# DOE Solar Energy Technologies Program Peer Review

**Technical Track: Evaluation, Validation and Analysis**
**Project Name: Test & Evaluation, SNL**
**Principal Investigator: Jennifer E Granata**

# Denver, Colorado
# March 9-10, 2009

**Primary Objectives**

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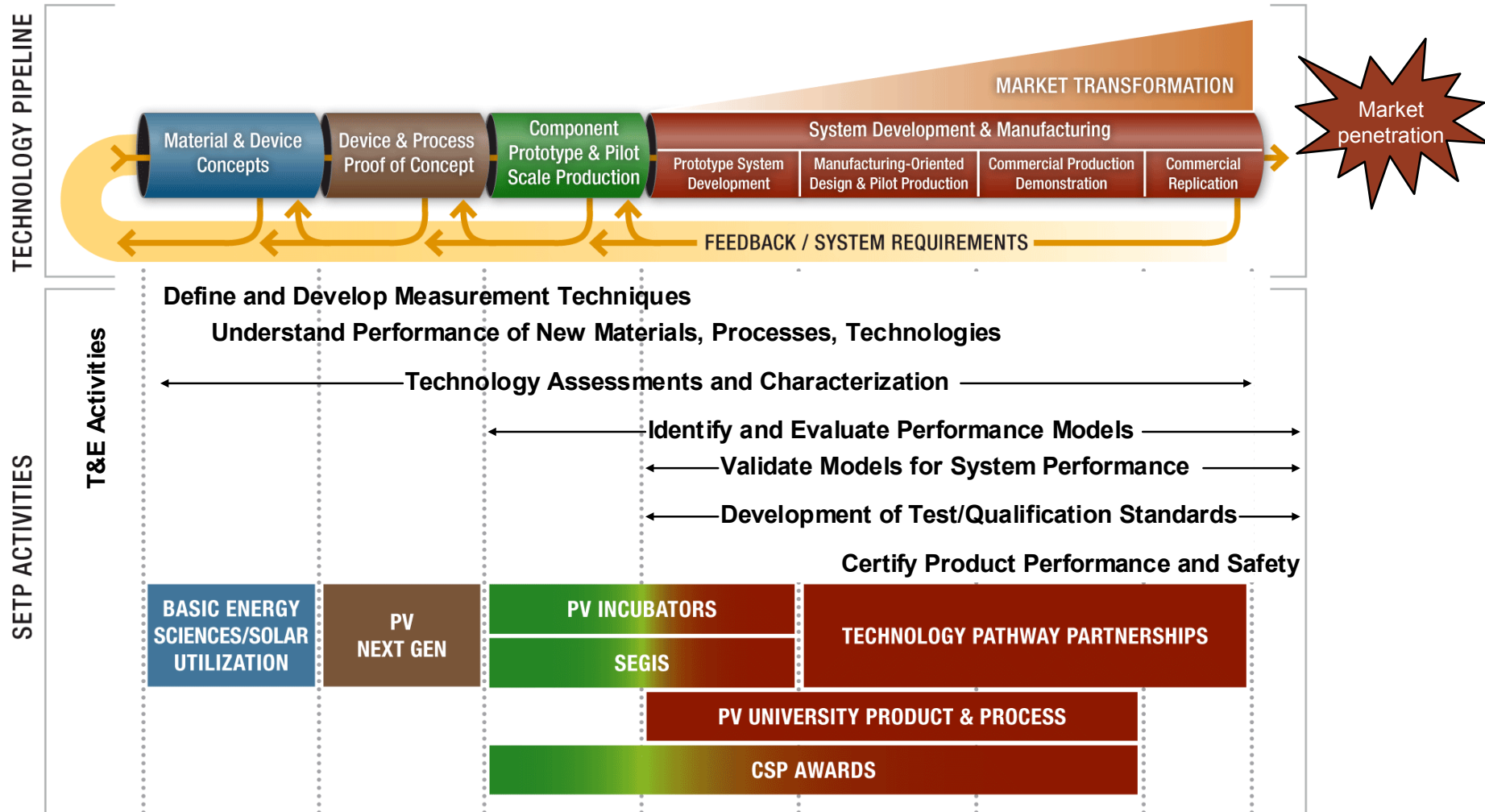
Primary Objectives of Sandia's T&E Program:

- Define and apply procedures for evaluating performance for unbiased technology assessment
  - Support development of new technologies and improvement of existing technologies
  - Provide detailed test and evaluation of cells, modules, inverters, balance-of-systems components, and integrated systems
  - SAI and SEGIS partners have top priority
- Transfer Test Technology to industry
- Support the development and implementation of national and international Codes and Standards

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# Relevance of Program

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Improved PV System Performance, Reduced LCOE, Increased Market Penetration

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# Technical Approach
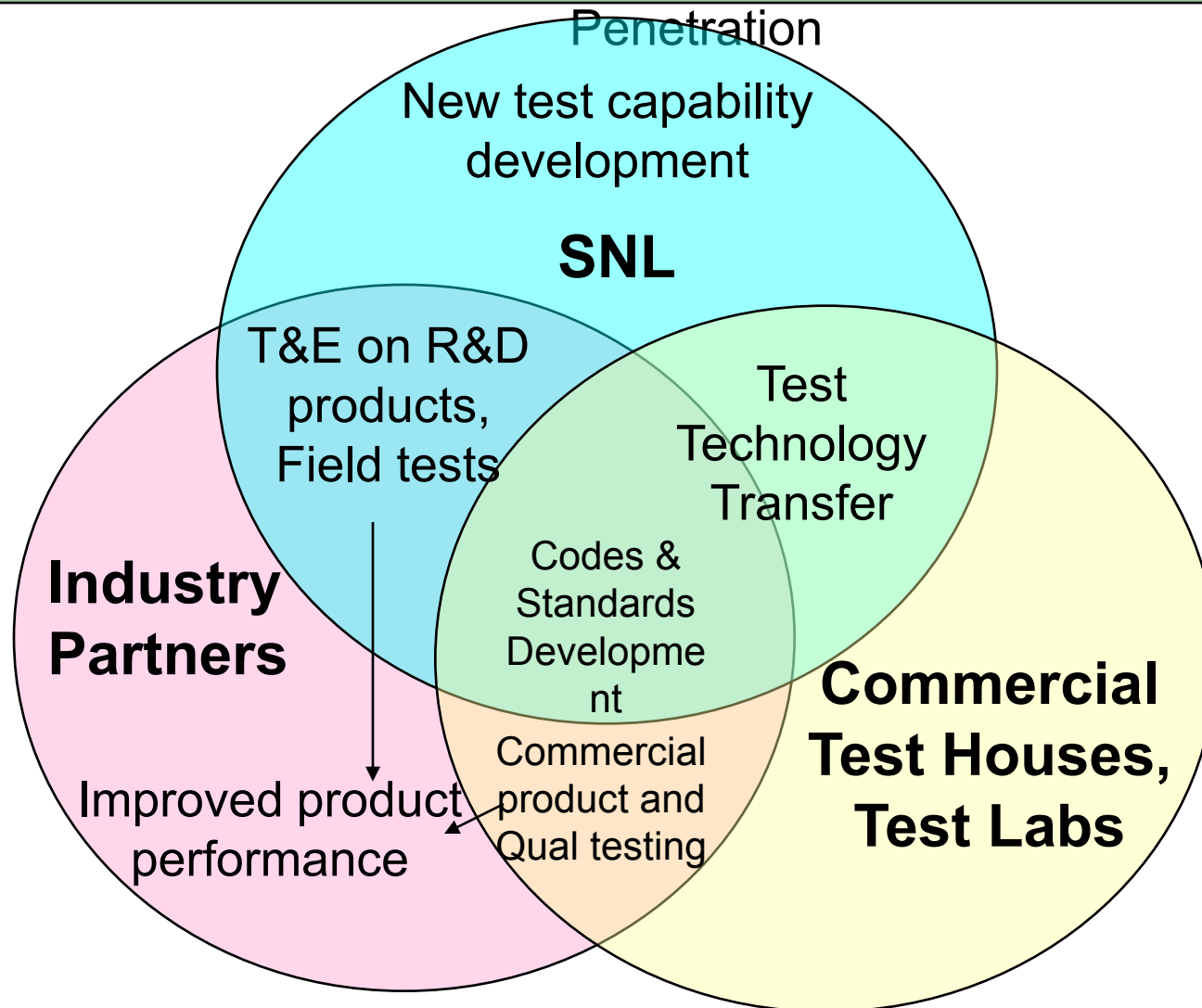
- Work with industry partners at all levels
  - Cells, modules, inverters, Balance-of-Systems (BOS) components, system
- Develop new T&E capabilities based on new technologies, industry needs
  - CPV, thin films, advanced inverter operation with new dc sources, micro-grid development analyzes different type of DR's advanced controls that adds value to utilities and micro-grid stability
- Test components and systems to high accuracy
  - Modules tested indoors (Dark IV, InfraRed Imaging) and performance tested outdoors on 2-axis tracker (~0.5 degree pointing accuracy)
  - Performance testing includes Light IV (LIV) curves over full illumination and temperature range, thermal response at steady sky conditions, Angle of Incidence (AOI)
  - Inverter testing includes CEC protocol efficiency evaluations, performance (array utilization, power quality) evaluations, heat mitigation and reliability analysis
  - Systems testing: dc and ac level, LIV curves using Data Logger and Curve Tracer, point-in-time (field testing) or performance tracking over time
  - Weather and irradiance data collection on site at SNL

