



# PV Systems Modeling and Analysis Tools



## **International Photovoltaic Reliability Workshop II** **Removing Barriers to Photovoltaic Technology Adoption:** **Reliability, Codes/Standards, and Market Acceptance**

**July 29–31, 2009 – Tempe Mission Palms Hotel, Tempe, AZ**

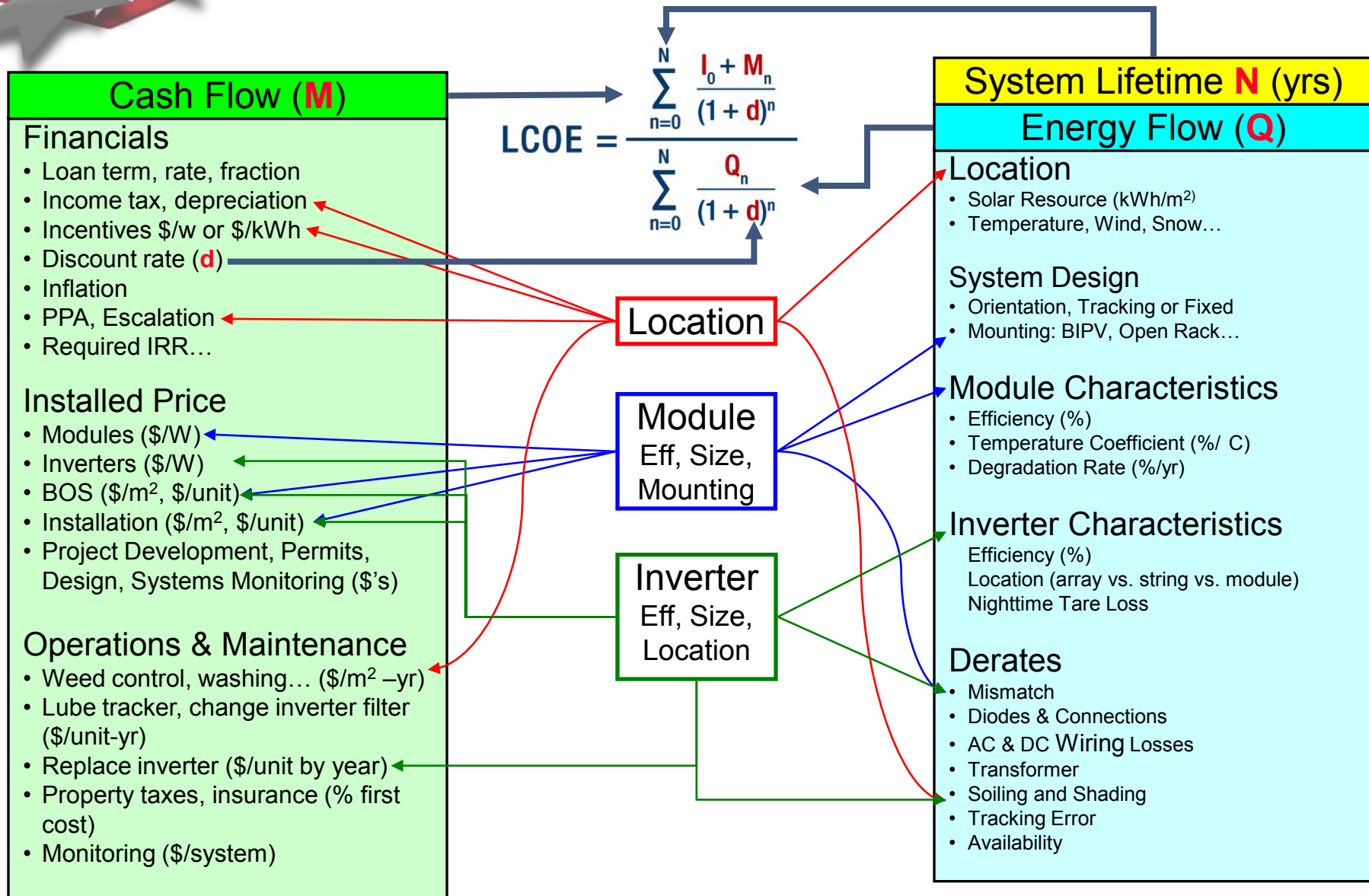
**Christopher Cameron**  
**Sandia National Laboratories**



# Outline

- **The Definition of DOE's Key Solar Program Metric: Levelized Cost Of Energy**
- **Overview of DOE's Solar Advisor Model**
- **Levelized Cost of Energy Analysis Examples**
  - LCOE is not just performance and cost
- **Current Efforts to Evaluate and Validate PV Performance Models**
  - Preliminary Results
- **Future Work**

# Levelized Cost of Energy (LCOE)



# DOE's Solar Advisor Model (SAM)

## Vision

- Combine PV, CSP, thermal solar technologies into a single model
- Make high-quality performance models developed by NREL, Sandia, and other partners available to a wider audience
- Facilitate comparison by handling performance, costs and financing consistently across technologies
- Facilitate calculating the impact of R&D on LCOE, NPV, etc. in various markets.
- Sensitivity analysis and graphing capabilities
- Over 6000 downloads
  - Download (no cost) at:  
<https://www.nrel.gov/analysis/sam>



Thanks to Nate Blair and his colleagues at NREL for developing SAM

# A Quick Tour of SAM

## Program Tab:

- Select technology
  - Photovoltaics
  - Concentrating Solar Power
  - Generic
  - To be added
    - Solar Water Heating
    - Other renewables
- Select market
  - Central Generation
  - Distributed (Buildings)

The screenshot displays the SAM software interface with the 'Program' tab selected. The 'Program' section is circled in black and contains the following settings:

- Technology: Photovoltaics
- Market: Central Generation
- Application: Electricity

The 'Environment' section includes:

- Climate: AZ Phoenix.tn2
- Utility Rates: N/A
- Financials: IPP and Utility
- Incentives: ITC
- Loads: Under Development

The 'System' section includes:

- Configuration: Flat Plate
- Array: Sys=10,001.10kWdc.In
- Module: Schott Solar ASE-300-D
- Inverter: Single Point Efficiency
- Storage: Under Development
- BOS: Under Development
- Costs: \$49,260,679.95

The 'Results' section at the bottom has buttons for 'Summary', 'Spreadsheet', and 'Time Series Graphs'. On the right side of the interface, there is a photograph of a solar farm and three configuration panels:

- Technology:**  Photovoltaics,  Concentrating Solar Power,  Solar Heating and Lighting,  Generic
- Market:**  Central Generation,  Distributed Generation,  Buildings (grid-tied),  Off Grid. Sub-options: Commercial, Residential
- Application:**  Electricity,  Hydrogen

# A Quick Tour of SAM

## Environmental Tab:

- Select climate
- Enter financial inputs
- Enter incentives

## Default values

- Included in example files
- Values specific to project should be used!

