System Advisor Model (SAM) General Description (Version 2017.9.5)

Nate Blair, Nicholas DiOrio, Janine Freeman, Paul Gilman, Steven Janzou, Ty Neises, and Michael Wagner
National Renewable Energy Laboratory

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Technical Report
NREL/TP-6A20-70414
May 2018

Contract No. DE-AC36-08GO28308

NATIONAL RENEWABLE ENERGY LABORATORY

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Suggested Citation
Blair, Nate, Nicholas DiOrio, Janine Freeman, Paul Gilman, Steven Janzou, Ty Neises, and Michael Wagner. 2018. *System Advisor Model (SAM) General Description (Version 2017.9.5)*. Golden, CO: National Renewable Energy Laboratory. NREL/ TP-6A20-70414. https://www.nrel.gov/docs/fy18osti/70414.pdf.

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Executive Summary

This document describes the capabilities of the System Advisor Model (SAM) developed and distributed by the U.S. Department of Energy's National Renewable Energy Laboratory. The document is for potential users and others wanting to learn about the model's capabilities. SAM is a techno-economic computer model that calculates performance and financial metrics of renewable energy projects. Project developers, policy makers, equipment manufacturers, and researchers use graphs and tables of SAM results in the process of evaluating financial, technology, and incentive options for renewable energy projects. SAM simulates the performance of photovoltaic, concentrating solar power, solar water heating, wind, geothermal, and biomass power systems, and includes a basic generic model for comparisons with conventional or other types of systems. The financial models are for projects that either buy and sell electricity at retail rates (residential and commercial) or sell electricity at a price determined in a power purchase agreement (PPA). SAM's simulation tools facilitate parametric and sensitivity analyses, Monte Carlo simulation and weather variability (P50/P90) studies. It includes a full-featured, built-in scripting language called LK that automates simulations for batch processing and allows for more complex analyses and reading and writing data from files. Several macros written in LK come with SAM to help with tasks such as checking weather files, sizing photovoltaic systems, and other tasks. SAM's Excel Exchange feature can also read input variables from Microsoft Excel worksheets. For software developers, the SAM software development kit (SDK) makes it possible to use SAM simulation modules in their applications written in C/C++, C#, Java, Python, MATLAB, and other languages. NREL provides both SAM and the SDK as free downloads at https://sam.nrel.gov. SAM is an open source project, so its source code is available to the public. Researchers can study the code to understand the model algorithms, and software programmers can contribute their own models and enhancements to the project. Technical support and more information about the software are available on the website.

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1 SAM Overview

This document describes the System Advisor Model (SAM) developed by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), and is written to help potential users determine whether the software meets their modeling needs, and to provide information for readers who do not plan to use SAM but want to learn about its capabilities.

SAM is a techno-economic computer model designed to facilitate decision making for people involved in the renewable energy industry:

- Project managers and engineers
- Financial and policy analysts
- Technology developers
- Researchers

SAM is available in the following platforms:

- Desktop application for Windows, Linux, and Mac OS
- Application programming interface (API) with a set of programming tools in the SAM software development kit (SDK)
- A set of documented open source C++ code repositories

To model a renewable energy project in SAM, you choose a performance model and a financial model to represent the project, and assign values to input variables to provide information about the project's location, type of equipment in the system, cost of installing and operating the system, and financial and incentives assumptions. Once you are satisfied with the input variable values, you run simulations, and then examine results. A typical analysis involves running simulations, examining results, revising inputs, and repeating that process until you understand and have confidence in the results.

Figure 1. The SAM main window showing the results summary for a wind power system.

SAM's performance models are for photovoltaic systems with optional battery storage, concentrating solar power, industrial process heat, solar water heating, wind, geothermal, biomass, and conventional power systems that either deliver electricity directly to the power grid, or interact with the electric load of a grid-connected building or facility. SAM does not model off-grid power systems, or hybrid power systems with more than one power generation source. The financial models are for projects that either buy and sell electricity at retail rates (residential and commercial), or sell electricity at a price determined in a power purchase agreement (PPA). SAM can model large or small projects, ranging from residential rooftop photovoltaic installations to large concentrating solar power generation projects and wind farms.

