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Fuel Cells in SAM: User Guide

Nicholas DiOrio, Steven Janzou
National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Executive Summary

A fuel cell model was added to the public version of System Advisor Model (SAM). The fuel cell technology model can be incorporated with PV and battery storage models, allowing users to model the interaction of these three technologies. By adding this capability to a public version of SAM, a broad audience can consider the system performance and financial benefits of installing a fuel cell generator in conjunction with PV or energy storage systems. This work was prepared as a contract deliverable. More comprehensive, publicly available works will be published for reference.

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1 Introduction

The goal of this project was to add a fuel cell model into SAM (public). This standalone technology can be incorporated with PV and battery storage systems, allowing a user to model the interaction of these three technologies. Users will be able to model charging a battery with a fuel cell in addition to the existing capability of charging a battery with PV generation.

2 Fuel Cells

The fuel-cell model was added to SAM as a new technology model for **Commercial (distributed)** and **PPA single owner (utility)** financial models. The model was developed in collaboration with other fuel cell modeling experts at NREL, who have developed other tools for internal research [1].

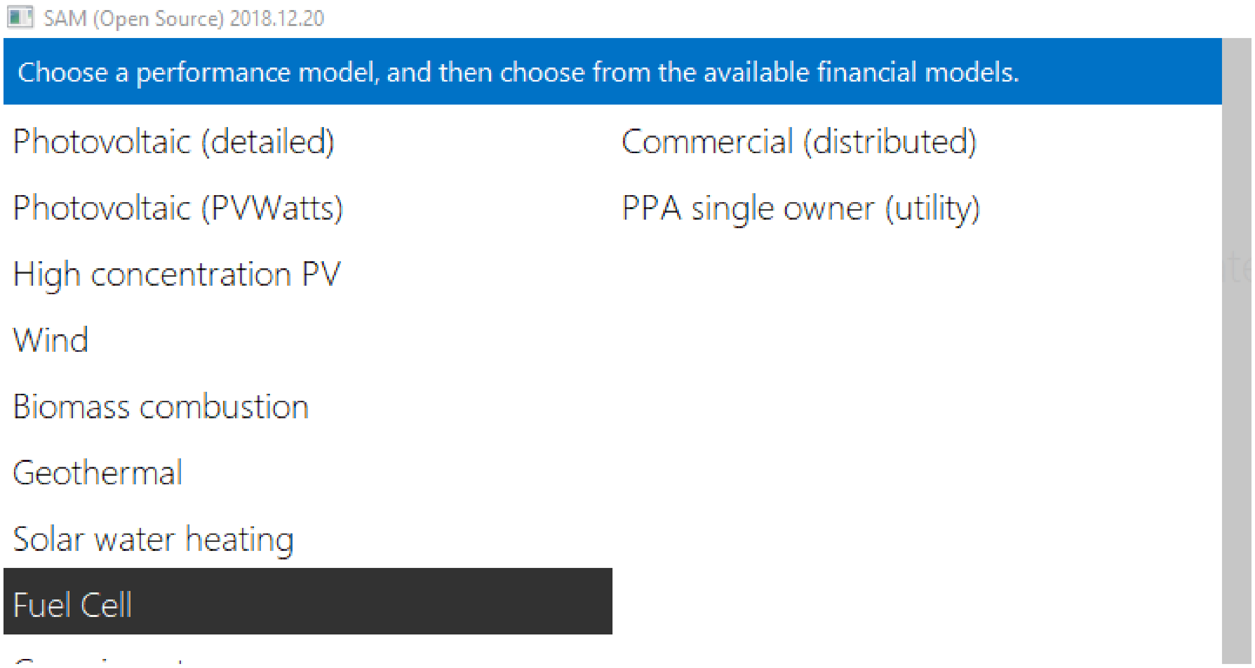


Figure 1: Fuel cell model selection

2.1 Description

The fuel cell model allows you to analyze the performance of the following types of fuel cells:

- Molten Carbonate (MCFC)
- Phosphoric Acid (PAFC)
- Solid Oxide (SOFC)
- Custom

The model provides a generic representation of a fuel cell or other generator, allowing the modeling of dynamic response limits, minimum turn down limits, degradation, and fuel usage.