The screenshot shows the SAM software interface with the following details:

- Program:** Technology: Photovoltaics; Market: Central Generation; Application: Electricity.
- Environment (circled):** Climate: AZ Phoenix.tn2; Utility Rates: N/A; Financials: IPP and Utility; Incentives: ITC; Loads: Under Development.
- System:** Configuration: Flat Plate; Array: Sys=10,001.10kWdc,ln; Module: Schott Solar ASE-300-D; Inverter: Single Point Efficiency; Storage: Under Development; BOS: Under Development; Costs: \$49,260,679.95.
- Results:** Summary, Spreadsheet, Time Series Graphs.
- General:** Type of Financing: IPP and Utility; Analysis Period: 30 years; Inflation Rate: 2.50%; Real Discount Rate: 6.00%.
- Taxes and Insurance:** Federal Tax: 35.00%/year; State Tax: 8.00%/year; Property Tax: 0.00%/year; Sales Tax: 0.00%; Insurance: 0.50%.
- Power Purchase Agreement (PPA):** PPA Escalation Rate: 0.6%.
- Constraining Assumptions:** Minimum Required IRR: 15.00%; Minimum Required DSCR: 1.40; Positive Cashflow: checked.
- Loan:** Amount: \$19,704,272; Term: 20 years; Rate: 6.00%/year; Loan (Debt) Fraction: 40.00%.
- Weighted Average Cost of Capital:** WACC: 10.44%.
- Federal Depreciation:** MACRS Mid-Quarter Convention.
- State Depreciation:** MACRS Mid-Quarter Convention.

# A Quick Tour of SAM

## System Tab:

- Configuration
- Array characteristics
- Module and model
- Inverter and model
- Cost Data

The screenshot displays the SAM software interface for a 'Residential Flat Plate System'. The 'System' tab is active, showing various configuration options. The 'Module' field is highlighted with a blue oval, indicating the selected module model: 'Photowatt Pw1000 (95)'. Other configuration options include 'Configuration: Flat Plate', 'Array: Sys=3.81kWdc,Inv=4.0', 'Inverter: SMA America SB4000U', 'Storage: Under Development', 'BOS: Under Development', and 'Costs: \$34,214.72'. The 'Results' section at the bottom offers options for 'Summary', 'Spreadsheet', and 'Time Series Graphs'. The main window also features a large image of a house with solar panels and a 'System' configuration panel with radio buttons for 'Flat Plate' (selected), 'Concentrating', 'Rack', 'Building Integrated', 'Inverter', 'AC Modules', 'No Batteries', and 'Batteries'.

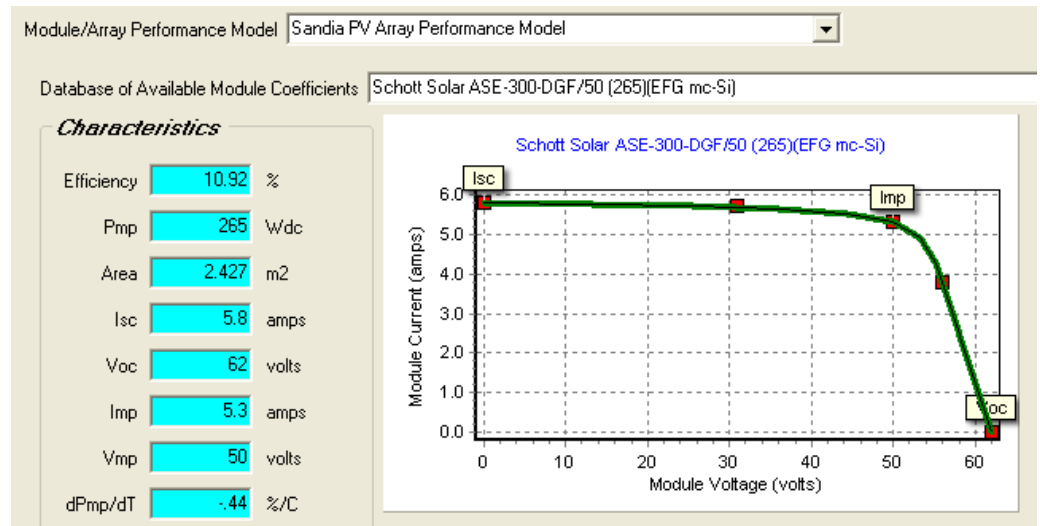
# A Quick Tour of SAM

## Select Module Model and Accompanying Database

- Sandia Array Performance Model
  - Empirical model for modules in database
    - Coefficients Derived from Outdoor Testing on 2-axis Tracker
    - Testing Technology being Transferred to TUV Rhineland PTL
  - Also used in SolarDesignPro and Internal Industry Models
- CEC/Wisc. 5-parameter model
  - Diode model
    - Built from spec. sheet or independent test data
    - Includes modules in CEC database
    - Also used for CA New Solar Homes Partnership

