interaction.

Background

During this SAM project cycle, growth in solar with storage continued in utility-scale deployment, integration into existing power plants or buildings for electric vehicle charging, technological developments such as Li-Ion battery recycling and funding investment growth, and potential policy support. SAM continued to make improvements in its PV + battery modeling capabilities to keep up with the continued growth in these areas. New work in the 2020.11.29 SAM release included resilience metrics for modeling the probability of surviving outages, allowing analysis of mini-grids for improving energy access in remote communities.

Similarly, the larger question of adding PV and batteries to existing power plants or buildings has many combinations: hybrid systems from expanding existing wind sites to increase valuable interconnection capacity, addition of solar and batteries to mixed-use buildings for a variety of purposes. Interest in integrating electric vehicle charging stations in buildings with energy storage increases as uptake of EVs pick up pace. The SAM team contributed to BTMS, a buildings + EVs + PV + storage analysis project, which will be using the battery model for its detailed cell-level modeling.

As both existing battery technologies improve and novel formulations are developed, the modeling capabilities of SAM allowed users to capture differences such as long-duration versus high-power storage, flow batteries, and modeling new chemistries. As storage continues to play a bigger role in large scale, interconnected systems, the performance modeling requires realistic and smart dispatch options and the SAM team has worked on exploring this space.

Hybrid generation and storage projects continue to experience significant growth in U.S. markets, but questions remain as to the optimal siting of storage resources [1]. Existing interconnection limit features within SAM as well as planned updates to financial models could help developers size and site future systems.

The release of the 2020.2.29 version of SAM included resilience calculations for sizing behind the meter storage systems. Literature shows that this, or similar algorithms, could be adapted to front of the meter systems either through the existing PPA financial models[2], or through an updated capacity payments model that includes resilience [3]. Ongoing work with complementary projects included updates to the battery degradation models, which will enhance the forecasts for these systems.

Several members of the team attended the PVPMC Webinar on Solar Resource Assessment in June 2020, which included a talk by Manajit Sengupta on updates to the NSRDB [4]. Updates included increased spatial and temporal resolution and may inform updates to SAM's download interface with NSRDB.

A paper by Rodrguez-Gallegos et al. showed through a worldwide analysis of energy yeild and LCOE that installations with bifacial panels with single axis trackers have the lowest LCOE for 93.1% of the world's land area [5]. This helps reinforce continued interest

[1]Gorman, Will, et al. "Motivations and options for deploying hybrid generator-plus-battery projects within the bulk power system." The Electricity Journal 33.5 (2020): 106739.

[2]H. Shin and J. H. Roh, "Framework for Sizing of Energy Storage System Supplementing Photovoltaic Generation in Consideration of Battery Degradation," in IEEE Access, vol. 8, pp. 60246-60258, 2020.

[3]Gailani, Ahmed, et al. "Degradation Cost Analysis of Li-Ion Batteries in the Capacity Market with Different Degradation Models." Electronics 9.1 (2020): 90.

[4]Sengupta, Manajit A Status Update on the National Solar Radiation Data Base June 24, 2020 PVPMC Webinar on Solar Resource Assessment

[5]Carlos D. Rodrguez-Gallegos, Haohui Liu, Oktoviano Gandhi, Jai Prakash Singh, Vijay Krishnamurthy, Abhishek Kumar, Joshua S. Stein, Shitao Wang, Li Li, Thomas Reindl, Ian Marius Peters, Global Techno-

in SAM's bifacial modeling features, since the code used by the authors is closed-source.

Additional developments in photovoltaic performance modeling involve time-series analyses and model training aimed at developing correction factors that can correct the over-prediction of PV performance at low irradiance conditions at hourly data intervals without performing time-intensive sub-hourly analysis[6] [7]. SAM was used in two different projects presented at the 2020 Virtual Photovoltaic Specialists Conference (Virtual PVSC) to determine the correction that needed to be made to correct hourly performance predictions to that of minute predictions based on variables such as the Clear Sky Index (CSI), Plane of Array Irradiance (POA), and DC:AC ratio[6] [7]. Advancements in this modeling will allow for improvement in the accuracy of hourly PV performance models as calculated in SAM.

Our work continues to be adopted and used by the PV modeling community; within research as evidenced by papers citing the SAM General Description; and in the open source community.

Several members of the team attended the PVPMC Webinar on PV Performance Modeling Methods in August 2020, which included a talk by Branislav Schierer on updates to the Solargis PV simulation modeling software.[8]. Updates to the software include raytracing for shading calculations and PV Module parameters that come from the SAM database.

The August 2020 PVPMC Webinar also included a talk from Steve Ransome on the Loss Factor Model for predicting IV curves and the Mechanistic Performance Model for degradation studies [9]. These models could potentially offer improved understanding of the contributions of different loss mechanisms to overall PV performance loss if implemented in SAM.

In 2020, the following relevent work was published by other researchers, some using SAM:

- Photovoltaic String Sizing Using Site-Specific Modeling, IEEE Journal of Photovoltaics
- AIMFAST for heliostats: Canting tool for long focal lengths, AIP Conference Proceedings
- Modelling of PV systems installations using Geographical Information System:The case of Toluca (Mexico), Journal of Remote Sensing & GIS

Economic Performance of Bifacial and Tracking Photovoltaic Systems, Joule, 2020, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2020.05.005.

[6]K. Bradford, R. Walker, D. Moon, and M. Ibanez, A Regression Model to Correct for Intra-Hourly Irradiance Variability Bias in Solar Energy Models, in Proceedings of 2020 Virtual Photovoltaic Specialists Conference.

[7]M. Mikofski, S. Raju, M. Kula, and R. Kharait, Energy Yield and Clipping Loss Corrections for Hourly Inputs in Climates with Solar Variability, in Proceedings of 2020 Virtual Photovoltaic Specialists Conference.

[8]Orosi, Peter, Skoczek, Artur, Schnierer, Branislav, Self-shading analysis in PV simulation: comparison of different software packages August 5, 2020, PVPMC Webinar on PV Performance Modeling Methods

[9]Ransome, Steve, "How to use the Loss Factors and Mechanistic Performance Models effectively with PVPMC/PVLIB," August 5, 2020, PVPMC Webinar on PV Performance Modeling Methods.

These papers show the wide applicability of SAM's models for detailed PV modeling in the first, CSP model development in the second, and breadth of analysis in the third. SAM's open source status continuse to promote adoption for PV and battery analysis and development, as evinced by PySAM being used in three external Github repositories:

- SoDa: An irradiance-based synthetic Solar Data generation tool to generate realistic sub-minute solar photovoltaic (PV) power time series
- solarapp: An interactive dashboard to forecast various Solar PV Generation parameters
- opentaps SEAS: Smart Energy Applications Suite, an applications platform for clean energy

2020 saw growth in use of SAM in other tools, such as SETO's dGen model for Solar and Storage Futures studies; DOE's cross-lab BTMS Consortium project; an internal NREL Hybrid LDRD, among others. Hybrid modeling and battery-coupled systems continued to be a dynamic area of research, allowing for growth in both applications for and improvements to SAM's sophistication in PV, Battery, utility and financial models. SAM also continued to grow in value in portions of country undergoing energy transition, specifically Puerto Rico, as well as island locations.

Our work in SAM continued to grow in relevance in the field of battery energy storage modeling. This is evidenced by the 2020 Grid Energy Storage Grand Challenge Roadmap, which sets cost and performance targets for a variety of energy storage technologies including several battery technologies. The Roadmap specifically mentions our continued work to improve the lifetime battery modeling capabilities within SAM as a necessary part of achieving the goals set forth in the Roadmap. It also mentions other research such as the Annual Technology Baseline (ATB) that directly influence SAM model defaults.

In addition to the Roadmap, DOE also released two additional reports that informed the goals and pathways presented in the Roadmap: the 2020 Grid Energy Storage Technology Cost and Performance Assessment and the Energy Storage Market Report 2020. The Cost and Performance Assessment provides an assessment of the current costs and performance metrics for storage technologies including lithium ion, lead-acid, and vanadium redox flow batteries, all of which are currently modeled in SAM. The categorized costs presented in this report directly relate to the financial modeling of these battery storage technologies that is performed in SAM. The Market Report describes current and projected global markets for these different storage technologies through the year 2030. The report projects extensive growth in the lithium ion battery market based on decreasing costs, and projects that the market growth will occur primarily in storage systems tied to other renewable energy systems such as photovoltaics. This PV + battery configuration remains a current primary focus in the SAM modeling efforts and these reports further demonstrate the value of SAM to renewable energy stakeholders.

SAM continues to be a trusted tool in photovoltaic and battery technoeconomic analysis that is frequently cited in relevant reports and research. SAM was used to calculate real levelized cost of energy values as reported in the U.S. Solar Photovoltaic System and

Energy Storage Cost Benchmark: Q1 2020[10]. This report summarizes the decline of PV and battery costs over the decade ranging from 2010-2020 across all economies of scale. The fact that SAM is used in this quarterly NREL analysis that is heavily referenced throughout the solar and battery storage industries shows SAM's continued importance and relevance in the space.

Recent work presented at Energy System Integration Group's 2021 Technical Workshop by Lawrence Berkeley National Laboratory looking at ways to enhance the value of solar energy also used SAM's performance and financial models in its analyses[11]. This work aimed to maximize the value of solar systems in terms of both costs and value to the grid through some combination of solar orientation changes and storage deployment. SAM's use for these types of technoeconomic analyses by outside laboratories and other research entities is further evidence of its impact and value in the fields of PV and stoarge.

2021 marked the release of the first technical report of the Storage Futures Study, which details the potential for current and future cost-effective storage deployments. This report[12], and the subsequent reports scheduled to come from the Storage Futures Study, can inform the default cost values and battery performance model options present within SAM.

2021 also included the 48th IEEE Photovoltaics Specialists Conference, where there were many presentations relevant to SAM, or using SAM in their methods and results. Keelin et al. [13] presented an update to the SolarAnywhere data specification that better accounted for the impact of wildfire smoke on irradiance. They found that 2020 set a new record of 105 "high impact days" (defined as a 30% or greater reduction in DNI) across 7 geographically diverse locations, 2.5 times the previous record set in 2018. This work has two implications for SAM: first verifying that the NSRDB data for wildfire-prone locations correctly account for the impact of aerosols; second: consider developing a macro or other weather file modification to allow users to predict the impact of fires in future years.

A talk by Jennz Riesz of the Australian Energy Market Operator detailed issues that occur at a high generation by renewables. On October 11th, 2020, the South Australian grid reached 78% generation by distributed PV. Issues the grid operator has seen at that level include overvoltage on the distribution network causing distributed inverters to disconnect from the grid. This means a forward looking loss forecast for a high renewables future might need to include more and longer-term clipping for distributed systems than we expected previously. Connections to Cambium or similar could help SAM users model these scenarios.

[10] Feldman, D.; Ramasamy, V. ; Fu, R. ; Ramdas, A.; Desai, J.; Margolis, R. (2021) U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020. 103 pp.; NREL/TP-6A20-77324.

[11] Mills, A.; Wiser, R.; Bolinger, M.; Gorman, W.; Montanes, C.; O'Shaughnessy, E (2021) Enhancing the Value of Solar Electricity at High Penetrations. (PDF).

[12] Denholm, P.; Cole, W.; Frazier, W.; Podkaminer, K.; Blair, N. (2021), The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System. 42 pp. NREL/TP-6A20-77480.

[13] Keelin, Patrick, Alex Kubiniec, Akanksha Bhat, Perez, Marc, Dise, John, Perez, Richard, and Schlemmer, James. Quantifying the Solar Impacts of Wildfire Smoke in Western North America. In IEEE Photovoltaics Specialists Conference 48, Miami, FL, 2021.

Finally Larson and Hobbs[14] utilized PVWatts in their comparison of a Wavelet Variability Model forecast for fleet level PV variability. The paper highlights the need for data and modeling with increasingly higher temporal and spatial resolution.

The SAM team also contributed PV power output, module temperature, and nominal irradiance results modeled using the latest SAM version for systems specified in the 2021 Blind PV Modeling Comparison organized as part of the PVPMC workshop series. SAM's contribution to this blind modeling comparison offers an opportunity to evaluate SAM's performance models against other relevant industry modeling tools and allows for re-evaluation of default input assumptions in the SAM PV models based on comparative analysis against other tools. The modeling comparison is expected to be published in the coming months.

Members of the SAM team also attended the virtual Tracking the Sun Webinar for updates on PV system sizing and cost trends analyzed over the last year [15]. This webinar revealed strong market presence of Module Level Power Electronics (MLPE) in distributed PV systems, which could impact SAM's default inverter modeling values in future modeling of distributed PV systems.

Project Objectives

To continue to achieve a high level of impact for all NREL solar system modeling platform stakeholders, multiple avenues of research, model development, model improvement, user support, stakeholder engagement, and software maintenance are required in parallel. The goal of the open-source project is to further enable both commercial and research entities to contribute to and benefit from the detailed performance and financial models in SAM, thereby creating a foundational and open platform for detailed PV systems modeling and integration of solar with energy storage and other synergistic technologies. The platform improvement project task focuses on improvements to the suite of solar modeling capabilities as a platform for projects that seek to more fully understand the total value of PV systems, including how storage technologies could increase that value. Improving the platform to accurately value PV systems enables research and industry alike to focus on the technology and policy innovations, and still easily understand how those innovations reduce cost and increase deployment via a validated and accurate platform. To continue to enable accurate PV modeling, simulation capabilities must grow along with the technology, absorbing and informing the most up-to-date techniques and cutting-edge discoveries. This ensures that the community has access to high-resolution and accurate prediction models to value solar and storage systems and perform detailed grid integration studies. The goals of stakeholder engagement are to ensure that the state-of-the-art models developed for SAM reach the appropriate audience, are sufficiently validated, and meet the requirements of the user community. The goal of providing technical support is

[14] Larson, David P, and William B Hobbs. Fleet-Level PV Modeling with Realistic Sub-Hourly Solar Power Variability. In IEEE Photovoltaics Specialists Conference 48, Miami, FL, 2021.

[15] Barbose, G.; Dargouth, N.; O'Shaughnessy, E.; Forrester, S., Tracking the Sun: Pricing and Design Trends for Distributed Photovoltaic Systems in the United States. (Website).

to dramatically accelerate the learning process for users, as well as improve their overall analysis results by pointing them to the most effective way to model their desired cases or conduct their complex analysis. The goals of maintenance tasks are to ensure that critical tasks like bug fixes, cybersecurity updates, basic website updates, producing new releases and patches, updating defaults, and updating component databases are performed so that the SAM and PVWatts PV modeling platforms can continue to provide valuable services to the industry.

Project Results and Discussion

As context for the efforts described below, as of October 11, 2021, the newest version of SAM, 2020.11.29, has been registered by over 20,000 users since its release, with over 85% of SAM usage having already switched to the newest version (Figure 3). On average, SAM is started once every 2 minutes around the world, and usage continues steadily increasing each quarter and has now reached over 1.9 million cumulative starts since 2014. Table 1 shows SAM usage since November 2014. Figure 1 shows registered SAM users and usage by version, and Figure 2 shows each SAM version's contributions to the total number of starts in a given time period, demonstrating the adoption of new versions. Note that unfortunately, more granular statistics are not available prior to 2019.