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# Technical Approach

- Analyze data in detail
  - Analyze performance based on ambient conditions
  - Generate model parameters (modules, inverters) for modeling performance under any irradiance, temperature, electrical conditions
  - System performance over time by comparing measured vs modeled data

- Feedback results to industry partners for product improvements
  - Provide reports to industry, including detailed analysis and raw data (e.g., inverter MPPT performance assessments, module temperature coefficients)
  - Supply data to M&A group for model validation
  - Point-in-time performance checks in the field to assess performance versus model

- Transfer test technology to industry
  - Host interested parties on-site at SNL to observe test and analysis methodologies
  - Document test protocols and make available to PV community
  - Industry site visits to support test capability development

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# Quality: Team, Facilities

- Team qualifications
  - Bill Boyson, Jay Kratochvil, Gary Galbraith, Michael Quintana: Combined 100+ years experience in module and systems testing, evaluation, hardware and software development
  - Daniel Riley, Jason Finn: Recent engineering graduates bring hardware and software design capabilities
  - Jennifer Granata: 15 years experience in PV cell and module test, analysis, qualification, and program management
  - Sig Gonzalez, Scott Kuszmaul, Armando Fresquez, Ward Bower: Combined 60+ years experience in inverter testing, analysis and systems integration
- Facilities
  - Photovoltaic Systems Evaluation Lab (PSEL), Distributed Energy Technologies Lab (DETL), Photovoltaic Systems Optimization Lab (PVSOL), PV Cell Test Lab
- Coordination with NREL on SAI testing, data sharing for module and systems evaluations, complementary test capability development

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**Sandia Facilities: DETL and PSEL**

**Distributed Energy Technologies Lab**

- Inverter development/characterization

- Microgrid development facility

- Array utilization assessments

- Advanced controls/communications infrastructure

storage control







**PV Systems Evaluation Lab**

- Array and system characterization and optimization, data analysis

- Multi-faceted weather station

- Model validation through year-round data collection

- New high-accuracy tracker for CPV measurements

- Outdoor reference cell and pyronometer calibration

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## Sandia's Cell Characterization Laboratory

- One-sun and multi-sun simulators
  - Can measure individual solar cells from <1 mm$^2$ up to 15 cm x 15 cm in size
  - Temperature-control capability to measure temperature coefficients at 1-sun
- Dark IV
- Spectral Response and Reflectance/Transmission
- Laser-Beam Induced Current to assess single cell uniformity, current losses

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# Teaming with Industry

- SNL works with industry partners at all levels
  - Cells, modules, inverters, Balance-of-Systems (BOS) components, system
  - Modelers, integrators, system owners, system users (e.g. utilities)
- Maintaining company proprietary information is vital to teamwork
  - Many companies are sensitive to information being publicly released prematurely
  - Sandia ensures protection of proprietary information through NDAs, publishing aggregate data without "naming names", publishing company-specific data only with company approval
  - Limiting access to components on test if requested
- Supplying test results to industry partners creates the test-analysis-product improvement-retest feedback loop
- Recent Industry support demonstrated in next two charts

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# Teaming with Industry: TPP and Incubator Support