OR

- Enter module area, efficiency and  $P_{mp}$  temperature coefficient



# A Quick Tour of SAM

Minimum of 5 samples required

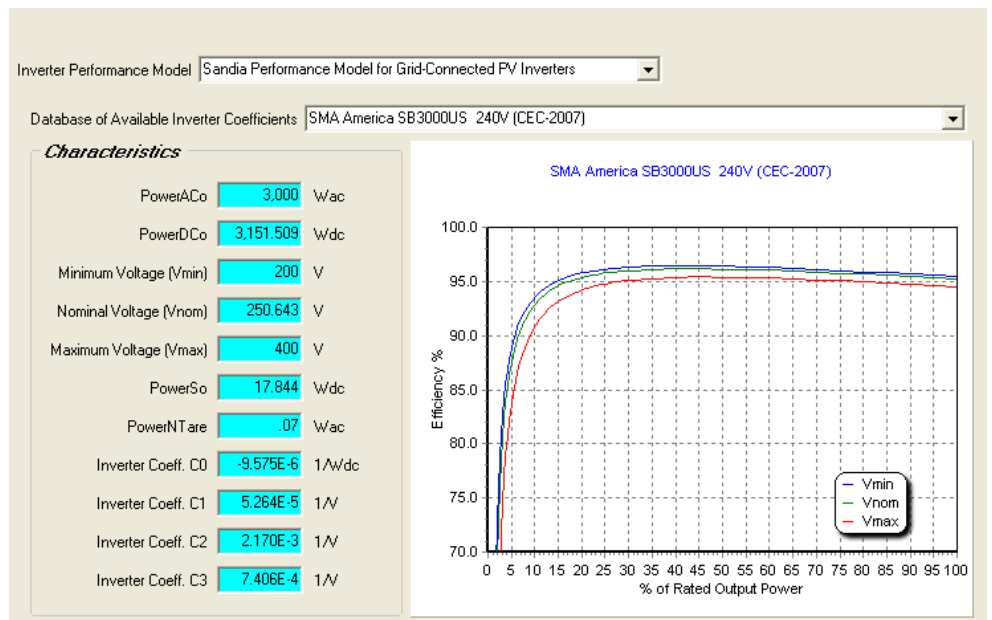
Specified		Sample #1			Sample #2			Sample #3		
Output Power	Input Voltage	Output Power	Input Voltage	Efficiency	Output Power	Input Voltage	Efficiency	Output Power	Input Voltage	Efficiency
(% of rated)	(Vdc)	(W)	(Vdc)	(%)	(W)	(Vdc)	(%)	(W)	(Vdc)	(%)
10%	Vmin	286.7	200.7	93.540	286.5	200.7	93.536	286.4	200.7	93.534
20%	Vmin	652	201	96.179	651.5	200.9	96.106	649.6	201	95.854
30%	Vmin	960.6	203	96.378	958.6	202.9	96.322	959.8	203	96.317
50%	Vmin	1364.8	201.2	96.561	1365.8	201.3	96.550	1363.6	201.2	96.497
75%	Vmin	2132	209.1	96.209	2130	208.9	96.206	2128	209	96.029
100%	Vmin	2896	210.1	96.053	2891	209.9	95.951	2887	210.2	95.691
10%	Vnom	292.4	250.6	92.649	292.2	250.6	92.556	292.1	250.5	92.525
20%	Vnom	648.9	250.6	95.849	648.3	250.6	95.775	648.3	250.6	95.775
30%	Vnom	953.9	250.6	96.033	953.8	250.6	96.023	953.7	250.6	96.013
50%	Vnom	1367.6	250.6	96.114	1366.9	250.6	96.071	1366.6	250.6	96.064
75%	Vnom	2116	250.7	95.877	2116	250.7	95.877	2115	250.7	95.831
100%	Vnom	2861	250.8	95.303	2956	250.8	95.171	2955	250.8	95.108
10%	Vmax	290.9	399.8	90.623	290.8	399.8	90.592	290.5	399.8	90.498
20%	Vmax	643.6	399.8	94.703	643.6	399.8	94.689	643	399.9	94.601
30%	Vmax	962.4	399.8	95.429	962.3	399.8	95.409	962.1	399.9	95.371
50%	Vmax	1367	399.9	95.288	1367	399.9	95.281	1366.4	399.9	95.259
75%	Vmax	2120	399.9	95.195	2119	399.9	95.193	2119	399.9	95.150
100%	Vmax	2854	399.9	94.660	2854	399.9	94.629	2854	400	94.629

## Select Inverter Model and Accompanying Database

- Sandia Inverter Model
  - Empirical model
    - Performance Data from a Nationally-Recognized Testing Laboratory
  - Data Published by California Energy Commission
  - All CEC-listed data is analyzed by Sandia and added to the SAM inverter database

OR

- Enter inverter efficiency and size
- Other inverter and system models may be added, e.g. PVWatts



# A Quick Tour of SAM

## Enter Array Parameters

- Array Layout and Orientation
- Tracking Type
- Degradation Rate
- Derate Factors
  - Often Estimated
  - Need to Understand and Document Derate Factors in Installed Systems

**Layout**

Modules per String	<input type="text" value="9"/>
Strings in Parallel	<input type="text" value="3150"/>
Total Modules	<input type="text" value="28,350"/>
Total Array Area	<input type="text" value="68,805.45"/> m <sup>2</sup>
Array Power	<input type="text" value="7,512.75"/> kWdc
Voc (string)	<input type="text" value="558"/> V
Vmp (string)	<input type="text" value="450"/> V
Vnom (dc-inverter)	<input type="text" value="368.592"/> V
Inverters	<input type="text" value="35"/>
Total Inverter Capacity	<input type="text" value="7,955.5"/> kW

**Tracking**

Fixed  
 1-axis  
 2-axis

**Orientation**

Tilt <sup>1</sup>	<input type="text" value="0"/> °
Azimuth <sup>2</sup>	<input type="text" value="0"/> °
Ground Reflectance	<input type="text" value="0.2"/>
Ground Refl. with Snow	<input type="text" value="0.6"/>

Note 1: 0° = horizontal, 90° = vertical  
Note 2: 0° = south, 90° = west, -90° = east

**Degradation**

System Degradation  %/year (compounded)

**Shading Factor for Direct Radiation**

On  Off

**Derate**

Detailed  Simple

PV module nameplate DC rating	<input type="text" value="100"/> %
Mismatch	<input type="text" value="98"/> %
Diodes and connections	<input type="text" value="99.5"/> %
DC wiring	<input type="text" value="98"/> %
Soiling	<input type="text" value="95"/> %
Sun-tracking	<input type="text" value="100"/> %
Total pre-inverter derate factor	<input type="text" value="90.78"/> % <input type="text" value="100"/> %
AC wiring	<input type="text" value="99"/> %
Transformer	<input type="text" value="98"/> %
System availability	<input type="text" value="98"/> %
Total post-inverter derate factor	<input type="text" value="95.08"/> % <input type="text" value="84"/> %
Total derate factor	<input type="text" value="86.31"/> % <input type="text" value="84"/> %

Note: Inverter efficiency handled on inverter page.

# A Quick Tour of SAM

## Cost Tab:

- Enter component, BOS, and installation costs
- Enter indirect costs
- Enter O&M costs
- An Excel-based systems cost model that can be linked to SAM is being developed by Navigant Consulting, Inc.
- This example includes
  - O&M Schedule, e.g. for inverter replacement
  - Parametric analysis of other O&M costs

0\SAM\Backup\Standard PV Systems\_backup.sam

at Plate System **Utility Flat Plate System - IPP** Utility Concentrating System

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*Capital Costs*

*Direct*

Module	37,740 units	265 W/unit	10,001.1 kWdc	\$3.33	\$/Wdc	\$33,303,663
Inverter	44 units	227,300 W/unit	10,001.2 kWac	\$51	\$/Wac	\$5,100,612
Storage						\$0
BOS						\$5,535,320
Installation						\$0
Contingency				1 %		\$439,396
<b>Total Direct Costs</b>						<b>\$44,378,991</b>

*Indirect*

Engineer, Procure, Construct	7 % of Direct Costs	\$3,106,529
Project, Land, Miscellaneous	4 % of Direct Costs	\$1,775,160
Sales Taxes 0 % applies to	100 % of Direct Costs	\$0
<b>Total Indirect Costs</b>		<b>\$4,881,689</b>

*Total Installed*

<b>Total Installed Costs</b>	<b>\$49,260,680</b>
<b>Total Installed Costs per Capacity (\$/Wdc)</b>	<b>\$4.93</b>

