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

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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

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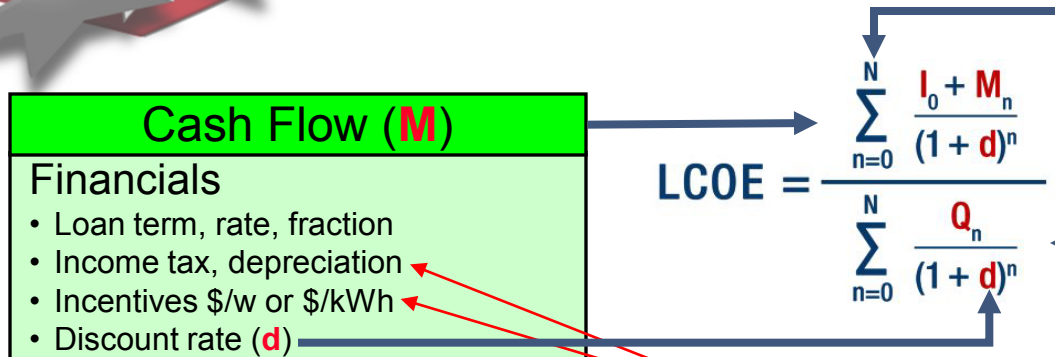
Levelized Cost of Energy (LCOE)



Cash Flow (M)

Financials
- Loan term, rate, fraction
- Income tax, depreciation
- Incentives $/w or $/kWh
- Discount rate (d)
- Inflation
- PPA, Escalation
- Required IRR…

Installed Price
- Modules ($/W)
- Inverters ($/W)
- BOS ($/m^2, $/unit)
- Installation ($/m^2, $/unit)
- Project Development, Permits, Design, Systems Monitoring ($'s)

Operations & Maintenance
- Weed control, washing… ($/m^2 –yr)
- Lube tracker, change inverter filter ($/unit-yr)
- Replace inverter ($/unit by year)
- Property taxes, insurance (% first cost)
- Monitoring ($/system)

Location

Module
Eff, Size, Mounting

Inverter
Eff, Size, Location

System Lifetime N (yrs)

Energy Flow (Q)

Location
- Solar Resource (kWh/m$^{2)}$
- Temperature, Wind, Snow…

System Design
- Orientation, Tracking or Fixed
- Mounting: BIPV, Open Rack…

Module Characteristics
- Efficiency (%)
- Temperature Coefficient (%/ C)
- Degradation Rate (%/yr)

Inverter Characteristics
Efficiency (%)
Location (array vs. string vs. module)
Nighttime Tare Loss

Derates
- Mismatch
- Diodes & Connections
- AC & DC Wiring Losses
- Transformer
- Soiling and Shading
- Tracking Error
- Availability

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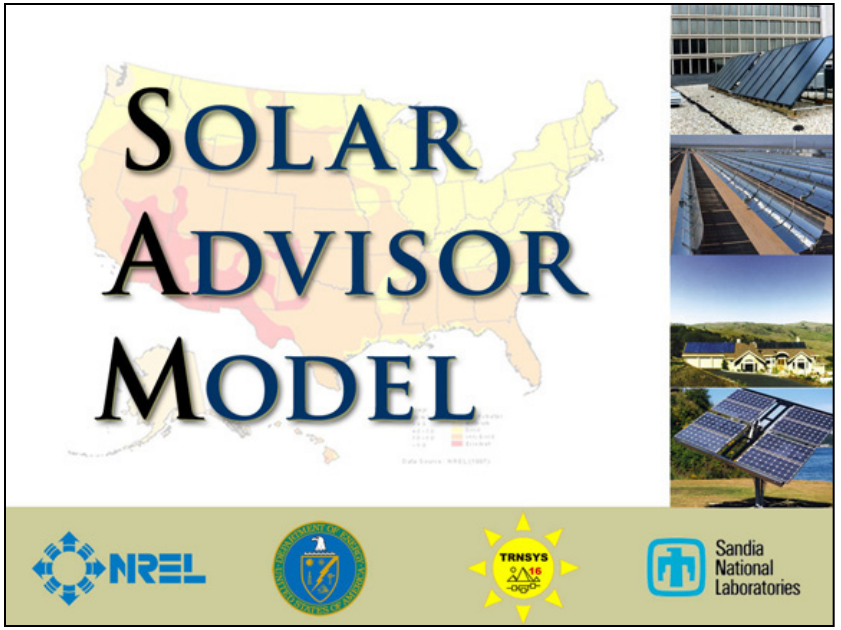
DOE's Solar Advisor Model (SAM)

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

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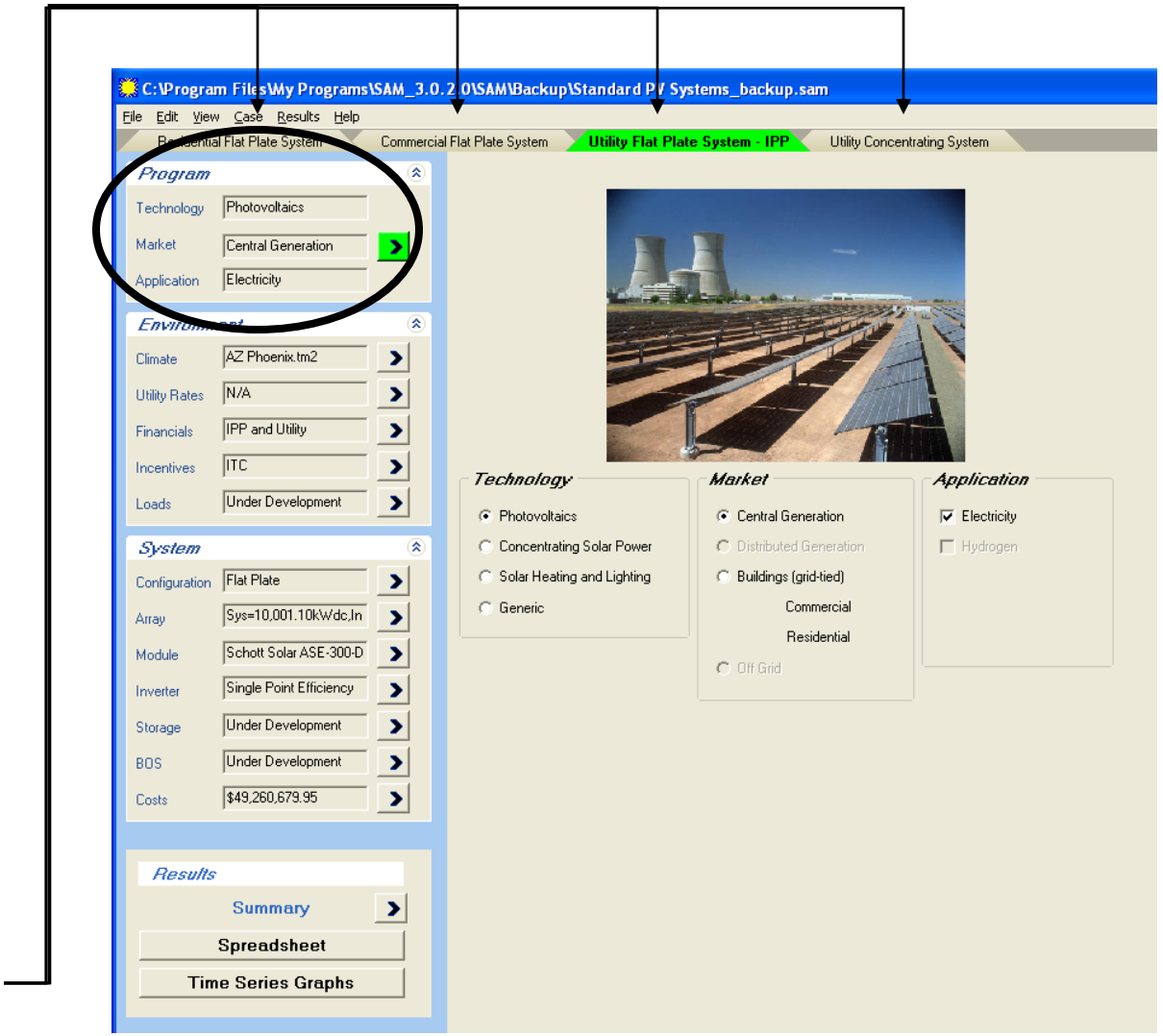
A Quick Tour of SAM