You can model a system with the battery connected on the AC side of a photovoltaic system as shown in the following block diagrams. The model assumes that the fuel cell system comes with its own inverter for converting DC to AC electricity. The electric load is optional depending on what financial model is being used.

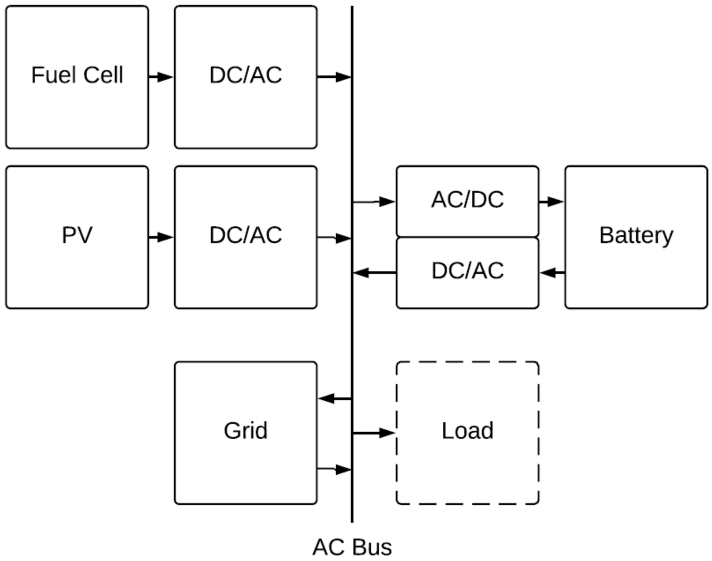


Figure 2: Fuel cell system topology

2.2 User Guide

To get started setting up a fuel cell project, there are several pages to be aware of:

- PV System – Setup a generic PV system using PVWatts
- Battery Storage – Specify a battery system using SAM's detailed model
- Fuel Cell – Specify properties of the fuel cell system
- Dispatch – Specify how to operate the hybrid system
- System Costs – Specify costs for each system component
- Thermal Rates – Specify the cost of heat
- Thermal Load – Specify the heating load at the site

This section will describe the relevant inputs on these pages.

2.2.1 PV System Properties

The PV System can be specified using standard PVWatts inputs [2].

2.2.2 Battery Storage Properties

The Battery System can be specified by using the assumptions outlined in the battery technical reference manual [3].

2.2.3 Fuel Cell Type

Selecting a fuel cell type updates defaults in SAM that have been prepopulated with best estimates for each chemistry. The user can modify the defaults if desired.

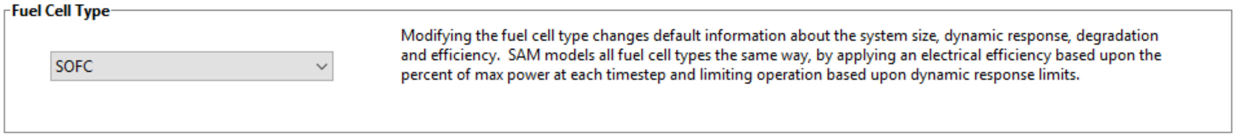


Figure 3: Fuel cell type selection

2.2.4 Fuel Cell System Properties

To specify a fuel cell size, dynamic response, degradation, and shutdown schedule, the system properties section contains these input (note, blue boxes indicate calculated values):

