Behind-the-Meter Solar + Storage Modeling Tool Comparison

Kathleen Krah, NREL
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<td>Big Picture: Energy Modeling of BTM solar + storage</td>
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Introduction

Kathleen Krah

• Engineer, NREL’s Integrated Application Center – Modeling & Analysis Team
  – Focus on techno-economic modeling and optimization of distributed energy resources for cost savings, clean energy, and resiliency targets
• BS Chemical & Biomolecular Engineering, University of Notre Dame
• MEngSc Sustainable Energy Engineering, University College Cork (Ireland)
Motivation

We’ve been receiving – and asking ourselves – many questions about:

• What tools should we use for different analyses?
• What assumptions are being made by the tools we’re using, and how accurate are they to the actual system we’re modeling?
• Where do our tools fit into the suite of tools available?
• What are the most important tool development and future modeling needs?
Behind-the-meter PV + storage technoeconomic modeling tools

REopt Lite
NREL
https://reopt.nrel.gov/tool

System Advisor Model (SAM)
NREL
https://sam.nrel.gov/

HOMER Grid
HOMER Energy

Distributed Energy Resources – Customer Adoption Model (DER-CAM)
LBNL
https://building-microgrid.lbl.gov/projects/der-cam

ESyst
Geli
https://esyst.geli.net/

Storage Value Estimate Tool (StorageVET)
EPRI
https://storagevet.com/
Model Capabilities to Consider

SOLAR PV MODEL
- RESOURCE, PERFORMANCE

BATTERY MODEL
- PERFORMANCE, DEGRADATION, REPLACEMENT

UTILITIES
- RATES, NET METERING, COST ESCALATION, GRID SERVICES

LOADS
- SIMULATION, CUSTOMIZATION, LOAD GROWTH

ECONOMICS
- COSTS, OWNERSHIP, INCENTIVES, DEPRECIATION, TAX

RESILIENCY
- OUTAGES, CRITICAL LOADS, BACKUP GENERATORS

OPTIMIZATION / SIMULATION
- SIZING, DISPATCH, FORECASTING, TIME RESOLUTION

USER INTERFACE
- INPUTS, OUTPUTS, USABILITY, COMPLEXITY

OTHER
- EMISSIONS, POWER FLOW, SINGLE/MULTI-NODAL, SENSITIVITY STUDIES, OTHER TECHNOLOGIES
Model Capabilities to Consider

**SOLAR PV MODEL**
- Resource, Performance

**BATTERY MODEL**
- Performance, Degradation, Replacement

**UTILITIES**
- Rates, Net Metering, Cost Escalation, Grid Services

**LOADS**
- Simulation, Customization, Load Growth

**ECONOMICS**
- Costs, Ownership, Incentives, Depreciation, Tax

**RESILIENCY**
- Outages, Critical Loads, Backup Generators

**OPTIMIZATION / SIMULATION**
- Sizing, Dispatch, Forecasting, Time Resolution

**USER INTERFACE**
- Inputs, Outputs, Usability, Complexity

**OTHER**
- Emissions, Power Flow, Single/Multi-Nodal, Sensitivity Studies, Other Technologies
### SOLAR PV MODELS

#### Solar resource
- NSRDB tmy2/tmy3, NASA, others
- custom

#### PV performance
- PV output profile
- simple efficiency
- NREL PVWatts
- specific product lines from manufacturers
- voltage/current tracking
- temperature effects
- losses (% detailed)
- shading (% 3D model)
- degradation
- separate inverter model (DC-to-AC ratio, detailed)