Program Tab:

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



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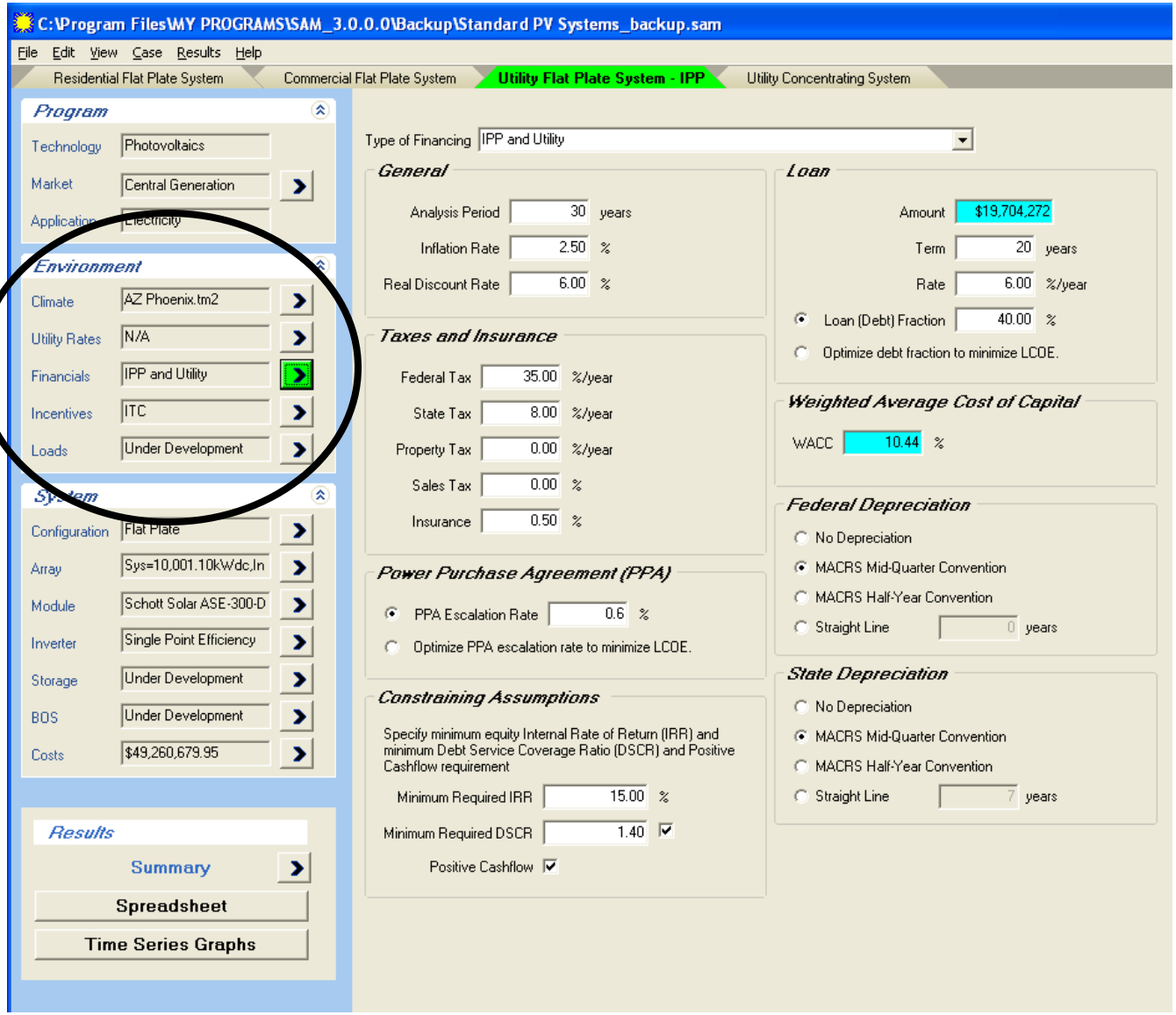
A Quick Tour of SAM

Environmental Tab:

- Select climate
- Enter financial inputs
- Enter incentives

Default values

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



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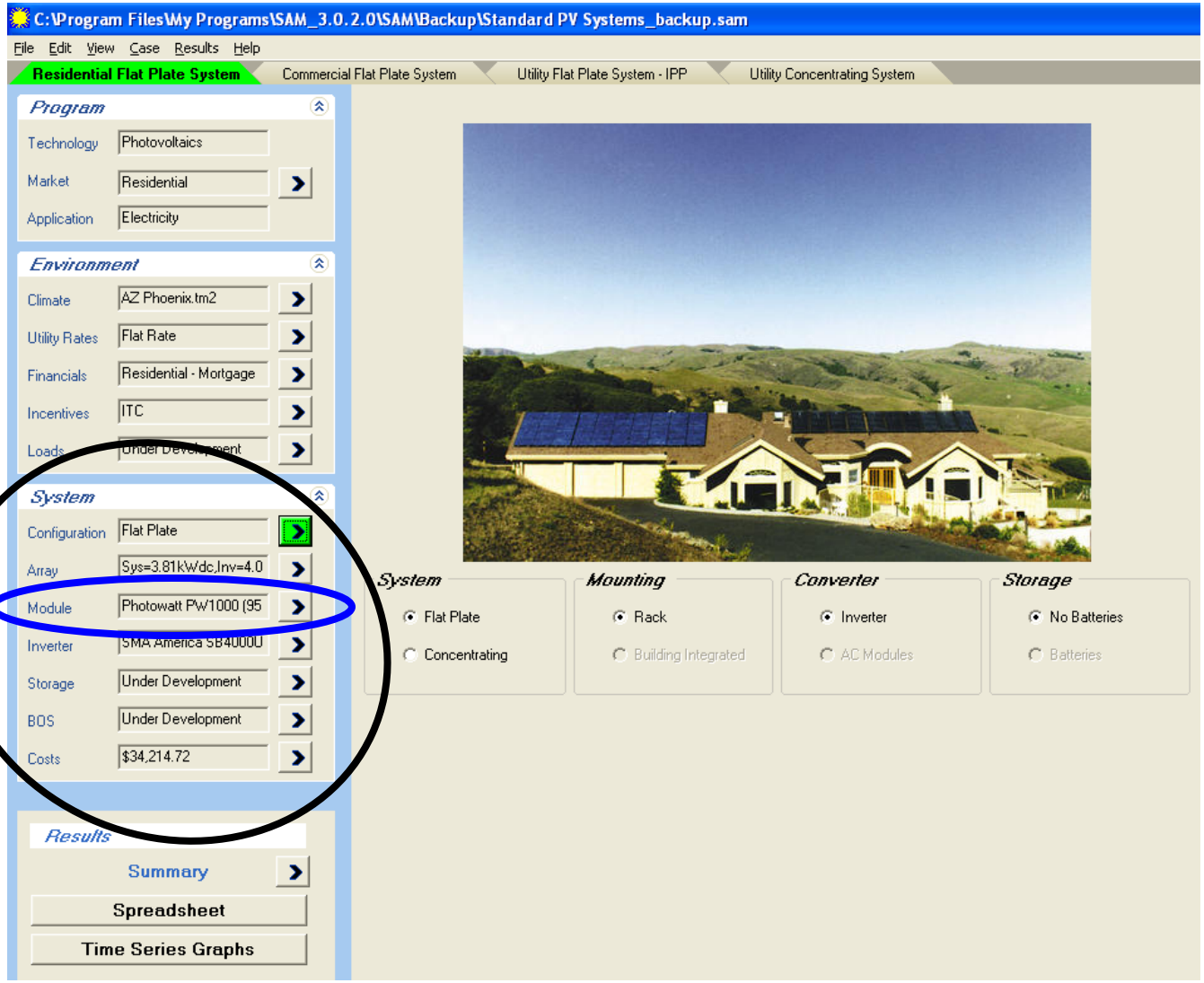
A Quick Tour of SAM

