DOE Solar Energy Technologies Program

FY 2008 ANNUAL REPORT

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

DOE Solar Energy Technologies Program

It has been my pleasure to serve as the Program Manager in 2008. As you will see in this report, the U.S. Department of Energy (DOE) Solar Energy Technologies Program (SETP) plays a key role in accelerating the development of the U.S. solar industry and the advancement of solar technologies.

The long-term objective of the program is to achieve high market penetration of solar energy technologies with an interim goal of achieving parity with conventional forms of electricity by 2015.

SETP is managed by a core group of technical and policy professionals at DOE and implemented through four separate subprograms: Photovoltaics (PV), Concentrating Solar Power (CSP), Systems Integration, and Market Transformation. The PV and CSP components focus on lowering the levelized cost of solar energy through a broad applied research and development (R&D) pipeline that covers device and process proof-of-concept, component and module prototyping, manufacturing scale-up, and system demonstration. Systems Integration and Market Transformation components address the diverse market and technical issues and challenges that must be surmounted to achieve high market penetration for solar technologies. All program efforts are conducted through an expansive set of partnerships with industry, government laboratories, universities, state and local governments, and other national organizations.

During fiscal year (FY) 2008, SETP continued to make progress toward both long- and short-term goals. Highlights from the past year include the following:

Photovoltaics

- Made awards totaling more than $65 million for 62 industry projects spanning early-stage to market development. The awards addressed the challenges of scaling up novel, low-cost manufacturing across technologies including crystalline silicon, thin film, and concentrating PV. Success stories include:
  - SunPower achieved a production record of 23.6% efficiency on its all back-contacted crystalline silicon solar cell.
  - SoloPower moved its novel electroplating-based technology from a batch pilot operation in a development laboratory to a roll-to-roll processing line in a manufacturing facility.
  - MicroLink Devices developed an epitaxial lift-off process to manufacture solar cells for concentrator systems that reduce substrate costs while retaining high efficiency.
- Achieved world-record efficiencies through applied research at the national laboratories. Successes include the new record of 20.0% for CIGS thin-film PV device and the record-setting Inverted Metamorphic Multijunction solar cell with 40.8% efficiency at the National Renewable Energy Laboratory.

Concentrating Solar Power

- Established 15 partnerships with universities and CSP companies to support innovations in advanced high-temperature, heat-transfer fluids and thermal storage systems as important stepping stones for CSP to become cost-competitive with conventional energy sources.
- Partnered with the Bureau of Land Management to initiate a Programmatic Environmental Impact Statement and conducted other joint activities necessary for the development of federal land in the Southwest for utility-scale solar projects.

Systems Integration

- Awarded funds to 12 industry teams through the Solar Energy Grid Integration Systems project to develop new inverters and controllers with interfaces to energy-management systems. As much as $24 million in DOE investments is committed to completing these pilot-production-phase projects.
- Established monitoring of large-scale PV performance at high-penetration sites in California, Colorado, and Hawaii to better understand how high levels of PV impact the grid and reduce installation costs.

Market Transformation

- Strengthened the responsiveness, effectiveness, and accessibility of PV codes and standards through the Solar America Board for Codes and Standards. The board tracks key issues and released three studies on interconnection procedures for utility regulators, solar access laws, and external disconnect switches.
- Expanded the Solar America Cities activity from 13 to 25 partnerships to further accelerate the adoption of solar energy technologies in a comprehensive citywide approach.

In FY 2008, it was very encouraging for all in the solar industry to again see significant market growth and adoption of solar technologies both within and outside the United States. At both the state and federal level, solar technology was increasingly seen as a solution to long-term concerns about the environment, energy security, and price stability of energy sources. The industry, however, was not spared from the events and conditions that have impacted the global economy as whole. As we look toward the future, the DOE team will continue to structure program activities within a framework that can adjust to short-term industry and market conditions while also supporting long-term investments in research, development, and deployment.

We look forward to working with all our stakeholders and partners to accomplish program goals and objectives in this important and exciting field, and we welcome your continued support and feedback.

Sincerely,

John Lushetsky
Program Manager
Solar Energy Technologies Program

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Photovoltaic Subprogram Overview

After launching several new programs under the Solar America Initiative (SAI) in fiscal year (FY) 2007, FY 2008 represents the first full-year implementation of SAI funding towards achieving grid parity by 2015.

Funds were allocated among four key photovoltaic (PV) research and development areas (R&D):

- Technology Pathway Partnerships (TPPs) are industry-led, public-private partnerships. The 11 awardees bring together key players across the supply chain to focus on innovations that reduce costs.
- University PV Process and Product Development projects are leveraging the knowledge of universities to bring technology from laboratory to marketplace.
- PV Technology Incubators are developing promising module technologies that have been successfully demonstrated on a small scale.
- Next-Generation Research projects investigate high-risk/high-payoff PV device and process concepts.

These subprograms areas comprise 62 projects that span early stage, applied R&D through market-oriented product and process development. In regards to the PV Technology Incubator awards, the second round of winners were announced with the selection of six new projects and seven of the original 10 projects proceeding to the second 9-month phase of their projects.

In addition, the PV subprogram expanded efforts in technology transfer through an activity to bolster the efforts of lab staff who work with industry partners though cooperative research and development agreements (CRADAs) at the National Renewable Energy Laboratory. Through cost shared partnerships with industry, these projects seek to mature national lab research into marketable technologies.

Other key efforts in PV reliability were expanded to help accelerate market acceptance of modules based on new materials. Internal “seed” research was funded to help bridge gaps between the traditional core research efforts at the national labs and to ensure that novel research topics are given an opportunity to demonstrate their promise.