#### Existing PV

<table>
<thead>
<tr>
<th>Tool</th>
<th>SOLAR PV MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td>REopt Lite</td>
<td>User enters location, tool calls PVWatts using NSRDB tmy3 data. Considers existing PV.</td>
</tr>
<tr>
<td>SAM</td>
<td>Two options: 1) detailed PV model- NSRDB or custom resource data; 3D shading model and detailed losses; tracks PV module and inverter current, voltage, temperature effects, and degradation (% annual degradation); applies actual manufacturer PV and inverter specs. 2) PVWatts model- NSRDB or custom resource data; tool calls PVWatts</td>
</tr>
<tr>
<td>HOMER Grid</td>
<td>Pulls solar resource data from NREL or NASA database; HOMER synthesizes solar radiation using V.A. Graham algorithm for daily/hourly variability applied to downloaded or user-defined monthly averages. Generation calculated using equation considering generic or specific PV cell characteristics, incident solar radiation, PV cell temp, and derating factor</td>
</tr>
<tr>
<td>DER-CAM</td>
<td>Custom solar resource data. how do they calculate PV output? Inverters modeled as piecewise linear function of power in and power out- DC to AC ratio?? Considers existing PV.</td>
</tr>
<tr>
<td>ESyst</td>
<td>User uploads PVWatts, HelioScope, or PVsyst results or generic table of generation; annual % degradation; considers time-based inverter replacement</td>
</tr>
<tr>
<td>StorageVET</td>
<td></td>
</tr>
</tbody>
</table>

1 [https://pvwatts.nrel.gov/pvwatts.php](https://pvwatts.nrel.gov/pvwatts.php)
## Battery Models

**Battery Performance**
- Simple efficiency
- Voltage/current tracking
- Temperature effects on capacity and lifetime
- Battery chemistries
- Specific battery product lines from manufacturers
- Maximum charge/discharge rates
- Strings/paralleling of batteries
- Ancillary equipment losses

**Degradation**
- Calendar degradation
- Cycling degradation
- Replacement

### Tool Comparison

<table>
<thead>
<tr>
<th>Tool</th>
<th>BATTERY MODELS</th>
</tr>
</thead>
<tbody>
<tr>
<td>REopt Lite</td>
<td>Simple roundtrip efficiency with time-based replacement</td>
</tr>
<tr>
<td>SAM</td>
<td>Two options: 1) detailed PV model- considers current and voltage measurements and constraints; temperature effects, operating point on I-V curve, maximum charge/discharge rates; different battery chemistries for voltage models and degradation; cycling and calendar degradation with option to replace based on either; applies specific manufacturer specs. 2) PVWatts model- simple roundtrip efficiency and % degradation, doesn’t track current, voltage, temperature effects, operating point, etc.</td>
</tr>
<tr>
<td>HOMER Grid</td>
<td>Three models: simple battery model, kinetic battery model, modified kinetic battery model (option to consider temperature effects on capacity and lifetime); considers voltage and maximum charge/discharge power, and batteries in strings and in parallel; user selects generic or specific batteries; cycling and calendar degradation with option to replace based on either or both</td>
</tr>
<tr>
<td>DER-CAM</td>
<td>Considers efficiency, self-discharge, temperature effects?, user-specified maximum charge/discharge power. Applies cycling degradation model for Li-ion batteries to calculate capacity. replacement? AccurateBattChargeDischarge?</td>
</tr>
<tr>
<td>ESyst</td>
<td>Simple roundtrip efficiency (user-specified or from specific battery manufacturer info); User-specified calendar degradation rate + internally calculated cycling degradation model (based on information directly from battery manufacturers); replace when effective capacity reaches 80% or in calendar-based replacement year, whichever occurs first</td>
</tr>
<tr>
<td>StorageVET</td>
<td></td>
</tr>
</tbody>
</table>
**OPTIMIZATION / SIMULATION, RESILIENCY**

### OPTIMIZATION / SIMULATION

- **Sizing**
- **Dispatch**
  - peak shaving / demand charge reduction
  - energy arbitrage
  - load control
- **Forecasting / lookahead**
- **Maximum technical potential vs expected savings**
- **Chronology and resolution of data and analysis**
- **Objective function**
  - costs (lifecycle costs, NPV, electricity costs)
  - emissions
- **Type of optimization** (MILP, grid search, simulation only)

### RESILIENCY

- **Outages** (frequency, duration, planned/unplanned)
- **Critical loads** (% of full load, custom load, prioritization of load curtailment, value of lost loads)
- **Backup generators** (fuel rates, minimum load, fuel availability)