System Tab:

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



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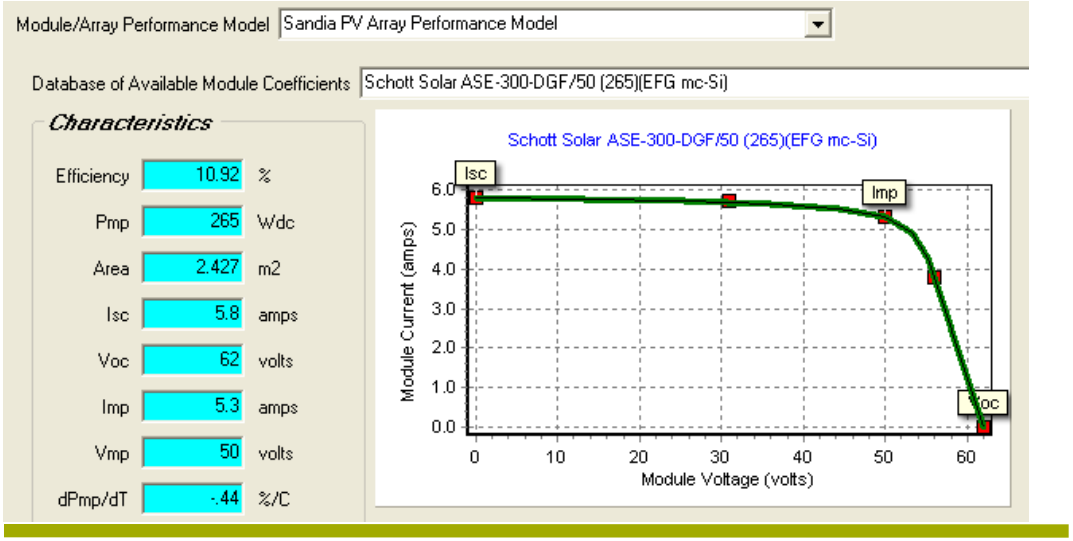
A Quick Tour of SAM

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



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A Quick Tour of SAM

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

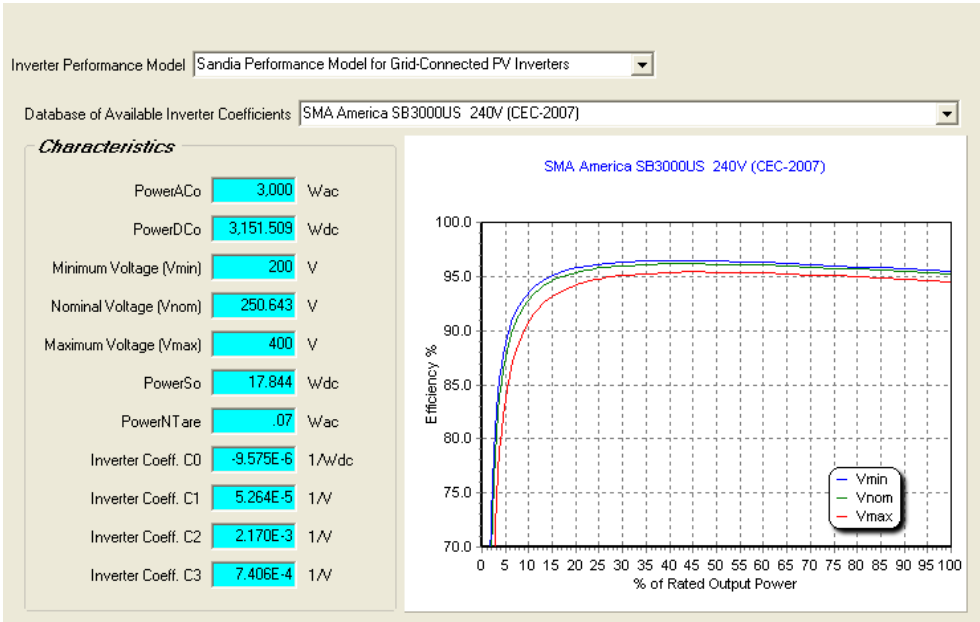
OR

- Enter inverter efficiency and size

Other inverter and system models may be added, e.g. PVWatts

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



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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

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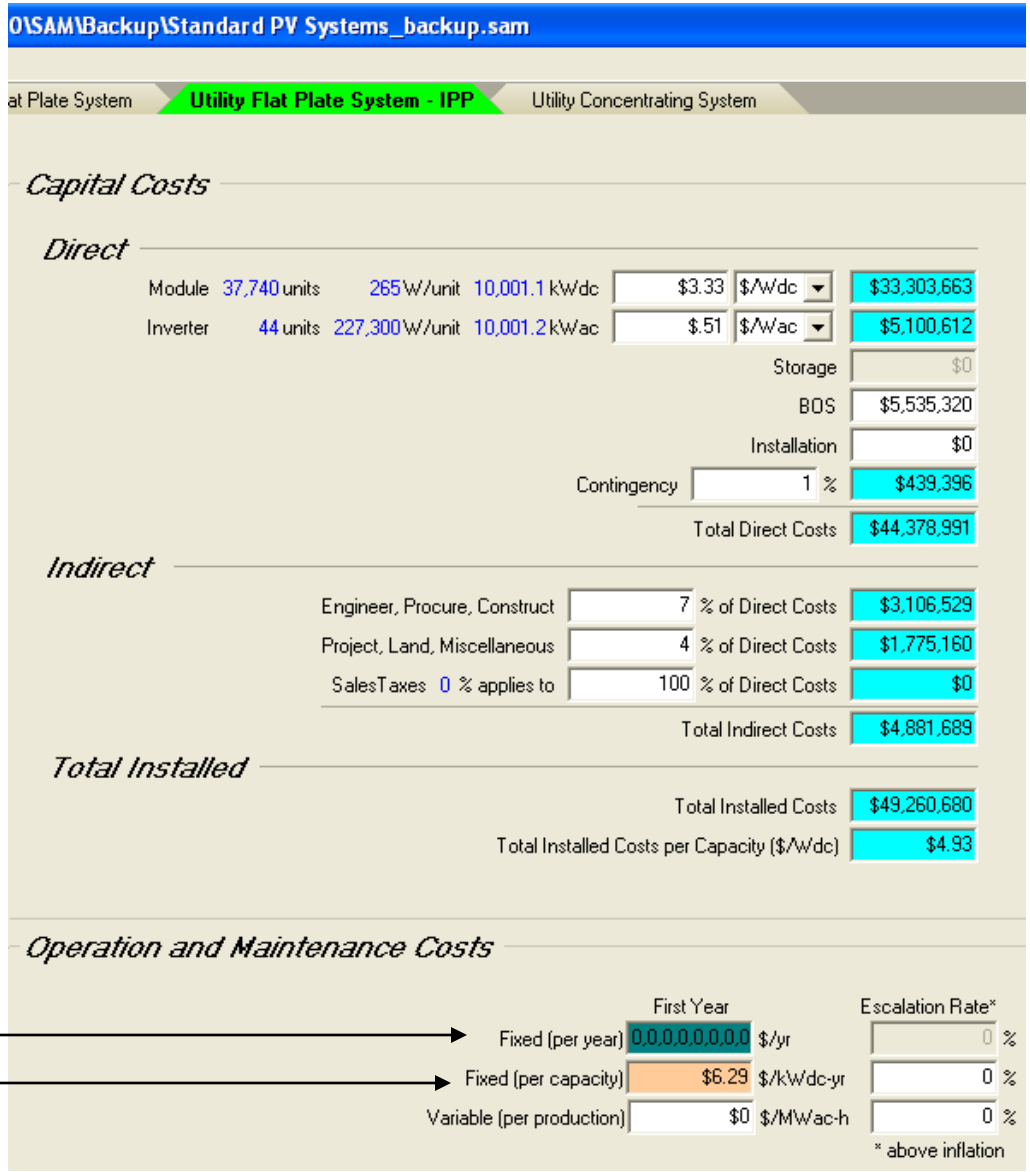
Cost Tab:

- 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



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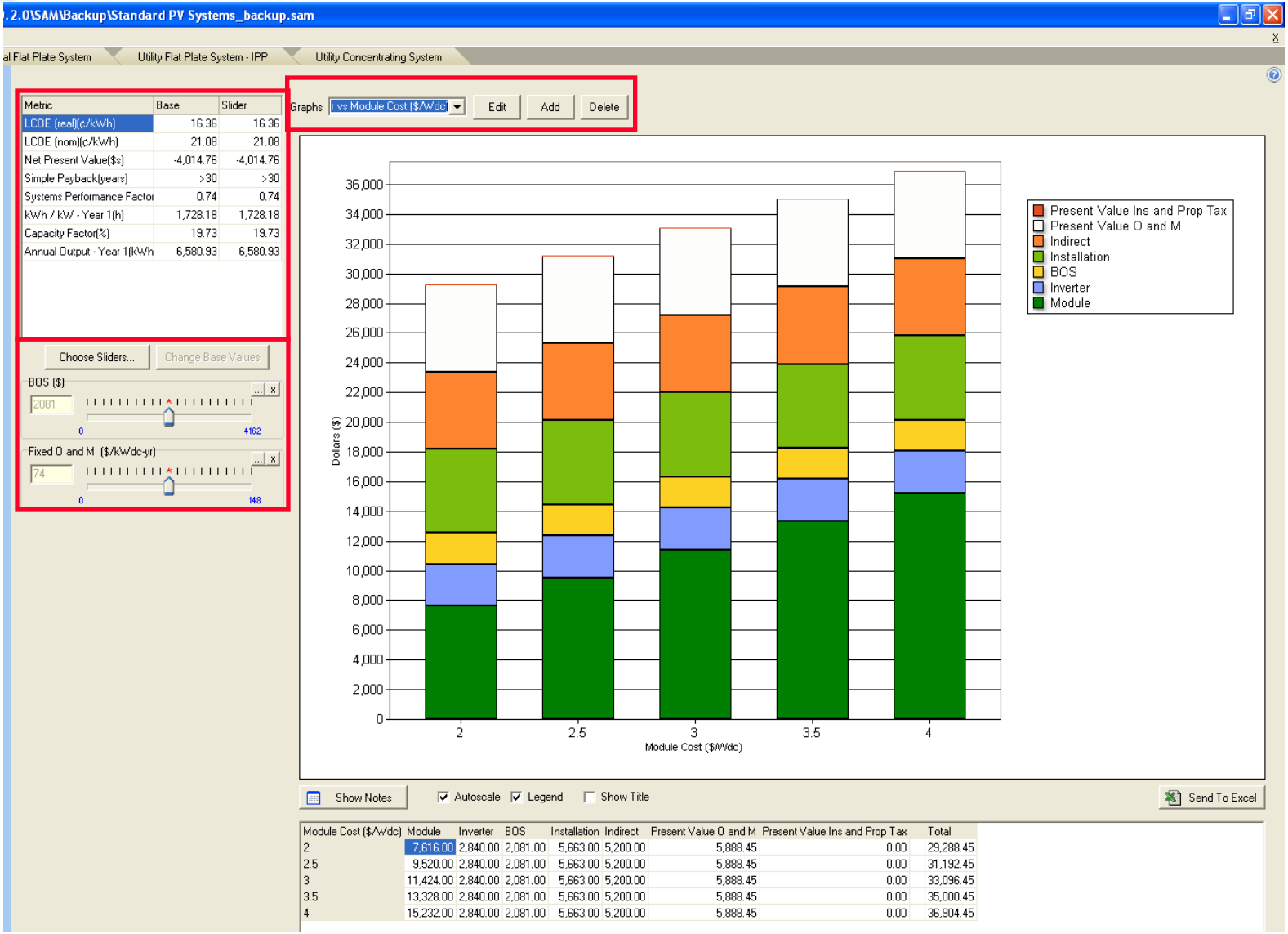
A Quick Tour of SAM: Results Page



