2008 Solar Annual Review Meeting

Systems Modeling

Session: Modeling and Analysis
Sandia National Laboratories

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Budget and Solar America Initiative Alignment

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FY07 Budget	**FY08 Budget**
$850k	$730k

- This project supports the Solar America Initiative by:
  - Developing and validating performance models to enable accurate calculation of Levelized Cost of Energy (LCOE)
  - Compiling component and system performance and operations and maintenance data to support, validate, and improve models
  - Supporting development of manufacturing and system cost models
  - Conducting modeling and analysis in support of program elements such as the Technology Pathway Partnerships

Project Overview – PV Performance Algorithms

- Goal: to calculate annual energy production using validated algorithms
- Sandia PV module and array performance algorithms already in use
  - Solar Advisor Model
  - PV Design Pro
  - Internal industry models
- Inverter algorithm developed (6/07)
  - SAND report published (9/07).
  - Incorporated in 4/08 release of the Solar Advisor Model
  - Translates CEC or other measured data to performance equations

CEC Inverter Test Data

Inverter Efficiency Data

W

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)	(kW)	(Vdc)	(%)	(kW)	(Vdc)	(%)	(kW)	(Vdc)	(%)
10%	Vmin	268.65	232.74	85.543	268.55	232.73	85.484	268.31	232.22	85.412
20%	Vmin	663.65	231.34	93.684	663.87	231.11	93.662	663.6	230.96	93.663
30%	Vmin	1015	232.11	95.439	1015.1	232.25	95.429	1016.9	232.57	95.421
50%	Vmin	1726.9	231.19	96.377	1727.9	231.3	96.373	1727.5	231.43	96.364
75%	Vmin	2282.1	230.48	96.373	2282.6	230.54	96.362	2282.5	230.56	96.367
100%	Vmin	3249.6	232	95.900	3250.5	232.07	95.881	3250.9	232.14	95.937
10%	Vnom	273.36	274.01	83.482	273.65	273.8	83.527	273.39	273.67	83.502
20%	Vnom	668.03	273.61	92.507	667.91	273.5	92.514	667.61	273.41	92.542
30%	Vnom	1021	274.2	94.599	1021.6	274.37	94.617	1021.3	274.32	94.614
50%	Vnom	1733.5	274.59	95.817	1734.1	274.45	95.824	1733.7	274.32	95.8
75%	Vnom	2294.3	274.83	95.900	2293	274.65	95.909	2294.1	274.63	95.908
100%	Vnom	3267.9	274.18	95.607	3265.6	274.07	95.564	3267.4	274.03	95.575
10%	Vmax	278.74	401.08	78.114	278.92	401.21	78.104	278.66	400.75	78.044
20%	Vmax	660.78	402.3	89.193	661.04	402.56	89.196	661.1	402.75	89.191
30%	Vmax	1014	402.95	92.213	1014.2	402.9	92.227	1014.9	403.18	92.228
50%	Vmax	1731.2	401.38	94.185	1730.8	400.89	94.205	1732.1	401.1	94.214
75%	Vmax	2293.5	402.27	94.572	2293.1	402.23	94.590	2294.7	402.63	94.603
100%	Vmax	3271	400.36	94.548	3268.3	399.97	94.567	3264.7	399.94	94.530

5-7 tests are done on a single inverter at each power level and voltage.

Coefficients are derived from this or similar data

Model vs. Weighted Inverter Efficiency

Rated Maximum Continuous Output Power: 3.20 kW   Night Tare Loss: 3.00 W

Vmin: 230 Vdc   Vnom: 274 Vdc   Vmax: 400 Vdc

Input Voltage (Vdc)		Power Level (%; kW) 10% 0.32	20% 0.64	30% 0.96	50% 1.60	75% 2.40	100% 3.20	Wtd
Vmin	230	85.5	93.7	95.4	96.4	96.4	95.9	95.7
Vnom	274	83.5	92.5	94.6	95.8	95.9	95.6	95.1
Vmax	400	78.1	89.2	92.2	94.2	94.6	94.5	93.3

CEC Efficiency = 94.5%

	Vmp	Average Efficency	AC/DC rating
Phoenix	264	95.1%	~1
	396	93.4%	~1
Portland	264	94.0%	~1
	264	91.9%	~1.5
	396	91.2%	~1