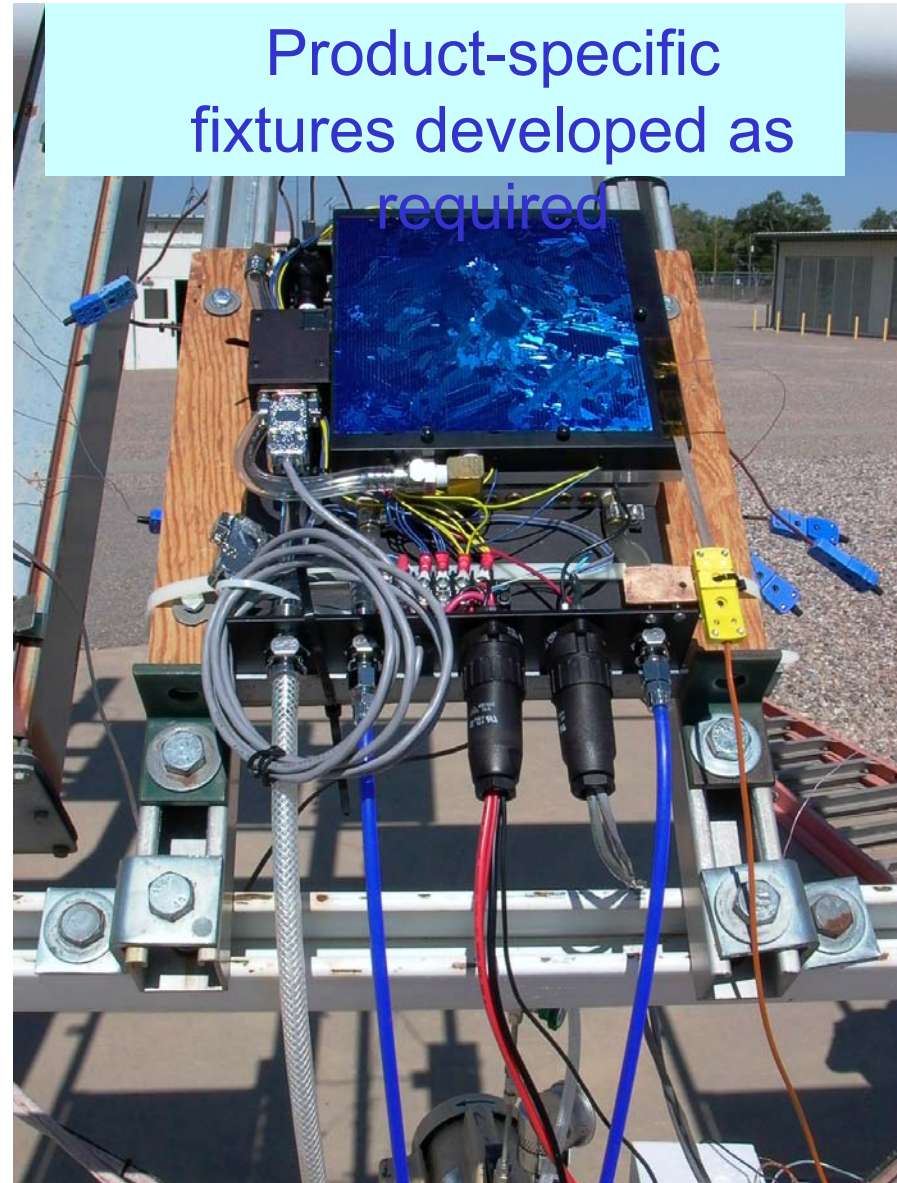| Program | Company Supported | Support Activity | Begin Test | Stage Gate |
|---|---|---|---|---|
| Incubator | AVA Solar | Install grid-tied system and evaluate reliability and degradation | 3/09 | |
| Incubator | Plextronics | Outdoor measurements, energy ratings | TBD | X |
| Incubator | SolFocus | Module outdoor characterization | 3/09 | |
| TPP | Amonix | SG T&E: Outdoor system performance testing<br><br>Drive tests, Inverter characterization, Evaluation of field installation process, MJ cell characterization | SG 1: 4/08<br>SG 2: 4/09<br>TBD | X |
| TPP | Greenray | SG T&E on module and inverter<br>Performance and utility compatibility tests alpha II product<br>Performance and utility compatibility tests beta I product | SG 1: 3/08<br>SG 2: 1/09<br>SG 2: 7/09 | X |
| TPP | Boeing | Witness array performance test, Gen 1<br>Outdoor exposure Baseline subpanel test<br>Witness array performance test<br>Verification/certification of new inverter | 4/08<br>10/08<br>5/09<br>TBD | |
| TPP | Konarka | Outdoor measurements, energy ratings | 5/09 | X |
| TPP | BP Solar | Baseline module testing<br>SG 1 T&E: PV charge controller testing | 3/09<br>7/09 | X |
| TPP | Nanosolar | Baseline module testing, Outdoor module exposure<br>Possible mechanical testing, Inverter testing | 5/09<br>8/09 | X |
| TPP | Sunpower | Baseline module testing<br>SG 2 T&E: Inverter performance | 10/08<br>TBD | X |
| TPP | GE | Inverter performance testing verification | 11/08 | X |
| TPP | Dow | Baseline module testing, Long term exposure<br>Inverter performance testing verification | TBD<br>7/09 | X |
| TPP | Soliant | Gen1 beta panel performance testing<br>Stage Gate 1 T&E: Gen2 beta panel performance testing | 4/08<br>10/08 | X |

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# Teaming with Industry: Other Support

| Program | Company Supported | Support Activity | Begin Test |
|---|---|---|---|
| SEGIS | Various – Up to 12 participants | Inverter evaluations (based on outcome of kickoff meetings in FY08) | TBD |
| Industry | Advent | Indoor and outdoor module characterization<br>2-year long-term test on PVSOL (completed 2/09) | Ongoing since 2006 |
| Industry | Emcore | Multisun cell characterization<br>Indoor and outdoor CPV module characterization | Ongoing since 2005 |
| Industry | Evergreen | Long term soiling study<br>One year study complete in 3/09 | 3/08 |
| Industry | Sunpower | Indoor and outdoor module characterization<br>2-year long-term test on PVSOL (completed 2/09) | Ongoing since 2006 |
| Industry | Recurrent Energy | Indoor and outdoor module characterization | Ongoing |
| Industry | Solaria | Outdoor measurements, energy ratings | 3/09 |
| Industry | Xantrex, PVPowered, Fronius, Petra, Enphase, Satcon | Developmental Inverter evaluations | Ongoing |
| Industry | Entech, Prism Solar, others | Indoor cell characterization, calibrations, analysis<br>*Supported 8 companies between 4/07 and present* | Ongoing |
| Industry | AND, Others | Support to new industry sector regarding module and inverter optimization – testbed opportunities at labs<br>*Support to 8 companies between 4/07 and present* | Ongoing |
| Industry | Atlas, Sunpower, Advent, Atonometrics, Others | Support to growing industry sector – test technology transfer of module and inverter test protocols<br>*Support to 9 companies between 4/07 and present* | Ongoing |

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# Accomplishments:
# Facilities Enhancements

Product-specific fixtures developed as required

Above: Expand outdoor module test capabilities - two-axis tracker with > 0.1 degree pointing accuracy to enhance testing of CPV module, optics, BOS components
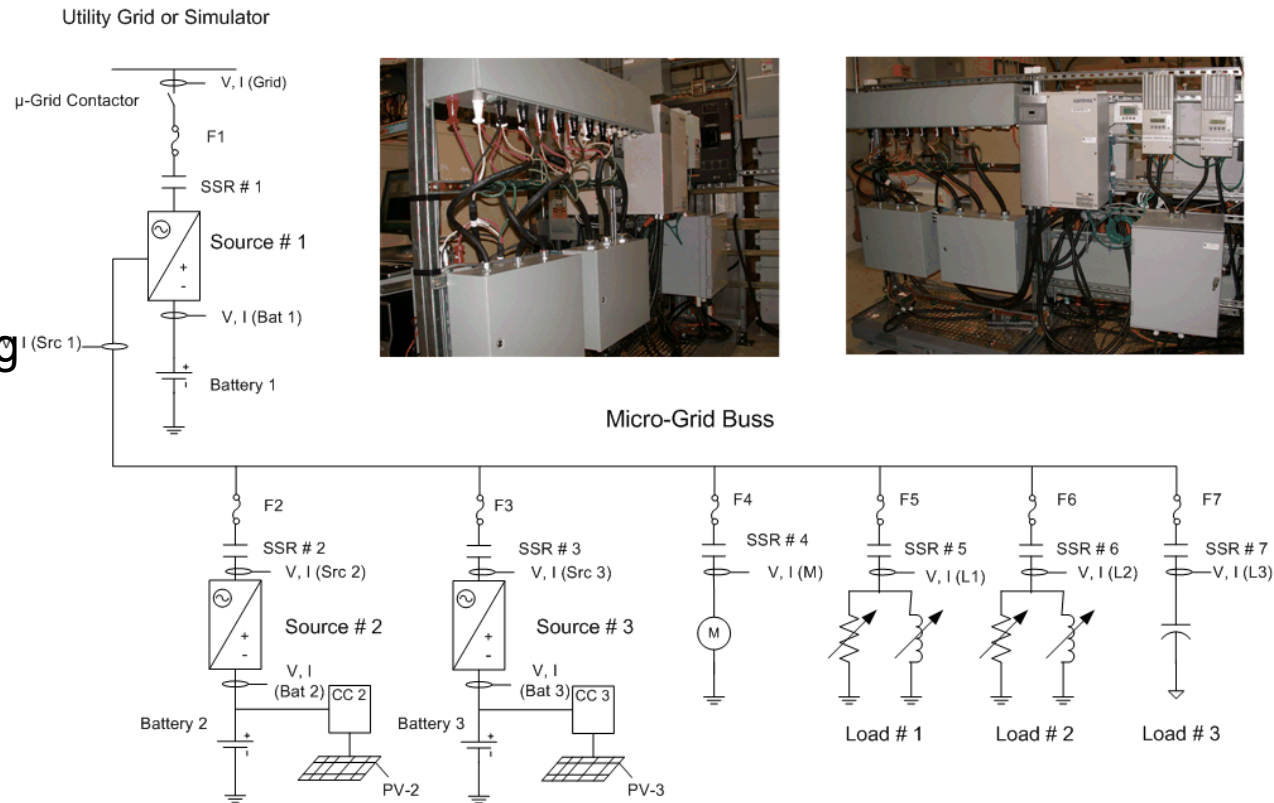
Doubling data acquisition capacity to allow real-time simultaneous characterization of up to eight