SAM is an open source project, so its source code is available to the public. Researchers can study the code to understand the model algorithms, and software programmers can contribute their own models and enhancements to the project. Reference manuals describing the model algorithms are also available for download from the SAM website.

2 Software Downloads

NREL distributes SAM for free at https://sam.nrel.gov. It is available in the three packages for different applications as described below.

2.1 Desktop Application

SAM is available as a desktop application for Windows, Mac, and Linux computers. The current version at the time of this writing is Version 2017.9.5, released in September 2017. The desktop version of SAM is a complete application that provides a graphical user interface to set values of inputs, configure and run simulations, and generate tables and graphs of results. The SAM desktop application is available at https://sam.nrel.gov/download.

NREL releases one or two desktop versions of SAM each year, and makes available legacy versions on the SAM website.

2.2 Software Development Kit

The SAM Software Development Kit (SDK) is a package of tools for software developers to create applications that interact with the SAM Simulation Core (SSC). It provides access to SSC via the same application programming interface (API) that the SAM desktop application uses. The SAM SDK is available at https://sam.nrel.gov/sdk.

The SDK contains:

- The SSC API, sscapi.h
- The SSC dynamic library and supporting libraries for Windows, Mac, and Linux
- The SDKtool application
- The SSC Guide
- Code examples

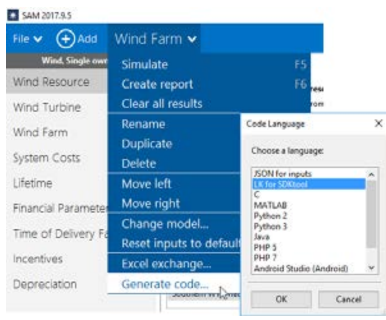

Figure 2. The Generate Code command on the Case menu exports ready-to-run code from the desktop application to use with the software development kit.

The desktop application's Code Generator can generate ready-to-run code in any of the following languages from the inputs in a SAM case:

- C
- MATLAB
- Python 2 and 3
- Java

- PHP 5 and 7
- C#
- VBA
- JSON

The Code Generator also generates code for applications on mobile platforms:

- Android
- iOS

2.3 Open Source Repositories

SAM Open Source is the set of public code repositories that NREL uses to build the desktop applications. The repositories are available for SAM users who want to explore the code to find equations and algorithms to understand how SAM's models work. It also available for model developers who want to adapt and modify SAM for their own use, and for collaborators who want to make contributions to SAM by helping to fix bugs or add features.

The SAM code repositories are hosted on GitHub.com at https://github.com/nrel/sam.

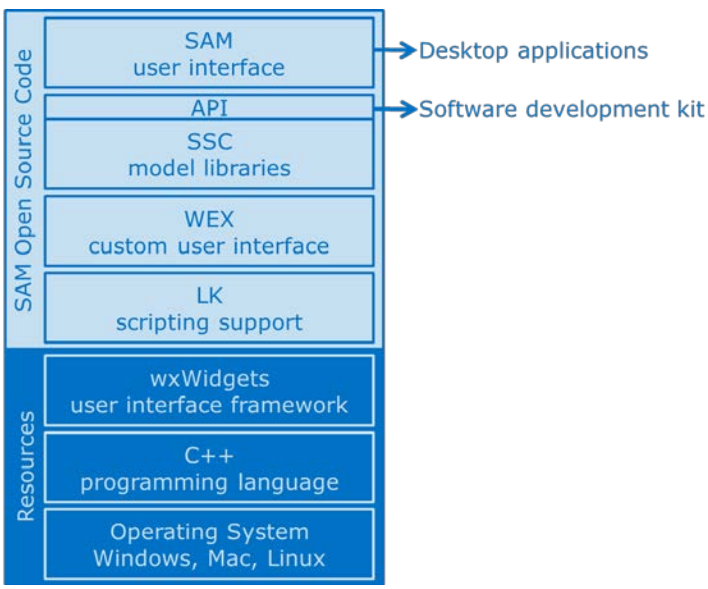

Figure 3. Diagram of SAM's structure.