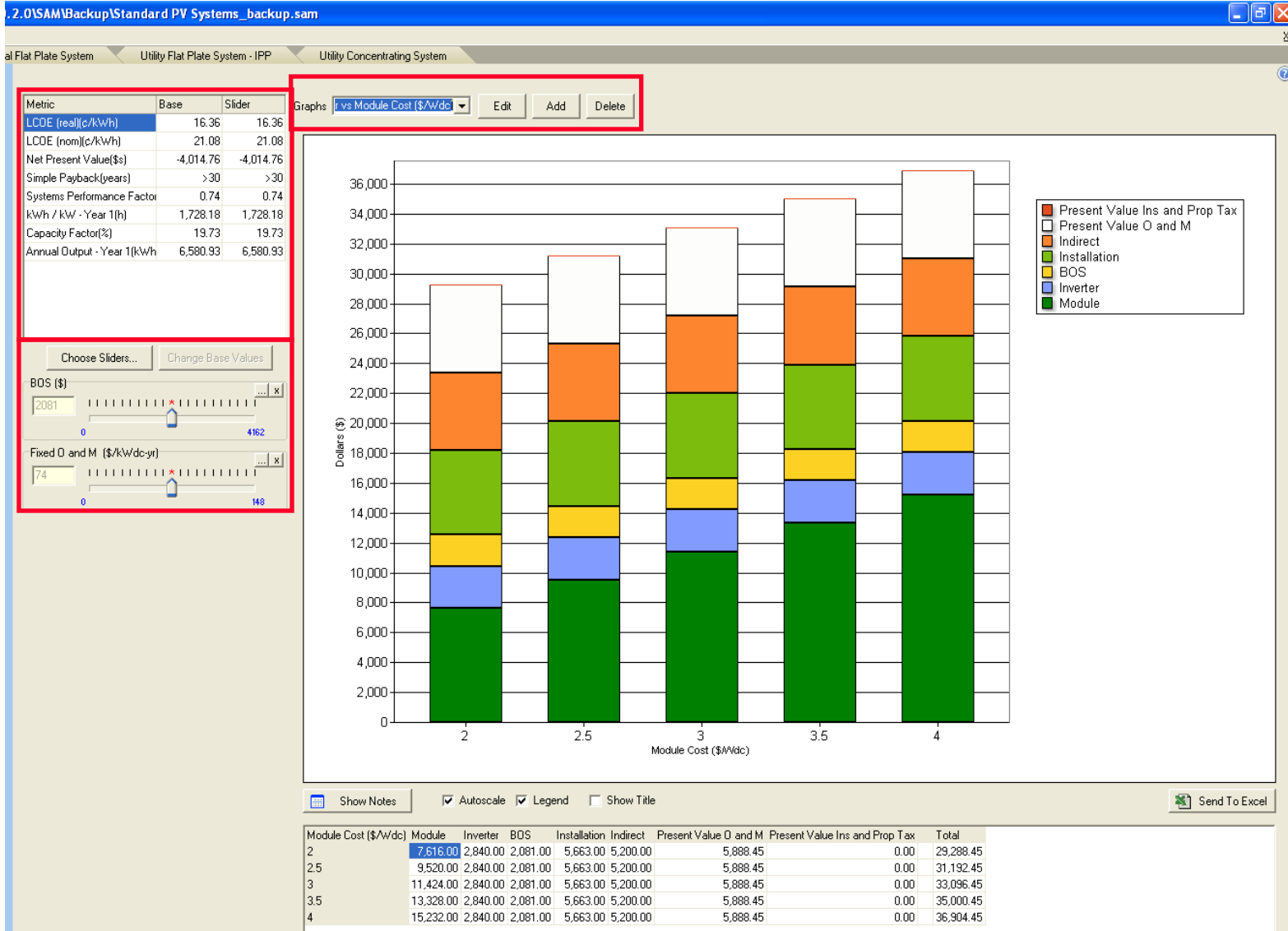
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*Operation and Maintenance Costs*

	First Year	Escalation Rate*
Fixed (per year)	0.00000000 \$/yr	0 %
Fixed (per capacity)	\$6.29 \$/kWdc-yr	0 %
Variable (per production)	\$0 \$/MWac-h	0 %