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**Accomplishments:**
**Facilities Enhancements**

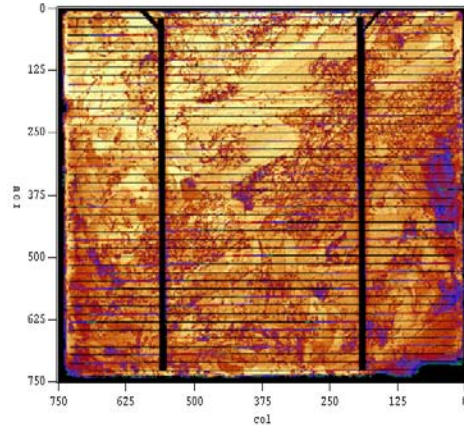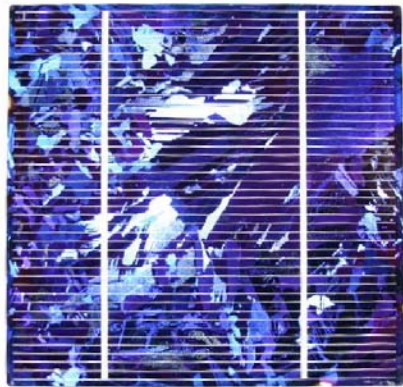# Develop a test bed needed to validate SAI and SEGIS stage-gate deliverables at DETL, including:

• Capabilities of advanced controls to minimize the energy flow from the utility and maximize the energy flow to the utility

• Communication monitoring and load shedding capabilities

• PV array utilization under low irradiance conditions

• Heat mitigation issues

•Storage control included as part of the energy management system



## Single Phase µGrid Test Bed

07/28/2008

S:\DETL\Micro_Grid\Drawings

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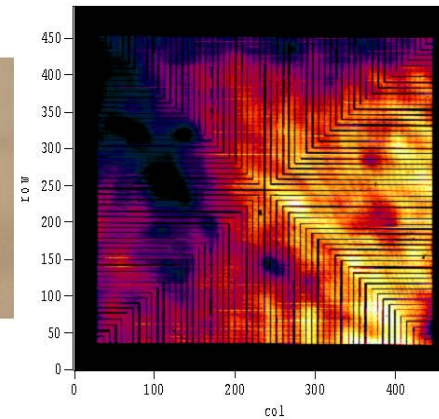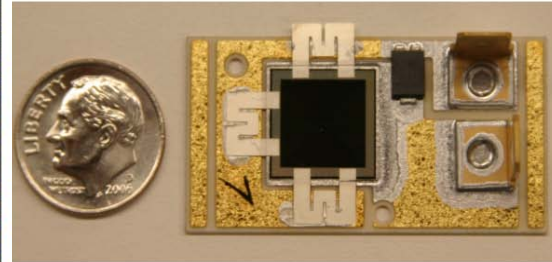
# Accomplishments: Cell Lab Upgrades

LBIC for single junction Si works well losses by junction



Upgrading LBIC for MJ cells to pinpoint
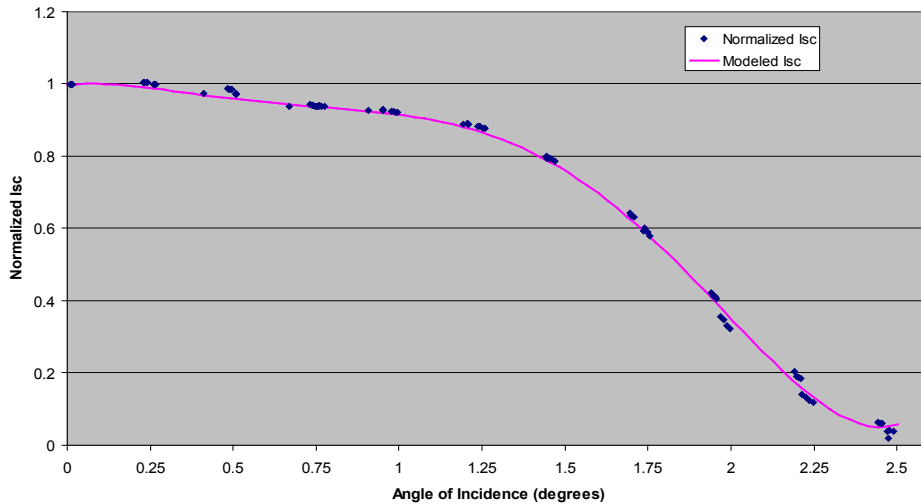
## Cell Characterization Lab Upgrades

- Increasing the Test Accuracy
  - Implementation of more efficient data collection algorithms
  - Purchase of numerous hardware items to increase data collection capabilities
- Additional System Traceability
  - Calibration of several items such as spectral response detectors, reflectance and transmittance standards, and reference cells used in one-sun IV measurements
  - Round-robin testing with NREL and others to produce more consistent measurements across laboratories

## New Capabilities in Development for CPV

- Multiple Junction LBIC Device Characterization
  - System will allow numerous custom configurations to characterize current CPV cells as well as future devices
  - Will allow manufacturers to accurately pinpoint junction specific device flaws and manufacturing issues
  - Initial data expected May 2009
  - Submitted to 2009 PVSC
- Ability to Take IV Curves of Small CPV Cells Under Concentration
  - Customization of multi-sun tester to characterize CPV cells with an Isc less than 1 Amp

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# Accomplishments: CPV Testing