PV Performance Model Validation

- Process
  - Simultaneously monitor weather and performance
  - Quality check and convert 2-minute data to hourly average
  - Convert weather data to Typical Meteorological Year format file
  - Compare model prediction to measured data
    - Plane-of-array radiation from radiation model
    - Measured array dc output, module operating temperature, and dc voltage
    - Measured ac output
- Evaluate models
  - In Solar Advisor Model
    - Four solar radiation models
    - 3 module models
      - single-point efficiency with temperate coefficient
      - Sandia PV array performance model (uses measured coefficients)
      - CEC/University of Wisconsin 5-parameter model (uses nameplate data)
    - Sandia inverter model
  - PVWatts
  - Others to follow

Model Validation Results (Preliminary)
Albuquerque – South-Facing Latitude Tilt

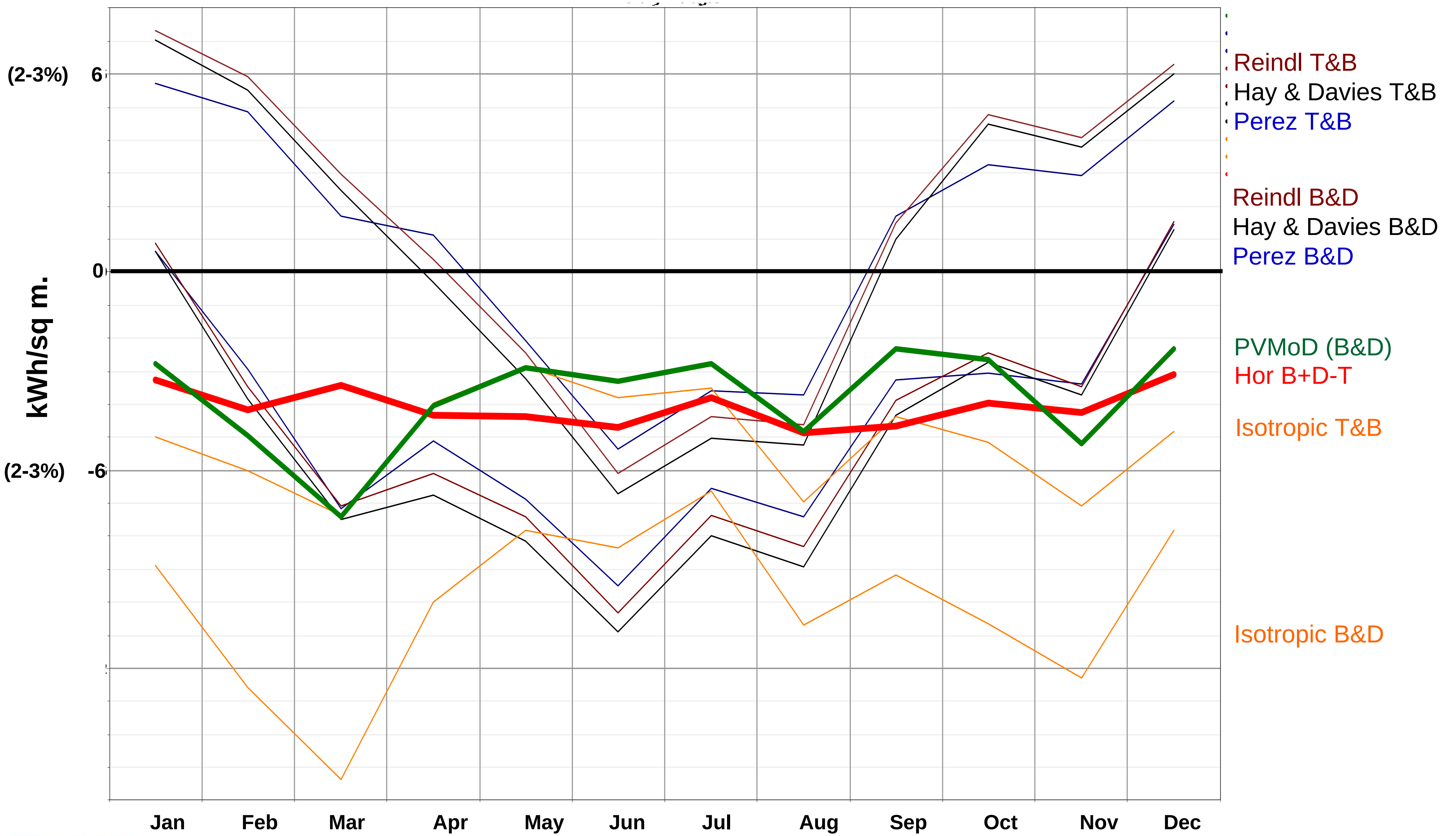
- Radiation Model Estimates Plane-of-Array Irradiance from
  - **T**otal Horizontal & **B**eam
  - **B**eam & **D**iffuse
- Future work – repeat for diffuse environment (Florida)