To improve system modeling and analysis, a new version of the Solar Advisory Model (SAM) has been developed by the national laboratories. Widely used within the solar industry, SAM provides a standardized tool for assessing PV system performance through a levelized cost of energy metric.

Several projects also supported test and evaluation R&D. One example is the lab- and field-testing of industry-supplied products through the national labs. Products from more than 60 solar companies were tested for this purpose, and the testing data gathered was used to develop a better test database, test methods, and standards.

Another key activity involved the development of new PV inverters, controllers, and energy-management systems for distributed PV systems through the program’s Solar Energy Grid Integration Systems project.

During FY 2008, several new market transformation activities begun in late FY 2007 were more fully developed. These activities included the Solar America Board for Codes and Standards, 25 Solar America City partnerships, three state technical outreach partnerships, one utility technical outreach partnership, and seven Solar America Showcases. The market transformation activities served to reduce the barriers to widespread solar implementation nationwide.

These and many more activities are detailed in the following reports.

Silicon Center of Excellence
University Crystalline Silicon Photovoltaics Research and Development

Performing Organization: Georgia Institute of Technology (GIT)

Key Technical Contact: Carolyn Elam, (303) 275-4953, carolyn.elam@go.doe.gov

DOE HQ Technology Manager: Scott Stephens, (202) 586-0565, Scott.Stephens@ee.doe.gov

FY 2008 Budgets: $713K (DOE), $178K (GIT)

Objectives

- Advance state of crystalline silicon (Si) solar cell technology to make photovoltaics (PV) more competitive with conventional energy sources.
- Emphasize fundamental and applied research to develop low-cost, high-efficiency cells on commercial silicon substrates.
- Utilize strong PV industry involvement and support strong PV education program domestically.
- Reduce c-Si module price to $1.25/W by 2020 with installed PV system cost of $3.30/W and levelized cost of energy (LCOE) of 9¢/kWh.

Accomplishments

- Developed cost model to show 18% to 20% efficient thin c-Si cells can reduce levelized cost of PV-generated electricity to 5–10¢/kWh.
- Developed clear roadmap for 20% efficient cells that involves development of:
  - Narrow Silver (Ag) grid & improved contacts: +1%.
  - High sheet resistance emitter: +1%.
  - Dielectric passivation and reflective back contact: +1.
- Developed new experimental method to measure amount of hydrogen injected into Si during firing of screen-printed contacts.
- Developed Ag-colloid back surface reflector that enhances light trapping and improve short circuit current by 2.6%.
- Achieved 18% efficient commercial-ready cells using high sheet resistance emitters.
- Developed 19% efficient 4-cm2 cells with passivated Boron-Back Surface Field (B-BSF).
- Developed 19%-efficient 4-cm2 cells with rear dielectric passivation without parasitic shunting.

Future Directions

- Ended on June 30, 2008, so no further work is planned for this award.

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1. Major FY 2008 Publications

A. Das; D.S. Kim; V. Meemongkolkiat; A. Rohatgi. "19% efficient screen –printred cells using a passivated transparent boron back surface field." *33rd IEEE PVSC Proceedings*; 2008, San Diego, California.

D.S. Kim; M.H. Kang; B. Rounsaville; A. Ristow; A. Rohatgi; Y. Awad; G. Okoniewski; A. Moore; M. Davies; R. Smirani; M.A. El Khakani; J. Hong. "High performance solar cells with silicon carbon nitride (SiCxNy) antireflection coatings deposited from polymeric solid source." *33rd IEEE PVSC Proceedings*; 2008, San Diego, California.

A. Ebong; D.S. Kim; A. Rohatgi; W. Zhang. "Understanding the mechanism of light induced plating of silver on screen printed contacts for high sheet resistance emitters with low surface phosphorus concentration." *33rd IEEE PVSC Proceedings*; 2008, San Diego, California.

S. Ramanathan; V. Meemongkolkiat; A. Rohatgi. "Spin on based process for simultaneous diffusion and passivation for high efficiency LBSF solar cells." *33rd IEEE PVSC Proceedings*; 2008, San Diego, California.

Next Generation Projects

Performing Organizations:	Arizona State University (ASU); California Institute of Technology (CIT); Massachusetts Institute of Technology (MIT); Mayaterials, Inc.; Pennsylvania State University (Penn State); Rochester Institute of Technology (RIT); Solasta, Inc.; Solexant Corporation; Soltaix LLC; Stanford University (Stanford); University of California, Davis (UC Davis); University of California, San Diego (UC San Diego); University of Colorado (CU); University of Delaware (UD); University of Florida (UF); University of Illinois; University of Michigan (U-M); University of South Florida (USF); University of Washington (UW); Voxtel, Inc.; Wakonda Technologies, Inc.
Key Technical Contacts:	Carolyn Elam (DOE/GO, Primary Contact), 303-275-4953, carolyn.elam@go.doe.gov Joe Lucas (DOE/GO), 303-275-4849, joe.lucas@go.doe.gov Jim Payne (DOE/GO), 303-275-4756, jim.payne@go.doe.gov Brad Ring (DOE/GO), 303-275-4930, brad.ring@go.doe.gov Holly Thomas (DOE/GO), 303-275-4818, holly.thomas@go.doe.gov
DOE HQ Technology Manager:	Marie Mapes, 202-586-000, marie.mapes@hq.doe.gov
FY 2008 Budgets:	$6,000K (DOE/GO)

Objectives

- Make solar electricity from photovoltaics (PV) cost-competitive with conventional forms.
- Address long-term technological and scientific challenges for improved performance, lower cost, and improved reliability of PV components and systems.