## Normalized Isc vs. AOI for sample CPV module



Legend:
- Normalized Isc
- Modeled Isc

Y-axis: Normalized Isc (0 to 1.2)
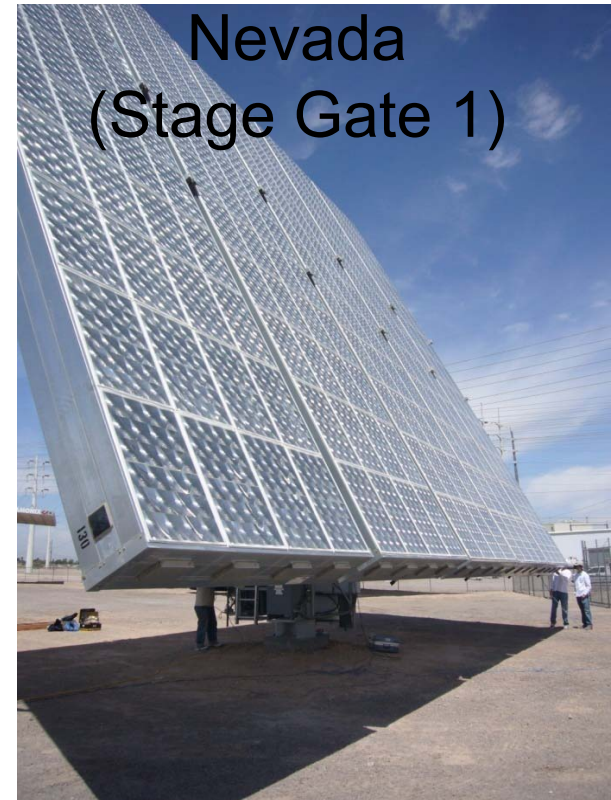X-axis: Angle of Incidence (degrees) (0 to 2.5)

**Above: Enhanced AOI method for CPV off-tracking Isc loss analysis**

*Even 1 degree off-tracking can reduce current by 10%! Needed for accurate tracker designs and feedback loops as well as minimization of damage during test sequences*

*\* Limited data shown to maintain data at proprietary level as requested*

CPV Field Test:
Simultaneous field testing of two generations of Amonix MegaModules
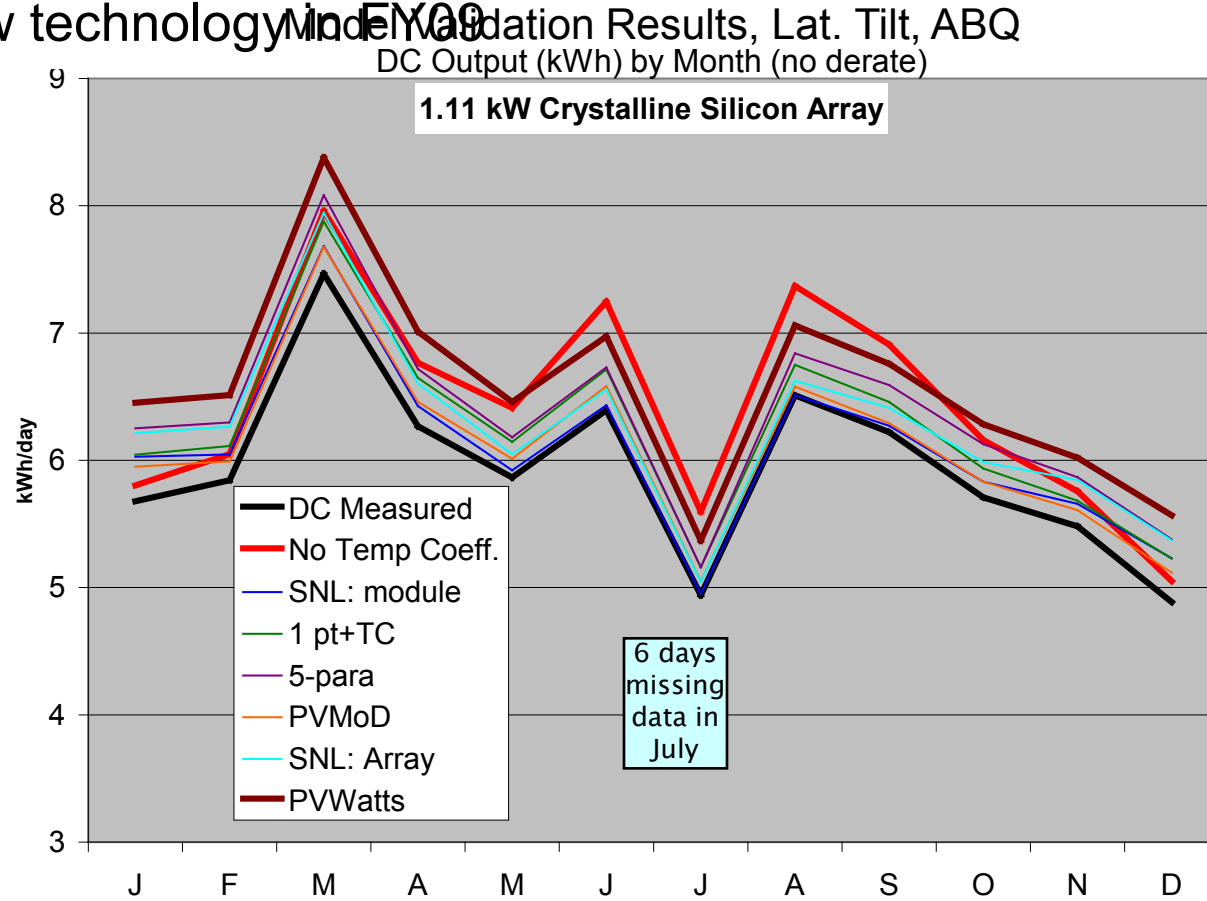(~5 kW) in Las Vegas, Nevada
(Stage Gate 1)

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# Accomplishments:
# Data for Model Validation

- One year of data collection on three, 1-kW size grid-tied PV systems installed at Sandia's PV Systems Optimization Laboratory (PVSOL). Key system parameters, solar radiation, and weather data collected at two-minute intervals.

- Data set was used to validate performance models against measured data for the models used in the Solar Advisor Model (Published at 33rd PVSC)

- Updating system with new technology in FY09



Model Validation Results, Lat. Tilt, ABQ
DC Output (kWh) by Month (no derate)

**1.11 kW Crystalline Silicon Array**

Legend:
- DC Measured
- No Temp Coeff.
- SNL: module
- 1 pt+TC
- 5-para
- PVMoD
- SNL: Array
- PVWatts

6 days missing data in July

y-axis: kWh/day
x-axis: J F M A M J J A S O N D

Coordinated with M&A program

*Graph reference: Cameron's Presentation*

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# Accomplishments:
# Array Degradation Study

## SNL PV array field: Retest and degradation analysis underway (coordinated with Reliability program)

• Retested 40 kW array of various technologies at DETL (shown below left)

• Noted varying yearly system power degradation rates for silicon technology (<0.5%/yr to >8%/yr)