3 Inputs and Default Values

SAM requires input data to describe the performance characteristics of physical equipment in the system, and project costs and financial assumptions. The desktop application comes with default input values and tools for downloading some inputs from online data services. For SDK users, when you run SSC via the API, you must assign values to the inputs in your code. (You can use the code generator described in Section 2.2 above.)

SAM requires a weather data file as input to describe the renewable energy resource and weather conditions at a project location. In the desktop application, you either choose a weather data file from a list, download one from the internet, or create the file using your own data.

The desktop application comes with several libraries of performance data and coefficients that describe the characteristics of commercially available system components such as photovoltaic modules and inverters, parabolic trough receivers and collectors, wind turbines, and biopower combustion systems. For those components, you simply choose an option from a list, and SAM applies values from the library to the input variables.

The desktop application comes with a set of component libraries that store input parameters for the photovoltaic, solar water heating, wind and parabolic trough performance models:

- Module parameters from the California Energy Commission
- Inverter parameters from the California Energy Commission
- Solar hot water collector parameters from the SRCC
- Trough receiver parameters from NREL
- Trough collector parameters from NREL
- Wind turbine power curves from NREL

The desktop application can also automatically download data and populate input variable values from the following online databases:

- OpenEI Utility Rate Database for retail electricity rate structures for U.S. utilities.
- NREL National Solar Radiation Database for solar resource data and ambient weather conditions.
- NREL Wind Integration Datasets for wind resource data.
- NREL Biofuels Atlas and DOE Billion Ton Update for biomass resource data.

For the remaining input variables, you either use the default value or change its value. Some examples of input variables are:

- Installation costs including equipment purchases, labor, engineering and other project costs, land costs, and operation and maintenance costs.
- Numbers of modules and inverters, tracking type, and derating factors for photovoltaic systems.
- Collector and receiver type, solar multiple, storage capacity, and power block capacity for parabolic trough systems.
- Analysis period, real discount rate, inflation rate, tax rates, internal rate of return target or power purchase price for utility financing models.
- Building load and time-of-use retail rates for commercial and residential financing models.
- Tax and cash incentive amounts and rates.

4 Performance Models

SAM's performance models make timestep-by-timestep calculations of a power system's electric output, generating a set of timeseries data that represents the system's electricity production over a single year. The simulation timestep depends on the temporal resolution of the data in the weather file, which can be hourly or subhourly.

You can explore the system's performance characteristics in detail by viewing tables and graphs of the timeseries performance data, or use performance metrics such as the system's total annual output and capacity factor for more general performance evaluations.

The current version of SAM includes performance models for the following technologies. It does not limit the size of systems, so can be used to model small residential-scale systems or large utility-scale systems:

- Photovoltaic (PV) with optional electric battery storage
- High concentration PV
- CSP parabolic trough
- CSP power tower (molten salt and direct steam)
- CSP linear Fresnel
- CSP integrated solar combined cycle
- CSP dish-Stirling
- Process heat parabolic trough and linear direct steam
- Conventional thermal (a simple heat rate model)
- Solar water heating for residential or commercial buildings
- Wind power
- Geothermal power and geothermal co-production
- Biomass power