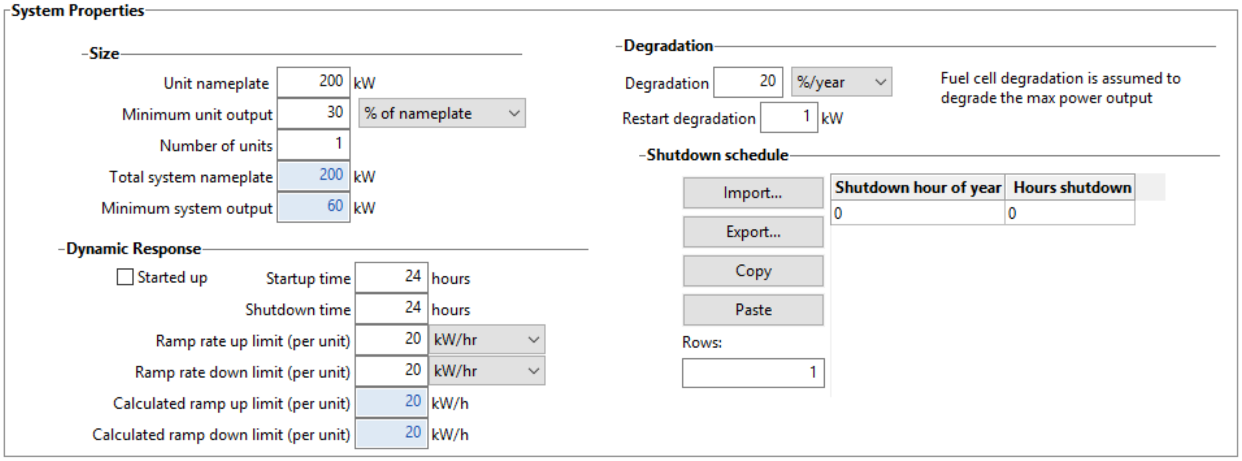


Figure 4: Fuel cell system properties

Size

- Unit nameplate: The nominal max power of one fuel cell stack
- Minimum unit output: The minimum power at which the fuel cell can be run without shutting down
- Number of units: Specify the number of fuel cell stacks

Dynamic Response

- Started up: Indicate if the fuel cell has already been started before the simulation starts. The fuel cell operation will attempt to match the selected dispatch strategy in the first hour.
- Startup time: The time it takes for the fuel cell to start up
- Shutdown time: The time it takes for the fuel cell to shut down
- Ramp rate up limit: The maximum ramp rate when a fuel cell is powering up
- Ramp rate down limit: The maximum ramp rate when a fuel cell is powering down

Degradation

- Degradation: The amount of degradation that occurs to the maximum power output of a stack as the fuel cell runs
- Restart degradation: The reduction to stack maximum power output due to restarting the fuel cell

Shutdown schedule

Each row describes one shutdown throughout the year. For each row, define:

- Shutdown hour of the year: Specify hour between 0 and 8759 when the shutdown starts
- Hours shutdown: Specify the number of hours the shutdown lasts

2.2.5 Fuel Cell Stack Replacement

Throughout the lifetime of a financial project, it's possible that a fuel cell stack will need to be replaced. This section provides options for that replacement.