• Degradation mechanisms under investigation; to be presented at 2009 PVSC



| Array | Test Date | Isc [A] | Imp [A] | Voc [V] | Vmp [V] | Pmp [W] | FF |
|---|---|---|---|---|---|---|---|
| System #1 a-Si, 3.06 kW | 2002* | 55.09 | 43.12 | 101.00 | 71.00 | 3061.5 | 0.550 |
|  | %/year | -7.0 | -7.1 | -0.7 | -0.6 | -7.4 | -0.1 |
| System #2 mc-Si, 5.42 kW | 6/16/2004 | 18.888 | 17.011 | 431.49 | 324.62 | 5828.2 | 0.715 |
|  | %/year | -1.1 | -1.8 | -0.3 | +0.8 | -2.3 | -0.9 |
| System #3 mc-Si, 6.87 kW | 9/26/2005 | 19.008 | 17.660 | 474.59 | 373.36 | 6593.4 | 0.731 |
|  | %/year | -8.0 | -8.1 | -0.7 | -0.3 | -8.3 | +0.3 |
| System #4 mc-Si, 7.00 kW | 10/3/2005 | 19.168 | 16.816 | 468.33 | 355.27 | 5974.0 | 0.665 |
|  | %/year | -0.3 | -0.3 | +0.3 | +0.2 | -0.1 | -0.1 |
| System #5 mc-Si, 7.99 kW | 9/26/2005 | 22.487 | 20.191 | 479.33 | 381.79 | 7708.6 | 0.715 |
|  | %/year | -5.6 | -5.4 | -0.1 | -0.1 | -5.5 | +0.2 |
| System #6 mc-Si, 6.93 kW | 10/5/2005 | 14.341 | 13.139 | 608.18 | 478.85 | 6291.8 | 0.721 |
|  | %/year | -0.6 | -1.1 | -0.1 | -0.8 | -1.9 | -1.2 |
| System #7 a-Si, 3.26 kW | 8/15/2006* | 15.30 | 12.39 | 368.8 | 264.0 | 3264 | 0.58 |
|  | %/year | -1.2 | +0.2 | -0.5 | +0.1 | +0.4 | +2.0 |
| System #8 c-Si, 5.69 kW | 11/20/2006 | 17.195 | 15.668 | 444.16 | 359.30 | 5629.6 | 0.737 |
|  | %/year | -1.3 | -5.6 | +0.1 | +1.5 | -4.2 | -3.1 |

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**Accomplishments: Inverter Performance Model**

# Inverter Performance Modeling

- Implemented and continue to validate empirically derived inverter performance model; provides indication of the ability for the inverter under test to utilize and convert available PV into usable ac power.

- The graph shows 1 week's worth of measured data and array model data. An energy calculation for the week indicates how well the measured and modeled data agree and demonstrates how the modeled data can be used as a MPPT analysis tool.

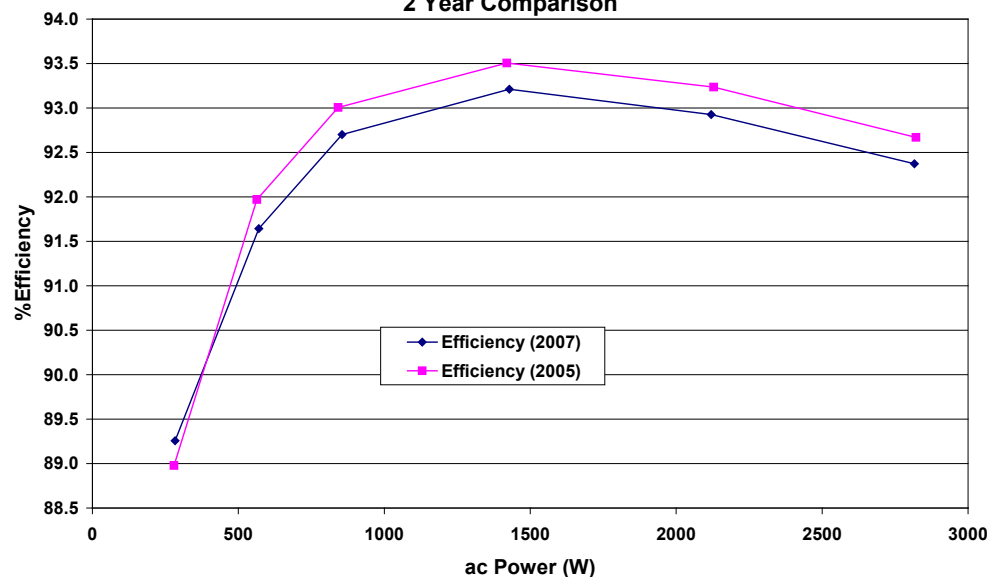- Simplified diagram of single phase PV inverter used in Matlab/Simulink
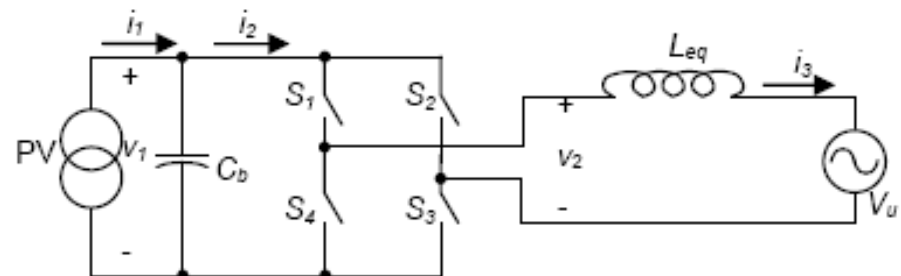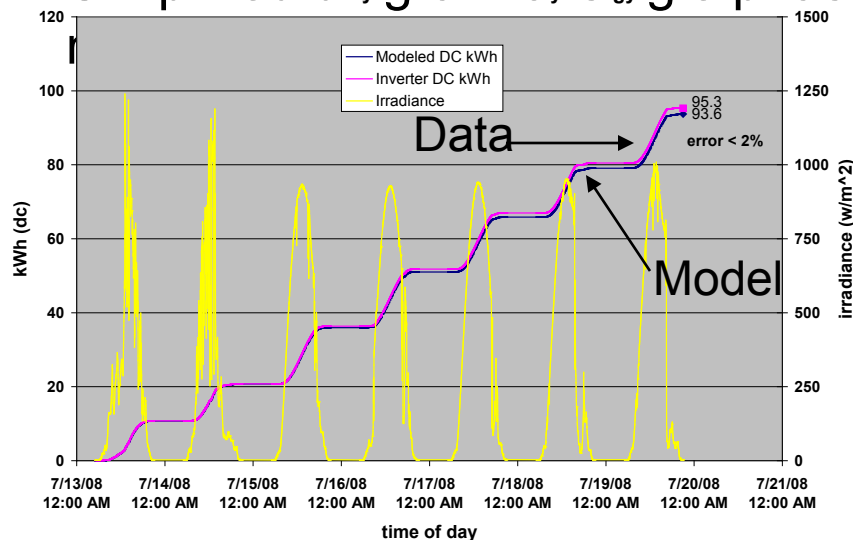