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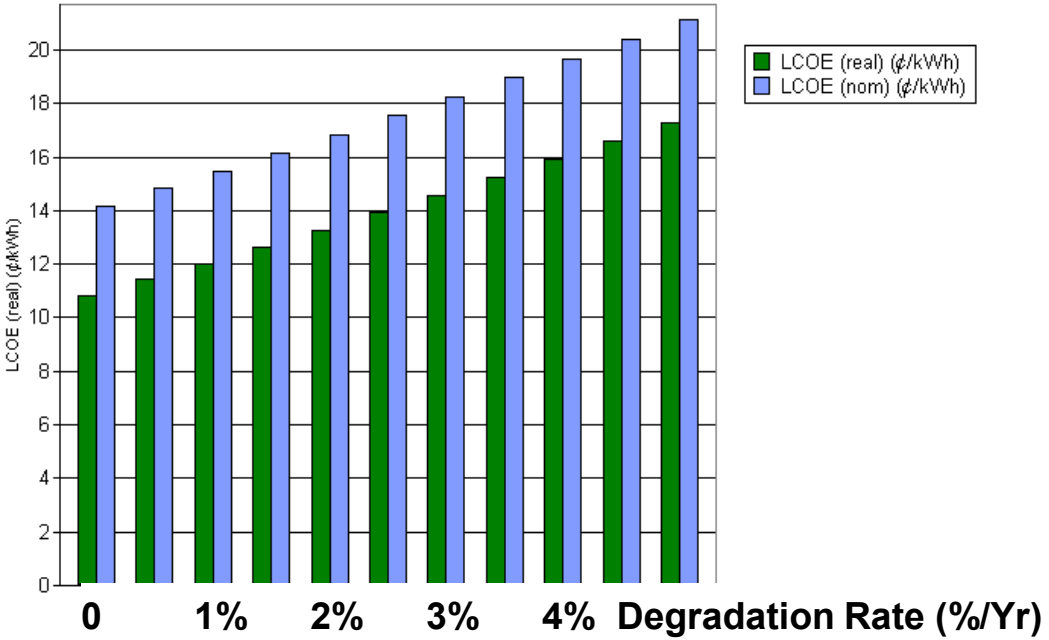
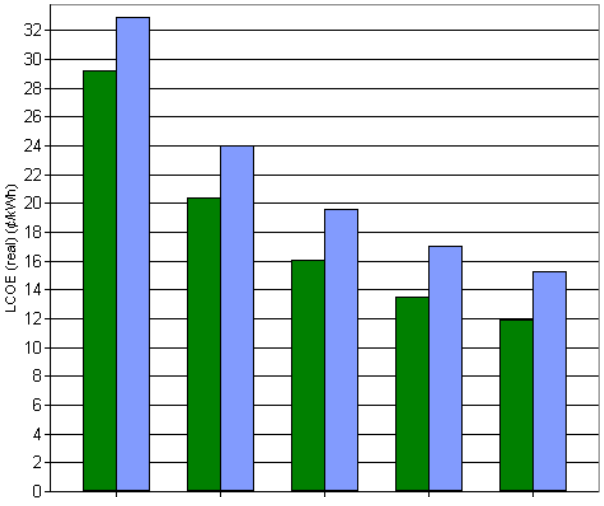
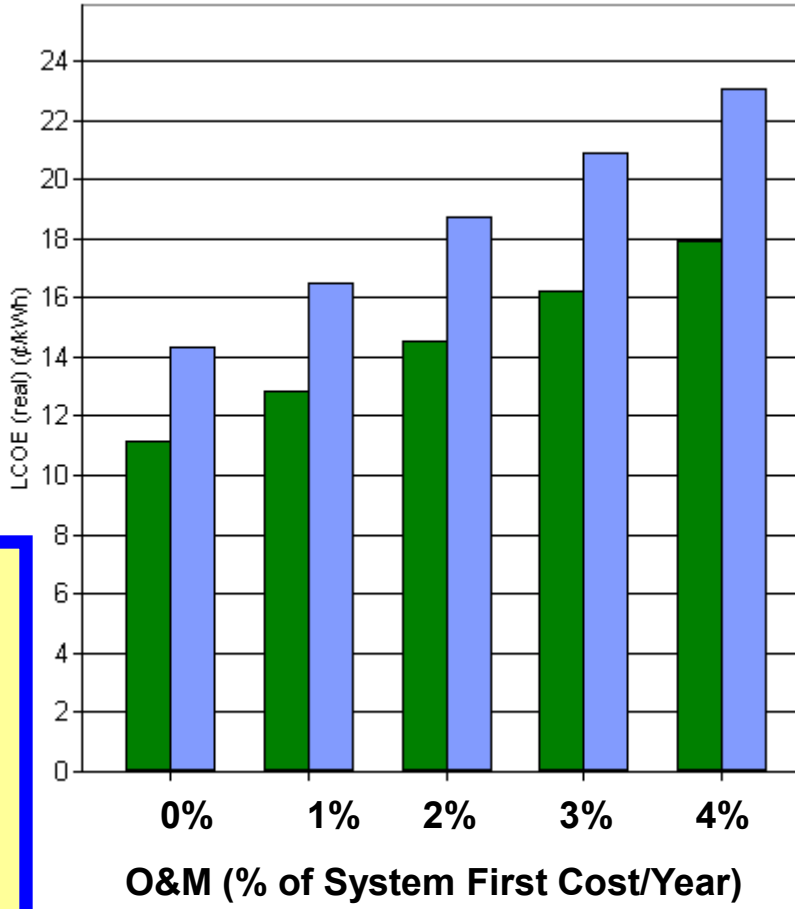
Analysis Examples

LCOE is about more than initial cost and performance





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



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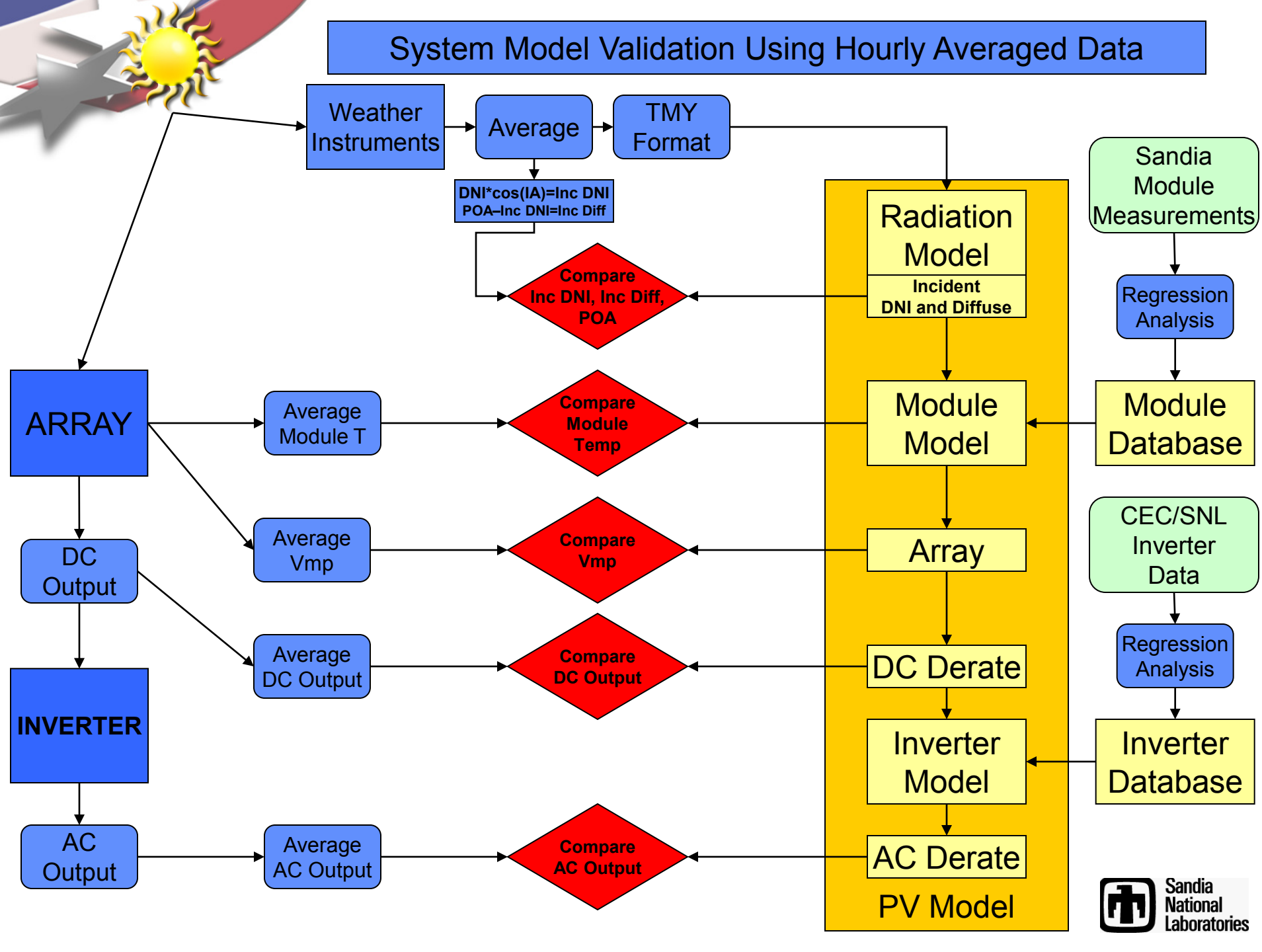
PV Performance Model Validation