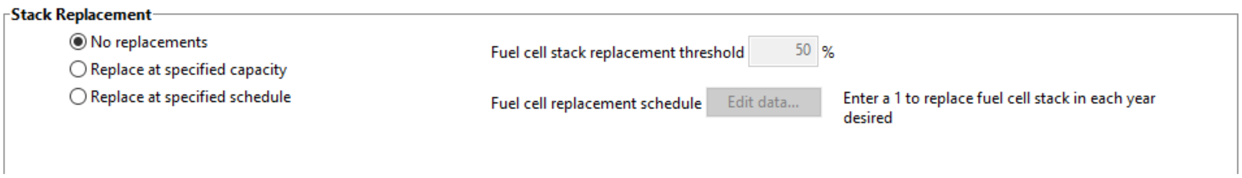


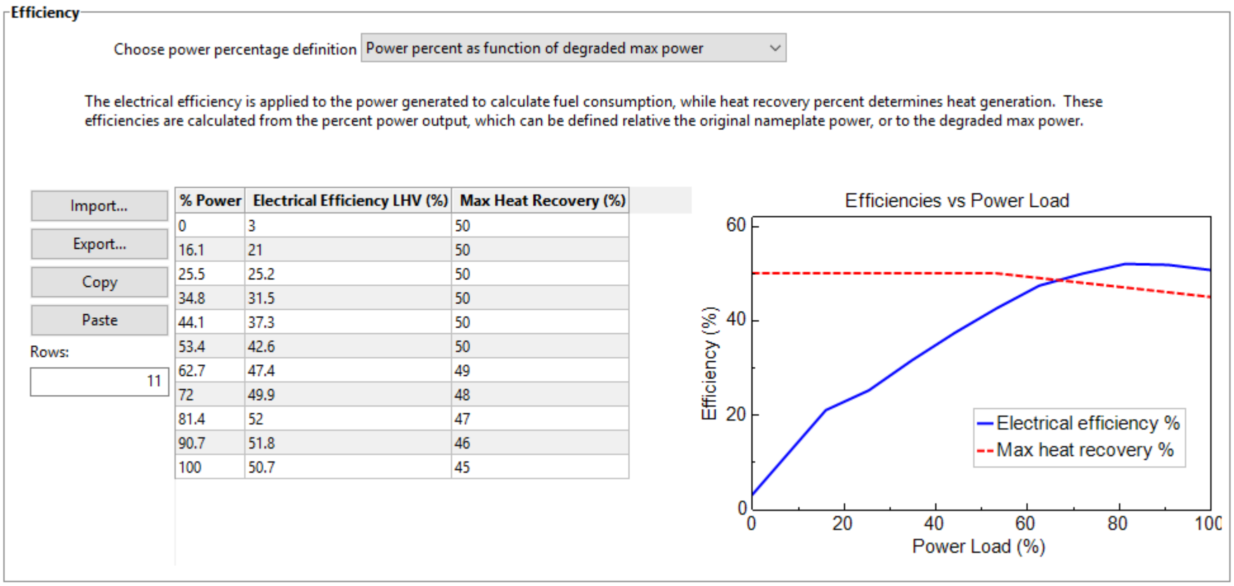
Figure 5: Fuel cell stack replacement

Options

- No replacements: Don't replace the stack
- Replace at specified capacity: Once the maximum power of a stack has degraded to a specified percentage of the original maximum, replace the stack.
- Replace at specified schedule: Within the schedule, place a 1 for any year where a stack replacement is desired.
- Fuel cell stack replacement threshold: Specify percent degradation of maximum power of a stack at which to replace the stack.
- Fuel cell replacement schedule: Schedule to input replacements

2.2.6 Fuel Cell Efficiency

The fuel cell efficiency curve describes the electrical and heat-recovery efficiency at different output percentages, which allows the calculation of fuel consumption and heat generation. Several definitions can be assumed for the power percent, or load of the fuel cell. Thus, SAM allows selecting how this quantity is defined:



% Power	Electrical Efficiency LHV (%)	Max Heat Recovery (%)
0	3	50
16.1	21	50
25.5	25.2	50
34.8	31.5	50
44.1	37.3	50
53.4	42.6	50
62.7	47.4	49
72	49.9	48
81.4	52	47
90.7	51.8	46
100	50.7	45

Figure 6: Fuel cell efficiency

Power percentage definition

- As function of original nameplate – At each time step, the fuel cell power percentage will be calculated relative to the original nameplate power.
- As a function of degraded max power – At each time step, the fuel cell power percentage will be calculated relative to the degraded max power.

Columns

- % Power: Power output percentage of the fuel cell
- Electrical Efficiency LHV (%): The electrical efficiency of the stack at the given % power
- Max Heat Recovery (%): The maximum heat recovery percent at a given % power output. For example, if the power output at a given percent is 100 kW, and the heat recovery is 50%, then 50 kWt of heat can be recovered.

2.2.7 Fuel Properties

This section allows the specification of fuel properties, which are primarily used to calculate fuel consumption and heat recovery.

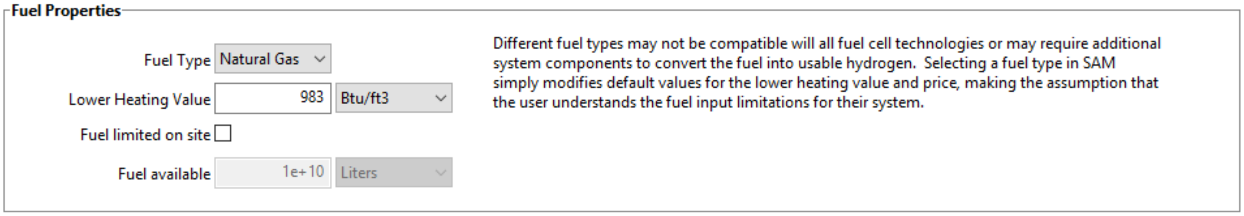


Figure 7: Fuel cell fuel properties

- Fuel Type: Selecting a fuel type will populate a default for the heating value
- Lower Heating Value: The lower heating value of the fuel
- Fuel limited on site: Indicate whether the fuel on site is limited
- Fuel Available: If the site is fuel limited, indicate the amount of fuel on site

2.2.8 Fuel Cell System Operation

To specify how the fuel cell is operated, several options are available.