Table 1: SAM Usage Statistics Since November 2014

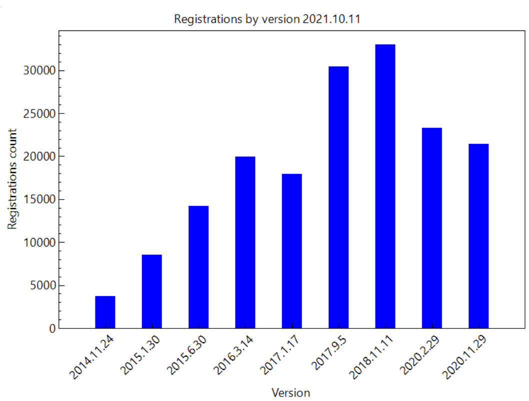
Total number of users	175,555
Total number of starts	1,894,010
Starts per person	10.79
Days since 2014/11/24	2,513
Average usage per day	753
Total number of countries	216
Total number of domains	22,299

In this project, 10 high-level tasks were specified. However, two of the tasks repeated once each budget period, so they are listed together here for ease of summarizing. Tasks 1, 4, and 7 were the same task for years 1, 2, and 3 respectively; and similarly, Tasks 2, 5, and 8 were the same task for years 1, 2, and 3 respectively. Within each task, there are several subtasks.

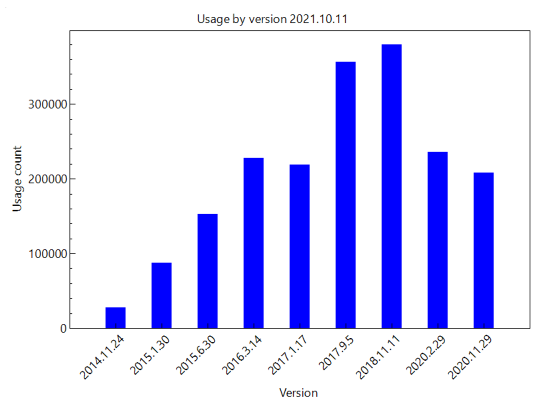
Tasks 1, 4, and 7: Open Source Community and Stakeholder Engagement (FY19, FY20, and FY21 Respectively)

1.1, 4.1, 7.1: Provide direct user support for open-source users

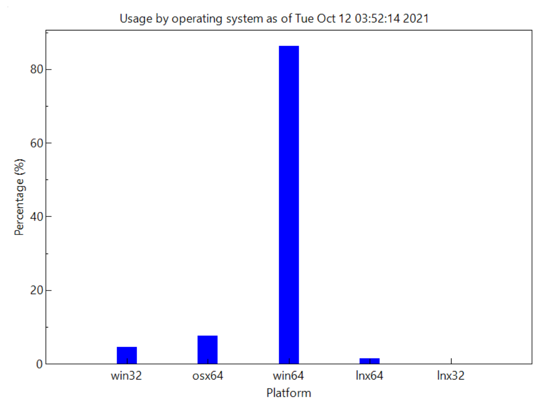
In FY19, these are some of the support queries provided to open-source users: a user submitting code developed for their PhD at the University of Wisconsin to the SSC and



(a) SAM registrations by version



(b) SAM usage by version



(c) SAM usage by operating system

Figure 1: SAM usage statistics

SAM repositories, a new option for modeling the condensor and cooling system of a CSP power tower; a user interested in submitting code for using PV energy to provide electricity for hydrogen electrolysis; and a user interested in submitting tests for the CSP power tower molten salt model.

In FY20, we provided support for a variety of models and functionality including inverter model, module losses, the battery model, utility rates, display features, bifacial modeling, PVWatts version 7, ReOpt integration, building SAM, NSRDB and WindToolkit download features and PySAM support.

We exchanged emails with an engineer at EDF Renewables who had questions about PySAM. We also received a pull request from an open source user at Cypress Renewables who had added bifacial modeling to the PVSyst module model which was added to SAM by another open source user.

We were engaged with a university professor using SAM for international PV analysis work, who also reported a few bugs. We had three contributions to PySAM from external collaborators. A user from Sandia helped fix a backward compatibility issue. An NREL user helped with formatting improvements of the documentation, which had been submit-

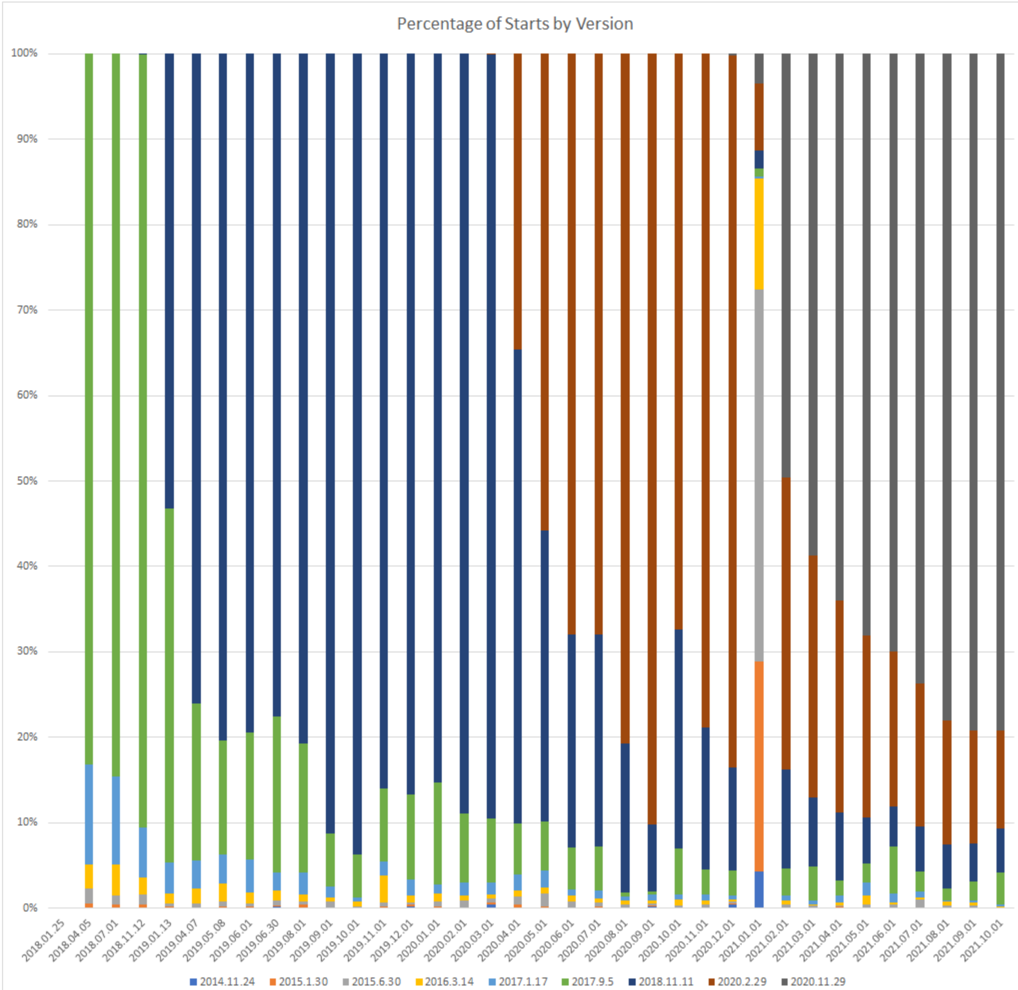


Figure 2: Percentage of starts for each version of SAM since tracking started in 2014

ted by the aforementioned university professor who made significant improvements to the documentation and contributed some examples from his work.

We provided support to PySAM users, internal and external to NREL. A bifacial bug was reported and resolved. We supported a SULI intern's project using single-timestep PV modeling and NREL's Renewable Energy Potential (reV) model's migration to PVWatts version 7 from 5, fixing some slow-down issues. We received a request from an open-source user for expanded ReOpt integration, and were able to complete a part of it; the remaining, larger piece was added to our Feature Requests list. We also helped resolve some software building issues.

We also received a request for a new figure and a bug report in the CSP models, both of which were completed. In PySAM, there were issues opened by the community regarding the resource download functions, such as needing to update the API call given changes in the NSRDB and WindToolkit, UTC timezone issues, and request for features. There were also issues opened for building PySAM, installing PySAM on an uncommon Linux distribution and a type notation error in the PySAM stubs package.

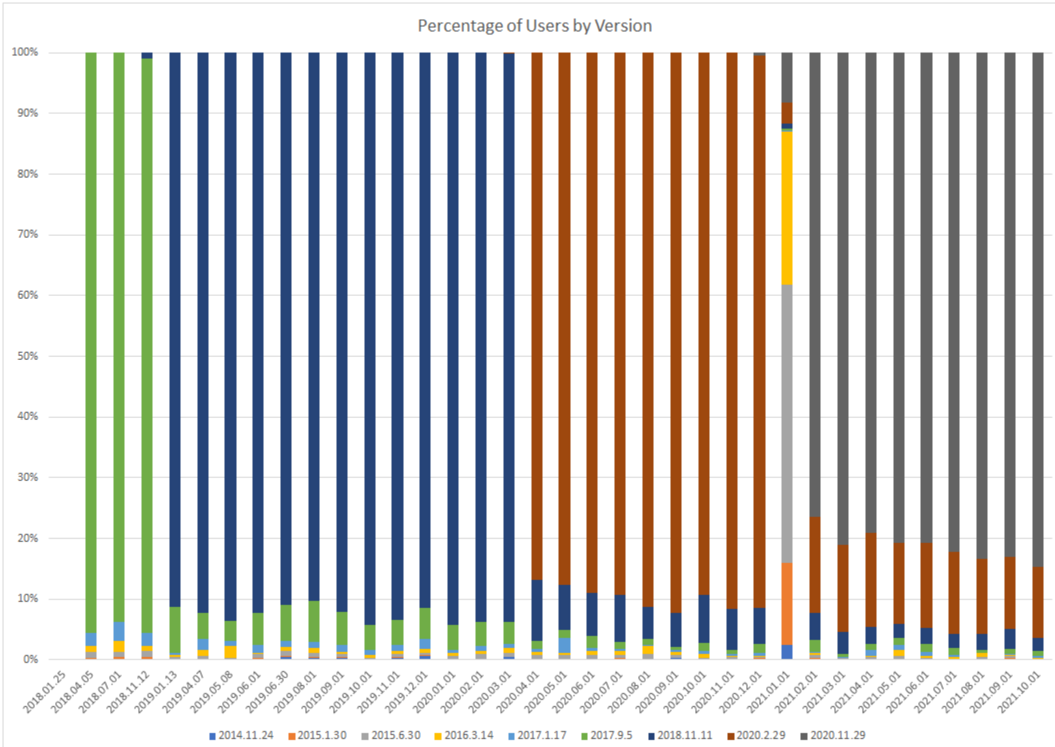


Figure 3: Percentage of users for each version of SAM since tracking started in 2014

We provided support to SAM users, internal and external to NREL. These users included dGen integrating first the simple battery model then using the detailed battery model for its superior dispatch results. We also supported the integration of single timestep PVWattsv5 into EnergyPlus.

In FY21, we provided support for issues related to weather data and weather processing from 3 users in SAM, PySAM, the SSC build process using CMake, and variety of other issues.

We had issues brought up related to weather data and weather processing. One was for minute timestep files producing unexpected spikes in calculated DNI, another was for SolarAnywhere v3.4 file conversion, and the last was about the difference between the weather file year from the year displayed in the results viewer. The first two were not deemed high priority enough to fix at the moment, whereas the last one was responded to explain the source of the difference. Two additional issues were about SolarAnywhere weather files: the first about updated SolarAnywhere format and the second for incorrect unit conversion of snow depth during conversion to the SAM weather format. These two were added to the list of upcoming patch fixes.

There was another issue about switching utility rates for the distributed - third party financial model, whose fix was bundled up in a related issue. Another issue was reported for SAM crashing while using an LK function. The last one was for the code-generator for Python, where the fix was explained to the user and will be included in the next patch.

We had an issue reported for the snow model, and issues regarding segmentation faults, which we helped debug. There were also an issue around GUI appearance on different Linux distributions.

On the PySAM repo, there were issues opened regarding availability of PySAM. Regarding the SSC build process using CMake, where a dependency of SSC wasn't handled correctly during the CMake install process, this issue was fixed via a pull request from the reporting user. Another issue in SSC was reported by a frequent SAM user interested in batteries and was about a hard crash in Matlab when simulating large battery systems. Another issue was opened about the battery's thermal parameters and assuming large enough battery systems would consist of multiple modules (this was fixed by the user via a pull request), about defaults for unsupported CSP models and one about PySAM crashing, likely due to an encoding issue. These were all answered by the team. Other issues were around the download resource feature, the higher priority ones of which were handled by the team.

Relevant statistics over the project period for open-source repositories are shown in Table 2, as well as Figures 4 and 5.

Table 2: Open Source Usage Statistics 9/30/19 – 9/30/21

Repository	Stars	Clones	Unique Clones	Unique Visitors	Views
LK	25	3495	2919	1990	5885
WEX	41	3346	2766	11310	27460
SSC	52	9688	5513	11141	49280
SAM	179	7421	3736	21042	84240
pySAM	65	960	655	5107	21800

1.2, 4.2, 7.2: Monitor issues submitted to open source repositories

The SAM team uses the "Issues" feature of GitHub repositories to document work on new features and bug fixes to the software. SAM users and members of the SAM team open an issue to make feature a request or report a problems. When the feature is implemented or problem resolved, the issue is closed. Opening an issue involves writing a description of the feature or problem, and as work progresses to address the issue, description of the work is added to the issue. This documentation is stored with the code repository so there is a permanent record of these issues and the work done to resolve them.