**Accumulated energy error from model and measured data**

**MATLAB/Simulink Model of a Single-Phase Grid-Connected Photovoltaic System**

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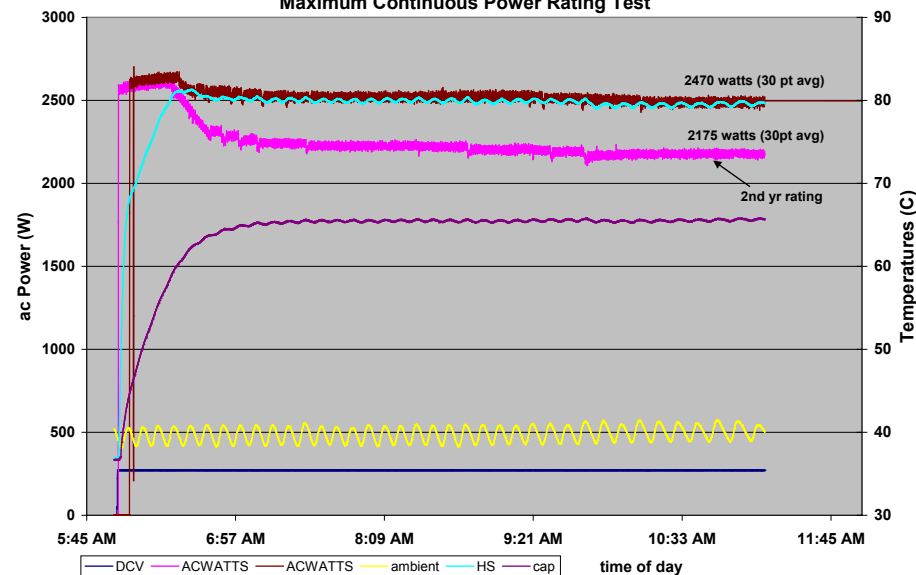**Accomplishments:
Long-Term Inverter
Performance**

- Re-characterization after field exposure of test bed inverters. 6 of 12 inverters retested after 2 years in the field. First round of re-characterizations indicate:

  – Continued utility interconnect standard compliance,

  – Conversion efficiency changes are basically within measurement error,

  – Maximum continued power rating evaluation indicates diminishing capability. Investigation continues and will be presented in 2009 PVSC

  *4 year re-characterization to be completed October 2009

**Test A Efficiency Curve
2 Year Comparison**

Efficiency (2007)
Efficiency (2005)

x-axis: ac Power (W)
y-axis: %Efficiency

**Maximum Continuous Power Rating Test**

2470 watts (30 pt avg)

2175 watts (30pt avg)

2nd yr rating

y-axis left: ac Power (W)
y-axis right: Temperatures (C)
x-axis: time of day

DCV   ACWATTS   ACWATTS   ambient   HS   cap

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- Hosted personnel from six companies (four test houses including Atlas and Atonometrics, two module/systems manufacturers – Sunpower, Advent) for hands-on "training" of SNL module and/or systems test and analysis methodologies
- Continuously respond to emails/phone calls on SNL test methodologies
- Prepared solicitation for transfer of SNL's PV Module Database maintenance and routine outdoor PV module testing to populate database; expect to announce award in 3Q
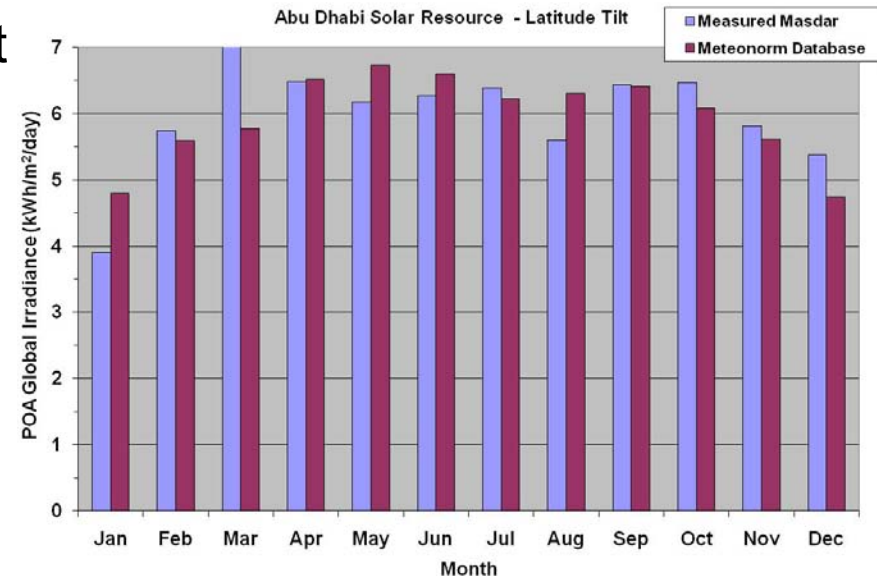


- SNL Module Test Protocol documentation under development to support efficient test technology transfer
- Field test protocol under development to ensure accurate and safe field testing
    - SNL leading the effort with input from a team of field test experts from NREL, SWRES (NMSU), and SERES (FSEC); draft to be ready for industry review by the end of FY09

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# Accomplishments: International Involvement

Sandia's International Involvement gaining ground

- Masdar
  - On-site visit to Masdar City development, providing real-time feedback on plans for PV use as a primary energy generation source
  - Aiding Masdar in analysis of International PV Competition (41 1-kW sized grid-tied PV systems in Abu Dhabi, UAE)
  - Technical contribution towards test/certification facility
- Asia-Pacific Partnership
  - Detailed presentations of cell, module, and systems measurement techniques required for believable performance and reliability assessments at workshop in China
  - 2nd workshop to be held in US June 2009
- International standards development



Abu Dhabi Solar Resource - Latitude Tilt — Measured Masdar, Meteonorm Database; POA Global Irradiance (kWh/m²/day) by Month (Jan–Dec)

Sample of data gathering in Abu Dhabi: Comparison of global irradiance measurement against database

**Additional Accomplishments**

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- Provided T&E expertise to 49 SAI/SEGIS and Industry partners*
  - Leads to product design optimizations
  - Provided T&E performance data and reports for 3 TPP Stage Gate 1 assessments
- Doubled the number of modules in Sandia's PV Module database to 422
  - Detailed model parameters required for modeling module and system performance in any environment; used in the Solar Advisor Model, Maui Solar Model, other developmental performance software
  - Numerous requests from industry partners for continuously updating the database
- Participated in Codes and Standards development: NEC 2008, NEC 2011, IEC 62108, UL 8703 for CPV, IEEE 1547 series; Creating Solar ABCs working groups to coordinate efforts
  - Improved PV performance and safety necessary for high grid penetration

*Specific results for these industry partners will not be shown to protect proprietary information

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# Productivity: Funding and Milestones