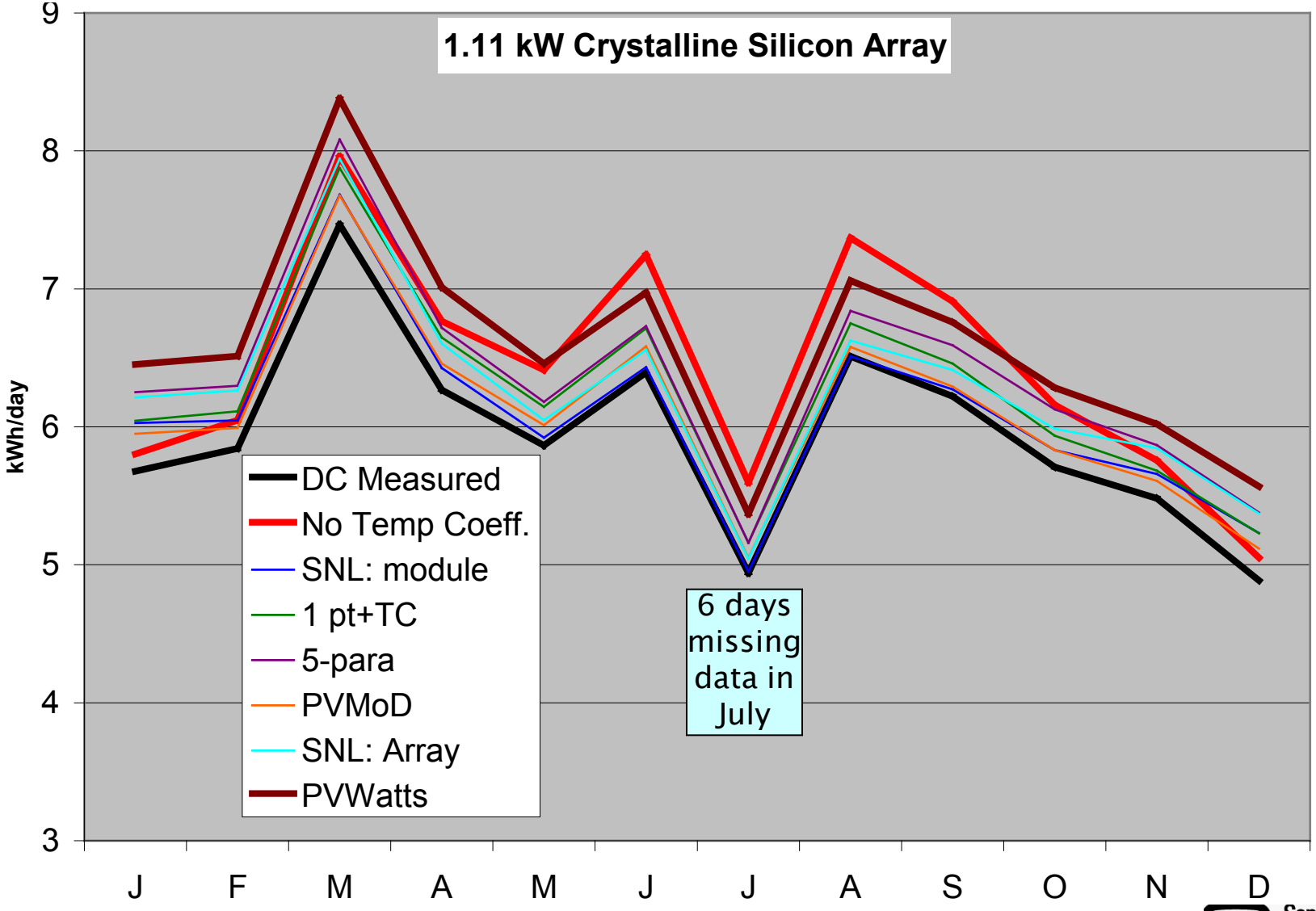
- Two Activities Underway in Collaboration with Industry
  - Evaluate/Validate Models Used to Predict PV System Performance
    - In Choosing Between Technologies or Designs
  - Evaluate/Validate Models Used to Monitor System Performance
    - Determine When Performance is Less than Expected Given Weather 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

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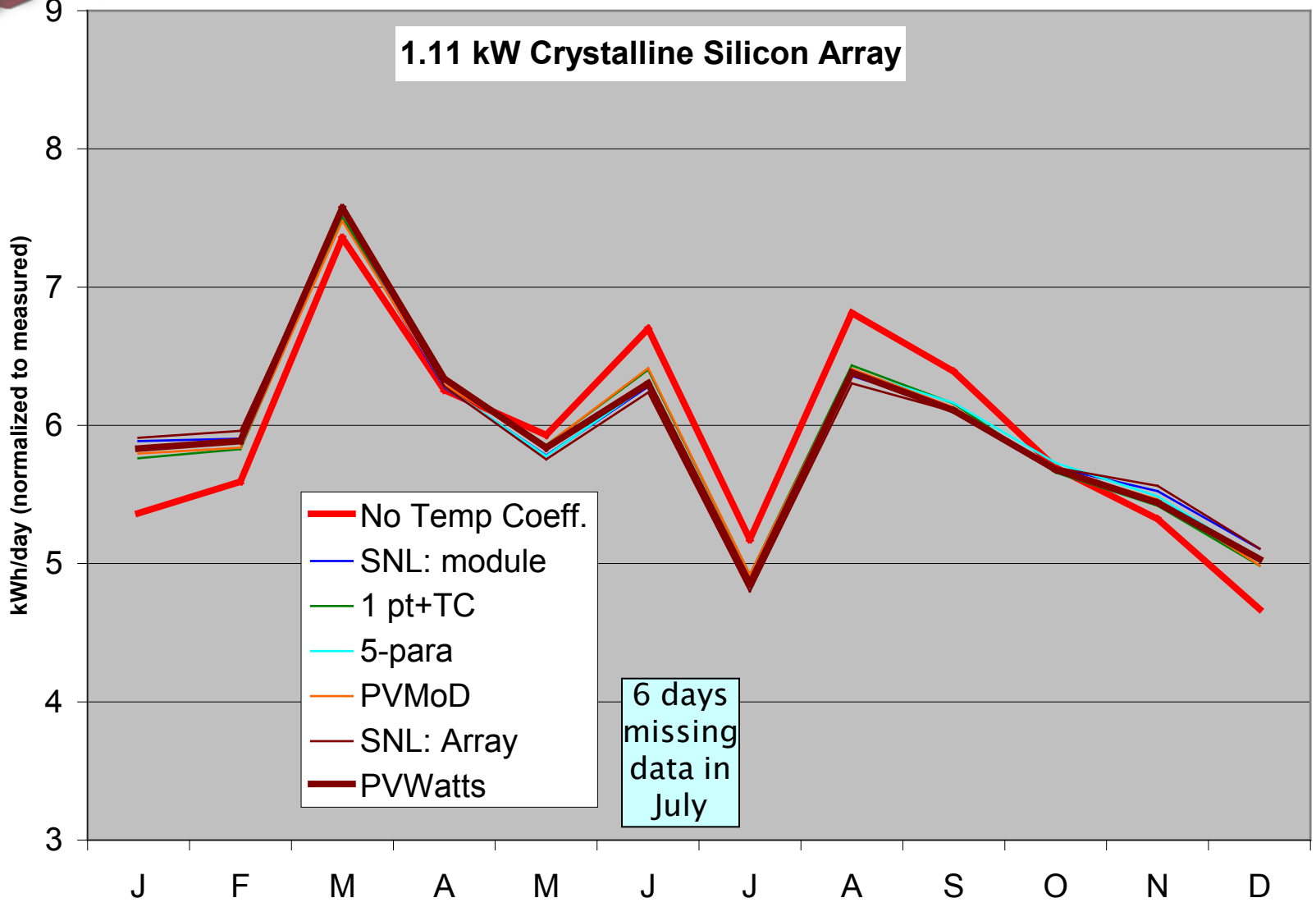
Monthly Output
Normalized to Measured Data