	Modeled vs. Measured Plane-of-Array									Meas vs Meas
	Perez		Hay and Davies		Reindl		Isotropic Sky		PVMod	Inc Beam + Diff
	T & B	B & D	T & B	B & D	T & B	B & D	T & B	B & D	(SNL)	vs. Global Hor.
Root-Mean-Square-Error	4.5%	5.4%	5.4%	6.2%	5.5%	6.3%	5.7%	8.3%	6.1%	4.0%
Mean-Bias-Error	0.4%	-1.7%	0.5%	-1.8%	0.3%	-2.0%	-1.9%	-3.8%	-1.4%	-1.8%
Mean - Absolute-Error	2.4%	2.7%	2.9%	3.0%	2.9%	3.1%	2.8%	4.2%	2.7%	2.0%

Systematic error within SAM in calculations from beam and diffuse found and corrected.

Model Validation Results (Preliminary)

Seasonal variation in POA (modeled-measured)



Module Model Validation

Single-point efficiency with temperature-coefficient

- Use enters manufacturer or CEC PTC efficiency, area, and max-power point temperature coefficient

CEC 5-parameter model

- Uses manufacturer's specifications as input to a proprietary coefficient generator
  - short circuit current
  - open circuit voltage
  - current and voltage at maximum power point
  - temperature coefficient of the open circuit voltage
  - temperature coefficient of the short circuit current

Sandia Array Performance Model

- ~40 coefficients measured in ½ day test on two-axis tracker
  - Coefficients for similar modules can be estimated
- Model uses beam and diffuse data
- Coefficients include:
  - I_{sc}, V_{oc}, I_{mp}, V_{mp} with 4 temp coeff.
  - Polynomial representation of air mass
  - Angle of incidence modifier
  - Thermal model for cell and module operating temperatures vs wind speed and ambient temperature
- Demonstrated for moderate concentration
- Believed applicable to high concentration and multijunction cells