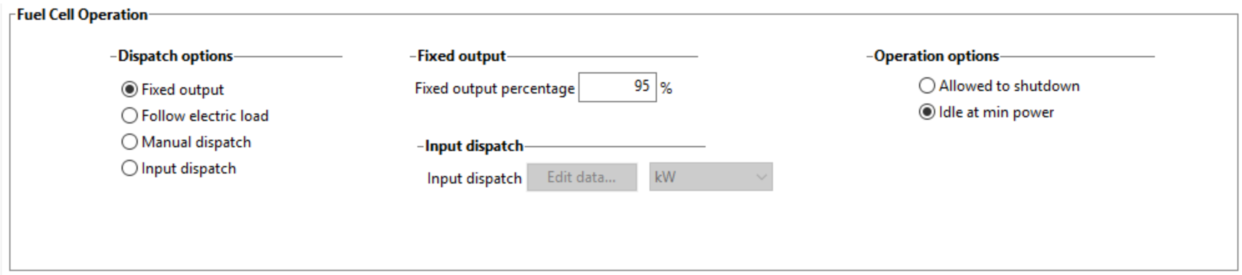


Figure 8: Fuel cell operation

Dispatch options

- Fixed output: Run the fuel cell at a fixed percentage
- Follow electric load: The fuel cell will ramp up or down to try and meet the electric load
- Manual dispatch: Manually specify how the fuel cell operates
- Input dispatch: Input a output power signal for the controller to follow

Fixed output

- Fixed output percentage: If running at fixed output, specify the output percentage

Input dispatch

- Input dispatch: If using this dispatch option, input the power signal of the fuel cell to follow

Operation options

- Allowed to shutdown: Select if you want to allow the fuel cell to shut down when not needed

- Idle at min power: Select if you want the fuel cell to idle at min power when not needed

2.2.9 Fuel cell system costs

On the **System Costs** page, the user can specify direct and indirect capital costs for the PV, Battery, and Fuel Cell system, and Operation and Maintenance Costs.

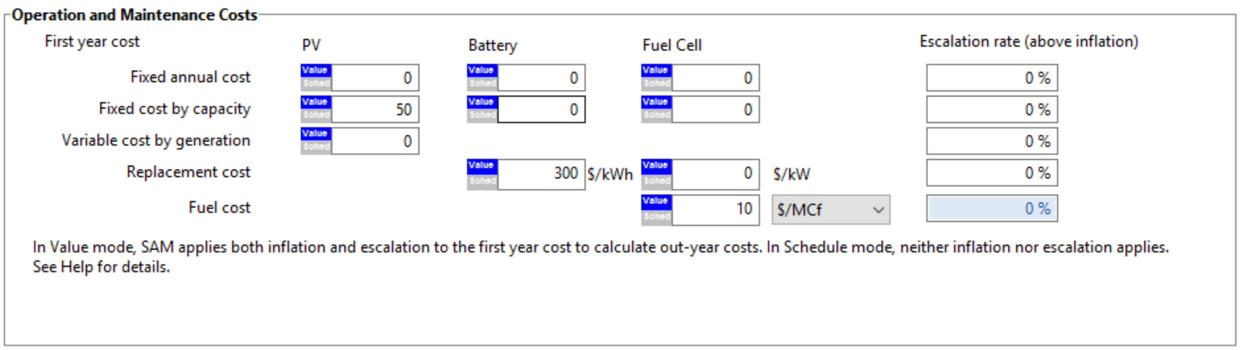


Figure 9: Operation and maintenance costs inputs

2.2.10 Thermal rates

The thermal rates page contains inputs for the buy and sell rate of heat and provides the ability to set the buy rate to the fuel cost through a nominal heat conversion efficiency assumption.