A complete list of all issues for the four SAM GitHub repositories are available at:

- SAM: `https://github.com/NREL/SAM/issues`
- SSC: `https://github.com/NREL/SSC/issues`
- WEX: `https://github.com/NREL/WEX/issues`
- LK: `https://github.com/NREL/LK/issues`

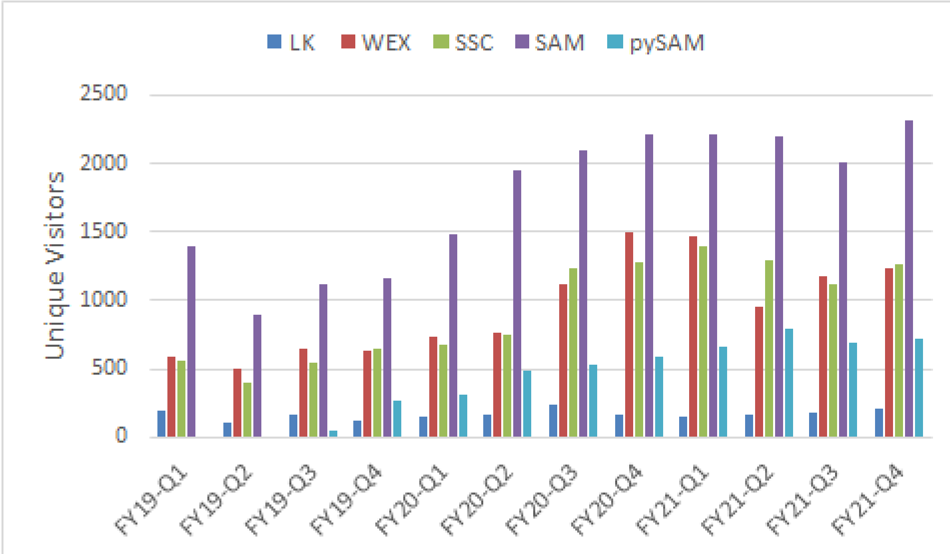


Figure 4: Open-source unique visitors

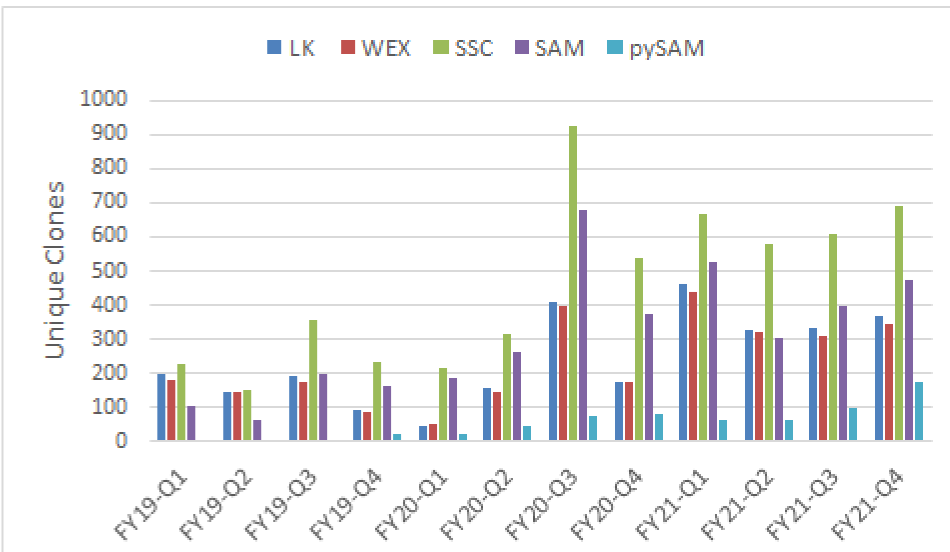


Figure 5: Open-source unique clones

The lists below summarize the issues submitted by SAM users by year. Note that this list does not include the majority of issues created by and resolved by the SAM team.

1.2: Issues submitted by users and resolved in FY2019

- WEX: Issue addressed where DView was trying to inadvertently convert the hours unit from SI to standard
- SAM: Issue addressed to address dynamic exception specifications depreceating in C++11

- SAM: Issue addressed to expose values for bandgap voltage used in CEC module model
- SAM: Issue addressed to correct CEC inverter file with missing values
- SSC: User support requested for Mermoud Lejeune module model, a recent open-source addition
- WEX: Issue addressed where DView was trying to inadvertently convert the hours unit from SI to standard
- SAM: Issue addressed to address dynamic exception specifications depreceating in C++11
- SAM: Issue addressed to expose values for bandgap voltage used in CEC module model
- SAM: Issue addressed to correct CEC inverter file with missing values
- SSC: User support requested for Mermoud Lejeune module model, a recent open-source addition
- LK: Issue addressed with floating point number representation.
- SAM: Enhancement made to hide some information on the battery page using drop-downs.
- SAM: Issue with the snow loss being reported incorrectly
- SAM: Issue with DC power output not reported for subarrays
- SSC: Bifacial rear irradiance reported incorrectly
- SSC: Issue with PV lifetime simulations.
- SSC: Enhancements to battery for PVWatts BattWatts model.
- SAM: Issue with Third Party Ownership Host / Developer model PDF report.

4.2: Issues submitted by users and resolved in FY2020

- SSC: Solar performance models fail when solar resource data contain only POA irradiance data without GHI, DNI, or DHI data.
- SSC: Clean up CSP variable naming issues.
- SAM: Default capacity payment values for technologies with no batteries causes an error.
- Lifetime Daily Losses input tables for Detailed PV does not expand to correct length.
- Battery front-of-meter controller does not respond to PPA price TOD factors.
- PV negative azimuth value results in pvsamv1 POA simulation error instead of input range warning.

- LK simulate() function not working properly, resolved issue as not a bug.
- DC custom losses (”Adjust”) were being applied even when the enable checkbox was not applied.
- Formatting of latitude and longitude in NSRDB data requests was too strict.
- Fixed an issue with net metering credits for subhourly simulations.
- Allow LK scripts to be run from command line to facilitate automated processes.
- Fixed an issue with transformer loss units.
- Fixed the single time step version of PVWatts V5.
- Cash flow Send-to-Excel with Equations for Merchant Plant financial model.
- Fixed an issue with output labels that made it unclear whether DC power included battery power.
- Fixed Download Electric Load macro using http instead of https.
- Fix issue with battery nameplate capacities specified as DC or AC values.
- Fix several issues with time series buy and sell rates for electricity bill calculations.
- Updates to weather file downloads to reflect recent updates to the NSRDB.
- Fix an improve inputs for battery manual dispatch schedules.
- Improve battery response to weather files containing interpolated data.
- Fix battery current calculations to improve battery state of charge results.
- Apply electricity rate escalation to time series price inputs.
- Fix battery voltage calculations to avoid roundtrip efficiency greater than 100 percent.

7.2: Issues submitted by users and resolved in FY2021

- WEX: Issue addressed where DView was trying to inadvertently convert the hours unit from SI to standard
- SAM: Issue addressed to address dynamic exception specifications depreceating in C++11
- SAM: Issue addressed to expose values for bandgap voltage used in CEC module model
- SAM: Issue addressed to correct CEC inverter file with missing values
- SSC: User support requested for Mermoud Lejeune module model, a recent open-source addition
- WEX: Issue addressed where DView was trying to inadvertently convert the hours unit from SI to standard

- SAM: Issue addressed to address dynamic exception specifications depreceating in C++11
- SAM: Issue addressed to expose values for bandgap voltage used in CEC module model
- SAM: Issue addressed to correct CEC inverter file with missing values
- SSC: User support requested for Mermoud Lejeune module model, a recent open-source addition
- LK: Issue addressed with floating point number representation.
- SAM: Enhancement made to hide some information on the battery page using drop-downs.
- SAM: Issue with the snow loss being reported incorrectly
- SAM: Issue with DC power output not reported for subarrays
- SSC: Bifacial rear irradiance reported incorrectly
- SSC: Issue with PV lifetime simulations.
- SSC: Enhancements to battery for PVWatts ”BattWatts” model.
- SAM: Issue with Third Party Ownership Host / Developer model PDF report.
- Fix issue with time zone for NSRDB Himawari data.
- Fix issue with battery capacity value being overwritten in user interface.
- Add new option to specify battery capacity as kW maximum discharge rate and hours of storage.
- Report minute in simulation messages about weather data issues.
- Disable sell rate for FOM battery electricity rate table.
- Improve solar resource download macro for SolarAnywhere.
- Fix issue with electricity bill calculator failing when TOU periods have different tiers.
- Fix lable of subarray short circuit current output variable.
- Fix issues with battery dispatch.

1.3, 4.3, 7.3 Validate user contributions across platforms

Several Github issues and pull requests were reviewed and incorporated into the 2018.11.11 SAM public release with revision 4 released on May 21, 2019. The contributions were tested and updated to work on Windows 10, CentOS 7, and MacOS 10.14. Several unit tests were built to further validate user contributions.

Several Github issues and pull requests were reviewed and incorporated into the numerous beta releases that were distributed internally and externally for pier review and feedback. The contributions were tested and updated to work on Windows 10, CentOS 7, and MacOS 10.14. Several unit tests were built to further validate user contributions.

The SAM code was continuously tested and updated to work on Windows 10, CentOS 7, and MacOS 10.15 in preparation for our 2020.2.29 patch released. User contributions this quarter did successfully build on all three platforms.

The SAM code was continuously tested and updated to work on Windows 10, CentOS 7, and MacOS 10.15. We released a new version 2020.11.29. User contributions this quarter did successfully build on all three platforms and tested contributions were included in the release.

The SAM code was continuously tested and updated to work on Windows 10, CentOS 7, and MacOS 10.16. User contributions were evaluated throughout the project period and tested on all three platforms and updates were included in the patches to the releases. Incorporated into 2020.11.29 patches 1 and 2.

1.4, 4.4, 7.4: Integrate user contributions

In FY19, several new features have been integrated from external users. The PVyield (https://pvyield.com) implementation of the Mermoud Lejeune model was contributed by Timo Richert to the ssc open source repository. The model was reviewed and incorporated into the ssc SDK release 202 on 11/11/2018. Unit tests were made in cooperation with the original author. A separate spline interpolation was used in the official ssc open source repository to adhere to NREL/DOE licensing standards. The original author and the SAM team are jointly performing ongoing review and user support.

We subsequently integrated a pull request from Cypress Creek Renewables to address bugs and increase usability of the of the Mermoud Lejeune module model, including additional outputs. In February, we incorporated a pull request from a known user in Australia that provided fixes to the Python wrapper. We've also incorporated a request from a graduate student at the University of Wisconsin to incorporate a radiant cooling model for CSP. This contribution is the first to include user interface modifications, shown in Figure **??**.

In Q4, we integrated a pull request from Cypress Creek Renewables that improved the diffuse shading model and added diffuse shading models to multiple scenarios where they should be applied, but weren't previously. His submission included results from multiple test scenarios comparing the improved diffuse model to the diffuse models available in PVsyst.

In FY 20, we integrated a pull request from Cypress Creek Renewables that fixed errors in the IEC-61853 module model. We also integrated our second pull request to modify the user interface: a colleague at Envision Digital modified the user-specified CEC module model interface to display additional helpful calculated values.

We also integrated an additional massive code contribution from our colleague at Envision Digital: an updated version of PVWatts (Version 7) with many new features including updated shading estimates applied to more system types, diffuse shading, updated module cover losses, the addition of spectral corrections, and optional models for wind stow, snow cover, bifacial modules, separate transformer losses, and a separate soiling loss applied to irradiance. Lastly, in conjunction with this new version of PVWatts, we updated the default module coefficients. This new feature was the result of a lot of collaboration between NREL and Envision, with the first draft entirely coded by Envision, but significant changes and reviews added by NREL. This contribution was an excellent first step towards Task 9 in Year 3 of this project, to update PVWatts to use industry-standard underlying models, and as such we judged that it was an important contribution on which to spend open source collaboration time. This PVWatts update resulted in a paper at PVSC in FY19, and will be rolled out to the PVWatts website likely sometime in FY20.

We received an additional pull request to modify the bifacial modeling capabilities such that they more closely match PVsyst, but we do not anticipate integrating this pull request because our bifacial model is based on a different underlying model than the PVsyst model and we believe it represents the best view-factor-based model that is currently published. The author of the pull request acknowledged that their goals (to most closely match PVsyst) might not match our goals (to deploy the most cutting-edge, accurate published models) and that as such, we might not want to accept the pull request.

We also received user contributions to the PySAM repository. The improved SAM Python wrapper, released as part of this project last year, has experienced quick uptake and significant interest from the community. A university professor using the package extensively submitted additional help documentation and several examples, and a Sandia user helped fix a backwards-compatibility issue. A contributor from NREL and added the functionality to access and correctly format downloads from NSRDB and Wind ToolKit, mirroring the functionality already available in the SAM GUI within PySAM. This allows a PySAM simulation to be quickly paired up with NREL's data. A RE engineer from Australia contributed many pull requests with warning and formatting fixes to all five repositories, improving code quality and maintainability.

A SAM user contributed to cleaning up the source code in the SAM and SSC repositories to reduce the number of compilation warnings. While removing these warnings does not necessarily improve the peformance of the model, it does make it easier for people outside of the SAM team to understand and contribute to the code.

In FY 21, an EnergyPlus developer is working on integrating SSC source code for the single timesteps PV Watts model. This quarter, he contributed two small changes. The first was to add a shading factor input to single timestep PVWatts to allow the externally calculated shading factors that EnergyPlus produces. The second was to the CMakeLists.txt that define the build process. An NREL researcher working on PV reliability also contributed this quarter updates to the backtracking algorithm, replacing the iterative algorithm with a mathematical formulation.

A large model contribution was completed with the integration of a new battery degradation model specific for the NMC/graphite chemistry. This was complex contribution due to both the integration in the existing SAM battery code and the requirements of the user, requiring extensive collaboration such as direct coding support, some refactoring of the existing code for a more robust integration, and the addition of other new features.

This degradation model, published in 2017 by NREL which performed detailed testing on industry-best cells, provides much greater fidelity and predictive power than the original life modeling capabilities in SAM. However, this feature is so far only available in SSC, the open-source code or SDKs, but will be made available via the SAM GUI as part of a battery modeling task.

We received a bug fix to the PySAM repo to resolve changing coordinates when downloading multiple years of weather files.

1.5, 4.5, 7.5 Attend and present at relevant industry conferences

In October 2018, Nick attended the Linux Foundation Open-Source Summit and Energy Workshop in Edinburgh, Scotland. As part of this trip, meetings were completed between the director of a new branch of the Linux Foundation, LF Energy, and participants in LF Energy from the French grid operator, RTE. Opportunities for collaboration and participation in LF Energy were discussed.

In May 2019, Janine, Darice, and Nate traveled to the Sandia/EPRI/CFV PV Performance Modeling Collaborative workshop in Albuquerque. We presented a total of three presentations between the PV performance track and the grid integration track, "Recent and Planned Improvements to the System Advisor Model (SAM)" (Janine), "Storage and Resiliency Modeling Options in Publicly Available NREL Tools" (Nate, funded by a different task), and "PV + Storage for Resiliency and Ancillary Services" (Janine). There were also several discussions with interested open source stakeholders about potential contributions and collaborations.

In June 2019, Nick attended the the Photovoltaic Specialists Conference (PVSC), presenting a poster on "DC-connected Solar Plus Storage Modeling and Analysis for Behind-the-Meter Systems in the System Advisor Model". Janine and Nate collaborated with Aron Dobos at Envision Digital Corporation integrating some new features into the PVWatts model, which was also accepted as a poster at PVSC which Aron presented. The paper details many new additions to the PVWatts model that were contributed from Envision Digital Corporation, and shows the impact of some of those features on analysis of a typical system. The NREL team then validated the new model features against operational data from our existing dataset of 9 systems, and showed that the new features decreased the average error compared to the measured data. The full conference paper, *Improvements to PVWatts for Fixed and One-Axis Tracking Systems'*, is available as a pre-print at https://www.nrel.gov/docs/fy19osti/74097.pdf.

In September 2019, Janine attended Solar Power International in Salt Lake City, Utah. There, she helped facilitate an in-person workshop entitled "Leveraging Open Source Data and Models to Make Your Case & Improve Results". She also participated in a panel discussion, "Trust dont verify I: Improving Reproducibility in Modeling" as part of the DOE solar data workshop. She had several good discussions with industry about upcoming projects.