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

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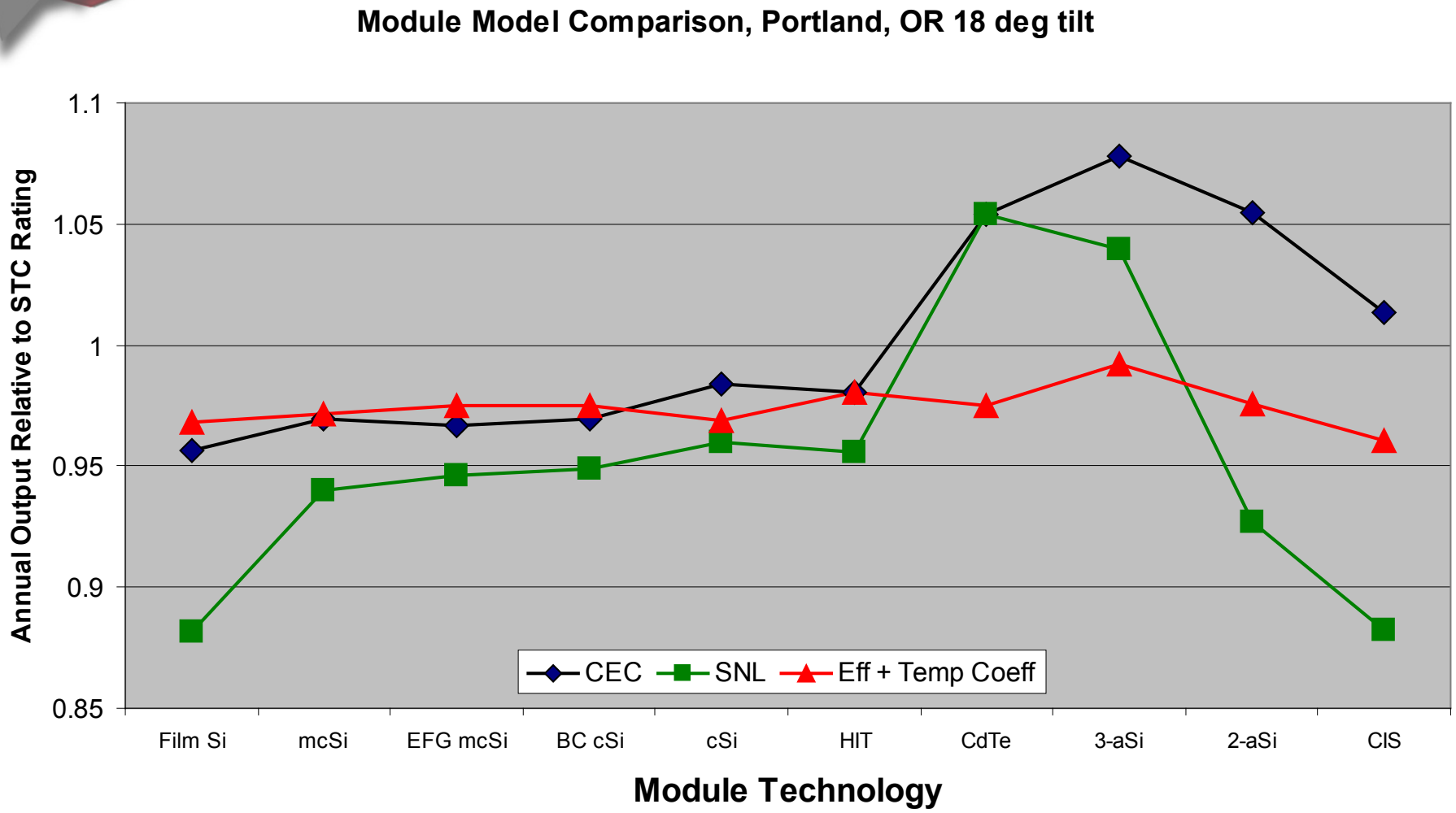
Model Results Differ for Other Technologies



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

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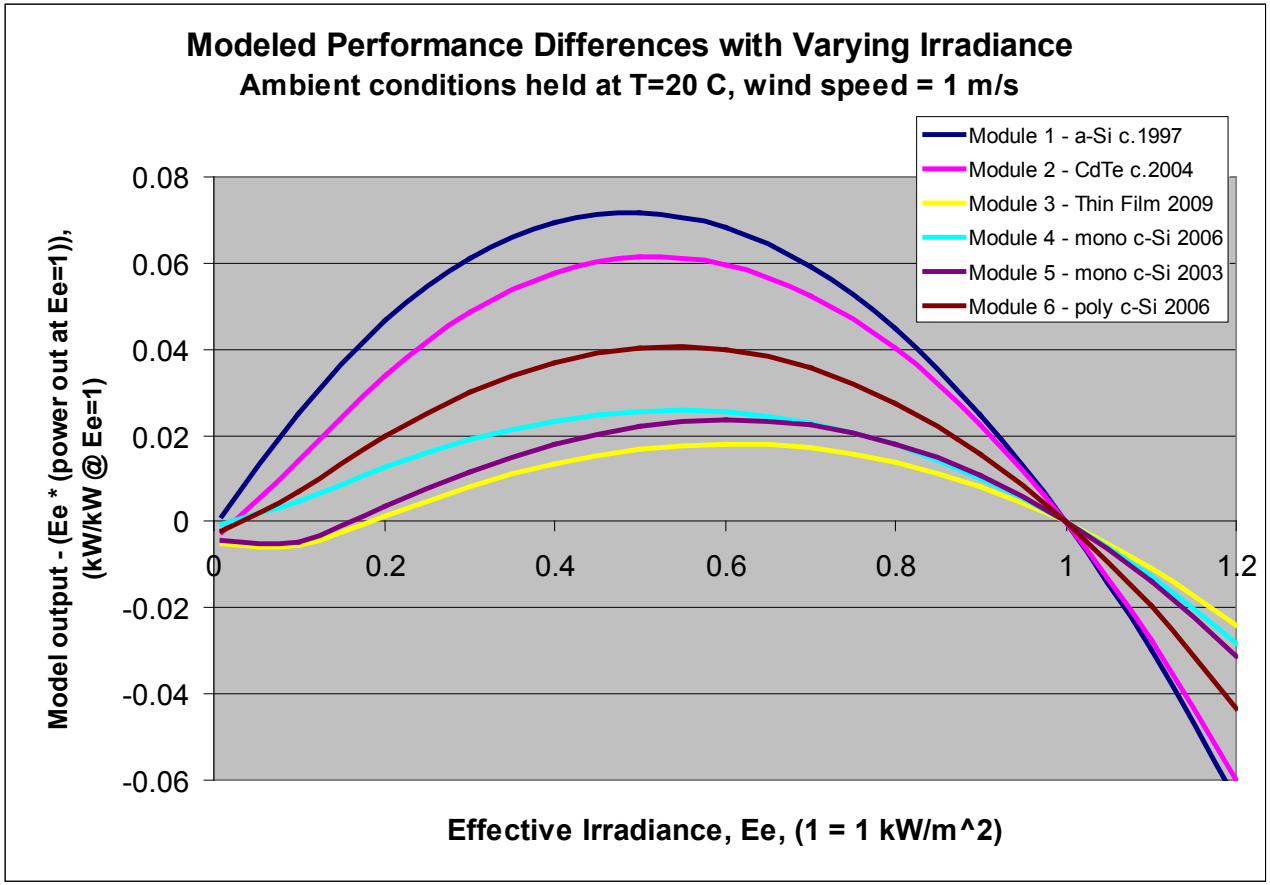
Solar input to models is an hourly average

- 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



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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
- Complete evaluation of impact of hourly averaging
  - Can modeling be improved by synthesizing sub-hourly data from existing hourly-averaged data sets?