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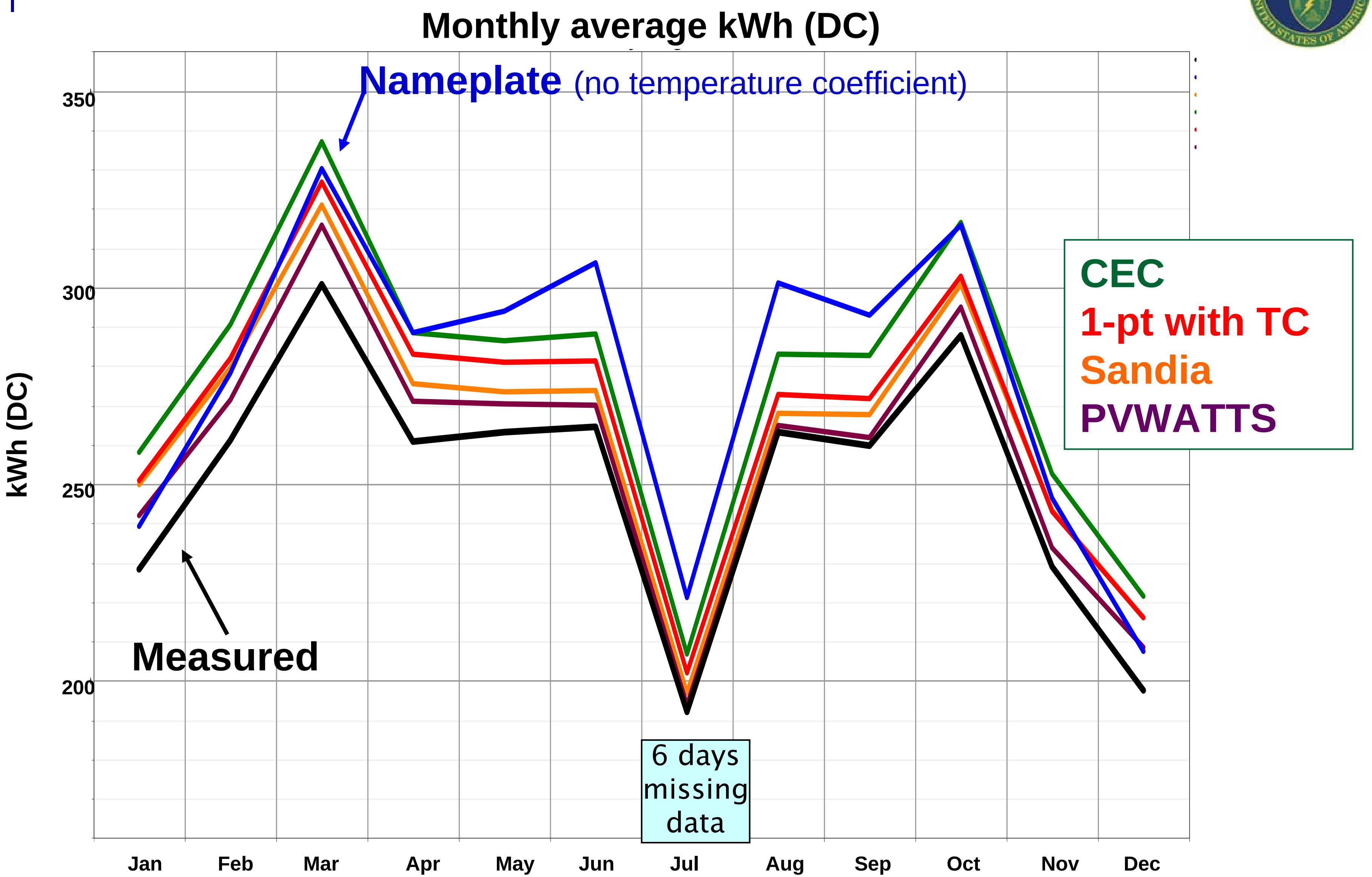
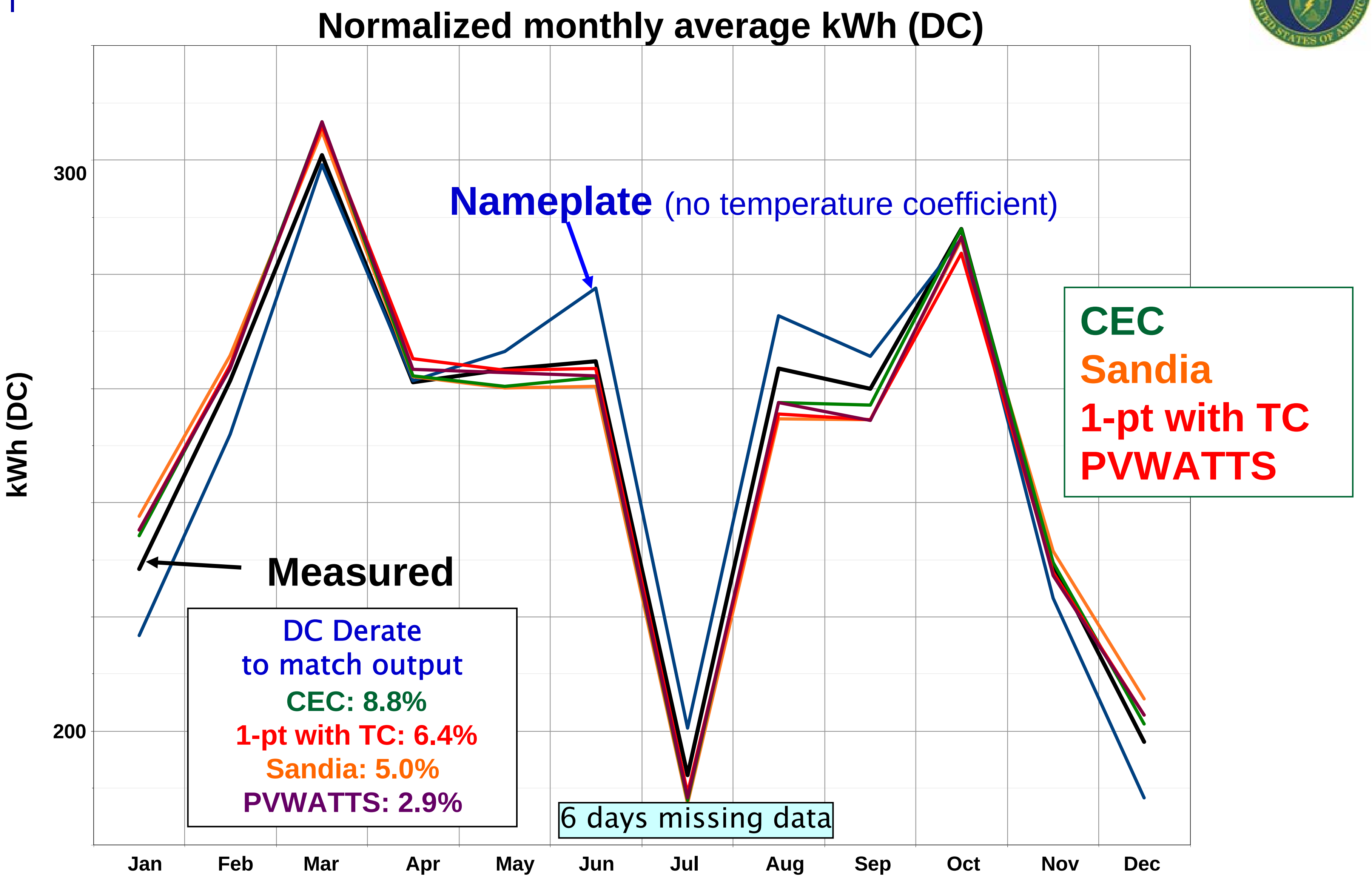
Model Validation Results (Preliminary)