\* above inflation

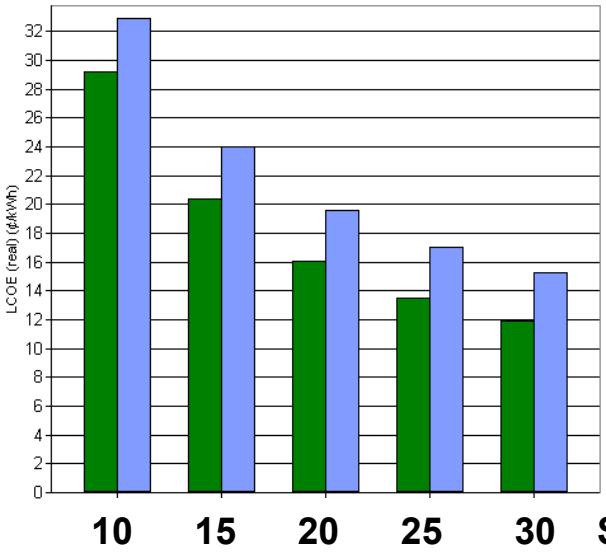
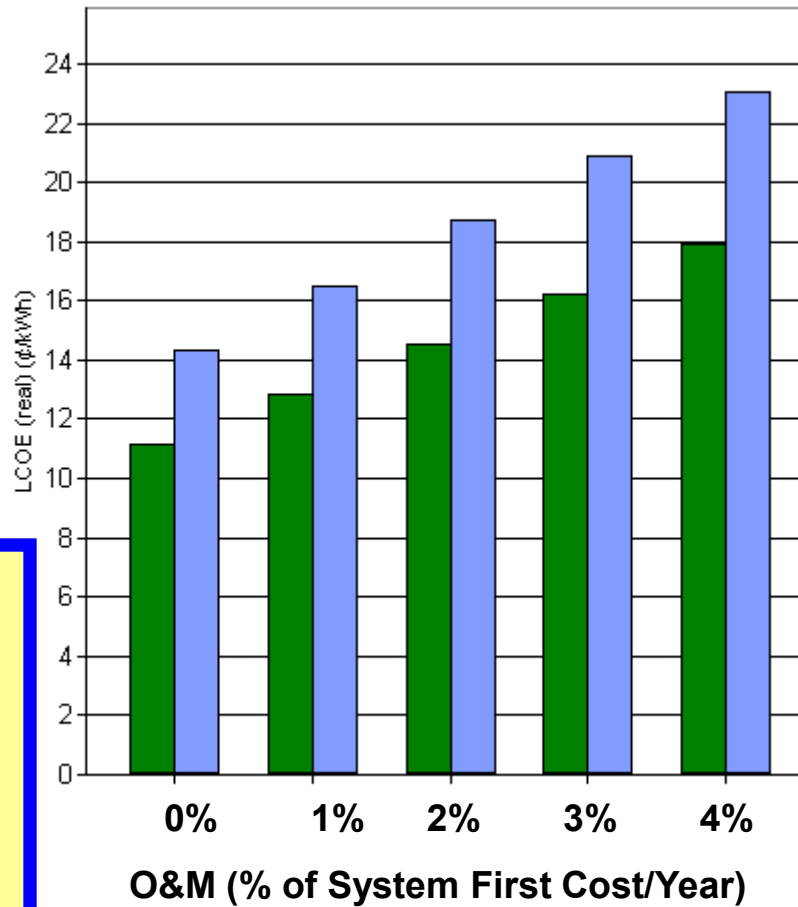
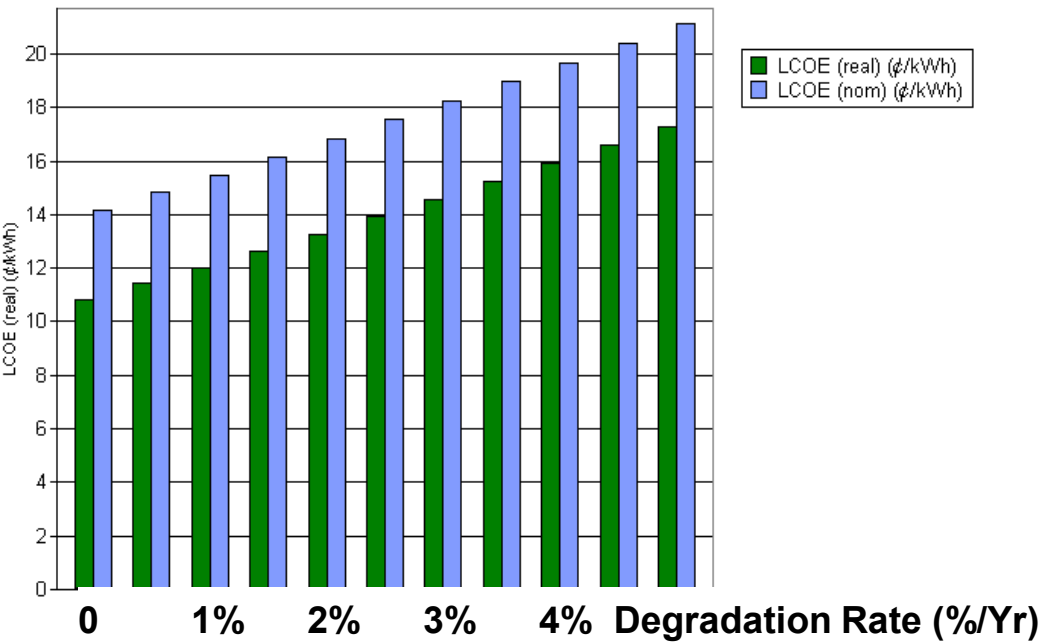
# A Quick Tour of SAM: Results Page





# Analysis Examples

## LCOE is about more than initial cost and performance



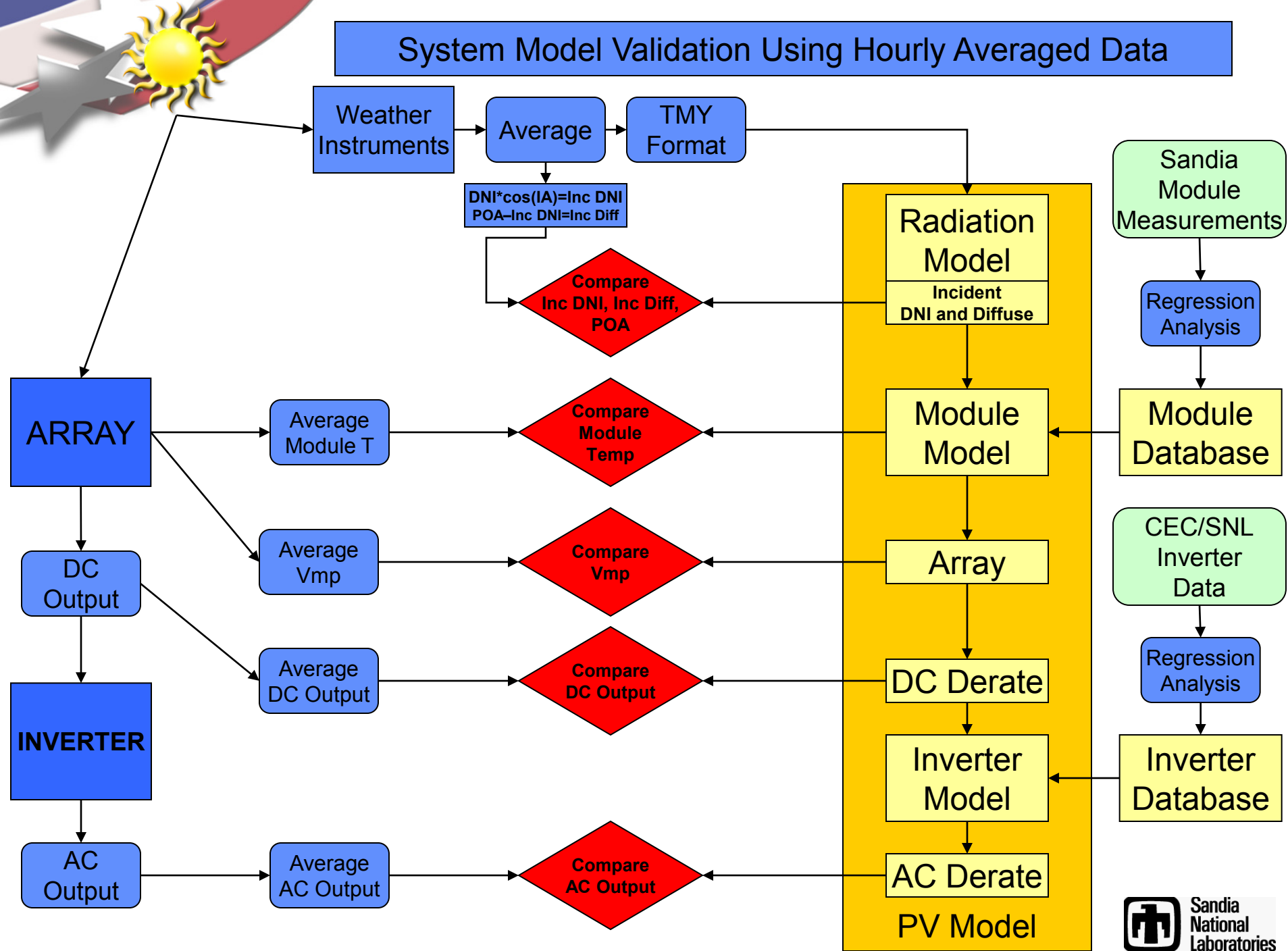
**CAUTION !**  
Financial,  
performance,  
and cost  
assumptions  
will impact  
results.