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Questions

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DOE's Solar Advisor Model (SAM)

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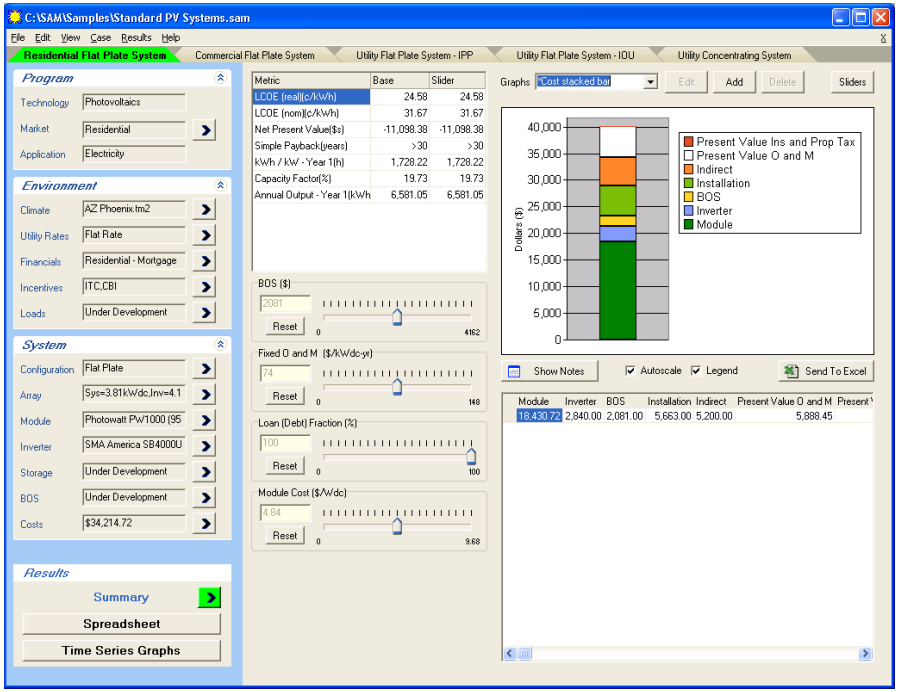

Thanks to Nate Blair and his colleagues at NREL for developing SAM

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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

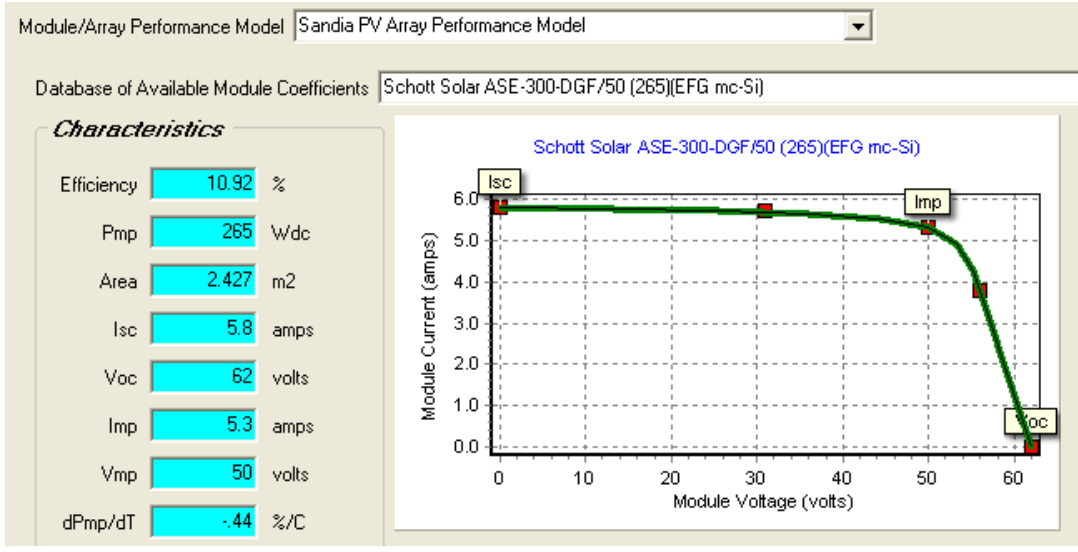
OR

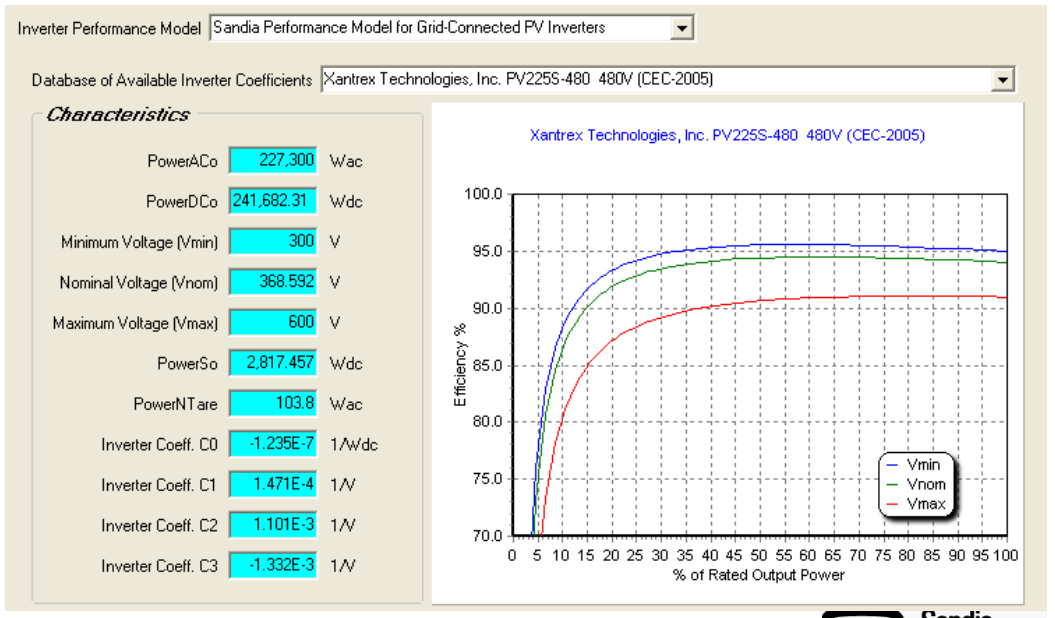
- Enter module area, efficiency and P_{mp} temperature coefficient
- Enter inverter efficiency and size

OR

- Use Generic Energy Input

PV Watts to be added to SAM





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