Conference participation in FY20 was highly modified by COVID-19. No in-person conferences were held; instead, we participated in virtual events. In June 2020, Matt virtually attended PVSC and was able to report multiple interesting talks back to the team, including multiple talks on clipping losses being underestimated when using hourly modeling. This appears to be an important issue facing industry right now that we may want to consider including in SAM.

In Q3 FY20, we held a virtual introduction to SAM workshop targeting newer users that walks through the user interface and new features. In Q4 FY20, the SAM team held the online workshop ”PySAM Workshop 2020” to demonstrate new features in the SAM package for Python and to give users an opportunity to share their experiences using the package with their Python projects. Of the 163 people who registered, 65 attended the live session. A video recording of the workshop and links to supporting materials were sent to all registrants, and are availabe on the SAM website at https://sam.nrel.gov/software-development-kit-sdk/pysam.html. Since the video recording was posted on YouTube October 20, 2020, there have been 2070 views as of October 13, 2021.

In June 2021, the SAM team presented a poster at IEEE PVSC 48, ”Heuristic Dispatch Based on Price Signals for Behind-the-Meter PV-Battery Systems in the System Advisor Model.” The paper describes the price signals dispatch algorithm, and compares it to the existing dispatch algorithms within SAM on two reference buildings in California. One of the systems is also used to analyze the impact of 625 hypothetical utility rates on the economic performance of the various dispatch algorithms. A poster detailing the work was presented at the area 10 poster session at PVSC. A preprint of the paper is available at https://www.nrel.gov/docs/fy21osti/79575.pdf.

1.6, 4.6, 7.6: Give webinars on new features and topics of high interest

The SAM team conducted 12 webinars during the project, which are listed below:

- Introduction to PySAM
- Modeling Wind Systems in SAM **funded by a different project*
- Modeling Fuel Cells in SAM
- PV Systems in SAM 2020.2.29- Aug 5 2020
- Batteries in SAM 2020.2.29: Focus on Battery Technology- Aug 19 2020
- Batteries in SAM 2020.2.29: Behind-the-Meter Systems- Sep 2 2020
- Batteries in SAM 2020.2.29: Front-of-Meter Systems- Sep 16 2020
- Merchant Plant Financial Model with Cambium Integration - Aug 4 2021
- Marine Energy Models in SAM - Aug 19 2021 **funded by a different project*
- New Battery Model Features for Fall 2021 - Sept 2 2021
- New Community Solar Model for Fall 2021 - Sept 15 2021
- Electricity Bill Calculations - Sept 29 2021

Recordings of all of these webinars were posted to the YouTube and linked to the SAM website.

We also hosted and posted materials from the SAM Virtual Conference 2019, which consisted of presentations by SAM users at NREL and in the industry describing applications they developed using either the SAM Software Development Kit or open source repositories.

Finally, the team hosted a PySAM workshop in 2020, which covered a series of detailed PySAM examples.

1.7, 4.7, 7.7: Continue SAM Round Table presentations

SAM round tables are 30-minute online open meetings hosted by the SAM team for SAM users to ask questions about and provide feedback to the team. They are an opportunity for SAM users to get direct help using SAM, get answers to technical questions directly from the model developers, and to make feature requests or report issues with SAM. They also provide an opportunity for the SAM team to learn more about how people are using SAM. SAM round tables were initially held bi-weekly and switched to monthly in June 2019.

Table 3: SAM Round Tables

Year	Registrants	Participants
FY19	61	27
FY20	103	60
FY21	88	49
Total	252	136

Round Table topics over the FY19 - FY21 included:

- Battery degradation
- Net metering for New Hampshire
- Sources of weather data for international locations.
- Modeling IAM losses for photovoltaic systems.
- Autosizing PV systems in SAM 2018.11.11.
- Modeling buy-all-sell-all billing option.
- Comparing SAM, PVWatts, and REopt.
- PV plus battery modeling
- PV heat transfer model
- Solar market prospects
- Determining PV capacity of a rooftop

- Simple vs discounted payback period
- Future inverter replacements with improved models
- Layout of large scale arrays with complex terrain
- NREL plans for Solar for Agriculturel model development in SAM.
- PV-Battery dispatch to load vs grid.
- Options for modeling standalone PV systems.
- Demonstrate PV-battery for resiliency and critical loads.
- Sources of international weather data.
- How to determine maximum Voc over multiple years.
- PV-battery for merchant plant financial model.
- How to model benefits distribution and subscriber fees for community solar.
- Combining PV, storage and ”generic system” model.
- Battery degradation data available from manufacturers.
- Introduction to modeling PV-battery systems.
- Importing weather data from other software.
- Modeling standalone battery storage.
- Modeling DC-connected battery storage with multiple MPPT input inverters.
- Using currencies other than U.S. Dollar.
- Modeling battery dispatch options in PySAM.
- Modeling PV hybrid systems..
- How battery manufacturers can work with NREL to add battery input parameters for SAM.
- Effect of albedo data on results.
- Modeling PV hybrid systems.
- Choice of inverters for large systems.
- Interpreting P50/P90 results.
- BTM battery dispatch.
- Matching load data to subhourly weather data.
- Updating files from old versions of SAM.
- Fastest way to learn SAM.

- Optimizing array tilt and azimuth.
- Modleing standaline batteries.
- Inverter thermal derate.
- Isotropic vs Perez irradiance models.
- Import 3D CAD shading data.
- REopt Lite weather data.

1.8, 4.8, 7.8: Monitor and answer questions on the SAM support forum

The SAM team moderates a SAM user forum hosted on the SAM website at `https://sam.nrel.gov/forum` where users post questions and comments about SAM. The forum supplements the SAM user documentation that comes with the software and the information and videos provided on the SAM website to help people learn to use SAM. It also provides a way for the SAM team to get feedback on SAM, and reduces repetition in email requests. Users who send an email to sam.support@nrel.gov receive an autoreply requesting that they post their question or comment on the forum if they want a quick reply. The forum is public but requires a SAM website registration to post questions or comments. SAM forum posts appear in web search results for Google and other search providers. The forum has four categories:

- General SAM How-To
- Software Development Kit (SDK)
- SAM Open Source
- Announcements

On May 13, 2019, the SAM team completed a migration of the SAM website from Drupal to Joomla with the forum implemented as Kunena component of Joomla.

Table 4 shows the number of people who posted questions on the forum by quarter for each of the three fiscal years FY2019, FY2020, and FY2021. Each contact represents a conversation that may have involved several replies. Note that table does not show the number of times conversations were viewed or the number of people who viewed them.

Forum topic highlights for FY2019:

- Net metering and incentives.
- PV solar position calculations.
- Using weather data with different irradiance components.
- 3D shade calculator roofline shadows.
- Using Combine Systems macro to model more complex system designs.
- Optimizing PV system size using parametric simulations

Table 4: SAM User Forum Contacts by Quarter

Quarter	Contacts
FY19 Q1	45
FY19 Q2	100
FY19 Q3	67
FY19 Q4	61
FY19 Total	**273**
FY20 Q1	54
FY20 Q2	88
FY20 Q3	88
FY20 Q4	130
FY20 Total	**360**
FY21 Q1	111
FY21 Q2	106
FY21 Q3	110
FY21 Q4	92
FY21 Total	**419**

- Net metering in Michigan
- Modeling DC optimizers and multiple MPPT inputs.
- Dependence of battery efficiency on state of charge.
- 3D Shade Calculator for different roof shapes.
- Battery dispatch and sizing.
- Modeling different PV module cover coatings.
- Relationship between PPA price and location.
- PV model validation.
- Mechanics of using SAM SDK with Python.
- Questions about net present value (NPV).
- Using SAM to generate PV generation profile.
- 3D Shade Calculator for microinverters.
- PV-battery for utility-scale project.
- Generating plots of results for PV-battery systems.
- Battery cost modeling.

- Value of electricity for behind-the-meter PV projects.
- Troubleshooting results for one-minute simulations.
- Modifying coefficients for IEC 61853 module model.
- Details of 3D Shade Calculator algorithms.
- P50/P90 capability in SSC / SDK.
- Battery model with measured PV generation data.
- Cover loss category.
- Battery model for peak shaving.
- Issue with monthly albedo input.
- Issue with positive module loss.
- Comparing SAM results to measured data.
- Request to model system with different types or sizes of inverters.
- Modeling systems with DC optimizers.
- Inverters with multiple MPPT inputs.
- Troubleshooting issues with custom weather file.
- Working with building load data.
- Subarray layout macro.
- Modifying cell temperature equation.
- Mermoud-Lejeune IAM calculations.
- Off-grid PV system.
- Net billing.
- Inverter maximum voltage ratings.

Forum topic highlights for FY2020:

- DC output of PV systems.
- Stochastic analysis algorithm documentation.
- Self shading and edge effects.
- Modeling PV systems with no inverter.
- Modeling PV-wind hybrid systems.
- Financial incentives to host in Third Party Ownership projects.
- Using POA irradiance data in weather files.

- Battery storage costs.
- Modeling electric load for home efficiency retrofits.
- Net metering for rooftop solar.
- Battery storage for energy arbitrage.
- Reporting IRR for residential and commercial projects.
- Unit conversion between imperial and metric.
- Seasonal tracking.
- Font size in Linux versions.
- Retrofit existing PV with battery storage.
- Accounting for costs of project term debt.
- Issues with sizing PV system.
- Issues with battery dispatch.
- Reporting of subarray voltages.
- Effect of load size on payback period.
- Installation cost for Combine Cases macro.
- Hourly electricity rates.
- Power consumption of DC trackers.
- Modeling off-grid systems.
- Modeling battery systems using SSC API with MATLAB.
- Interpreting battery results.
- Large-scale arrays on complex terrain.
- Power electronics in PV-battery systems.
- Working with plane-of-array data as input to the PV model.
- Battery storage for peak shaving.
- Working with power generation data as input.
- PDF report issues.
- Grid power connection limit.
- Modeilng unreliable grid.
- Ground coverage ratio effect on results.
- Modeling half-cell modules.

- Integrating Orange Button with SAM.
- Assigning multiple MPPT inputs to inverters.
- Simple battery in PVWatts for battery-only application.
- Battery storage dispatch options.
- Modeling a retrofit project.
- Battery front-of-meter dispatch options.
- Questions about battery efficiency.
- Battery DC capacity.
- Third-party-owernship financial model.
- Use VBA to create weather file.
- French version of SAM.
- Using LK script to input load data.
- Customer monthly electricity calculations.
- Grid interconnection limit.
- Hybrid PV-CSP plant.
- Module loss value.
- Battery degradation and state of charge.
- Project cash flow and payback period for commercial PV.
- Battery area parameters.
- SDK for MATLAB for PV-battery modeling.
- Power production vs time of day.
- Battery calendar degradation.
- PV-battery state of charge.
- PVGIS and MERRA weather data for PV model.
- Energy charge rates for weekday/weekend.
- Optimizing seasonal tilt.
- Modeling PV-CSP hybrid systems.
- Dispatching battery to 8760 dispatch signal.
- Options for net metering rollover credits.
- Modeling battery-specific incentives.

- Multiple MPPT input inverters.
- Multiple revenue streams for PV-battery project.
- Allow behind-the-meter battery to export to grid.
- Community solar with battery storage.
- Distinguishing between battery inverter and PV inverter.
- Bifacial solar cells.
- Battery dispatch questions.
- Model PV array with more than 4 subarrays.
- Sizing battery for peak shaving application.
- Self shading and backtracking options.
- Battery augmentation strategy.
- Modeling PV modules with half-cut cells.

Forum topic highlights for FY2021:

- Battery state of charge limit for lead acid batteries.
- Bifacial module transmission fraction input definition.
- Time series outputs for PV-battery model.
- Help with PVWatts results.
- Question about entering electric load data.
- Working with Excel via LK script.
- Issue with custom weather data.
- Clarification on IRR for Commercial financial model.
- Issues installing SAM on Windows.
- One axis tracking night-time stow for snow model.
- Clarification on time-of-delivery (TOD) data in outputs.
- High current PV modules issue resolved in SAM 2020.11.29.
- Clarification on annual and lifetime outputs.
- Determining optimal array tilt angle.
- Allocation of electricity export for Third Party Ownership model.
- Clarification on PV inverter vs battery inverter.
- Clarification on loss outputs in PVWatts vs Detailed PV model.

- Calculating subarray ”operating current” from subarray power and voltage.
- Clarification of net metering vs net billing.
- Role of cable length in SAM.
- Shading error reported for EPW files with incorrect time stamps.
- Bidirectional inverters for PV-battery systems.
- PV-Battery / Merchant Plant battery response to cleared capacity.
- Option to normalize ITC over analysis period.
- Tracking with bifacial modules.
- Three-phase inverters
- Accounting for optimizers in PV system.
- Revenue generation for Merchant Plant projects.
- Understanding metering options with sell rates.
- Modeling floating PV.
- Handling of excess generation.
- Multiple MPPT inverter effect on annual energy production.
- Battery cycle degradation for Li-ion LFP batteries.
- Vertical bifacial modules.
- Request to start simulation on custom date.
- Modeling systems with microinverters.
- Parametric study on flat energy rate.
- Options for 3D shade calculator.
- BTM battery discharge to grid discussion.
- Customizing cell temperature equations.
- System sizing of PV array and battery.
- Clear sky data in weather file.
- Using POA irradiance data as input.
- Grid limit for solar plus storage.
- Negative electric power.
- Modeling hybrid systems with Combine Cases macro.
- Working with 1-minute weather data.

- SSC libraries for SDK with MATLAB.
- Shading data from Solmetric Suneye.
- Bifacial input parameters.
- Incident irradiance calculation details.
- Self-shading in PVWatts.
- Battery losses for DC-connected battery.
- P50/P90 simulations and weather files.
- Battery replacements.
- Including EV charging in residential load data.
- PV cells in series for CEC coefficient calculator.
- Access to module library file.
- PVWatts standard vs. premium module.
- Interpretation of negative NPV.
- SDK with Python.
- Floating PV.
- Bi-directional inverter for PV-battery system.
- SOC calculations for PV-battery model.

1.9, 4.9, 7.9: Respond to email technical support questions for SAM and PVWatts

The SAM team monitors the email addresses sam.support@nrel.gov and pvwatts@nrel.gov for questions and comments from users of SAM, the SAM SDK, PySAM, the online PVWatts Calculator, and PVWatts API.

Table 5 shows the number of individual user contacts for FY 2019, FY 2020, and FY 2021.

Figure 6 shows the annual number of users since 2010.