# PV Performance Model Validation

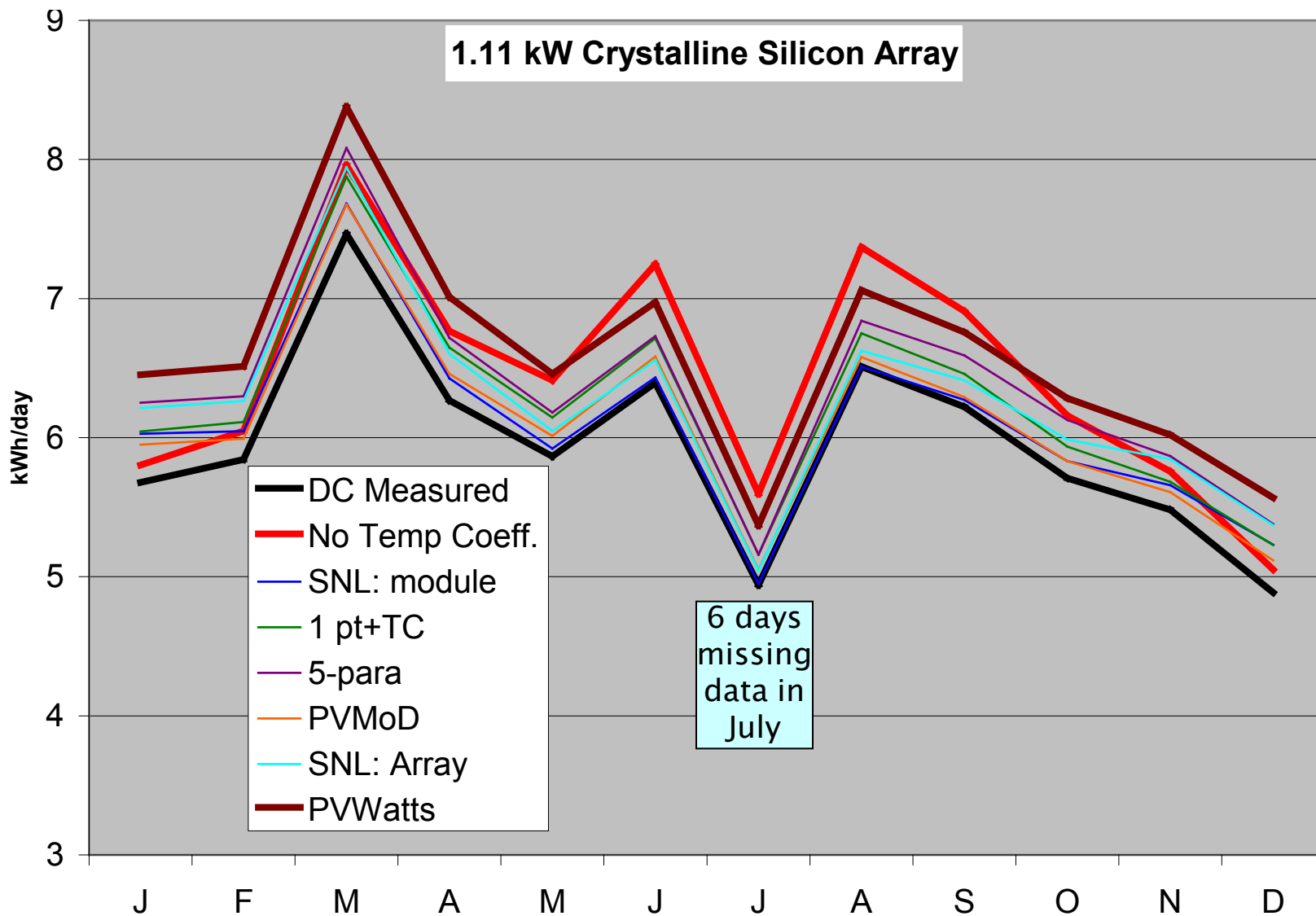
- **Two Activities Underway in Collaboration with Industry**
  - **Evaluate/Validate Models Used to Predict PV System Performance**
    - **In Choosing Between Technologies or Designs**
  - **Evaluate/Validate Models Used to Monitor System Performance**
    - **Determine When Performance is Less than Expected Given Weather and Solar Resource → O&M Needed**
    - **Also Relevant to Acceptance Testing**
- **Goal – Understand Accuracy and Uncertainty**
  - **More accurate models may require more accurate input data (components and solar resource)**

# System Model Validation Using Hourly Averaged Data



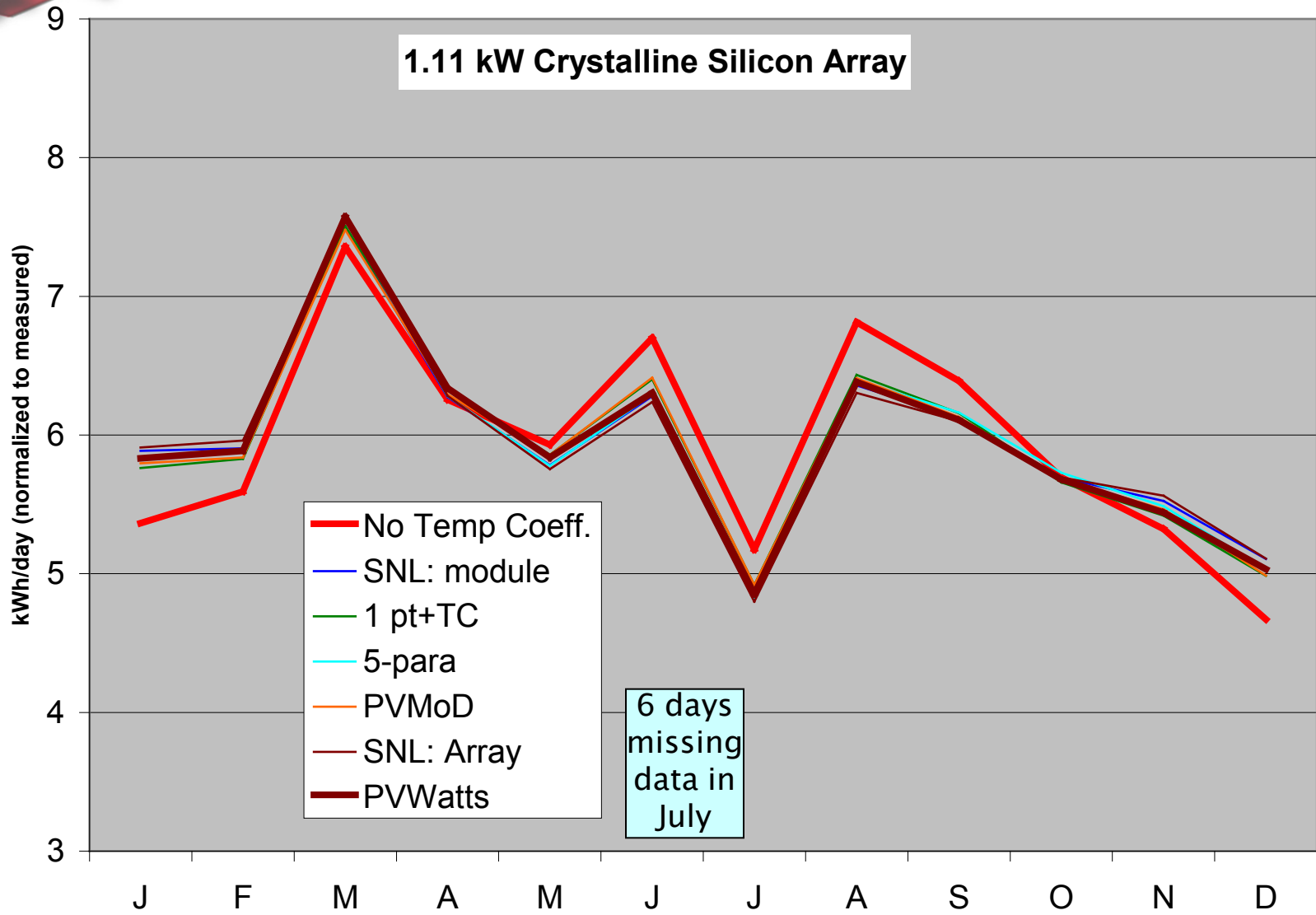
# Model Validation Results, Lat. Tilt, ABQ