### TOOL COMPARISON

<table>
<thead>
<tr>
<th>Tool</th>
<th>OPTIMIZATION / SIMULATION</th>
<th>RESILIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>REopt Lite</td>
<td>MILP; optimizes PV and battery storage sizes to maximize system NPV using energy arbitrage and demand charge reduction; assumes perfect forecasting for maximum technical potential; optimization performed on one year of chronological annualized data applied to project lifetime</td>
<td>✔</td>
</tr>
<tr>
<td>SAM</td>
<td>Simulation only, parametrics for pseudo-optimization; day-ahead or day-behind peak-shaving or custom dispatch strategy- currently minimizes grid purchases, but in future will consider utility rate</td>
<td>---</td>
</tr>
<tr>
<td>HOMER Grid</td>
<td>Grid search or proprietary non-derivative optimization; currently models 1 year of chronological timesteps- planned implementation of multi-year analysis in Q3 of 2018.</td>
<td>✔</td>
</tr>
<tr>
<td>DER-CAM</td>
<td>Maximize savings on the utility bill based on interval data, PV data, and utility tariff using same algorithms used in run-time controls (forecasting/optimization/dispatch). User selects between optimal (theoretical maximum) savings, estimated savings (more realistic based on Geli load forecaster and demand charge management), and conservative savings (like estimated, but with a more conservative demand charge management)</td>
<td>✔</td>
</tr>
<tr>
<td>ESyest</td>
<td></td>
<td>---</td>
</tr>
<tr>
<td>StorageVET</td>
<td></td>
<td>---</td>
</tr>
</tbody>
</table>
LOADS

- **Shape**
  - DOE commercial reference buildings
  - other generic load profiles
  - custom load input
  - outputs from UtilityAPI, Green Button, etc.

- **Magnitude**
  - scaling to monthly or annual totals

- **Load growth**

UTILITIES

- **Utility rate**
  - database (URDB, Genability)
  - custom utility rate inputs
  - energy and demand charges; TOU, tiered, real-time, seasonal, weekend/weekday/holiday etc.
  - post-solar rate study

- **Net metering**
  - net metering limit
  - export limitations
  - true net metering vs avoided cost payments
  - net metering accounting

- **Energy cost escalation rates**

ECONOMICS

- **Costs considered** (capital, O&M)
- **Ownership models** (direct purchase, 3rd party/PPA, etc.)
- **Financial parameters considered** (discount rates, inflation, cost escalation rates)
- **Incentives**
  - capital-based (%), such as federal ITC
  - capacity-based ($/kW)
  - production-based ($/kWh)
  - federal, state, utility/local
  - depreciation (straight line, MACRS, bonus MACRS)

- **Tax models**
  - income, property, sales, etc.
  - Interplay between tax and incentives

RESILIENCY

- **Outages** (frequency, duration, planned/unplanned)
- **Critical loads**
  - % of full load
  - custom load
  - prioritization of loads for curtailment
  - value of lost loads
- **Backup generators**
  - fuel rates
  - minimum load
  - fuel availability

USER EXPERIENCE

- **Access, cost**
- **User account**
- **Inputs** (user expertise and data requirements)
  - data requirements and level of detail and expertise desired for stage and emphasis of analysis
  - tradeoff between simplicity vs customizability
- **Outputs** (content and format)
  - system sizing
  - dispatch
  - maximum technical potential vs expected savings
  - proforma (interactive with formulas vs static)

OTHER

- **Other technologies**
- **Emissions modeling**
- **Power flow modeling**
- **Single or multi-nodal analyses**
- **Sensitivity study capabilities**

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2 https://www.energy.gov/eere/buildings/commercial-reference-buildings
3 https://utilityapi.com
4 http://www.greenbuttondata.org
5 https://openei.org/wiki/Utility_Rate_Database
6 https://www.genability.com
Thank you!