Some highlights of SAM support email topics received in FY 2019:

- Questions about high-concentration PV model.
- Bifacial model and shading of rear surface.
- Working with snow depth data for snow loss model.
- Working with hourly sell rates for buy all - sell all billing option.
- Sources of weather data.
- P50/P90 simulations
- Row-to-row shading

Table 5: Individual SAM Users Contacted by Year

Month	Email	Forum	Total	Hours per Person
FY 2019 Q1	230	45	275	0.20
FY 2019 Q2	240	100	340	0.16
FY 2019 Q3	150	67	217	0.22
FY 2019 Q4	122	61	183	0.22
FY 2019 Total	**742**	**273**	**94**	**0.20**
FY 2020 Q1	97	54	151	0.28
FY 2020 Q2	119	88	207	0.22
FY 2020 Q3	107	88	195	0.27
FY 2020 Q4	129	130	259	0.26
FY 2020 Total	**452**	**360**	**812**	**0.28**
FY 2021 Q1	126	111	237	0.21
FY 2021 Q2	89	106	195	0.24
FY 2021 Q3	81	110	191	0.29
FY 2021 Q4	86	92	178	0.21
FY 2020 Total	**382**	**419**	**178**	**0.24**

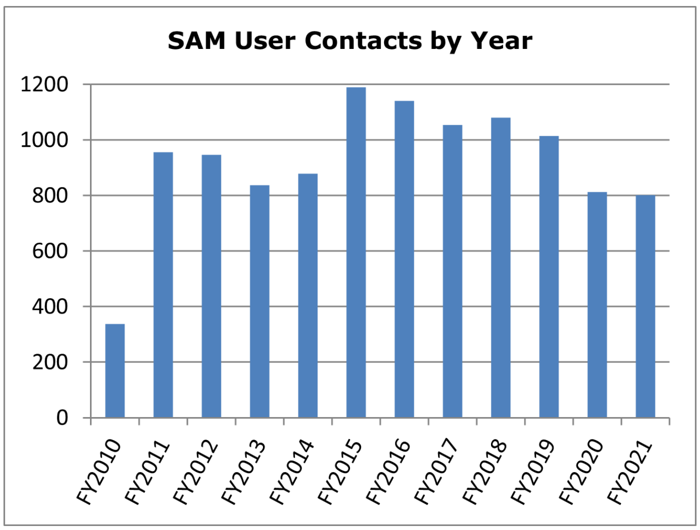


Figure 6: SAM User Contacts from FY 2010 to FY 2021

- PPA project with capacity rate ($/kW) in addition to energy rate$/kWh.
- Running SSC from VBA for 32-bit Excel.
- Several questions about battery dispatch.
- Question about accuracy of array operating voltages.

- Explain self shading results.
- Options for modeling floating PV.
- Comparison with Energy Toolbase.

Some highlights of PVWatts support email topics received in FY 2019:

- PVWatts for electricity bill calculations.
- Assumptions for PV module type.
- DC/AC ratio.
- TMY weather files.
- Technical reference for model equations.
- Interpreting results in hourly CSV file.
- Modeling of PV module degradation.
- Changes in weather data.
- Modeling high DC-AC ratio system.
- Justification of default values.
- Effect of GCR input on results.
- Modeling array with sections in different orientations.
- Request for training in PVWatts and SAM.
- Question about effect of module efficiency and temperature coefficient inputs (from module type) on results, and confusion about why thin film system with same capacity as premium generates more electricity over the year.
- How PVWatts models self shading for one-axis trackers.

Some highlights of SAM support email topics received in FY 2020:

- Offgrid PV-battery systems.
- Validation of high-concentration PV system.
- Battery dispatch control.
- PV-battery sizing.
- Benefits of different module types.
- Downloading electricity rates.
- CdTe modules and LID and IAM factors.
- Year value in time stamps.
- Inverter current limits.

- Adding storage capacity over time.
- Time-of-use rates in parametric simulations.
- Inveter replacements.
- Snow losses.
- Net billing and sell rates.
- Modeling bifacial moddules.
- Modeling multiple MPPT inverters with more than one inverter.
- PV-battery sizing for agricultural irrigation.
- Modeling battery-only systems.
- Modeling rate-switching scenarios using Value of RE macro.
- Request for compressed-air storage model.
- Modeling PV-storage with zero export.
- Modeling SolarEdge inverters.
- Working with snow depth data.
- Scripting and battery losses.
- Request for ”merchant tail” financial structures.
- Formatting custom weather data.
- Limitation of multiple MPPT inputs for more than 4 string lengths in array.
- Customizing SAM to account for temperature effects of green roof on PV performance.
- Determining maximum Voc over multi-year period.
- Building energy load calculator methodology.
- Accessing battery model parameters in PySAM.
- Time and calendar assumptions for electricity bill calculations.
- Modeling RECs and SRECs for solar installer.
- Concentrating PV model enhacements.
- Battery degradation and state of charge.
- Bifacial module backside shading.
- CEC equipment list and SAM PV module library.
- PVWatts V7 bifacial modules via SDK.

- DView scaling for lifetime 5-minute data sets.
- Transmission fraction for bifacial modules.
- Exporting parametric results to Excel.
- DC/DC converters for voltage control.
- Combine System s macro for PV systems with multiple inverter types.
- Standalone battery storage.
- Multi-year simulations.
- PV one-second simulations.
- PVWatts / Detailed PV comparison.
- NSRDB download issues.
- Fixed charges in residential electricity bill calculations.
- Battery dispatch and merchant pricing.
- Array orientation.
- Access to latest NSRDB datasets.
- LCOE calculations for PV-battery system.
- Adjusting load data for monthly usage totals.
- Time convention for bill calcuations and simulatinos.
- Front-of-meter battery modeling options.
- High wattage modules and issues with 6-parameter coefficient generator.
- Vehicle-to-grid battery modeling.
- TMY vs P50/P90.
- Net present value calculations.
- Stochastic simulations.
- Perspectives for third party ownership models.
- One minute simulations.
- Community solar.

Some highlights of PVWatts support email topics received in FY 2020:

- PVWatts and shading.
- Solar panel size effect on results.
- Locations not in database.

- Losses at low irradiance.
- Ground coverage ratio.
- Effect of temperature.
- Output as percentage of irradiance in different locations.
- Time of use rates.
- Clarify meaning of capacity factor and DC-AC ratio.
- PVWatts API for POA irradiance calculations.
- Distance between location and center of grid rectangle.
- Time stamp of sunup and sundown hour.
- Estimating PV production by region.
- Embedding PVWatts in a website.
- PV array sizing.
- Electricity rates modeling.
- PVWatts versions.
- Hourly results.
- PVWatts API rate limits.
- PVWatts for locations outside the U.S.
- Time convention for hourly results.
- Accuracy of weather data for Brazil.
- Using PVWatts to generate production estimates by state.
- Differences between website and API results.
- Modeling PV array on sloped terrain.
- Azimuth angle for southern hemisphere locations.
- Modeling systems with multiple subarrays.
- Documentation of underlying equations.
- Weather data for international locations.
- Time stamps convention (local time vs daylight savings).
- P50 vs typical year results.
- Homeowner auestions about modeling installer's proposed system design.
- Strategies for modeling building-integrated PV.

- Time scale questions for Thailand weather file.
- Vertical array in Alaska.
- Units for monthly totals data.
- Resource variation by location in Chile.
- Questions about father-daughter research project.
- Request for physical dimensions and weight of PV modules.
- Automating PVWatts and exporting to Excel.
- DC/AC ratio for microinverters.
- Snow loss.
- Electricity savings for multiple-building facility.
- PVWatts API for website at www.legacipower.com
- Negative tilt angle vs Azimuth = 0.
- PVWatts with storage.
- PVWatts for bifacial modules.
- Results higher than measured from installed system.
- Tesla solar shingles.
- Questions about PVWatts API versions.
- Options for modeling bifacial modules.
- PVWatts API rate limits.
- PVWatts solar irradiance data vs NSRDB.
- Modeling large scale systems.
- Inverter efficiency calculations.
- Weather data time resolution.
- Service outages.

Some highlights of SAM support email topics received in FY 2021:

- Questions about best weather data to use for analysis.
- Help resolving text formatting for importing load data.
- Discussion of negative NPV when discounted payback period is less than analysis period.
- Running PVWatts from Excel VBA.

- Modeling systems with different types of inverters.
- GCR in PVWatts for fixed arrays.
- Output variable names for LK script.
- SAM for California NEM-3 proceedings.
- P50/P90 simulations
- Row-to-row shading
- PPA project with capacity rate ($/kW) in addition to energy rate$/kWh.
- Running SSC from VBA for 32-bit Excel.
- Several questions about battery dispatch.
- Question about accuracy of array operating voltages.
- Explain self shading results.
- Options for modeling floating PV.
- Comparison with Energy Toolbase.
- Custom LK script to calculate PV generation as PPA price for BTM project.
- Accounting for battery thermal losses.
- Using SAM to replicate ”reverse LCOE” calculation.
- Reconciling differences between cash flow in SAM and exported to Excel.
- Importing latest format weather data from SolarAnywhere.
- One-minute simulations for PV and PVWatts models.
- Clarification about bifacial PV simulation messages.
- Strategy for estimating PV capacity from available roof area.
- Working with weather files that have GHI / DHI instead of DNI / GHI data.
- Clarification of monthly bill calculation data.
- Importing shading data from PVsyst.
- Accounting for snow losses.
- Rules of thumb vs PVWatts results.
- NSRDB data and simulation errors.
- Subhourly load data units kWh vs kW.
- Battery power targets and dispatch.
- Gap behind module for cell temperature calculations.

- Troubleshooting issue with excessive DC loss.
- PVWatts module types.
- Modeling systems with more than 4 MPPT inputs.
- Energy production vs DC/AC ratio for one-minute simulations.
- Modeling offgrid PV-battery system.
- REopt API calls and critical loads is slow.
- IRR for residential and commercial financial models.
- Module size in PySAM.
- Inverter size effect on system output.
- Battery augmentation.
- Marginal cost of battery ageing.
- Python with PySAM for array orientation optimization.
- Battery temperature effect on life.
- Module model equation details.
- Negative NPV with merchant plant model.
- Downloading state incentive data.
- Problems with module with user-entered specifications.
- Self-shading calculation details.
- Difference between standard and premium module in PVWatts.
- Module library data.
- Inverter clipping.
- Cell temperature effect on PV loss diagram.
- Weather data from Solcast.

Some highlights of PVWatts support email topics received in FY 2021:

- Concerns about outages for business users.
- Azimuth angle for NE-facing array.
- Modeing DC-connected battery with online PVWatts Calculator?
- Displaying hourly irradiance data.
- Calculating daily average values of outputs.
- Modeling inverter clipping.

- Modeling bifacial modules.
- Determining power rating of individual module.
- Modeling Sunpower modules.
- Changes in weather data.
- Modeling high DC-AC ratio system.
- Justification of default values.
- Effect of GCR input on results.
- Modeling array with sections in different orientations.
- Request for training in PVWatts and SAM.
- Question about effect of module efficiency and temperature coefficient inputs (from module type) on results, and confusion about why thin film system with same capacity as premium generates more electricity over the year.
- How PVWatts models self shading for one-axis trackers.
- Confusion about API version 6 vs PVWatts Version 5.
- Explanation of STC vs PTC ratings.
- Modeling multiple subarrays.
- Clarification of relationship between monthly irradiance and energy output data.
- Option for one-minute data for online simulations (suggest SAM).
- Option for uploading custom weather data (suggest SAM).
- Fixed vs one-axis tracking.
- Question about how current weather data is.
- Clarification on capacity factor output.
- Ground-mount vs roof-mount array.
- Question about model calculations.
- References for validation studies.
- Question about how PVWatts accounts for cloud cover.
- Shading and PVWatts.
- Monthly solar radiation units.
- Modeling bifacial modules.
- Integrating PVWatts API into marketing website.
- Effect of DC/AC ratio on results.

- Meaning of dollar value output metric.
- Estimating system size from available roof area.
- Evaluating PV production estimates provided by a solar installer.
- Meaning of tilt angle for single-axis tracking.
- Source of PVWatts Calculator weather data.
- Apparent reduction in output for month of June.
- Shading models.
- System size vs peak output.
- Module degradation.
- Integrating PVWatts into an app.
- Daylight savings time.
- Interpreting hourly results.
- Purpose of electricity rate data.
- North-facing array.
- Specifying size as number of modules.
- Bifacial modules.
- Manual tilt adjustment.
- Equation for capacity factor.

1.10, 4.10, 7.10: Write and update SAM help documentation

For FY 2019, we significantly updated the SAM Help system to reflect new features added in the SAM 2018.11.11 release, and for subsequent updates as needed.

For FY 2020, revisions and additions to the help documentation were completed for the release of SAM 2020.2.29 and subsequent updates.

- Make Detailed PV and PVWatts snow loss descriptions consistent.
- Revise PVWatts system design page.
- Revise battery topics for new features.
- Add bifacial transmission factor diagram and description.
- Revise weather file format section to make it easier to find descriptions, and publish standalone description for SAM website.

For 2021 Q3, we finsihed work on revisions to Help for the second update to SAM 2020.11.29 release and subsequent updates. These included:

- Revise cash flow energy line items to reflect changes in SAM for new revenue items.
- Revise inverter temperature model description for new transient thermal model.
- Revise battery inputs description to reflect separating inputs onto separate pages and improved battery cost inputs.
- Revise net metering output variable changes to make it easier to see how net metering affects electricity bill calculations.
- Fix debt fraction input description for behind-the-meter financial models.
- Add examples of merchant plant revenue calculations.
- Improve description of battery lifetime.
- Fix PV shading and layout description so calculated dimensions are in the correct section.
- Revise electricity metering option descriptions based on latest updates.
- Revise bifacial transmission factor description.
- Update descriptions of battery storage time series results.
- Clean up and revise battery input descriptions.
- Improve REopt optimization description.
- Fix broken help link for Parametric page and TPO Host page.
- Revise Stochastic simulations topic.
- Revise electricity rates topic.
- Improve battery calculation descriptions.
- Update results descriptions.
- Improve definition of metrics for third party ownership model.
- Add instructions for running LK script from the command line.
- Revise electricity rates description for new time series buttons and options.

1.11, 4.11, 7.11: Update SAM and PVWatts websites for cybersecurity

NREL is very serious about cyber security and will run a cyber audit with any significant change to a website's code or environment. Firewalls, servers and the general infrastructure are continuously updated with the latest security patches and configured to combat the latest threats. Over the past year, the cyber audits have become more frequent to investigate the risk new threats might have. Software used within the application is also upgraded cost effectively to include the latest security patches.

The SAM website platform has been converted from Drupal to Joomla to:

- Better integrate upgraded forum capability with a single sign-on

- Use an active open source project that are reviewed for potential cyber issues by people all over the world
- Better mitigate risk from cyber attacks seen by NREL and others in the past, particularly around registration attacks.
- Upgrade the platform to provide better performance and more secure operations.
- Decrease upgrade costs so more frequent upgrades are possible (which include minimizing cyber-attack risks)

PVWatts has had the overall infrastructure and software audited, monitored and upgraded. Notable enhancements are:

- Enhance the system to minimize the risk of CSRF and XSS attacks.
- Ongoing header enhancements to maintain a high level of security and reduce risk.

Additionally, during FY 21, NREL cybersecurity contacted the SAM team to implement NIST standards SA-10 and SA-11 into the SAM development process. The SAM team completed a developer configuration management plan and a security assessment plan to document how the team develops and maintains secure software. As a part of these plans, the SAM team will regularly request that NREL cybersecurity scan the SAM repository using the Checkmarx application security testing software. The SAM team has fixed flaws regarding indexing errors, and the fixes will be included in the upcoming release (Q1 FY22). Some additional issues flagged by the software in the API export code and help files were identified as false positives. The SAM team will receive additional Checkmarx scans quarterly and prior to major releases.