Accomplishments

- Completed merit review of the applications
- Selections announced March 2008 with 25 projects negotiated and awarded.

Future Directions

- Evaluate progress of critical milestones and decide at the end of the each project's first phase, starting in fiscal year (FY) 2009 and extending into FY 2010.

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1. Introduction

The Next Generation Photovoltaic (PV) Devices and Processes projects represent innovative, revolutionary, and highly disruptive next-generation PV technologies. These PV research and development (R&D) activities are expected to produce prototype PV cells and/or processes by 2015, with full commercialization by 2030.

2. Technical Approach

The selected projects below each received $240K.

Agreement Title
ASU; Mark van Schilfgaarde (II-IV-V Based Thin Film Tandem PV Cell)
ASU; John Kouvetakis (Advanced Semiconductor Materials for PV)
CIT; Harry Atwater (Solar Cells from Earth-Abundant Semiconductors)
MIT; Vladimir Bulovic (Colloidal Nanocrystal Quantum Dot PV Devices)
MIT; Emanuel Sachs (Recrystallization of Silicon Wafers in Thin Film Capsules)
Mayaterials, Inc.; Richard Laine (Solar Grade Silicon from Ag By-Products)
Penn State; Joan Redwing (High Aspect Ratio Semiconductor Heterojunction Cell)
Penn State; Harry Allcock (Improved Electrodes and Electrolytes for Dye-Based Solar Cells)

Agreement Title
RIT; Seth M. Hubbard (High Efficiency Nanostructured III-V Cells for PV Concentrators)
Solasta, Inc.; Michael Naughton (High Efficiency Power via Separated Photo and Voltaic Pathways)
Solexant Corporation; Alison Breeze (High Efficiency Quantum Dot Cells Based on Multiple Exciton Generation)
Soltaix LLC; Mehrdad Moslehi (Ultra-High-Efficiency, Thin-Film, Crystalline Silicon Solar Cells)
Stanford; Yi Cui ((Culn (Ga) Se2 (CIGS) Nanowire Solar Cells))
Stanford; Peter Peumans (Nanostructured Materials for Solution-Processed PV)
UC-Davis; Adam Moule (Functional Multi-Layer Solution Processable Polymer Solar Cells)
UC San Diego; Edward T. Yu (High-efficiency PV Based on Semiconductor Nanostructures)
CU; Josef Michl (Exciton Fission for an Ultra-High Efficiency, Low Cost Solar Cell)
UD; William Shafarman (Novel Approaches to Wide Bandgap CuInSe2 Based Absorbers)
UF; Jiangeng Xue (High Efficiency Hybrid Organic-Inorganic PV Cells)
University of Illinois; John Rogers (Transfer Printed Microcells with Micro-Optic Concentrators)
U-M; Stephen Forrest (Crystalline Organic PV Cells)
USF; Christos Ferekides (Next Generation CdTe Technology: Substrate Foil-Based Cells)
UW; Alex Jen (Interfacial Engineering for p-Conjugated Polymer-Based Heterojunction Devices)
Voxtel, Inc.; David Schut (Optimization of Impact Ionization in Composite Nanocrystal Devices)
Wakonda; Leslie Fritzemeier (Novel Manufacturing of Flexible III-V Thin Films)

3. Results and Accomplishments

3.1 II-IV-V Based Thin Film Tandem PV Cell (ASU-Schilfgaarde)

Accomplishments

- Developed methods to synthesize II-IV-V2 targets for pulsed laser deposition and sputtering with a range of compositions.
- Initiated systematic study of thin film ZnGeAs2 growth using pulsed-laser deposition.
- Carried out calculations for new II-IV-V candidates: MgGeAs2 and MgSnAs2.

Future Directions

- Optimize growth conditions of ZnGeAs2, ZnSnP2, and other II-IV-V2 compounds and alloys deemed to be useful for PV work for stoichiometry, defect density, and doping.
- Perform density function calculations, including advanced technique to model bulk and defect properties of II-IV-V2 compounds and alloys, emphasis on low cost and low volatility elements.
- Develop heterostructure and tandem PV devices and measure performance.

3.2 Advanced Semiconductor Materials for PVs (ASU-Kouvetakis)

Accomplishments

- Completed scale-up of deposition chemistry to transition ASU Ge-on-Si technology from laboratory-scale substrates to 4” Si platforms.
- Synthesized new families of SiGeSn alloys lattice-matched to Ge to serve as fourth junction in PV stack Si(100)/Ge/SiGeSn/InGaAs/InGaP.
- Developed proof-of-concept materials growth of fully lattice matched Si(100)/Ge/SiGeSn/InGaAs structures en route to four-junction structure.
- Determined optical properties for SiGeSn/Ge structures demonstrating independent tuning of band structure at a fixed lattice constant for the first time in group-IV materials.

Future Directions

- Complete scale-up of growth of Ge-on-Si to commercial-size large area wafers (4” ≤ φ ≤ 12”) in collaboration with industrial partners, ASM America and Epiworks, Inc.
- Fabricate p- and n-doped GeSiSn layers and subsequent formation and measurements of GeSiSn PIN diodes to demonstrate integration in hybrid Group IV / III-V PV designs.
- Complete ongoing characterizations of compositional dependence of bandgap in SiGeSn alloys for use in four-junction cells.
- Fabricate p- and n-doped GeSn layers and measurements of GeSn PIN diodes en route to two junction prototypes.