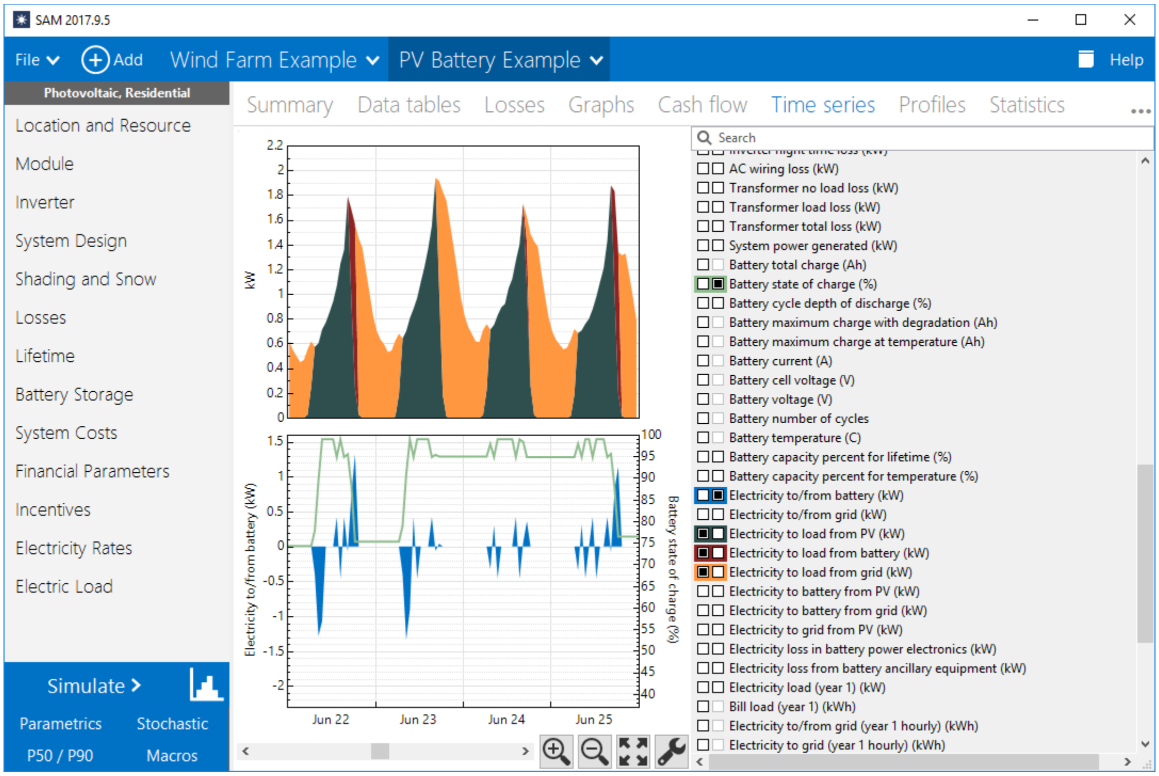

Figure 4. The Results page showing time series results for a photovoltaic system with battery storage. This file contains two cases, one for a wind farm and one for a photovoltaic system.

5 Financial Models

SAM's financial models calculate financial metrics for various kinds of power projects based on a project's cash flows over an analysis period that you specify. The financial model uses the system's electrical output calculated by the performance model to calculate the series of annual cash flows.

SAM’s financial models can be used for a wide range of projects:

- Residential building (retail electricity rates)
- Commercial facility (retail rates)
- Third party ownership
- Power generation (power purchase agreement):
- Single owner
    - Leveraged partnership flip
    - All equity partnership flip
    - Sale leaseback
- The LCOE calculator is general, simple model that uses a fixed charge rate, installation cost, and annual operating cost as input to calculate the levelized cost of energy for any financial structure.

Residential and commercial projects generate electricity to reduce a building or facility’s consumption of electricity from the grid. They are financed through either a loan or cash payment, and recover investment costs through savings from reduced electricity purchases from the electricity service provider. For electricity pricing, SAM can model simple flat buy and sell rates, monthly net metering, or complex rate structures with tiered time-of-use pricing and demand charges. For these projects, SAM reports the following metrics:

- Levelized cost of energy
- Electricity cost with and without renewable energy system
- Electricity savings
- After-tax net present value
- Payback period