www.nrel.gov

kathleen.krah@nrel.gov

NREL/PR-7A40-71804
## Tool Overview

<table>
<thead>
<tr>
<th>Tool</th>
<th>REopt Lite</th>
<th>System Advisor Model (SAM)</th>
<th>HOMER Grid</th>
<th>DER-CAM</th>
<th>ESyst</th>
<th>StorageVET</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organization</strong></td>
<td>NREL</td>
<td>NREL</td>
<td>HOMER Energy</td>
<td>Desktop</td>
<td>Web</td>
<td>Web</td>
</tr>
<tr>
<td><strong>Type of application</strong></td>
<td>Web</td>
<td>Desktop; Software development kit; Open source code</td>
<td>Desktop</td>
<td>Web and desktop</td>
<td>Web</td>
<td>Web</td>
</tr>
<tr>
<td><strong>Cost/Access</strong></td>
<td>Free, Publicly available</td>
<td>Free; Open source code</td>
<td>For purchase</td>
<td>Free, Publicly available</td>
<td>Free, Publicly available</td>
<td>Free, Publicly available</td>
</tr>
<tr>
<td><strong>Optimization/Simulation</strong></td>
<td>MILP</td>
<td>Simulation; Parametric for pseudo-optimization</td>
<td>- Enhanced grid search - Proprietary derivative-free optimization</td>
<td>MILP</td>
<td>Simulation</td>
<td>Simulation</td>
</tr>
<tr>
<td><strong>Technologies</strong></td>
<td>PV, battery, diesel generator, existing PV</td>
<td>PV, high concentration PV, wind, biomass, geothermal, solar hot water, CSP, process heat</td>
<td>PV, wind, CHP, boiler, electric heater, diesel generator, battery</td>
<td>PV, solar thermal, wind, hydro, CHP, energy storage (battery, EVs, thermal), controllable loads, HVAC</td>
<td>PV, battery</td>
<td>PV, wind, battery</td>
</tr>
<tr>
<td><strong>Technology location(s)</strong></td>
<td>Behind-the-meter; Resiliency (outages)</td>
<td>Behind-the-meter</td>
<td>Behind-the-meter; Resiliency (outages)</td>
<td>Behind-the-meter; Resiliency (outages)</td>
<td>Behind-the-meter</td>
<td>Behind-the-meter, utility-scale</td>
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- **Shape**
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- **Energy cost escalation rates**

### Tool | LOADS | UTILITIES
--- | --- | ---
REopt Lite | DOE commercial reference buildings, custom, critical load | URDB database; custom rate planned for end of 2018. True net metering option up to net metering limit or annual load.
SAM | DOE commercial reference buildings, custom | URDB database, custom rates; several net metering options
HOMER Grid | DOE commercial reference buildings; generic commercial, industrial, residential, community loads; custom; critical load | Genability database for commercial North American tariffs; detailed custom tariff builder. Net metering based on rate. User can also set a kW grid sale limit.
DER-CAM | Typical weekday, weekend, and “peak day” load for each month; load database based on ASHRAE regions [DOE commercial reference buildings?](https://www.energy.gov/eere/buildings/commercial-reference-buildings) | Limited options for representative existing rates in select cities. Also custom rate input option-TOU, tiered, or hourly energy charges, coincident, non-coincident, and TOU daily and monthly demand charges.
ESyst | Custom load, incl. UtilityAPI and Green Button outputs | Genability database for commercial North American tariffs; custom rate planned for upcoming release. Net metering based on rate, with NEM and NEM2.0 for CA rates. User can select separate post-solar utility rate.
StorageVET | | |