3.3 Solar Cells from Earth-Abundant Semiconductors (CIT–Atwater)

This project has just begun, but objectives include:

- Synthesize two-junction cells with top subcells composed of earth-abundant compound semiconductors including quantum dots (QD), earth-abundant Zn3P2 films, and bottom subcells composed of Si pn junction cells.

- Exploit recent advances in plasmonics to realize high efficiency solar cells based on enhanced absorption and carrier collection in ultrathin film and QD absorber layers.
- Design plasmonic structures to enhance solar light absorption in ultrathin film Si and wide bandgap earth-abundant Zn3P2 films and low-dimensional semiconductor structures.

3.4 Colloidal Nanocrystal Quantum Dot PV Devices (MIT-Bulovic)

Accomplishments

- Demonstrated morphology of printed QD films can be improved with use of parylene-C coating, resulting in uniform QD surface coverage, enhanced short circuit current, open circuit voltage, and built-in potential.
- Demonstrated high open circuit voltage can be achieved with stable and transparent indium tin oxide electrodes.
- Demonstrated new synthesis of core-shell IR QDs of PbS.
- Demonstrated scale-up of QD synthesis.
- Applied chemical treatment of thin QD films to facilitate QD tight-packing.

Future Directions

- Discern which interface dominantly contributes to exciton dissociation processes in QD-PVs.
- Fabricate All-Metal-Oxide PVs.
- Incorporate IR QDs in the PV structures.
- QD thin film process development to minimize pin-holes responsible for QD-PV device shunting.

3.5 Recrystallization of Silicon Wafers in Thin Film Capsules (MIT-Sachs)

Accomplishments

- Scaled up size of wafers processed by almost a factor of four.
- Improved thickness control of wafers.
- Demonstrated low dislocation density in recrystallized wafers.
- Initiate work on grain nucleation and modeling of crystal growth.

Future Directions

- Focus on attaining good electronic properties and making efficient solar cells.

3.6 Solar Grade Silicon from Agricultural By-Products (Mayaterials-Laine)

Accomplishments

- Developed extraction and purification technique that results in silica with dopant levels that meet target objectives.
  - Total silica impurities are at or below 10 ppm total – 99.999% purity.
  - Process scaled to 500g batch sizes and testing procedures have been established to ensure fast turnaround resulting in faster program execution.

Future Directions

- Convert high-purity silica into solar grade silicon.
- Remove as much of remaining impurities as possible from silica prior to conversion.
- Investigate alternative paths to solar-grade silicon through silane-based process.

3.7 High Aspect Ratio Semiconductor Heterojunction Cells (Penn State-Redwing)

Accomplishments

- Controlled growth of Si wires with diameters of 700 nm using a gold catalyst contained within pores etched into SiO2/Si substrates.
- Fabricated 25 μm long Si wires with diameters ranging from 1.5 – 2.5 μm by deep reactive ion etching (DRIE) to be used as a control.
- Grew single crystal of an n-type coating on to p-type vapor-liquid-solid (VLS)-grown Si nanowires by low pressure chemical vapor deposition.
- Intrinsic a-Si coating on VLS-grown Si nanowires and etched Si wires using PECVD.
- Developed ITO coating of etched Si wires.
- Fabricated radial junction using etched Si wires and gas phase dopant diffusion, resulting in diode like I-V characteristics.
- Measured Voc of 320 mV measured on VLS-grown Si nanowires obtained from a redox couple using a non-aqueous solution of [Ru(bpy)3]2+.

Future Directions

- Improve VLS growth of Si wires to achieve 1:1 relationship between wire and SiO2 pore diameters and increase density of Si wires to maximize absorption area.
- Optimize radial junction solar cell fabricated using etched Si pillars and gas phase diffusion for use as control structure.
- Fabricate and test radial junction wire devices formed, using doped VLS Si wires and LPCVD n-type coating process.
- Fabricate and test radial junction devices formed using a-Si PECVD coating process.
- Transfer patterning and growth process to glass substrates to reduce production costs.

3.8 Improved Electrodes and Electrolytes for Dye-Based Solar Cells (Penn State-Allcock)

Accomplishments

- Synthesized methoxyethoxyethoxy phosphazene oligomer and polymer materials as base for dye solar cell electrolytes. Formulated electrolytes with phosphazene and LiI / I2 components and performed electrochemical testing.
- Fabricated TiO2 electrodes with microsphere-patterned nanoporous type and nanorod/nanotube type structures, performed electrochemical testing under traditional dye solar cell conditions.
- Performed test assembly of phosphazene electrolytes with nanoporous and nanotublar electrodes, obtained preliminary results.
- Formulated gel electrolytes based on polymeric phosphazene and propylene carbonate. Preformed electrochemical experiments and assembled test cells for efficiency evaluation.
- Developed characterization standard for electrolyte infusion into nanoporous substrated using SEM method. Identified ease or difficulty of penetration of polymeric compounds into various nanoporous electrodes.

Future Directions

- Optimize cell fabrication of existing electrolyte and electrode pairs.
- Synthesize anion-conduction promoting phosphazene electrolyte materials and electrochemical/assembled cell testing.
- Fabricate electrodes with alternate nanopatterns and assembly/testing of corresponding dye cells.
- Fabricate procedures to improve electrolyte infiltration and viability of mass production.
- Explore suitable additives for formulation of cost effective, thermally stable gel electrolytes.