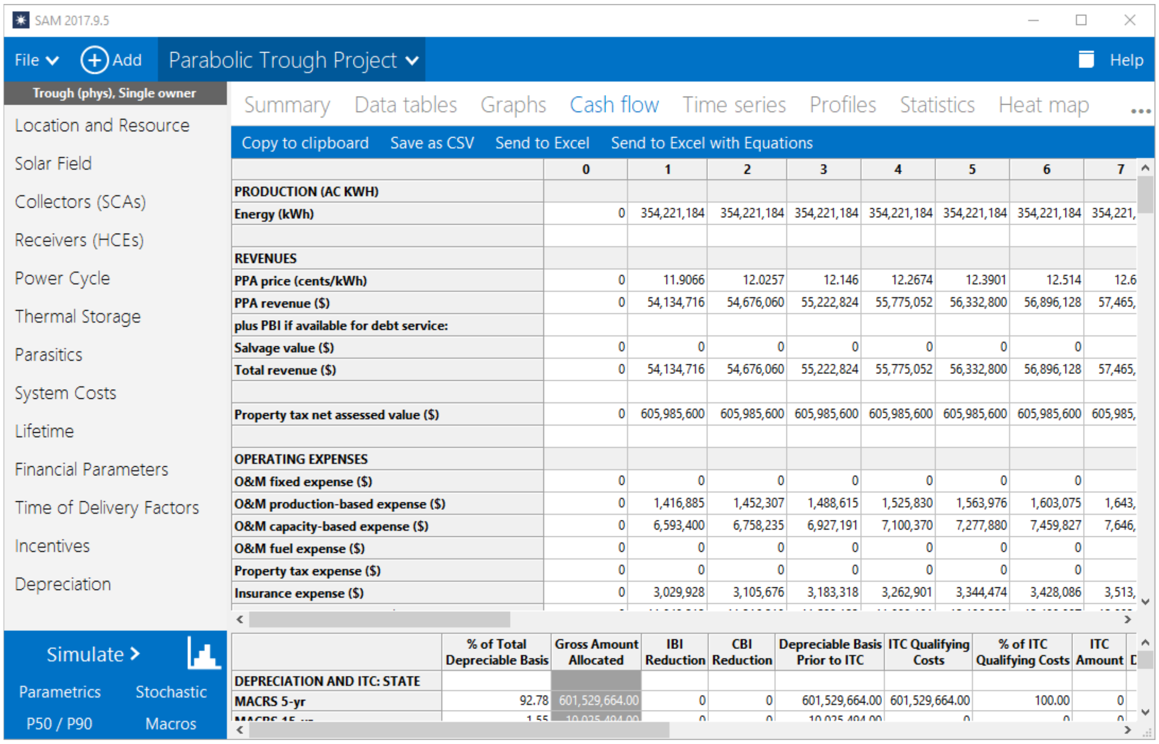

Figure 5. The first several rows of the pro-form cash flow for a PPA power generation project.

PPA projects for power generation sell electricity through a power purchase agreement at a fixed price with optional annual escalation and time-of-delivery (TOD) factors. For these projects, SAM calculates:

- Levelized cost of energy
- PPA price (electricity sales price)
- Internal rate of return
- Net present value
- Debt fraction or debt service coverage ratio

SAM can either calculate the internal rate of return based on a power price you specify, or calculate the power price based on the rate of return you specify.

SAM calculates the levelized cost of energy (LCOE) from after-tax cash flows, so that the LCOE represents the cost of generating electricity over the project life, accounting for taxes and incentives.

The project annual cash flows include:

- Revenues from electricity sales and incentive payments
- Installation costs
- Operating, maintenance, and replacement costs
- Loan principal and interest payments
- Tax benefits and liabilities (accounting for any tax credits for which the project is eligible)
- Incentive payments

- Project and partner's internal rate of return requirements (for PPA projects)

The financial model can account for a wide range of incentive payments and tax credits:

- Investment based incentives
- Capacity-based incentives
- Production-based incentives
- Investment tax credits
- Production tax credits
- Depreciation (MACRS, Straight-line, custom, bonus, etc.)

6 Simulation Tools

A simulation in SAM involves calculating the power system's output for each hourly or subhourly timestep in a year, and calculating a project cash flow over a multi-year period. SAM's simulation tools make it possible to conduct studies involving multiple simulations for parametric and stochastic modeling for analyses that investigate the impacts on model results of variations and uncertainty in assumptions about weather, performance, cost, and financial parameters:

- Parametric Analysis: Assign multiple values to input variables to create graphs and tables showing the value of output metrics for each value of the input variable. Useful for optimization and exploring relationships between input variables and results.
- Stochastic Analysis: Create histograms showing the sensitivity of output metrics to variations in input values.
- Probability of Exceedance Analysis (P50/P90): For locations with weather data available for many years, calculate the probability that the system's total annual output will exceed a certain value.
- Excel Exchange (Windows only): Use Excel to calculate the value of input variables, and automatically pass values of input variables between SAM and Excel.
- LK Script: Write your own programs within the SAM user interface to control simulations, change values of input variables, and write data to text files and interact with Excel spreadsheets.