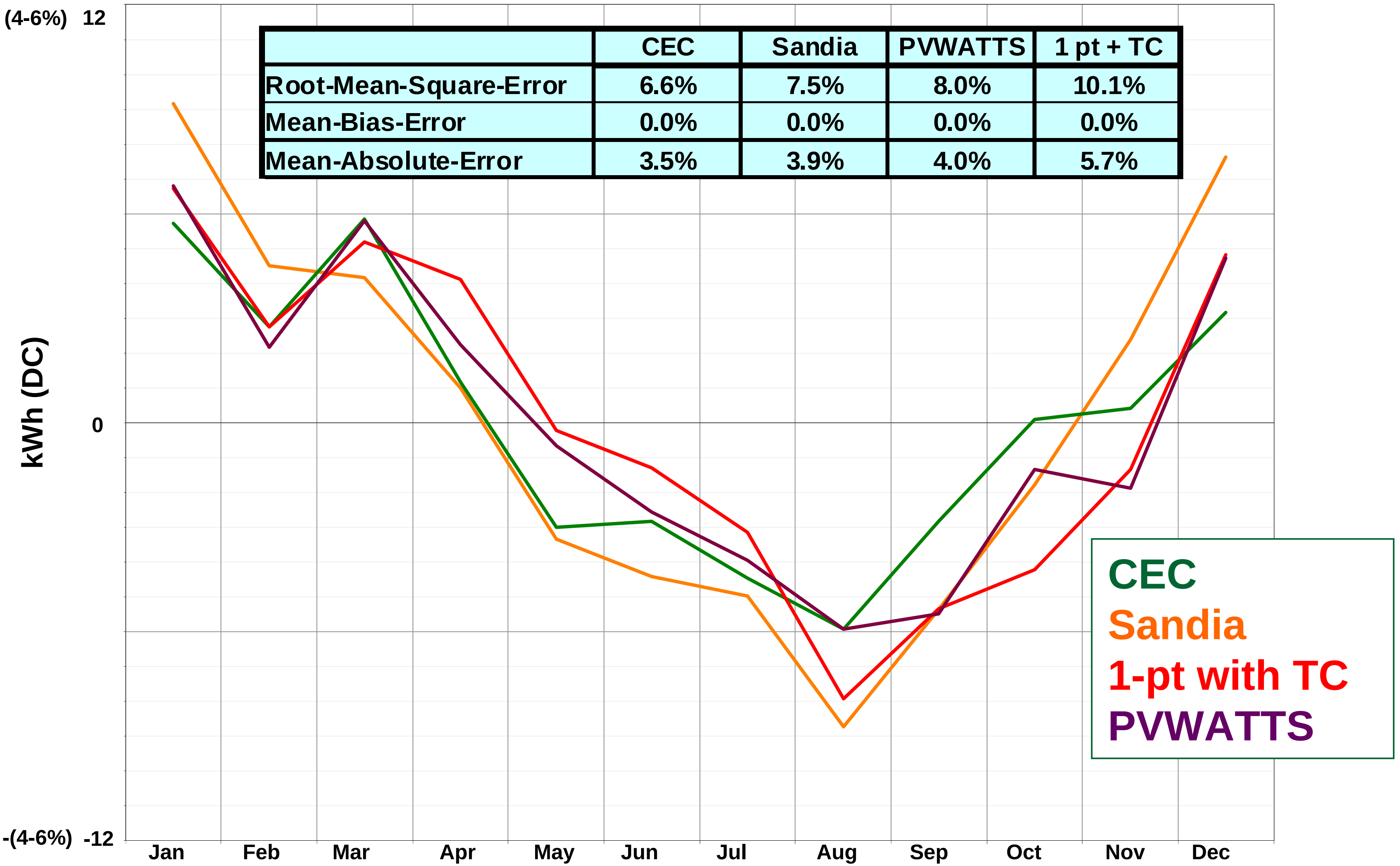
Model Validation Results (Preliminary)