1.12, 4.12, 7.12: SAM and PVWatts website content updates

In FY 2019, we completed the SAM website migration from the Drupal platform to Joomla with new design templates. A new Amazon Web Services (AWS) bucket was set up to store SAM files in preparation for migration to the new website. A new platform for the SAM Support forum was set up and content from current forum was transferred to new platform.

We also added a new Events page on the SAM website to publicize SAM team participation in workshops and conferences at https://sam.nrel.gov/events.html.

In FY 2020 and FY 2021, there were minimal website updates, with a few content updates and revisions.

2.1, 5.1, 8.1: Battery model improvements

Throughout the project, we wrote unit tests for all the components of the battery model and dispatch models, to enable regression testing during continued development of improvements and dispatch algorithms. These tests led to fixing several bugs. Some were reported as GitHub issues and others were discovered during the testing process. In particular, some subhourly features were fixed to be consistent with results from hourly simulations. We have also been supporting other projects as they integrate the battery

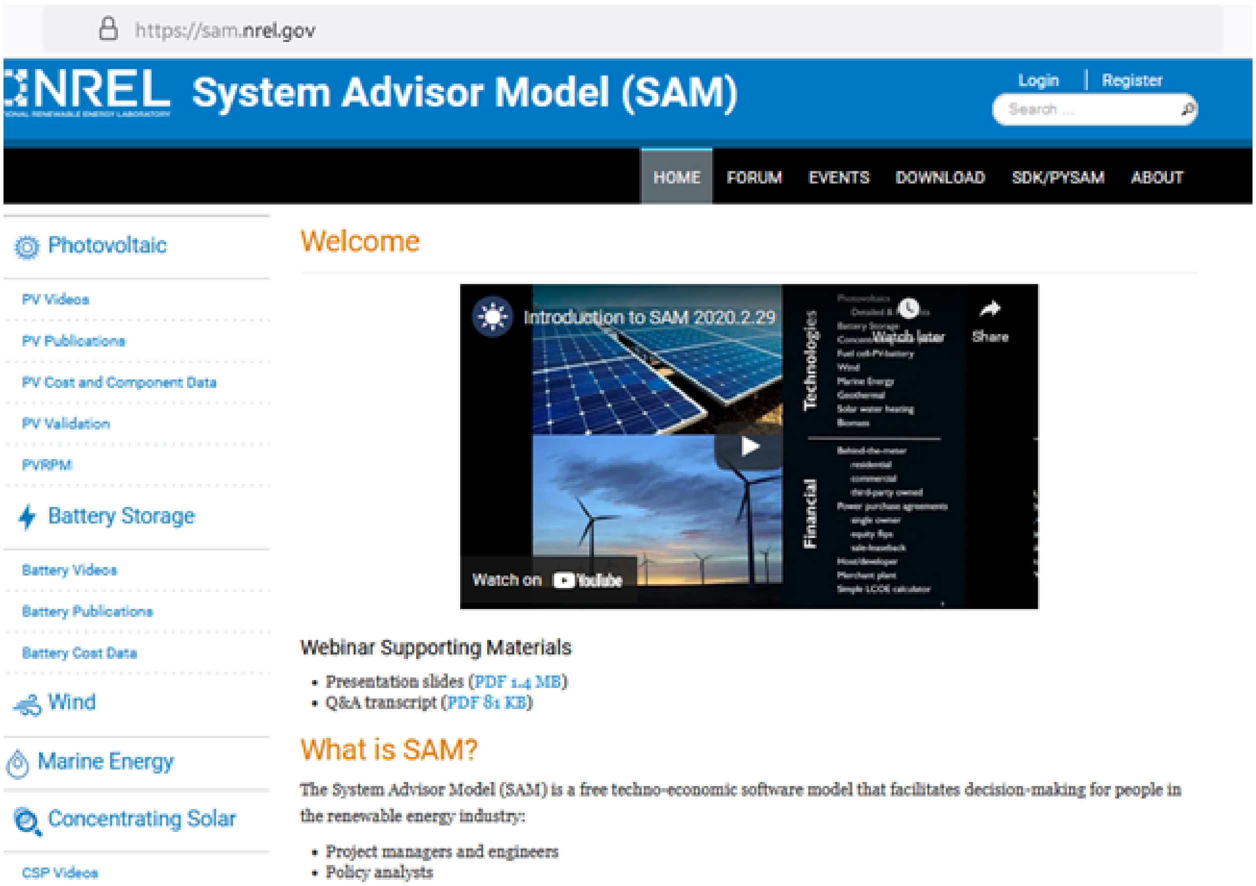


Figure 7: Screenshot of SAM Website

model via PySAM, and partly from these interactions, we modified the structure of the PySAM model for easier, more intuitive use.

The battery model's current controller was modified in order to provide more precise control over the battery's dispatched power. These improvements have enabled the battery to meet the target power for a greater range, and provide functions for estimating the maximum discharge and charging power and current, enabling better planning for operation. Figure 8 below shows the change in difference between the target/desired battery power and what was actually provided in every timestep, analyzed for a single-year simulation.

Unit tests were written for these improvements, and integration testing ensured that downstream effects were correctly handled. The simulation results compared to previous versions show improvements in dispatched versus target power error, which resulted for most configurations a higher NPV and reduced LCOE for the system. Figure 9 below shows how the nominal levelized cost of electricity, when applicable, and the bill savings have changed in the PV models with different financial models. For the detailed model, the changes in LCOE and bill savings were calculated for 4 different scenarios per financial model: combination of dc- or ac-connected and whether charging from grid was allowed); the average percent change from the previous release across the four cases is shown. The PVWatts changes reflect a dc-connected battery with grid charging.

		PV DETAILED		PVWatts	
		Residential	Commercial	Residential	Commercial
		Peak Shaving	Peak Shaving	Peak Shaving	Peak Shaving
2018	total diff (abs)	6675.27	689999.23	7905.66	735432.20
	avg diff (abs)	0.72	78.77	0.90	83.95
	dispatch net kW	-237.26	-2452.73	-449.43	-3268.32
	target net kW	-6575.38	-691280.93	-8014.98	-736472.85
	total diff/total dispatch	1.58	40.05	2.90	79.32
2020	total diff (abs)	323.76	686281.44	234.50	52652.98
	avg diff (abs)	0.78	78.34	0.70	75.34
	dispatch net kW	-409.13	-4575.05	-328.79	-2828.75
	target net kW	-6978.11	-689657.26	-6143.88	-661627.74
	total diff/total dispatch	0.07	35.50	0.06	3.03

Figure 8: Effects of battery current controller on detailed and simple battery operation

	PV DETAILED				PVWatts		
	Residential	Commercial	Third Party	Host Developer	Residential	Commercial	Third Party
AEP (%kW)	3.55	1.04	4.00	1.06	17.83	4.88	17.83
LCOE nom (%$)	-9.93	-9.07		-1.19	-20.74	-5.57	
Bill savings (%$)	1.01	0.46	1.50	0.40	24.87	14.09	12.89

Figure 9: Changes in detailed and simple PV + Battery simulation results

Across all the cases, the annual energy, defined as the PV and battery discharged energy, has increased, partly due to increased battery efficiency, the amount of power discharged relative to charged across the simulation period. The nominal LCOE dropped in all cases and the bill savings increased. The largest improvements are to the simple PV model, especially in the Residential case, where LCOE dropped 20% and bill savings increased 24%. We believe these results reflect more accurate battery modeling, as model operation now better reflects target operation, but further testing is required. These improvements were also important in developing new dispatch algorithms since they ensure the battery can more accurately follow those instructions.

The rigorous test suite also allowed an overhaul of the thermal component of the battery model as well as the refactoring of the physical components (i.e. not the dispatch) into models that can be simulated statefully and on a single timestep by timestep basis. The tests allowed complex changes to be made with confidence that the original functionality was preserved and enhanced when applicable. The new stateful model allows for co-simulation and co-optimization with other software because it can be run one timestep at a time and carries within the model all the data needed to restart a simulation at any given point. The model can run at subminute timesteps, which allows us to do detailed comparisons to detailed battery test data from NREL's transportation center, for further battery model validation. This reason for this separate capability was due to the Behind-the-meter-storage project with SETO, VTO and BTO, but in the process, the refactoring allowed for minor bug fixes, code improvements and additional tests. Since it was released, this model has been used in parallel with a battery dispatch optimization effort in NREL's Hybrid Optimization LDRD.

These changes include how the thermal properties are computed; by changing from a numerical method which did not properly account for timestep size to an analytic solution, several instabilities from the thermal effects were resolved. This included the requirement of unrealistically high cooling rates of the battery for normal operating temperatures, which in turn affected many downstream components. Also, more realistic values for thermal properties such as heat transfer coefficient and surface area were collected from experts at NREL and will be implemented as SAM defaults the following quarter.

Battery defaults and the default configurations were modified in SAM to streamline modeling of various use cases. By splitting out the PV-battery configuration from the PV into its own separate configuration, PV-battery-specific defaults were designed to highlight aspects of the battery and dispatch model. Improvements in the GUI design has also made it easier to choose between the various cell parameters and dispatch algorithms available, as well as to align battery features added by other projects during this quarter with the new GUI organization. Default cell parameter assumptions such as for thermal modeling were modified, and ongoing work will be to update other assumptions with the state-of-the-art in industry. We have also initiated investigations into bidirectional inverters and whether these need to be improved to capture different PV + battery topologies.

We have also improved SAM's capabilities in regard to using custom forecasts for getting a realistic estimate of battery value. Previously, a custom forecast was only available for weather file in the front of meter economic dispatch algorithm. We have expanded the forecast input to be used by the front of meter PV smoothing algorithm, and added an input for load forecasts for the behind the meter peak shaving algorithm and the price signals dispatch algorithm.

To improve SAM's modeling of battery degradation, we added a state-of-the-art battery degradation model for NMC/graphite cells via a contribution from NREL researchers on the EnergyPlus team. To fully integrate this model, the existing battery lifetime model framework was generalized to allow chemistry-specific models to be used in place of the original calendar-cycle model. This involved rather extensive re-working of the battery code, but the addition of this model allows for characterizing degradation behavior that was previously not possible, thereby allowing better prediction. A similar degradation model for LMO/LTO cells was integrated using the same approach. Additionally, we enhanced the cycle degradation model to allow computation of degradation at different cycle depths, rather than always applying the average cycle depth at each timestep.

Additional battery bug fixes during the project included:

- Improved accuracy in the round trip efficiency of the Vanadium Redox flow model.

- Improved voltage table model allowing for realistic efficiencies and better control of dispatch constraints.
- Improved accuracy of sizing when using AC values.
- The ancillary loss inputs are now properly included in the battery powerflow calculations.
- Battery replacement costs now only include the percent of the battery capacity replaced, instead of assuming the cost was for 100% of the battery's capacity.
- The maximum charge and discharge power of the detailed battery model (DC and AC) are now calculated based on the correct computed properties
- The computed battery properties are more clearly displayed in the SAM UI, with the AC and DC values clearly differentiated

2.2, 5.2, 8.2: Update utility rate models

The energy charges for PPA financial markets were updated to include all columns to be editable by the user. This update allows incorporation of electricity rates as needed for battery charging for in-front-of-meter and behind-the-meter connections.

Partial refactoring of the utility rate code was performed to allow for direct use of utility rates in the SDK. Development was confined to branches in GitHub with further review before releasing in SDK.

The utility rate model was updated to handle different number of tiers for each period.

The utility rate model was refactored into libraries to allow for price signal dispatching battery algorithms. The hourly and subhourly buy and sell rates were separated to address additional use cases. An option was added to allow the user to select months other than December for their net-metering credits to ”true-up” and reset to zero.

Improvements to the utility rate models during the fourth quarter include improving the time-series buy and sell rate options. These options can now be selected independently, and are now subject to inflation over the analysis period. Users can now only select these models when choosing the ”net billing” or buy-all sell-all” rate options, better matching real world rates. These updates were released with our final patch for SAM version 2020.2.29.

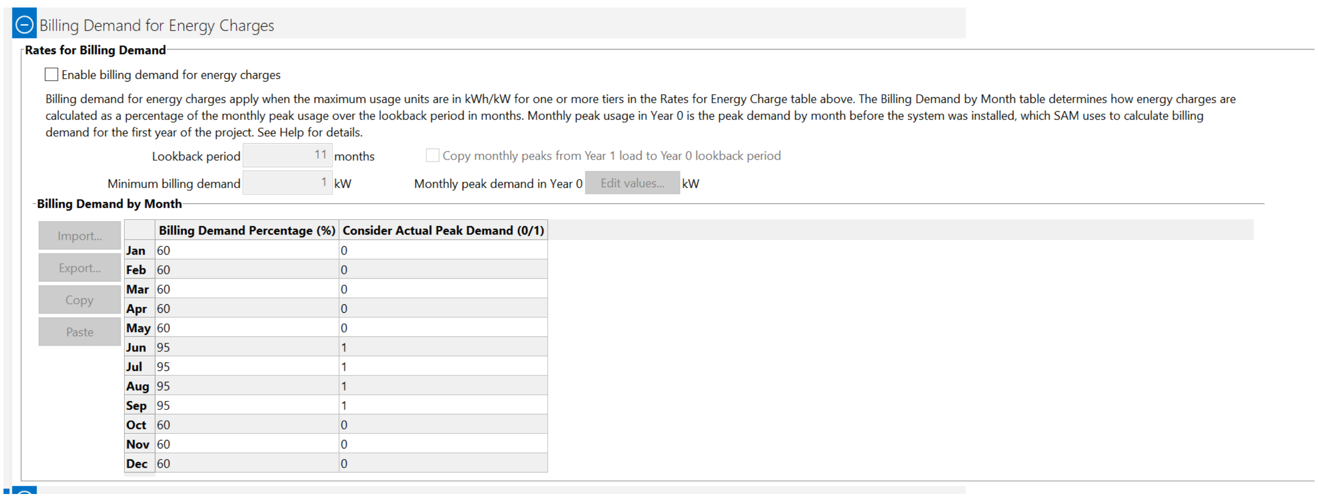
We implemented improvements to the utility rates including allowing bill credits for the ”net metering with dollar credits” option to roll over to future bills, subject to monthly and annual minimums. The prior implementation simulated the user receiving a check at the end of the true up period. Additionally, we reformatted the outputs reporting distributed generation credits in order to clarify when credits are earned and applied.

Bug fixes for the utility rate module include: front of meter systems now properly calculate battery charging costs using either PPA rates or retail electricity rates.

We fixed a number of bugs in the utility rates code, including a case where the distributed generation credits were being double counted. A longer standing bug with kWh/kW rates was also fixed, bringing SAM's calculations in line with the latest URDB formats for those rates.

Finally, the team implemented updates to the utility rates that allowed the "Value of RE" macro to work across a wider range of utility rates and behind the meter financial models.

Billing demand for energy charges was added to the electricity rates page in collaboration with EPRI and Southern Company. The user interface updates for this new utility rate structure is shown in Figure 10.