## Funding: $1795K FY2008/ $2025K FY2009

| FY08 Milestones | Completed |
|---|---|
| Completion of all stage-gate required tests and reports delivered for S-G reviews. | 9/30/08 |
| Baseline assessments of all TPP technologies completed, and capabilities in place for further assessment of technology developments. | 9/30/08 |
| Develop test protocols necessary to meet all T&E Stage gate requests. | 4/30/08 |
| Field assessment completed on one large (utility-scale) system. | 4/30/08 |
| Develop and apply methodology for accelerated entry of new modules into performance database. | 4/30/08 |
| Report demonstrating effectiveness of inverter performance model with measured data, including its use in SAM, and addressing new topologies promised or delivered by TPPs. | 5/31/08 |
| Conduct long-term inverter operation detailed laboratory re-characterization and make comparative evaluations to previous evaluations. | 9/30/08 |
| Complete all inverter and BOS-related stage-gate evaluation requirements, including feedback to review teams in a timely and complete manner to support the stage gate review process. | 9/30/08 |
| Complete performance and operational assessments of 3 new inverter and system controller topologies. Examples may include micro-inverters, utility-scale inverters, and new component integrations, such as transformerless designs. | 9/30/08 |
| Published Journal Article on linkage between field and lab operational data in determining inverter-related aspects of PV systems reliability. | 7/31/08 |
| Establishment of "Inverter/Controller/BOS/EMS Industry Advisory Group" for R&D Prioritization for Renewable System Integrations and Energy Management Systems with initial survey released to the membership. | 8/31/08 |

| FY09 Milestones | Planned Complete |
|---|---|
| All stage-gate evaluations completed for TPPs, Incubators, and other SAI participants | 9/30/09 |
| PV system hourly data sets in standardized format (coordinated with NREL) | 9/30/09 |
| Test technology transferred to at least one industry-supported test lab and report written on transfer process | 9/30/09 |
| Verify measurement accuracy of contractor selected for PV Module Database effort through comparative module testing | 9/30/09 |
| Field PV System Test protocol provided to industry | 6/30/09 |
| Exercise Field PV System Test data collection protocol through assessment of at least one large-scale system | 9/30/09 |
| SEGIS evaluation procedure completed and implemented | 9/30/09 |
| Continuation of long term inverter evaluation with summary report on progress | 9/30/09 |

- Reaching SETP's LCOE goals requires *accurate* performance parameters, system-level losses, and system derate factors (see M&A)

- SNL T&E provides these parameters to industry and modelers for cells, modules, inverters, BOS components, and fielded systems
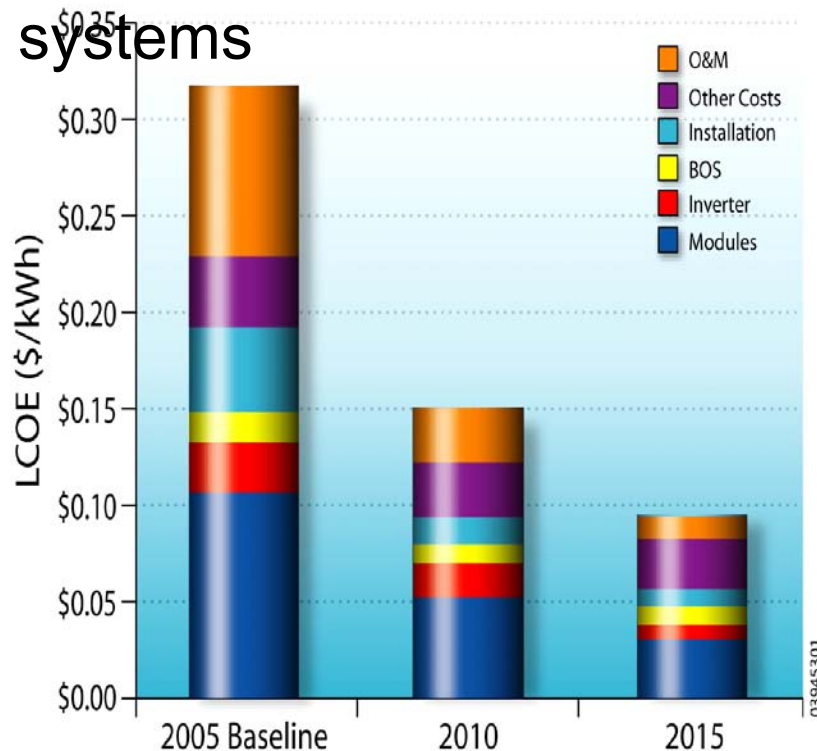


- T&E provides the *feedback loop* to industry to make the improvements necessary to reach these goals

- T&E independently *verifies* the goals have been met

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**Impact of T&E**

- Multiple stakeholders benefiting from T&E expertise at Sandia
  - SAI baseline testing and Stage Gate review recommendations led to *product redesigns for two SAI partners*
  - *Helped resolve an industry partner's issue* with inverter line noise interference in voltages
  - *Supported 49 industry partners* across the supply chain to enhance products and capabilities
  - Test technology transfer has already *enabled more rapid feedback on module design for Sunpower* and has *accelerated development of module test capability at two test houses*

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# Impact of T&E

- Sandia's T&E capabilities broadening the global knowledge base
  - PV array field system degradation analysis will *elucidate differences between module degradation rates and systems degradation rates*, enhancing performance models and predictions
  - Doubled the number of modules in SNL PV Module Database to *support modeling performance output, systems design decisions*
  - *Conducted beta testing* and crucial developmental support of 30kW bi-polar transformerless inverter
  - Verifying Codes and Standards methodologies will lead to high penetration of qualified, high-performing product PV
    - SNL continuing analysis for stability concerns for IEEE 1547 e.g. adjustable ramp rates to ensure believable results

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# Future Directions

- **Develop test technologies for new products/systems**
  - Thin films, CPV
  - SAI products (eg., SEGIS)
  - Generate year-long data sets for new technologies to support model validation work
- **New approaches to unsolved issues**
  - Arcing and ground faults
  - Soiling derate experiments
- **Support transfer of testing methods to industry**
  - Growth of PV support industry
  - Module test technology to at least two outside test houses
  - Transfer maintenance of PV Module Database to commercial test house
- **Enhanced assessment of high-penetration, grid-connected scenarios**
  - Micro-grid modifications to optimize community-scale systems integrations (Mesa del Sol, Hawaii, military bases, etc.)
  - Anti-islanding prevention and decision optimization
  - Evaluate price strategies for generation and load shedding
  - Advanced control and distributed monitoring capabilities to facilitate testing of new generation of inverters
  - Develop and implement communication enhancement capabilities for testing perturbation mitigation scenarios
- **Accelerate adoption of Codes and Standards**
  - Beta testing of proposed transitional anti-islanding methodologies per IEEE 1547.4 Draft protocol
  - Beta testing to demonstrate IEEE 1547.6 Draft standard compliance to allow DR interconnection to network systems

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# Key Publications

## Publications

- Cameron et al., Comparison of PV System Performance-Model Predictions with Measured PV System Performance, 33rd IEEE PVSC

- Ropp, Gonzalez et al., Development of a MATLAB/Simulink Model of a Single-Phase Grid-Connected Photovoltaic System, 33rd IEEE PVSC

- Granata et al., Long-Term Performance and Reliability Assessment of 8 PV Arrays at Sandia National Laboratories, submitted to 34th IEEE PVSC

- Finn et al., Multiple Junction Cell Characterization Using the LBIC Method, submitted to 34th IEEE PVSC

- Kuszmaul et al., DETL Advanced MicroGrid Demonstration, submitted to 34th IEEE PVSC

- Gonzalez et al., Long-Term Inverter Operation Demonstration at Sandia National Laboratories, submitted to 34th IEEE PVSC

## Presentations

- Granata, Cell and Indoor PV Module Measurements, Outdoor PV Module and System Measurements, International Photovoltaic Reliability Workshop, Shanghai, China, December 2008 (Invited Presentations).