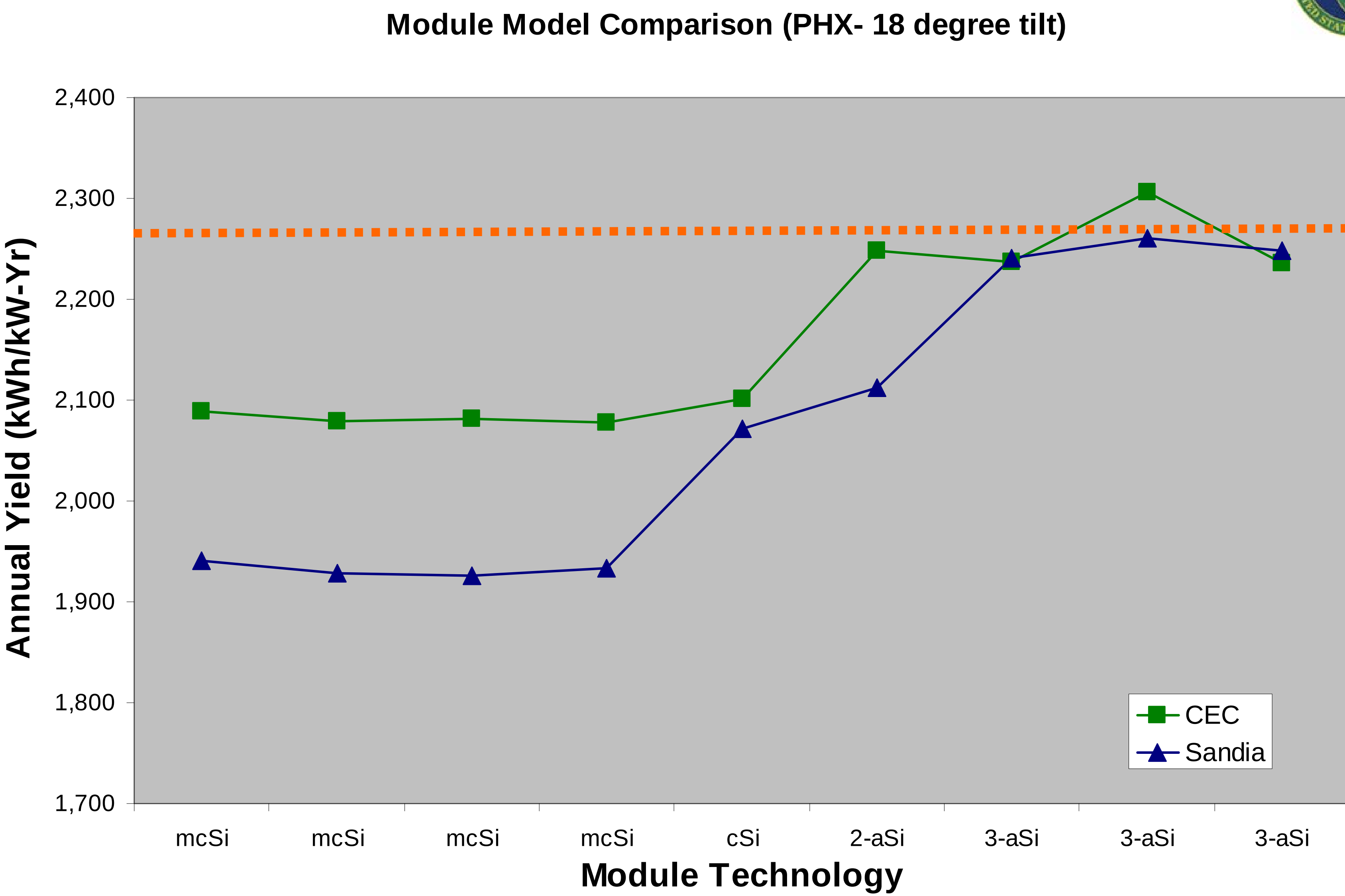
Model Validation Results (Preliminary)