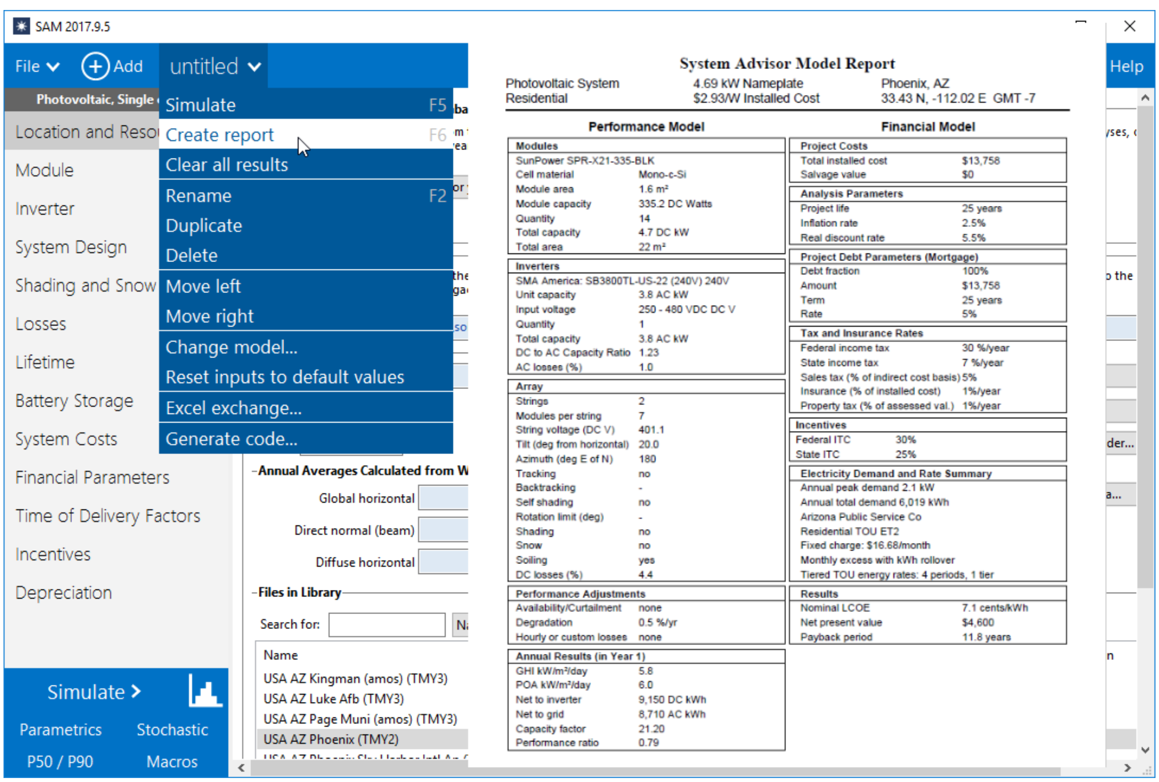

Figure 6. The report generator exports a PDF showing key assumptions and results from a SAM analysis case.

Additional tools include:

- Inputs browser: Display all inputs in each case in a SAM file as a single table that can be filtered to find input variables with different value and exported to a CSV file.
- Import cases: Import a case from one SAM file into another.
- Report generator: Create a PDF file with summary tables and graphs of inputs and results.
- Notes: Store text with each input page to document your analysis.

7 Extending SAM

For software developers, researchers and others who want to expand on SAM's capabilities, the SAM Software Development Kit (SDK) and open source repository provide tools for developing capabilities beyond those available in the SAM user interface.

The SDK provides an application programming interface (API) to the SAM Simulation Core (SSC) making it possible to write software to calculate values of SAM inputs, run simulations, and read values of simulation results in the API's native C, or in C++, Java, Python, MathWorks MATLAB, and C#. The SSC API is also used by the SAM user interface, so software you write interacts with the same high quality performance and financial models as SAM.

The open source repository hosted on GitHub.com is all of the C++ code used to develop the SSC library and user interface. Software developers and researchers can use the repository to build custom versions of SAM or to investigate the inner workings of SAM's performance and financial models.