3.9 High Efficiency Nanostructured III-V Cells for PV Concentrators (RIT-Hubbard)

Accomplishments

- Completed growth and strain balancing of 5X, 10X and 20X arrays of InAs QDs. Strain balancing was vital to reduction of nonradiative recombination in the QD stacks.
- Grew, fabricated, and measured initial baseline p-i-n and 5-20X array QD enhanced GaAs solar cells. Correct strain balancing lead to an improved short circuit current value compared to cells without QD stacks.
- Took high concentration measurements for baseline and 5X QD enhanced solar cell. An AM1.5d (low AOD) efficiency of 15.0% at 100X concentration was measured for the 5X QD cell, as compared to 12.8% for a baseline cell without QDs.
- Measured thermal conductivity of solar cell structure with and without QDs and compared structure thermal resistance with that of bulk GaAs. The results are important for thermal management of the concentrator solar cells.

Future Directions

- Optimize concentrator and QD cell growth. Specifically QD enhanced cell design and QD material. Increased stacking of QD layers through use of high quality strain balancing approach. Demonstrate further enhancement of short circuit current and efficiency under concentration.
- Investigate IB levels in InAs QD enhanced solar cells as well as other identified candidate materials (e.g., Sb based QDs).
- Develop model and computer simulation of QD enhanced solar cells and intermediate band solar cells.
- Continue experimental investigation of thermal properties of nanostructured solar cell structures to optimize heat removal from solar cells designed for concentrator applications.
- Measure performance and spectral response of cells as function of atmospheric and environmental conditions.

3.10 High Efficiency Power via Separated Photo and Voltaic Pathways (Solasta-Naughton)

Accomplishments

- Fabricated a-Si solar cells in Solasta architecture.
- Demonstrated increased light collection in Solasta cells as compared to conventional, planar cells having same absorber thickness.
- Demonstrated increased charge carrier collection and increased PV efficiency in Solasta cells as compared to conventional, planar cells having same absorber thickness.

Future Directions

- Improve absolute efficiency of a-Si cells, toward 15%-20%.
- Increase cell area to 100 cm2.
- Extend Solasta thin film solar cell architecture to other absorber media.
- Incorporate third generation phenomena in Solasta architecture.

3.11 High Efficiency QD Cells Based on Multiple Exciton Generation (Solexant-Breeze)

Accomplishments

- Developed layer-by-layer deposition technique for QD films with in-situ ligand exchange.

- Demonstrated 79% estimated peak internal quantum efficiency for planar QD solar cell device (year one milestone).
- Demonstrated improved near-IR performance for QD devices utilizing plasma and chemical processing of QD films.
- Established equipment and process for atomic layer deposition (ALD) of metal sulfide thin films.
- Created first QD/metal sulfide ALD hybrid devices.

Future Directions
- Finish development for complete coverage of high surface area substrates with QD sensitizers.
- Expand selection of metal sulfide ALD materials and ALD film process treatment.
- Advance QD/ALD devices from planar to nanostructured design.
- Develop barrier layer films to increase device efficiency via reduction of interface recombination.

3.12 Ultra-High-Efficiency, Thin-Film, Crystalline Silicon Solar Cells (Soltaix-Moslehi)

Accomplishments
- Confirmed improved mechanical integrity of Soletaix's structure compared to conventional crystalline silicon structures and enabled characterization of geometrical parameters on mechanical integrity.
- Obtained initial data from mechanical testing to establish integrity of starting material.
- Developed short and full flow wafers to define substrate generation process at low cost.

Future Directions
- Continue electrical and optical simulations to further optimize Soletaix's structure coupled with more mechanical experiments to determine a geometrical window which maximizes performance, lowers silicon consumption, and is mechanically robust.
- Demonstrate ability to further utilize less silicon to improve cost reduction.
- Complete process integration of working cell on Soletaix's substrates.
- Demonstrate 17% efficient cells.

3.13 CuIn (Ga) Se2 (CIGS) Nanowire Solar Cells (Stanford - Yi Cui)

Accomplishments
- Synthesized family of Cu-In-Ga-Se nanowire materials, including GaSe, In2Se3, In2-xGaxSe3, CuInSe2.
- Understood structure evolution during CuInSe2-CdS junction formation.

Future Directions
- Synthesize CuInGaSe2 nanowire materials.
- Perform single nanowire solar cell study.

3.14 Nanostructured Materials for Solution-Processed PV (Stanford-Peumans)

Accomplishments
- Demonstrated solution-processed silver nanowire transparent electrode with sheet resistance <10Ohm/sq and solar-averaged transparency >85%. The materials cost is ~$0.10/m2.
- Demonstrated basic organic solar cell on silver nanowire electrodes.
- Demonstrated solution-processed ZnO nanowire transparent electrode with sheet resistance ~1kOhm/sq.

Future Directions
- Improve performance of silver nanowire electrodes to sheet resistances <5hm/sq and transparencies>90%.
- Improve sheet resistance of ZnO nanowire electrodes. Transparency assessment of these electrodes.
- Integrate solution-processed transparent electrodes into single junction cells of various types to demonstrate technical viability.
- Analyze industrial-scale manufacturing.

3.15 Functional Multi-Layer Solution Processable Polymer Solar Cells (UC-Davis-Moule)

Accomplishments
- Prepared film samples and measurements using atomic force microscopy (topography, phase, conduction and Kelvin probe modes), neutron reflectometry, ultra-fast pump-probe optical laser spectroscopy, and scanning electron microscopy.
- Set up optical and electrical modeling of multi-layer films. First publication is in preparation.

Future Directions
- Develop multi-layer deposition method.
- Develop multi-layer devices.
- Develop predictive optical and electrical modeling tools.

3.16 High-efficiency PV Based on Semiconductor Nanostructures (UC San Diego-Yu)

Accomplishments
- Demonstrated absorption over increased range of wavelength in lattice-matched GaInAsP/InP quantum-well solar cells, relative to InP homojunction solar cells.