Seasonal variation from measured after DC derate

	CEC	Sandia	PVWATTS	1 pt + TC
Root-Mean-Square-Error	6.6%	7.5%	8.0%	10.1%
Mean-Bias-Error	0.0%	0.0%	0.0%	0.0%
Mean-Absolute-Error	3.5%	3.9%	4.0%	5.7%



Model Results Differ for Other Technologies



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Database Development

- Sandia Database of Module Coefficients Distributed with SAM
  - Also used by PVDesignPro
  - Future Work – Expand Database with Measured and Estimated Coefficients
- CEC Module Parameter Database also distributed with SAM
  - Future Work – Add CEC coefficients based on Sandia measured data to SAM database
- Sandia Database of Inverter Coefficients Distributed with SAM (4/08)
  - Future Work
    - Continue to add inverters as test results are available
    - Add inverters based on manufacturer's specifications
- One-year data sets of hourly measured weather and system data to be posted on internet to enable use by others for model validation

Cost Model Development

- Support Cost Model Development by Navigant Consulting Inc.
  - Primary goal to support independent review of cost metrics provided by Solar America Initiative Technology Pathway Partnerships
    - Especially Solar Advisor Model inputs
  - Work delayed by contract modifications and placement at DOE/GO
    - Contract and approach modified to address TPP concerns
- Release Draft Public Manufacturing Cost Model Spreadsheet (4/08)
- Future work – support development of systems cost model
  - Spreadsheet based
  - Will interact with Solar Advisor Model