	Billing Demand Percentage (%)	Consider Actual Peak Demand (0/1)
Jan	60	0
Feb	60	0
Mar	60	0
Apr	60	0
May	60	0
Jun	95	1
Jul	95	1
Aug	95	1
Sep	95	1
Oct	60	0
Nov	60	0
Dec	60	0

Figure 10: Billing Demand for Energy Charges User Interface

2.3, 5.3, 8.3: Maintain a list of user reported bugs and fix according to priority

In FY19, the team started creating issues on GitHub to track bugs reported through the user support channels so that all bugs are tracked in one place. Several bugs have been fixed to date this year, particularly following the 2018.11.11 release, which is a common pattern for new software releases. The bug fixes were identified as high priority depending on how commonly we know the feature to be used and how severe the bug is (e.g. does SAM completely crash, is there a workaround). Using GitHub issues also enables the community to see and comment on the issues and possible fixes, as well as giving the team an avenue to suggest helpful contributions external users could make.

FY19 also marked an exciting first in the open-source world: a user both posted two new feature request issues to the SSC GitHub issues page, and submitted the new features associated with those issues himself!

In FY20, we continued to track user-reported and team-discovered bugs in Github alongside with open-source user-submitted issues so that all issues are tracked in one place. In Q1, in SSC, 8 bug-tracking issues were created, of which 7 were closed. In SAM, 10 bug-tracking issues were created in Q1, of which 9 were closed. In Q2, 7 bug-tracking issues were created, all of which were closed. In SAM, 14 bug-tracking issues were create, of which 12 were closed. In Q3, in SSC, 13 bug-tracking issues were created, 9 of which were closed. In SAM, 51 bug-tracking issues were created, of which 36 were closed. In

PySAM, 11 issues were created, of which 8 were closed. In Q4, in SSC, 10 bug-tracking issues were created, 6 of which were closed. In SAM, 29 bug-tracking issues were created in Q4, of which 11 were closed. There remained 79 open, lower-priority issues. In PySAM, 11 issues were created, of which 6 were closed.

To enable us to more accurately maintain the code, we have made two improvements to our automated testing code this quarter. First, the SSC repository now automatically runs all of the tests for every pull request. Second, we automatically run all of the SAM default configurations for every pull request to the SAM repository. We can also manually trigger the SAM tests for SSC. These changes were enabled by contacting Travis CI and requesting a free upgrade, allowing two hours for automated tests. These improvements have already sped up development, catching required defaults updates for the new battery algorithm discussed in Milestone 2.5.1.

In FY 21, we continued to track user-reported and team-discovered bugs in Github alongside with open-source user-submitted issues so that all issues are tracked in one place. For Q1, in SSC, 19 bug-tracking issues were created, 8 of which were closed. In SAM, 48 bug-tracking issues were created in Q1, of which 23 were closed. In PySAM, 10 issues were created, of which 2 were closed. For Q2, in SSC, 25 bug-tracking issues were created, 12 of which were closed. In SAM, 47 bug-tracking issues were created, of which 17 were closed. In PySAM, 8 issues were created, of which 6 were closed. For Q3, for SSC, 3 issues were opened and 2 were closed; for SAM, 21 were opened and 16 were closed; for PySAM, 1 was closed. For Q4, for SSC, 10 were opened and 0 were closed; for SAM, 19 were opened and 11 were closed; for PySAM, 3 were opened and 6 were closed.

2.4, 5.4, 8.4: Update current financial models

The PPA single owner financial market was updated to handle subhourly generation and load profiles for the generic technology system. The Excel workbooks were updated to receive the residential loan market discounted payback information. The third party ownership financial market was updated to include load download macros.

The PPA single owner financial market was updated to handle ancillary services markets for the upcoming SAM release. A merchant plant financial market has been added and is currently undergoing peer review. The Excel workbooks were updated to include the new revenue streams. “Send to Excel with Equations” functionality was also developed for the Sale Leaseback and Partnership Flip financial models due to several user requests.

“Send to Excel with Equations” functionality was also developed for the Sale Leaseback and Partnership Flip financial models due to several user requests. Additional thermal value revenue stream was added for fuel cells for recapturing the value of heat produced. Funded by another project, the PPA single owner financial market was updated to handle capacity payments for the upcoming SAM release. Funded by that same project, the merchant plant financial market has undergone peer review and feedback has been implemented and validated. The Excel workbooks were updated to include the new revenue streams.

Funded by a complementary project, the merchant plant financial market feedback has been implemented and the new financial model was released in SAM 2020.2.29.

Development of a levelized cost of storage (LCOS) metric continued and was distributed in a beta release, but this metric will not be in a public version of SAM until additional feedback is received and reviewed. This metric will represent the estimated total lifecycle costs of battery storage systems divided by the total lifecycle energy that is discharged from the battery to the grid. The LCOS metric will provide users an easily interpretable value that will help them determine the financial performance of the storage system separate from the overall LCOE representing costs and generation for the overall generation plus storage project.

A new GEM program intern, Stephen Paul, has made valuable additions to the "Merchant Plant" financial model available in SAM that allows users to analyze the feasibility of plants participating directly in the energy and ancillary services markets. Stephen is linking the timeseries price inputs to a new NREL dataset, "Cambium", that includes modeled timeseries cost data based on REeDS runs for various scenarios. This data is available across the country, and represents a reasonable proxy for energy market prices in future scenarios. Thet user interface for downloading this data is shown in Figure 11. Making this new dataset available in the Merchant Plant user interface will greatly improve the usability of the model, since previously users had to find or produce this data on their own. Stephen is also adding the capability to specify a fixed percentage of the plant's generation as the "cleared capacity" in the market of choice, which again simplifies use of this model. We anticipate these new features will become highly used, particularly by researchers, as more and more plants consider participating directly in markets rather than signing Power Purchase Agreements.

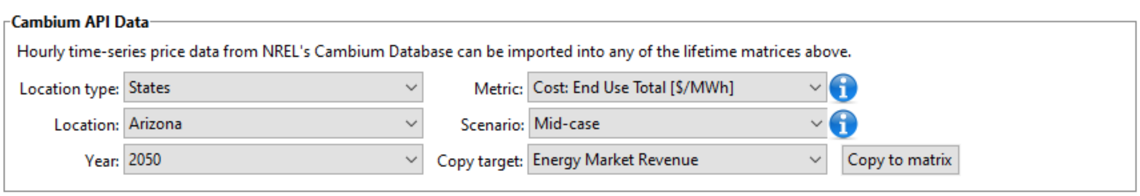


Figure 11: Cambium Data Download User Interface

8.5: Release 1 new version of SAM and 2 or more patches

This quarter, we released the first patch for the latest major version of SAM, 2020.11.29 Revision 1. The motivation behind releasing the patch in this quarter was primarily to provide fixes to smaller bugs and updates that would be beneficial to users. There was not a large bug or issue that necessitated the patch, which indicates the bolstered testing procedures and diverse skillbase of the team improved the stability of the initial release version as compared to prior SAM version releases.

Task 3: Model and Algorithm Improvement

3.1: Distribute PySAM, a Python wrapper for a new SAM library

A new SAM library bundling the SSC library was produced that defines in its interface the necessary variables for each technology and financial model. In contrast to the existing SSC API which had a couple dozen functions for setting and retrieving all variables across all models (which number over ten thousand and required external information, causing the process to be error-prone), this highly-expanded interface reveals a function per variable specific to each model for a given SSC version. This expanded interface includes type and error checking, documentation, and splitting of variables into logical groups similar to that found in the GUI. This C API is the basis for the PySAM C Extension.

The existing PySSC wrapper utilized a Python library for binding Python data with C data, so that the data conversion was done by the Python interpreter. PySAM, being a C Extension (a collection of compiled modules that the CPython interpreter can link with), does the data conversion in a binary, and thereby offers greater performance. PySAM is a wrapper around the SAM library that groups together the C API functions by model into native Python modules, allowing use of native Python functions, data types, and documentation. These modules are compatible with the old PySSC data type, allowing for easy migration. Defaults per technology-financial model configuration are available in PySAM, so that a given system can be created in a couple of lines. Each module, group, and variable appear in auto-complete suggestions and have docstrings that are used by Python's help module.

The usability is greatly enhanced due to innate error-checking, explicit input and output definition, and conversion between Python data types. In addition, PySAM is easy to use with Python's built-in multiprocessing module. Having been uploaded to PyPi with support for at minimum Windows 7 64-bit, MacOSX 10.6, and CentOS 5, and a minimum Python version of 3.5, it can be installed in a single line.

Despite the extra functionality, the speed of setting and getting SAM variables has improved, due to the direct execution afforded by using a C Extension. Three different cases for the basic task of setting up a few variables were measured across the three platforms, over 100 and 1000 repetitions. The results are below. Note that compared to the execution of a model, whose performance is unaffected by the interface, the passing of data is a tiny fraction of the computation time, so the primary benefit is still usability.

An Intro to PySAM webinar was given to about 40 attendees, both internal and external to NREL, and recorded to be posted on the SAM website. A shortened version was given during the SAM Virtual Conference which has also been posted online. A few bugs have been fixed and new developments added to the develop branch, currently not yet released. Several questions from users were addressed on Github and two pull requests with user contributions were merged in.

Task 6: Model and Algorithm Improvement

6.1: Incorporate emerging financial mechanisms

Calculations for a Levelized Cost of Storage (LCOS) metric have been added to SAM in 2021 to give users a metric representing the storage-specific lifecycle costs divided by the storage lifecycle energy discharge for generation + storage projects. The calculations for the LCOS include storage-specific investment costs and operating costs in terms of fixed dollars, per unit energy capacity, and per unit energy generation. The costs of the storage technology also include approximate calculations of the cost of charging the storage system from the grid and/or from the generation technology such as a PV system. There is also an additional new storage cost input accounting for the salvage value of the storage system at the end of the project based on the remaining battery capacity when considering battery replacements and degradation modeling. The main LCOS equation is based on the work of Schmidt, et. al [16]. The LCOS calculations will be available in the SAM output tables in the next released version of SAM.

We developed a new Community Solar financial model that makes it possible to evaluate PV and PV+Solar systems for projects that earn revenue from subscription payments by particpants in a community solar program. The model was developed in collaboration with NREL's work on with the DOE National Community Solar Partnership (NCSP). NCSP members participated in a webinar introducing the new model and provided feedback on a Beta version we prepared for testing before the release of the model in the Fall 2021 vresion of SAM. This new financial model is an adaptation of SAM's PPA Single Owner financial model and leverages that model's inputs for project costs, incentives, and financial parameters and cash flow outputs. Figure 12 shows the inputs for the new modoel.

Task 9: Model and Algorithm Improvement

9.1: Modernize the PVWatts model

The PVWatts model has been updated to a new version, pvwattsv8, that uses the same underlying models as the detailed photovoltaic model for the module model, inverter model, and module thermal model. This simplifies required code maintenance, and also improves agreement between the simple pvwatts model and the detailed photovoltaic model. Analysis shows that a majority of annual results are within +-1% of the previous model, pvwattsv5, without requiring any additional inputs from the user. A few optional features have been enabled with the new model as well, including bifacial modules. A forthcoming technical report will detail all of the changes to the algorithm, as well as provide detailed comparison between the pvwattsv5 model and the pvwattsv8 model.

Task 10: Quantifying the Difference Between Linear and Non-Linear Battery Modeling Approaches

10.1: Differences in net present value

In order to assess the efficacy of dispatch plans generated by an optimization of a linear battery model, we conducted a case study for two commercial buildings, which were also

[16] Schmidt, O. ; Melchior, S. ; Hawkes, A.; Stafell, I. (2019) Projecting the Future Levelized Cost of Electricity Storage Technologies. 19 pp.; Joule Vol. 3 Iss. 1.

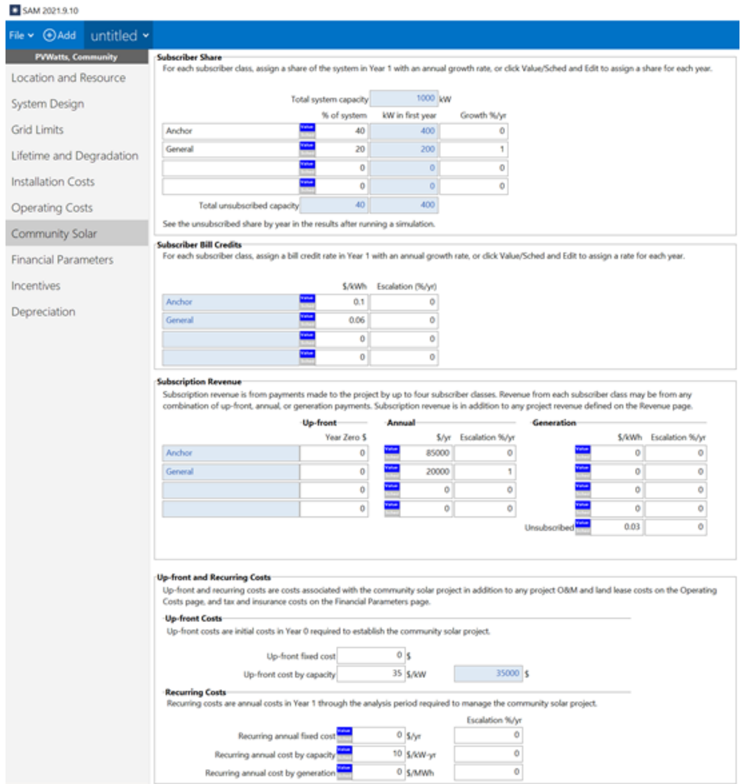


Figure 12: Input Page for New Community Solar Financial Model

utilized in Mirletz and Guittet's 2021 PVSC paper. [17] We generated load profiles using EnergyPlus based on weather profiles for a locations in San Francisco and San Diego. Based on these weather and load profiles, we used REopt Lite to determine optimal system sizing. System sizes used in the case study are shown in Table 6.

Table 7 shows the net present value results for each of SAM's heuristic dispatch algorithms, compared to REopt Lite's optimal dispatch using a perfect 8760 forecast. Within these results, the dispatch algorithm with the lowest utility bill in year 1 has the highest net present value. Note that the heuristic peak shaving dispatch algorithm outperforms REopt Lite's optimal dispatch in the San Francsico Shopping Center case, both for PV-only charging and grid charging. This is due to the differences between SAM's non-linear battery model and REopt Lite's linear battery model, primarily the voltage component model.

Differences between these results and those shown in Mirletz and Guittet 2021 are because the results in the paper are from SAM version 2020.11.29 r2, whereas results shown here are with the code that will be released in Q1 of FY22. Improvements in SAM's ability to match REoptLite's optimal dispatch and that enabled the more accurate comparison shown here are discussed in the following sections.