## DC Output (kWh) by Month (no derate)



On-sun measured module parameters input to all modules

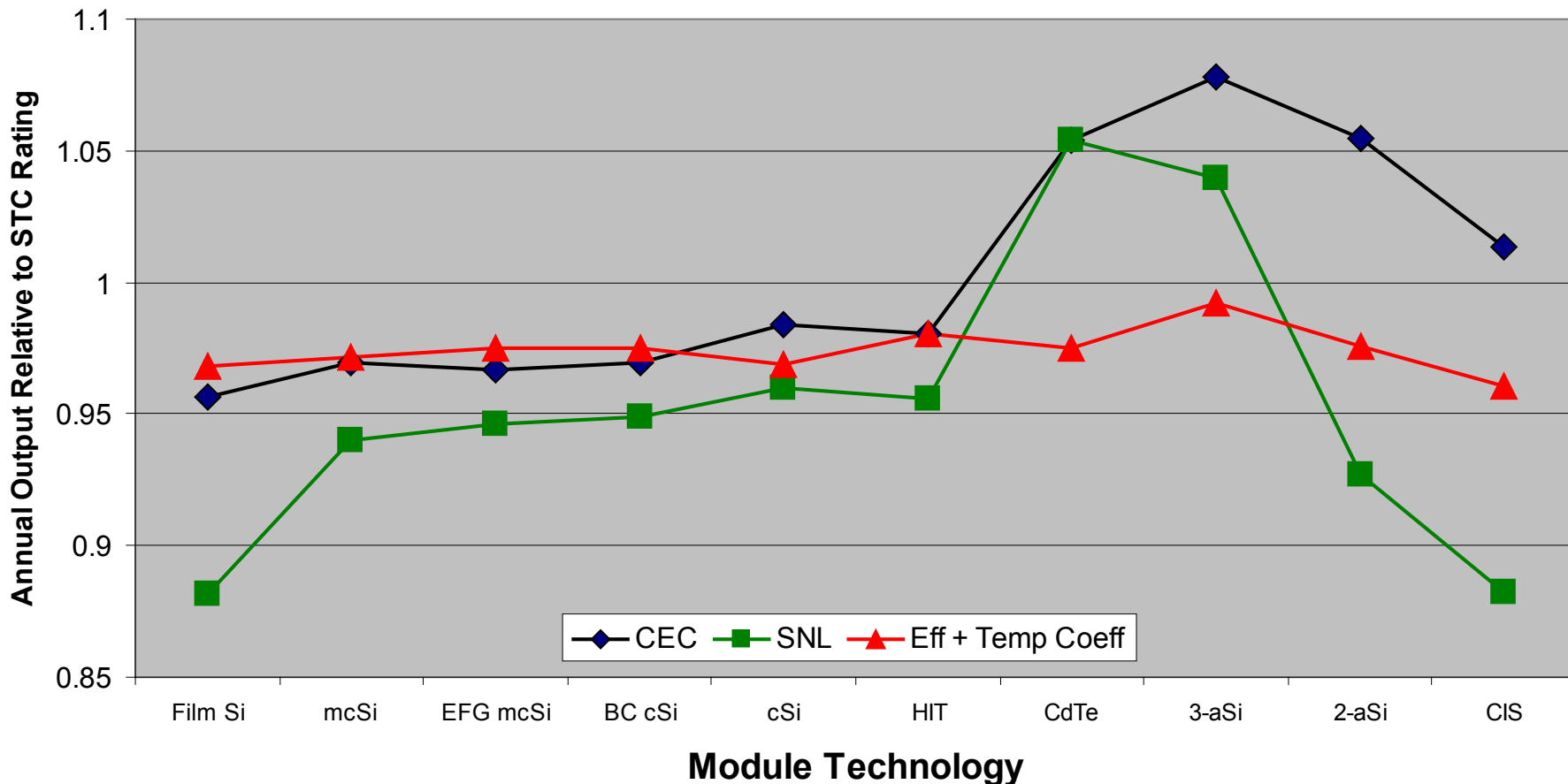
# Monthly Output Normalized to Measured Data



When derate is applied, modeled monthly output is similar, but implied derate factors vary