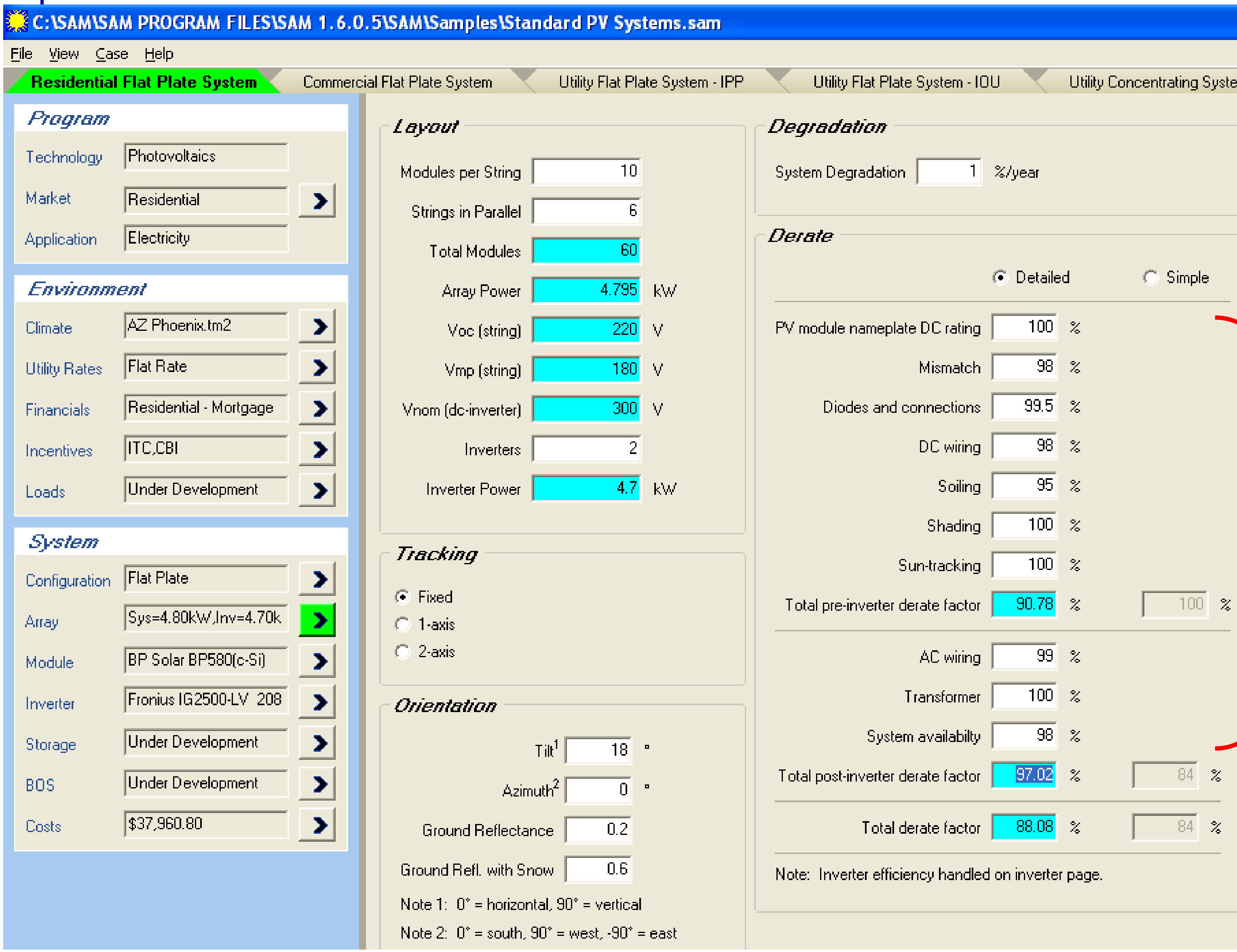
Program Analytical Support

- Provide analytical support for program initiatives
  - Analysis in support of inverter workshop
  - Analysis in support of Solar Energy Grid Integrated System concept paper
  - Support and Review of SAI Technology Pathway Partership Levelized Cost of Energy calculations at stage gates
- Provided updated MYPP benchmarks
- Supported HQ risk study
- Case studies – series of papers on system performance, cost and O&M
  - Five Years of Operating Experience at a Large, Utility-scale Photovoltaic Generating Plant (in press: Progress in PV)
  - Five-Years of Residential Photovoltaic System Experience at Tucson Electric Power (in review)

Future Work

- Conduct *system* level validation of performance models and modify if required for:
  - Diffuse climates (Florida)
  - Other PV technologies
    - Flat-plate technologies other than crystalline silicon
    - Multi-junction concentrators
  - Shading
  - TPP deliverables and baseline systems
  - Industry systems, as data becomes avaialble
- Develop performance models of energy storage systems
  - Supports grid integrated systems with storage
- Increase understanding of system derate factors

SAM PV Array Input Page



Nominal Derate Values from PVWatts

Project Update: Milestones

Planned work since last Program Review	**Status**
Develop system performance algorithms: Inverter algorithm developed. Paper published 9/07.	Jul-07
Compile performance, cost, and reliability data from selected systems (ongoing task)	Sep-07
Databases live on internet (modules, others being added)	Sep-07
New SAM release includes Sandia inverter model witch coefficients derived from CEC test data	Apr-08
Validate Solar Analysis Model vs. measured system data (IEEE paper)	May-08
System-data base with map interface operational	Anticipated Sept 2008

Past

Future

Obstacle Discussion

- Needs/requirements for systems-level database are evolving, in part in response to needs identified by reliability task and by industry interaction
- Modules for which performance degrades quickly or varies seasonally present new modeling challenges
- While SAM will be improved to address time-of-use utility rates, possible future efforts to model demand charges will require more frequent steps in modeling, weather data, and model validation data

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