10.2: Differences in power delivered

[17] https://www.nrel.gov/docs/fy21osti/79575.pdf

Table 6: PV and battery sizing for each system and load data for each location

System	PV Capacity	Battery Power	Battery Capacity	Peak Load	Annual Energy Consumption
San Francisco Shopping Center	1000 kWac	169 kW	711 kWh	747 kW	4,444 MWh
San Diego Hospital	1,500 kWac	974 kW	7,356 kWh	1,186 kW	5,475 MWh

Two major factors contribute to differences between power delivered from the battery to the load between REopt Lite's optimal dispatch when run through SAM's battery model. The first of these was the DC-DC efficiency within the battery. REopt Lite's default is that the round trip efficiency is 97.5%, but with SAM's voltage model the actual efficiency will depend on the state of charge encountered during a dispatch plan. Dispatch that spends more time in the extremes (0% or 100% state of charge) will be less efficient. Values for this efficiency in the case study ranged from 92.7% to 99.0%, all using SAM's NMC Lithium ion chemistry. When dealing with optimal dispatch this requires running the optimization once to get a rough idea of the efficiency, then iterating through the optimization again with the updated efficiency.

The second factor was policy assumptions around when the battery could charge and discharge. In SAM 2020.11.29, the battery was prohibited from charging unless PV generation exceeded load, and prohibited from discharging unless PV was less than load. REopt Lite assumed that the grid could meet load while PV charged the battery, and that PV could export to grid while the battery discharge met the load. We updated SAM's powerflow calculator for the upcoming release so that user can choose to operate with the relaxed set of assumptions that REopt Lite utilizes, and better match policy for their local jurisdiction.

With an accurate DC-DC efficiency number and the updated power flow assumptions, running REopt Lite's optimal dispatch through SAM resulted in greater than 99.999% of the expected power being delivered from the battery to the load in the first year of the case study. The discrepancy was less than 1 kWh out of 1067000 kWh. However, when this is extended for the lifetime of the battery the performance varies. Repeating the same optimal dispatch profile for each year leads to times where the dispatch is curtailed due to the reduced capacity after degradation. An example of this for the San Francisco shopping center is shown in Figure 13, where the battery delivered 91.1% of the expected power to the load over the system lifetime. In the San Diego hospital case the battery delivered 96.8% of the expected power to load.

10.3: Evaluate linearized battery degradation rates

Table 7: NPV results for each of the dispatch algorithms, in thousands of dollars.

System	Price signals dispatch	Peak shaving	Manual dispatch	REopt Lite	PV only
San Francisco Shopping Center w/ ITC	$2,040k	$2,241k	$1,485k	$2,153k	$2,060k
San Diego Hospital w/ ITC	$3,642k	$2,791k	$3,203k	$4,705k	$2,701k
San Francisco Shopping Center Grid Charging	$1,566k	$1,752k	$1,446k	$1,715k	N/A
San Diego Hospital Grid Charging	$2,949k	$1,671k	$2,037k	$3,238k	N/A

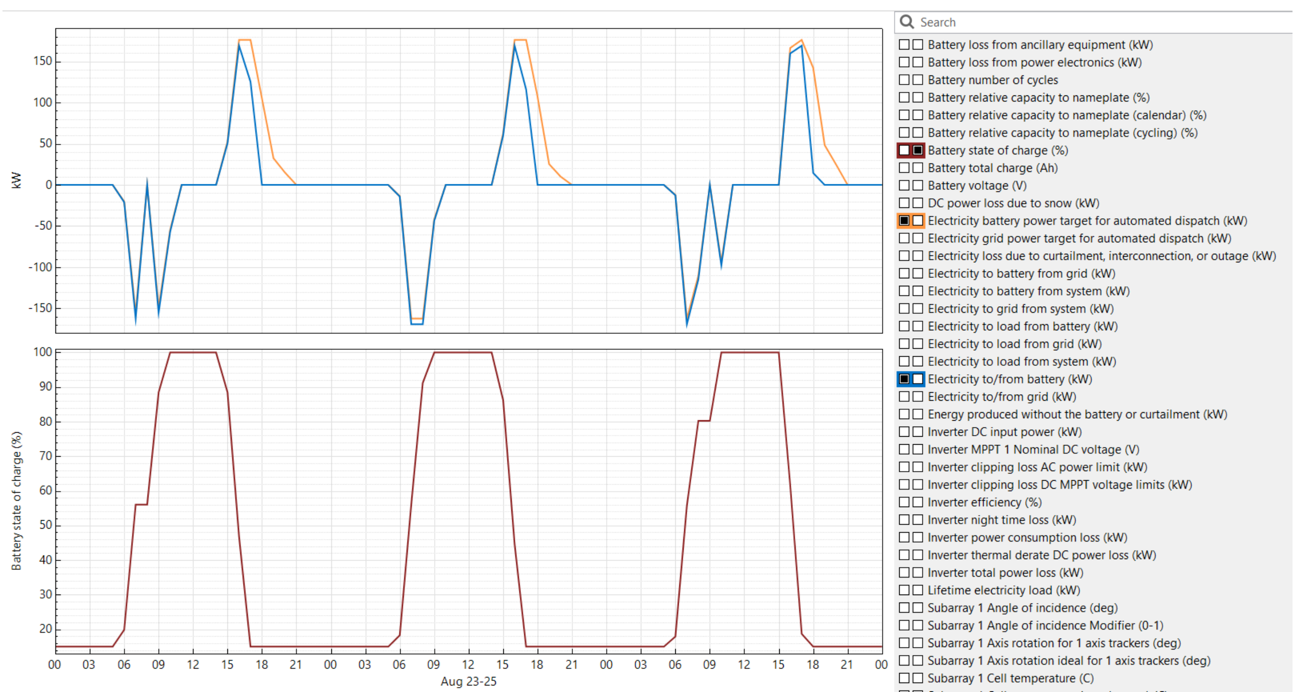


Figure 13: Showing the effect of degradation in the San Francisco shopping center case. The battery runs out of charge and is unable to complete the specified dispatch.

As a further examination of the relationship between battery dispatch and degradation, we extended the sensitivity analysis from Mirletz and Guittet 2021. The sensitivity analysis compared the performance of REopt Lite's optimal dispatch and SAM's heuristic dispatch for 625 hypothetical utility rates, by varying the parameters below:

- The energy charge in the highest cost TOU period, ranging from \$0.10 to \$0.50 per kWh
- The TOU ratio between charge in the highest cost period and the lowest cost period, ranging from 1 to 10
- The fixed demand charge, ranging from \$0 to \$59.05 per kW
- The TOU demand charge, ranging from \$0 to \$13.45 per kW

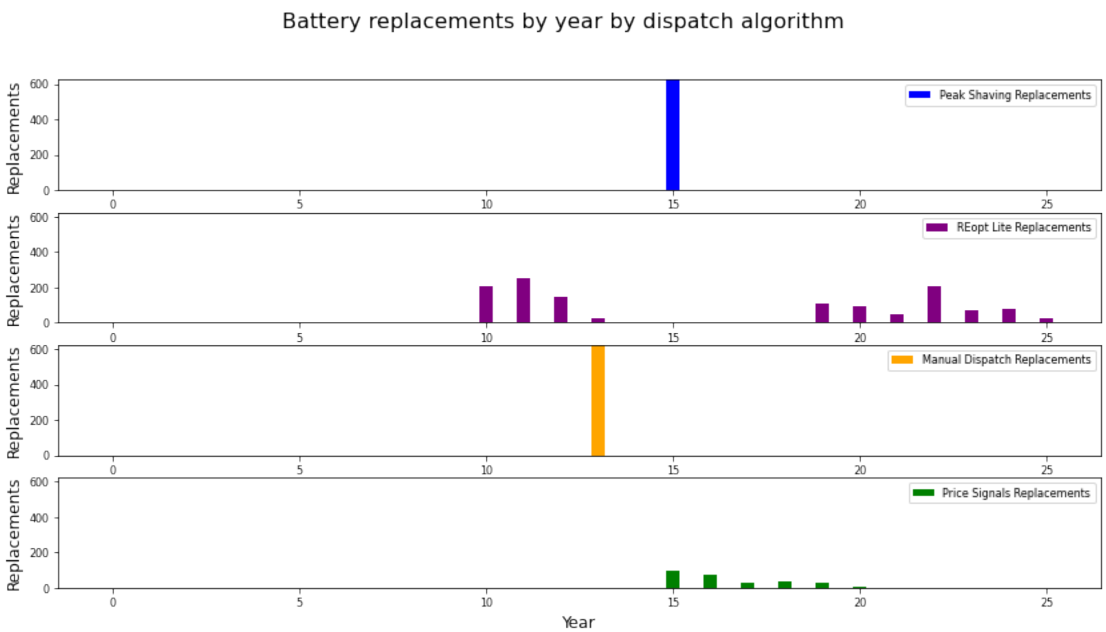


Figure 14: Battery replacements by year for the sensitivity analysis. Some REopt Lite dispatch profiles resulted in more than one replacement.

The battery replacements by year of analysis period are shown in Figure 14, where the battery is replaced when it reaches 50% of the nameplate capacity. SAM's peak shaving and manual dispatch algorithms only consider the PV and load profiles, so they always trigger replacements in the same year. Both REopt Lite and price signals dispatch are responding to the price, but REopt Lite does not consider degradation. Out of the 625 cases, REopt Lite triggers 1247 replacements (622 cases had two replacements), while only 275 of the price signals dispatch cases triggered a replacement. However, the REopt Lite dispatch achieves the highest net present value in 246 cases, compared to 7 for price signals dispatch. The lower capital cost of a PV system without a battery achieves the highest NPV in the remaining 372 cases.

10.4: Quantify difference in forecast length

Finally, we quantified the differences in NPV between a perfect 8760 forecast and a rolling 24 hour forecast. This required collaborating with the REopt team in order to implement the stateful battery model into the rolling forecast loop, which then updated the state of charge based on the battery's actual performance for that interval. The 24 hour forecast uses a 24 hour horizon and then runs for 24 hours before re-planning. Both forecast lengths use perfect forecasts, without any uncertainty in the weather file or load. Using this code to generate forecasts for year one yielded the results in Table 8. The San Diego hospital results differ from the results in section 10.1 due to the different code base used to generate them, while the San Francisco shopping center results differ because we had to switch the metering to net billing in order to use the model predictive control dispatch. Future work will allow the model predictive control code to correctly compute costs with net metering.

Table 8: NPV results by forecast length in thousands of dollars.

System	8760 forecast	24 hour forecast
San Francisco Shopping Center	\$1,173k	\$1,270k
San Diego Hospital	\$4,549k	\$4,460k

Which forecast length generates a higher NPV varies between the two systems. The San Diego hospital case has a 7.5 hour battery, so the additional forecast length allows for better utilization of that battery's large capacity. The 24 hour forecast tends to discharge the battery at the end of the forecast period, which is a low cost period. Re-running the forecast on an hourly basis could allow for the additional energy to be targeted at a higher cost time.

In the San Francisco shopping center cases, both forecasts finish their discharging during the high cost period, due to the smaller battery size. Based on it's linear model of the battery's DC-DC internal efficiency, the optimizer will predict it ends the forecast period at the minimum state of charge (20%). However, given the nominal voltage and voltage curve in SAM's voltage model, the non-linear battery will end the forecast period with a state of charge at 25%. Thus, the ability of the 24-hour forecast to synchronize with the detailed battery model allows for it extract more value from the additional stored energy. The lithium-ion voltage curves in SAM's model don't reach their nominal voltage until around 80% depth of discharge, so we would anticipate similar results with other lithium-ion chemistries. These results may differ with lead acid or flow batteries.

Significant Accomplishments and Conclusions

During this project, there were a variety of significant achievements. In the open source realm, we received many detailed contributions from industry, including reaching our milestone of 10 or more contributions with greater than 10 lines of code early. This milestone represented new feature additions or more complex bug fixes, rather than simple bug fixes.

Major new features have been added to the SAM Simulation Core (SSC) and SAM user interface by contributors outside of NREL:

- PVWattsV7 contributed in collaboration with NREL
- Exapnded bifacial capabilities and improvement of alignment with PVsyst
- Significant fixes to the IEC 61853 module model
- Improved treatment of diffuse self-shading and other self-shading improvements
- Adding multiple new inverter model outputs
- Fixing bugs in the [previously contributed by a different collaborator] Mermoud-Lejeune module model and increasing that model's usability
- Adding a new radiant cooling condensor and cooling system for CSP power towers
- Updating the user-specified CEC module model user interface page to display additional information
- Fixes to the python wrapper (prior to PySAM's creation)
- Addition of a new user interface for the radiant cooling condensor model option

Additionally, there have been several contributions from NRELians outside of the core SAM team, who are similarly taking advantage of the open source repository and making changes to help further the use of SAM within other projects, including the building simulation tool EnergyPlus; the large-scale Behind-the-Meter System project integrating buildings, renewables, and electric vehicles; and a detailed balance-of-system cost model for wind projects.

There are also at least five additional pull requests that are greater than 10 lines of code not included in the above list, because although they are in-depth, they are primarily to fix compiler warnings. However, this level of interest and investigation of the code deserve mention here because these types of detailed improvements still indicate a deeply engaged open source community.

Another significant achievement was the creation of the PySAM package, outlined in the discussion section. This wrapper is intuitive and easier to use and install than our previous wrappers, and has seen dramatic uptake by the industry and NREL researchers alike. This capability has significantly increased the usage of SAM's underlying algorithms throughout different research projects at NREL.

In the realm of model improvement, significant accomplishments include a new battery dispatch algorithm, also outlined previously, that can balance battery dispatch to perform well in complex utility rates that feature both demand charges and time of use rates. We've also made a variety of other battery model improvements that aid researchers in achieving accurate results. Furthermore, we made improvements to the utility rate models and financial models, including a new community solar financial model and improvements to the merchant plant financial model that enable broader research into the nuances of the value of solar or solar plus storage.

This project enabled the team to contribute to a journal article, "The 2020 Photovoltaic Technologies Roadmap", where Janine helped co-author the section on future modeling needs and improvements.

Finally, the impact of this project is best quantified by our usage statistics:

- SAM is started **once every 2 minutes around the world**
- PVWatts receives **over 17 million hits per month**
- We have over **130,000 users** in 190+ countries
- Our YouTube channel has 120+ webinars with **over 280,000 views**
- Major users include Sunrun, Enphase, AEP, Southern Company, EPRI, and more

Budget and Schedule

This project received a total budget of $1,850,000 over the three year project period. The budget and schedule followed the original plan, with the addition of a $50k plus-up in year 3 to complete additional battery dispatch comparison work.

Path Forward

The System Advisor Model and PVWatts tools, and solar energy modeling capabilities, have been identified as one of NREL's core capabilities, and as such will receive follow-on funding in the next lab cycle. There are many opportunities for improvement and expanding the reach and impact of the tool, with a few of the most promising areas including hybrid system modeling, improvements to optimal battery dispatch in a way that could be deployed on actual hardware, and many other ideas.

Inventions, Patents, Publications, and Other Results

Products resulting from this project include:

- Forthcoming journal article on battery dispatch comparisons
- Forthcoming technical report, outlining PVWatts updates
- Forthcoming SAM release, estimated December 2021
- Merchant Plant Financial Model with Cambium Integration - Aug 4 2021
- New Battery Model Features for Fall 2021 - Sept 2 2021
- New Community Solar Model for Fall 2021 - Sept 15 2021
- Electricity Bill Calculations - Sept 29 2021
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- Blair, Storage and Resiliency Modeling Options in Publicly Available NREL Tools, presented at PV Performance Modeling Collaborative Workshop, Albuquerque, NM, May 2019. *funded by a separate project but related to this project