- Demonstrated increased power conversion efficiency in GaInAsP/InP quantum-well solar cells compared to InP homojunction solar cells (~5-7% increase in conversion efficiency).
- Demonstrated plasmonic scattering by Au nanostructures of normally incident photons into lateral propagation paths associated with waveguide modes in quantum-well solar cells, and increase in photon absorption efficiency.
- Demonstrated Mie scattering by dielectric nanoparticles of normally incident photons into lateral propagation paths associated with waveguide modes in quantum-well solar cells, and increase in photon absorption efficiency.
- Demonstrated increased power conversion efficiency in quantum-well solar cells incorporating nanostructure scattering effects relative to quantum-well solar cells without nanostructured scatterers (~17% increase in power conversion efficiency).

Future Directions

- Design and demonstrate quantum-well solar cells with improved scattering-based coupling to quantum-well waveguide modes for further increases in photon absorption efficiency.
- Explore semiconductor nanowire heterostructure growth for high-efficiency PV.
- Fabricate and characterize semiconductor nanowire heterostructure PV devices.

3.17 Exciton Fission for an Ultra-High Efficiency, Low Cost Solar Cell (CU-Michl)

Accomplishments

- Built instrumentation needed for singlet fission (SF) studies.
- Discovered neat solid 1,3-diphenylisobenzofuran, designed for SF using first principles, exhibits a significant yield of triplet by SF (over 10%).
- Found dimers of 1,3-diphenylisobenzofuran only give significant SF when the constituent monomerichromophores are coupled very strongly (directly connected by a bond).
- Prepared previously computed new SF chromophore of the p-benzoquinodimethane type and discovered that it suffers from non-radiative processes in the excited singlet state, now being modified to avoid this difficulty.
- Discovered computationally two new families of promising SF chromophores.
- Performed theoretical studies of SF dynamics in the coherent and the non-coherent limits.

Future Directions

- Discover new SF chromophore families.
- Synthesize and photophysically characterize new SF chromophore family.
- Examine coupling of SF chromophores into dimers and oligomers.
- Develop procedures for SF chromophore nanocrystal formation and characterization.
- Develop combined coherent/incoherent dynamics model for SF.

3.18 Novel Approaches to Wide Bandgap CuInSe2 Based Absorbers (UD-Shafarman)

Accomplishments

- Developed source for controlled thermal evaporation of silver, and single phase (AgCu)(InGa)Se2 thin films were deposited with controlled composition over a wide range of compositions.
- Demonstrated An (AgCu)(InGa)Se2-based solar cell with 17% conversion efficiency, demonstrating viability of this alloy material for high efficiency solar cells.
- Fabricated An (AgCu)(InGa)Se2 cell with VOC = 0.86 V and efficiency >10%, indicating possible alloy to produce high voltage devices.
- Showed (AgCu)(InGa)Se2 films sub-bandgap optical transmission above 90%, greater than typical Cu(InGa)Se2 films, which is necessary for use as top cell in tandem device.
- Transient photocapacitance measurements of (AgCu)(InGa)Se2 showed low Urbach energies indicated by sharp optical bandtails, suggesting low alloy disorder and high quality material.
- Modified laser system at IEC for annealing of CuInSe2-alloy thin films and conditions for controlled reaction of films were established.
- Established anneal conditions for laser/film treatments to control Cu(InGa)Se2 surface modification and provide apparent melting or partial recrystallization of films.
- Produced laser annealing experiments using low power density with improved current collection and higher efficiency compared to unannealed control samples.

Future Directions

- Quantify effects of evaporation process modifications and relative Ag content in wide bandgap (AgCu)(InGa)Se2 films with respect to materials properties and device behavior.
- Analyze capacitance-based characterization of (AgCu)(InGa)Se2 devices to provide basis and guide for improvement of these devices.
- Expand laser-based annealing to include surface characterization and control as well as different anneal conditions.

3.19 Very High Efficiency Hybrid Organic-Inorganic PV Cells (UF-Xue)

Accomplishments

- Developed two classes of ternary nanosphere systems: a ternary Zn1-xCdxSe nanosphere with molar zinc concentrations of x=17%, 25% and 75% with good monodispersity and sharp emission spectra, and a ternary-core/shell nanosphere Zn1-xCdxS/ZnSe with x=17% and 1.8 eV band gap.
- Developed two synthetic approaches to facilitate separate needs to (1) mimic oligomer functionalized to nanorod surface and (2) quantify physical and electro-optical characteristics of pristine ternary nanostructures.
- Synthesized two main building blocks of mono-functionalized all-thiophene oligome, validating chosen synthetic route. A model compound bearing phosphonic acid functional group was synthesized, structurally characterized, and transferred to Holloway group for initial binding studies.
- Prepared and characterized two different series of poly(phenylene ethynylene) polymers, one containing amino end caps and one containing phosphonate end caps.
- Studied CdSe nanosphere size and post-deposition thermal annealing on device performance of P3HT/CdSe hybrid PV cells and achieved conversion efficiencies of 1.5%.

Future Directions

- Synthesize ternary nanorods with bandgap of 1.5-1.8 eV.
- Finalize synthesis of mono- and bi-functional oligomers and polymers and study effect of grafting oligomer/polymers onto CdSe or ZnCdSe nanocrystals on steady-state photoluminescence of materials.
- Optimize morphology of hybrid thin films and align nanorods assisted by an external field.
- Fabricate hybrid PV cells based on functionalized ologimer/polymers and ternary nanocrystals and study effect of ternary composition on Voc in these devices.
- Design and fabricate tandem hybrid PV cells to broadly cover the solar spectrum.