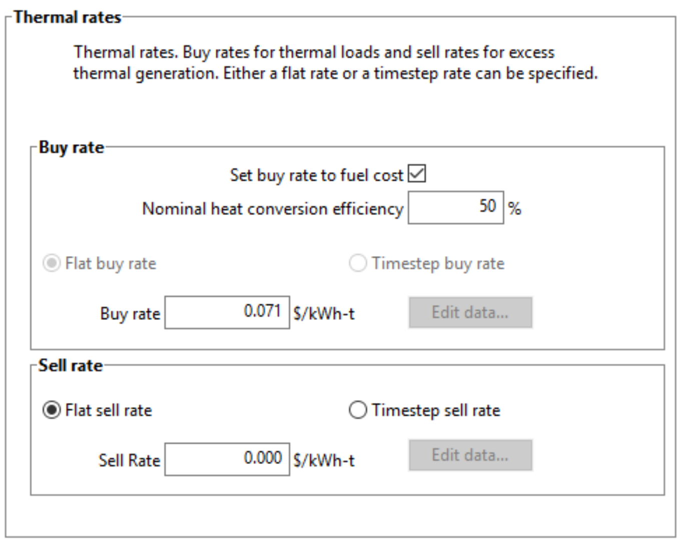


Figure 10: Thermal rates

2.2.11 Thermal load

The thermal load page contains inputs for the heating load of the site. The fuel cell will produce heat according to the heat recovery efficiency at a given output percentage. The heat produced by the fuel cell will go to offset the thermal load, thereby providing savings in the heating bill.

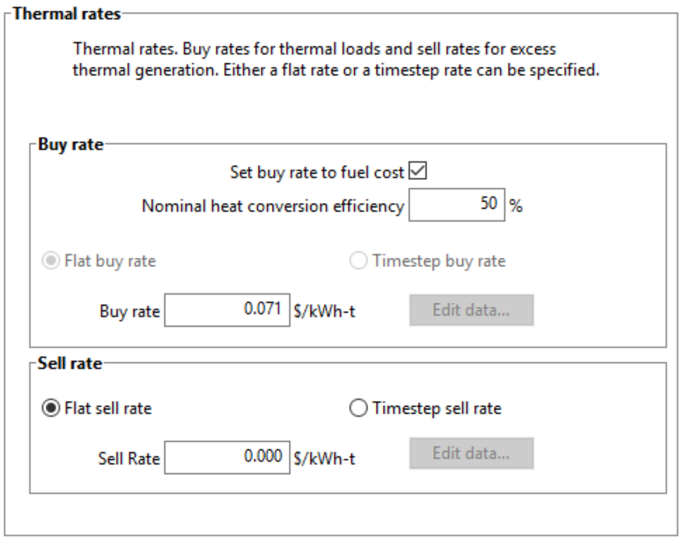


Figure 11: Thermal load

2.3 Fuel Cell Model Outputs

The fuel cell hybrid system model has several outputs which assist visualization of data. The following data variables can be visualized as time series data:

- Electricity from fuel cell (kW)
- Electricity to grid from fuel cell (kW)
- Electricity to load from fuel cell (kW)
- Fuel consumption of fuel cell (MCf)
- Heat from fuel cell (kWt)
- Thermal load (year 1) (kW-t)
- Thermal revenue with system ($)
- Thermal revenue without system ($)

The fuel cell model also introduces several line items to SAM's cash flow, including:

- Value of thermal savings ($)
- Fuel cell replacement cost ($)
- Fuel cell fixed expense ($)
- Fuel cell capacity-based expense ($)
- SyO&M fuel expense ($)

3 Summary

A generic fuel cell model was added to SAM. The model allows for deep customization of fuel cell behavior and operation, including coupling with a PV and energy storage system. The model considers both electricity and heat generated from a fuel cell and can offset electrical and thermal loads with the power produced, thus allowing for combined heat and power analysis.

4 References

[1] D. Steward, M. Penev, G. Saur, and W. Becker, "Fuel Cell Power Model Version 2: Startup Guide, System Designs, and Case Studies." National Renewable Energy Laboratory, Jun-2013.

[2] A. Dobos, "PVWatts Version 5 Manual." National Renewable Energy Laboratory, 04-Sep-2014.

[3] N. DiOrio, A. Dobos, S. Janzou, A. Nelson, and B. Lundstrom, "Technoeconomic Modeling of Battery Energy Storage in SAM." National Renewable Energy Laboratory, Sep-2015.