# Model Results Differ for Other Technologies

Module Model Comparison, Portland, OR 18 deg tilt



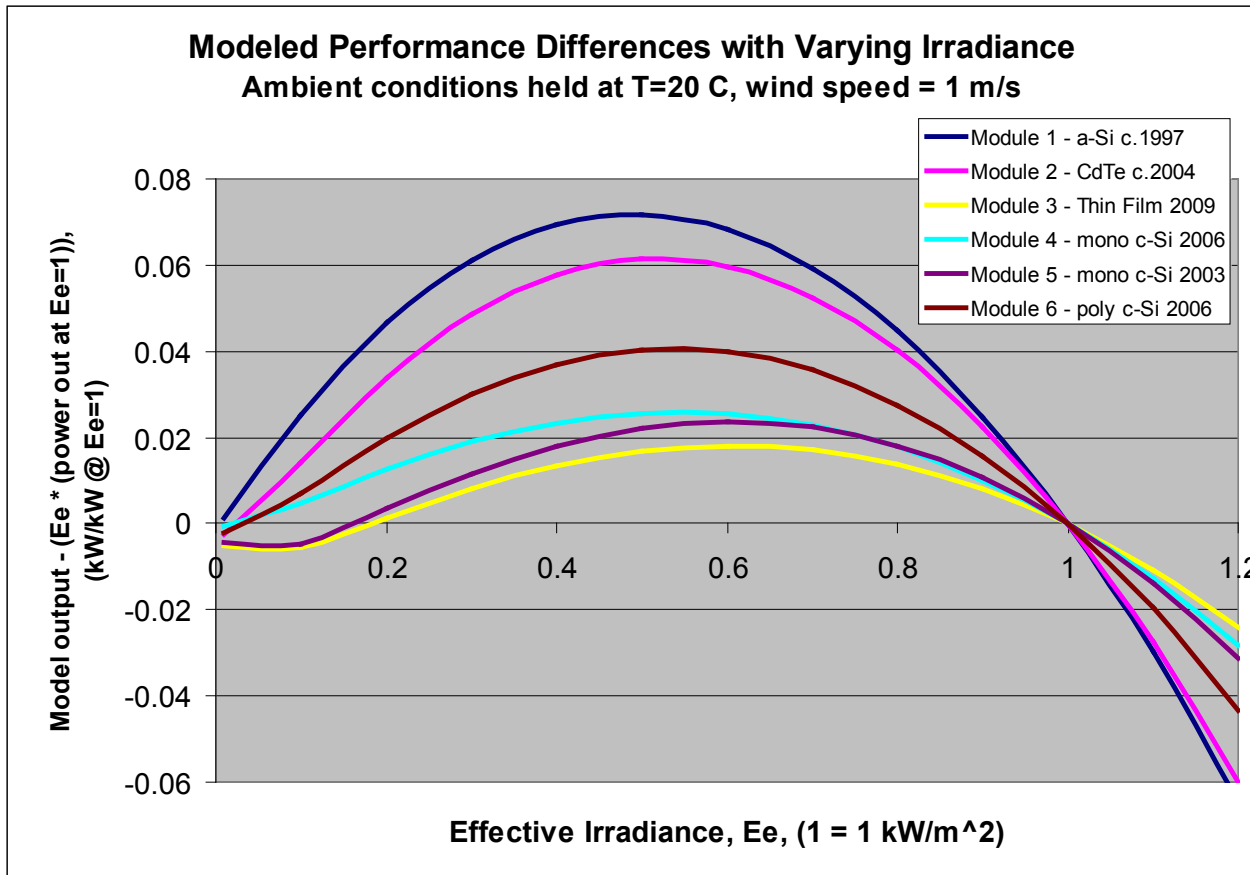
All analysis based on same physical parameters.

For illustration only - not necessarily representative of current module technology.

Missing: error bars (uncertainty analysis) and comparison with measured data

# Solar input to models is an hourly average

- Alternating clouds and bright sun is modeled as medium irradiance
- All modules have higher efficiency at medium irradiance
  - Lower cell temperature = higher efficiency
- Hourly-averaging may overemphasize impact of superior “low-light level performance”
- Hourly averaging may lead to undersizing the inverter





# Future Work

- **Continue Validation and Evaluation of Models**
  - Acquire cSi and thin-film data sets in bright and diffuse climates (Albuquerque; Golden, Co; DC; Cocoa, FL)
  - Conduct detailed evaluation vs. incident angle, solar radiation, temperature, wind speed...
  - No right answer: Requirement for accuracy may vary
- **Perform robust uncertainty analysis**
  - Incorporate stochastic analysis into models
  - Which parameters are most important?
- **Improve understanding of derate factors**
  - **Develop Web-Based Photovoltaic (PV) Database**
    - See [eere.energy.gov/solar/upcoming\\_opportunities.html](http://eere.energy.gov/solar/upcoming_opportunities.html)
- **Complete evaluation of impact of hourly averaging**
  - Can modeling be improved by synthesizing sub-hourly data from existing hourly-averaged data sets?

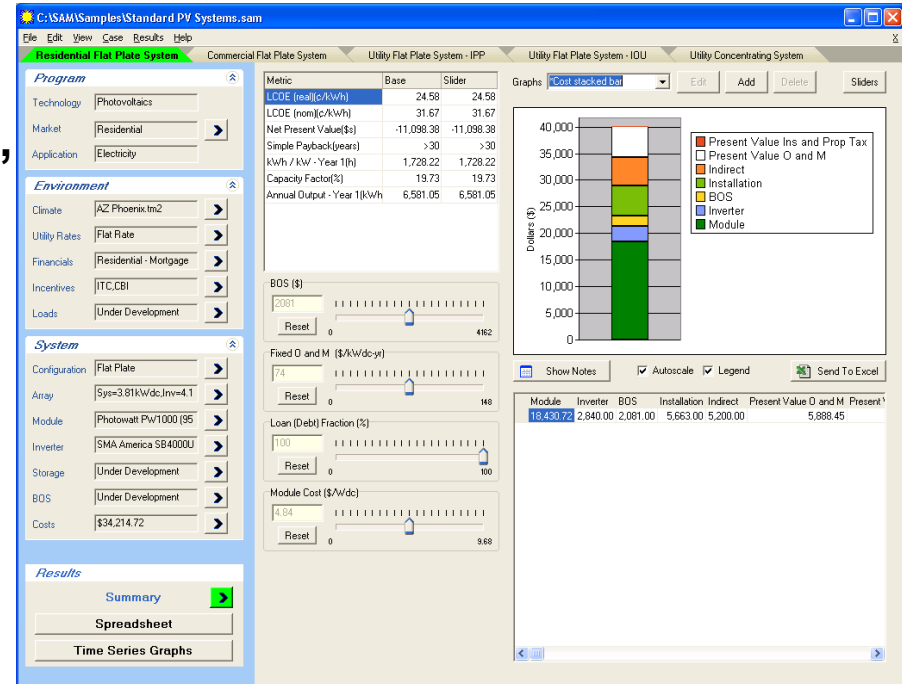


# Questions

# DOE's Solar Advisor Model (SAM)

## Vision

- Combine PV, CSP, thermal solar technologies into a single model
- Make high-quality performance models developed by NREL, Sandia, and other partners available to a wider audience
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Thanks to Nate Blair and his colleagues at NREL for developing SAM

# A Quick Tour of SAM

## Select Performance Models and Accompanying Databases

- Sandia Array Performance Model
  - Also used in SolarDesignPro
- CEC 5-parameter model
  - New Solar Homes Partnership
  - All modules in CEC database
- Sandia Inverter Model
  - All inverters in CEC database

## OR

- Enter module area, efficiency and  $P_{mp}$  temperature coefficient
- Enter inverter efficiency and size

## OR

- Use Generic Energy Input

**PV Watts to be added to SAM**