3.20 Transfer Printed Microcells with Micro-Optic Concentrators (University of Illinois-Rogers)

Accomplishments

- Perfected transfer printing of GaAs microcells from single source ink layers.
- Designed and fabricated lenticular micro-lens arrays.
- Developed new metallic inks for direct-write metallization of interconnects, advancing direct ink write design rules by ~100 times.
- Demonstrated full fabrication protocol and high efficiency operation in test platform, based on single crystalline Si PV microcells.
- Optimized printing tool for >99% assembly of medium-scale (900) GaAs microcell.
- Achieved better than 5 micron large area placement accuracy for printed GaAs cells.

Future Directions

- Interconnect direct ink write of microcells in GaAs-based arrays. Geometrically expanded array of printed microcells and conductive landing pads will be delivered from Semprius for interconnection by DIW between landing pads and microcells to form module backplane.
- Demonstrate effectiveness of a multilayer stack design that will significantly enhanced cost competitiveness of necessary wafer side processing of “III-IV” PV ink.
- Integrate full III-V module subsystems.
- Advance cell integration and printing strategies to embed new forms of performance.

3.21 Crystalline Organic PV Cells (U-M-Forrest)

Accomplishments

- Devised new method for accurately and quickly measuring exciton diffusion length in organic crystalline and amorphous thin films.
- Developed model for calculating efficiencies in organic PV cells.
- Invented and demonstrated new organic PV cell based on dual heterojunction architecture.

Future Directions

- Design high efficiency organic tandem cell, using diffusion lengths and absorption characteristics of a range of crystalline and polycrystalline organic materials.
- Determine growth conditions to achieve crystallinity of organic films in tandem cell.
- Fabricate and characterize tandem cells, using optimized materials and growth conditions.
- Begin reliability testing of tandem cells.

3.22 Next Generation CdTe Technology: Substrate Foil-Based Cells (USF-Ferekides)

Accomplishments

- Investigated structural properties of semiconductor films deposited by CSS-in substrate configuration on foil substrates.

- Established in-situ process for sequential deposition of substrate CdTe solar cells on foil substrates.
- Introduced three potential back-contact materials into solar cell structures.
- Initiated adhesion studies of solar cell stacks using tape and nano-indentation techniques.

Future Directions

- Continue adhesion studies of solar cell structures on foil substrates.
- Continue development/investigation of back contact materials.
- Optimize semiconductor deposition process (CSS and/or modified-CSS).
- Optimize heat treatment process.
- Optimize front transparent electrode configuration.

3.23 Interfacial Engineering for p-Conjugated Polymer-Based Heterojunction Devices (UW-Jen)

Accomplishments

- Demonstrated highest power conversion efficiency (4.9%) and good stability in inverted structure bulk heterojunction OPV device with C60-SAM modified ZnO nanoparticles to improve electron collection.
- Developed series of high-performance amorphous Pt-containing π-conjugated polymers with high hole-mobility (> 0.01 cm2V-1s-1) and power conversion efficiency (> 4 %). Broad absorption and high mobility of these polymers are very promising for all-solution process based polymer solar cells.
- Improved performance (35%) of inverted polymer solar cells with C60-SAM modified interface between TiO2 and P3HT:PCBM blend.
- Developed simple and effective method to tune interface of cathode in polymer solar cells by inserting a layer of solution-processable, ZnO/self-assembled monolayer (SAM) between polymer film and cathode. High work-function stable metals could be used as cathode to obtain high power conversion efficiencies that are comparable to state-of-the-art OPVs.
- Demonstrated nanopatterned surfaces could be used to guide phase separation in conjugated polymer/fullerene blends which result in both micro- and nano-scale changes in film morphology.
- Used scanning Kelvin probe microscopy (SKPM) to study the catechol-modified ZnO surfaces in efficient OPV devices.
- Discovered surprising effect using C60 and polythiophene as model compounds for optical studies, could have important implications for design of efficient donor-acceptor pairs.

Future Directions

- Develop low bandgap polymers with better matched absorption to solar spectrum.
- Optimize HOMO and LUMO energy levels of p- and n-type materials to increase Voc.
- Optimize mobility of both p- and n-type materials to improve efficiency.

3.24 Optimization of Impact Ionization in Composite Nanocrystal Devices (Voxtel-Schut)

Accomplishments

- Modeled inorganic and organic constituent components and selected optimal material sets.
- Synthesized needed nanocrystals.
- Designed initial hybrid inorganic/organic devices.
- Measured multiple excitons in nanocrystals.
- Formed monolayers of nanocrystals.
- Measured degree of alteration of exciton transitions through application of a Janus-II dipole.
- Evaluated binding and solvation mechanisms of monothiol and dithiol ligands on nanocrystals and published studies.
- Formed partnerships with Pacific Northwest National Laboratories (PNNL) and Sharp Research Laboratories (SRL) of America to further develop components and processes.

Future Directions

- Optimize quantum confined stark effect (QCSE) energy shifts through UPS characterization and supercritical fluid deposition of ligands.
- Detailed characterization of carrier extraction efficiency through scanning tunneling microscopy (STM) to facilitate seamless integration into full device structures.
- Demonstrated enhanced charge extraction from multi-exciton generated (MEG) carriers.

3.25 Novel Manufacturing of Flexible III-V Thin Films (Wakonda-Fritzemeier)

Accomplishments

- Established reliable and scalable source for substrate raw materials.
- Established internal capability for subscale manufacturing facilities.
- Increased baseline cell performance by 50%.