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### ECONOMICS & RESILIENCY

#### ECONOMICS

- **Costs considered** (capital, O&M)
- **Ownership models** (direct purchase, 3rd party/PPA, etc.)
- **Financial parameters considered** (discount rates, inflation, cost escalation rates)
- **Incentives**
  - capital-based (%), such as federal ITC
  - capacity-based ($/kW)
  - production-based ($/kWh)
  - federal, state, utility/local
  - depreciation (straight line, MACRS, bonus MACRS)
- **Tax models**
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<table>
<thead>
<tr>
<th>Ownership model</th>
<th>Tax models</th>
<th>Incentives</th>
<th>Depreciation</th>
<th>Resiliency</th>
</tr>
</thead>
<tbody>
<tr>
<td>REopt Lite</td>
<td>Direct</td>
<td>One overall rate</td>
<td>PV: federal, state, utility-capital/capacity-based; total production-based. Battery: federal % capital</td>
<td>PV, storage: 5-yr, 7-yr MACRS, none</td>
</tr>
<tr>
<td>SAM</td>
<td>Direct; 3rd party/PPA; others</td>
<td>Sales,</td>
<td>Overall: federal and state ITC, PTC; federal, state, utility, other direct cash, capacity-based, and production-based incentives- user select whether taxable and whether reduces depreciation and ITC bases</td>
<td>Overall: 5-yr, 7-yr MACRS, straight line, custom</td>
</tr>
<tr>
<td>Homer Grid</td>
<td>Direct</td>
<td>Individual marginal tax rate applied to each incentive</td>
<td>PV, wind, storage: ITC; SGIP; custom capital/capacity-based and production-based; user selects portion eligible for each incentive</td>
<td>PV, wind, storage: 5-yr, 7-yr MACRS, bonus MACRS, straight line, custom, none</td>
</tr>
<tr>
<td>DER-CAM</td>
<td>Direct</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>ESys</td>
<td>Direct</td>
<td>Federal and state income tax; state and city/county sales tax; utility tax</td>
<td>PV, overall: ITC. Overall: custom direct cash, capacity-based, production-based</td>
<td>Overall: federal and state 5-yr, 7-yr MACRS, 100% bonus MACRS, straight line</td>
</tr>
<tr>
<td>StorageVET</td>
<td>Direct</td>
<td>---</td>
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</tr>
<tr>
<td>Tool</td>
<td>ACCESS</td>
<td>OUTPUTS</td>
<td>OTHER</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>REopt Lite</td>
<td>Web interface, free.</td>
<td>Interactive proforma and annual/lifecycle costs summary</td>
<td>REopt Lite is a simplified version of a highly customizable desktop model that includes other technologies, developed and used at NREL for optimization analyses</td>
<td></td>
</tr>
<tr>
<td>SAM</td>
<td>Desktop interface with software development kit and open source code, free.</td>
<td>Interactive proforma and annual/lifecycle costs summary with detailed D-VIEW plots and CSVs of hourly, monthly, annual, lifecycle data</td>
<td>Sensitivity studies, P50/P90 analyses Other technologies: high concentration PV, wind, biomass, geothermal, solar hot water, CSP, process heat</td>
<td></td>
</tr>
<tr>
<td>HOMER Grid</td>
<td>Desktop interface, paid license.</td>
<td>Interactive proforma and annual/lifecycle costs summary with detailed D-VIEW plots and CSVs of hourly, monthly, annual, lifecycle data</td>
<td>Other technologies: wind, CHP, boiler, electric heater, diesel generator HOMER Energy’s other tool, HOMER Pro, focuses on off-grid systems, while HOMER Grid focuses on behind-the-meter systems</td>
<td></td>
</tr>
<tr>
<td>DER-CAM</td>
<td>Web and desktop interfaces, free. User account saves models.</td>
<td>Outputs</td>
<td>Multi-nodal; power flow modeling; emissions modeling; sensitivity studies Other technologies: solar thermal, wind, hydro, CHP, EVs, thermal storage, controllable loads, HVAC</td>
<td></td>
</tr>
<tr>
<td>ESyst</td>
<td>Web interface, free. User account saves models and results.</td>
<td>Interactive proforma and PDF report with visuals illustrating costs/benefits</td>
<td>Geli maintains commercial relationships with system integrators and provides a path forward beyond ESyst for users looking for hardware quotes and deploying an energy storage project</td>
<td></td>
</tr>
<tr>
<td>StorageVET</td>
<td>Web interface, free. User account with saved models.</td>
<td>XXX</td>
<td>Other technologies: wind XXX</td>
<td></td>
</tr>
</tbody>
</table>