8 Software Development History

The System Advisor Model was originally called the "Solar Advisor Model," and was first developed by the National Renewable Energy Laboratory in collaboration with Sandia National Laboratories in 2005 for internal use by the U.S. Department of Energy (DOE) Solar Energy Technologies Program in its systems-based analysis of solar technology improvement opportunities within the program. NREL released the first public version in August 2007 as Version 1, making it possible for solar energy professionals to analyze photovoltaic systems and concentrating solar power parabolic trough systems in the same modeling platform using consistent financial assumptions. Since then, DOE has continued to support NREL's development and free distribution of the software.

Since 2007, NREL has released one or two new version of SAM each year, adding new technologies and financial models with periodic updates between releases for bug fixes and minor updates. SAM was originally developed in Delphi Pascal, and converted in 2008-2009 to C++ with a user interface based on the wxWidgets 2.8 library, allowing for SAM versions to be compiled for Mac in addition to Microsoft Windows. In 2010, the name changed to "System Advisor Model" to reflect the addition of non-solar technologies. In 2013-2014, the code was largely re-written for a user-interface redesign based on the wxWidgets 3.0 library and extension called WEX, which allowed for more user interface features and more powerful LK scripting capabilities. The SAM Software Development Kit was first released in 2014, and Linux versions first became available in 2015. In 2017, SAM's source code was released as an open source project. NREL continues to release one or two new versions of the software each year, with periodic maintenance updates as needed.

For a list of software revisions from Version 1.1 (August 2007) to the present with historical details about feature additions and updates, see the SAM release notes:

https://sam.nrel.gov/sites/default/files/content/updates/releasenotes.html

9 User Support

NREL provides support for the desktop version of SAM, software development kit (SDK), and SAM Open source.

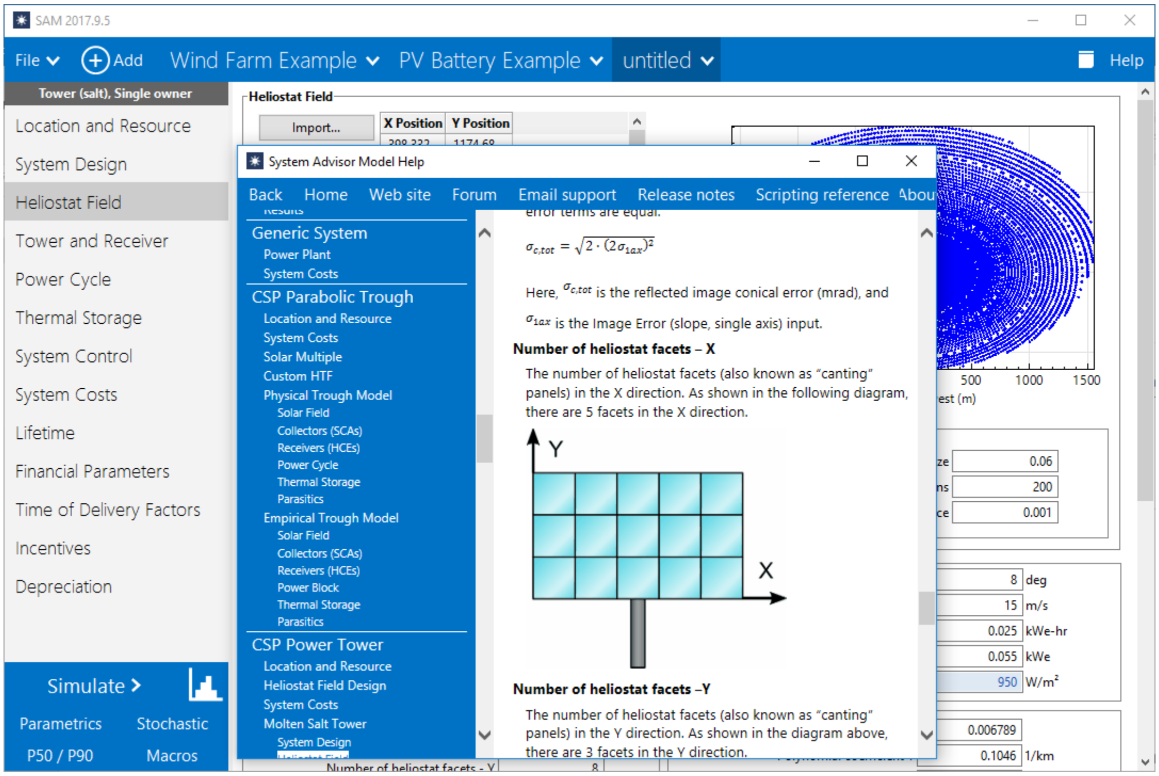

Figure 7. SAM's help system includes detailed descriptions of the user interface, modeling options, and results.

The following resources are available for learning to use SAM and for getting help with your work:

- SAM desktop version Help system: Press the F1 key in Windows or Linux, or Command-? on a Mac from any input or results page in SAM to view the Help topic for that page.
- User support forum for the desktop version of SAM https://sam.nrel.gov/support.
- User support for the SDK at https://sam.nrel.gov/sdk-support.
- GitHub Wiki and Issues pages for the open source repositories at https://github.com/nrel/sam/wiki and https://github.com/nrel/sam/issues.
- Video recordings of SAM webinars at https://sam.nrel.gov/webinars.

You can also contact the SAM support team via email by submitting a message on the website contact page: https://sam.nrel.gov/contact.

Guidelines for Citing SAM in Publications

In documentation of your research or analysis based on SAM results, NREL asks that you acknowledge your use of the System Advisor Model and mention the National Renewable Energy Laboratory (NREL), which develops the software, and the U.S. Department of Energy (DOE), which funds NREL's work.

Here are some suggestions for citing SAM in your articles and other publications. Refer to your publication guidelines for correct formatting.

Citing the SAM software:

System Advisor Model Version 2017.9.5 (SAM 2017.9.5). National Renewable Energy Laboratory. Golden, CO. Accessed October 31, 2017. https://sam.nrel.gov/download.

Citing a topic in the SAM user documentation:

System Advisor Model Version 2017.9.5 (SAM 2017.9.5) User Documentation. Weather File Formats. National Renewable Energy Laboratory. Golden, CO.

Citing content from the SAM website:

System Advisor Model Version 2017.9.5 (SAM 2017.9.5) Website. Simple Efficiency Module. National Renewable Energy Laboratory. Golden, CO. Accessed October 31, 2017. https://sam.nrel.gov/content/simple-efficiency-module.

Citing the SAM general description:

Blair, N.; DiOrio, N.; Freeman, J.; Gilman, P.; Janzou, S.; Neises, T. (2017). System Advisor Model (SAM) General Description. National Renewable Energy Laboratory. Golden, CO.

10 Software Structure

SAM consists of a user interface, an application programming interface (API), and the “SAM Simulation Core” or SSC. The user interface is the part of SAM that you see in the desktop application. (If you write your own software to access the API, you can develop your own user interface.) It provides access to input variables and simulation controls and displays tables and graphs of results. The API is a software mechanism that provides a connection between the user interface and SSC. SSC consists of a set of “compute modules” for the performance and financial models that perform a time-step-by-time-step simulation of a power system's performance, and calculate the project’s annual cash flow and financial metrics.

WEX and LK are code repositories that provide additional functionality to SAM. These components are also used by other NREL software projects. WEX is an extension of the open source graphical user interface framework called wxWidgets, and provides user interface elements designed especially for SAM. The time series data viewer called DView that comes with SAM is part of WEX, and can be compiled as a standalone application. LK is a scripting language developed for SAM with a script editor that is used by SAM and the SDKtool that comes with the SAM software development kit.

11 Software Legal Disclaimer and License

SAM may be used for any purpose, including commercial use. NREL asks that such use be acknowledged in any documentation of products or analysis involving the software with a credit to the National Renewable Energy Laboratory for developing the software, and the U.S. Department of Energy for supporting its development.

We have reproduced below the legal disclaimer from the desktop application's About window, and the license from the open source repositories (https://github.com/NREL/SAM/blob/develop/LICENSE.md) at the time of the writing of this document for your reference. Please see the originals for the most up-to-date text.

11.1 Disclaimer for Desktop Application and Software Development Kit

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