Future Directions

- Optimize large area processes for performance and manufacturability.
- Increase cell performance to high commercial levels.
- Demonstrate ability to scale to production volumes at competitive costs.

4. FY 2008 Special Recognitions and Patents

ASU

- M. van Schilfgaarde received ASU Gavin Professorship in the School of Materials.
- N. Newman elected fellow, American Physical Society.
- M. van Schilfgaarde elected fellow, American Physical Society.
- N. Newman began work as editor for IEEE Transactions on Applied Superconductivity.
- Kouvetakis filed provisional patent. (ASU Case – 08-198-PR2) "Thin PV cell structures comprising Ge or GeSn on thin Si substrates".
- Kouvetakis filed provisional patent filed. (ASU Case – 08-198) "Hybrid Group IV/III-V Semiconductor structures for applications in PVs and silicon photonics".

MIT

- M.G. Bawendi has been honored as the presenter of the Kavli Lecture in Nanoscience at the Materials Research Society Fall 2008 Meeting, in recognition of his outstanding contributions to nanoscience and nanotechnology.

Mayaterials, Inc.

- Patent filed. "Low cost routes to high purity silicon and derivatives thereof."

Stanford

- Yi Cui, King Abdullah University of Science and Technology (KAUST) Investigator Award (Among twelve scientists selected around the world, Yi Cui is the only assistant professor).
- 2008 Office of Naval Research (ONR) Young Investigator Award.

University of Florida

- J. Xue, co-organizer for fall 2007 meeting of the Materials Research Society (MRS) for a symposium on nanostructures solar cells.
- J. Xue, lead co-organizer for symposium on organic materials and devices for sustainable energy systems at MRS fall 2009 meeting.
- P. H. Holloway, AVS Society's Paul. H. Holloway Young Investigator Award at the 55th AVS International Symposium.

University of Illinois

- John Rogers - fellow, Materials Research Society (inaugural class) (2008).

University of Washington

- Christine Luscombe, NSF Career Award.
- Christine Luscombe, DARPA Young Investigator Award.
- Alex Jen, PMSE Fellow, ACS Polymeric Materials Science and Engineering Division.
- David Ginger, ACS Unilever Award.

5. Major FY 2008 Publications

ASU

- Y.Y. Fang; J. Xie; J. Tolle; R. Roucka; V. R. D'Costa; A.V.G. Chizmeshya; J. Menendez; J. Kouvetakis. "A molecular-based synthetic approach to new group IV materials for high-efficiency, low-cost solar cells and Si-based optoelectronics." *Journal of the American Chemical Society* (in press).
- Y.Y. Fang; J. Tolle; V.R. D'Costa; A.V.G. Chizmeshya; J. Menendez; J. Kouvetakis. "Independent band structure and strain tuning in group IV materials for optoelectronic and photovoltaic applications." *Physical Review Letters* (minor revisions requested).

MIT

- T.P. Osedach; J.H. Alexi; C. Arango; V. Bulovic; S. Geyer; M. Bawendi. "Lateral Organic Quantum Dot Photodetector." Electronic Materials Conference 2008, June 25-27, 2008, Santa Barbara, California.
- Silicon Cast Wafer Recrystallization for PV Applications, Eerik Hantsoo MS Thesis, MIT

Penn State

- S. Yoriya; G.K. Mor; S. Sharma; C.A. Grimes. "Synthesis of ordered arrays of discrete, partially crystalline titania nanotubes by Ti anodization using diethylene glycol electrolytes," *J. Mater. Chem.*, 18, 3332 (2008).
- K. Shankar; J. Bandara; M. Paulose; H. Weitasch; O.K. Varghese; G.K. Mor; T.J. LaTempa; M. Thelakkat; C.A. Grimes. "Highly efficient solar cells using TiO2 nanotube arrays sensitized with a donor-antenna dye," *Nano Lett.*, 8, 1654 (2008).
- S.H. Lee; N.M. Abrams; P.G. Hoertz; G.D. Barber; L.I. Halaoui; T.E. Mallouk. " Coupling of Titania Inverse Opals to Nanocrystalline Titania Layers in Dye-Sensitized Solar Cells," *J. Phys. Chem.* B, 112, 14415 (2008).

Rochester Institute of Technology

- S.M. Hubbard; C.D. Cress; C.G. Bailey; R.P. Raffaelle. “Effect of strain compensation on quantum dot enhanced GaAs solar cells”, *Appl. Phys. Lett.*, vo. 92, 123512 (2008).
- S.M. Hubbard; C. Bailey; C.D. Cress; S. Polly; J. Clark; D.V. Forbes; R.P. Raffaelle; S.G. Bailey; D.M. Wilt. “Short circuit current enhancement of GaAs solar cells using strain compensated InAs quantum dots”, 33rd IEEE Photovoltaic Specialists Conference Proceedings, vol. 1, 250 (2008).

Stanford

- H. Peng; C. Xie; D.T. Schoen; Y. Cui. “Large Anisotropy of Electrical Properties in Layer-Structured In2Se3 Nanowires.” *Nano Lett.* 8, 1511-1516 (2008).
- C.M. Hsu; S.T. Connor; M. Tang; Y. Cui. “Wafer-Scale Silicon Nanopillars and Nanocones by Langmuir-Blodgett Assembly and Etching,” *Appl. Phy. Lett.* 93, 133109 (2008).
- H.L. Peng; X.F. Zhang; R.D. Twesten; Y. Cui. “Vacancy Ordering and Lithium Ion Insertion in In2Se3 Nanowires,” Nano Letter (in preparation).

University of California, Davis

- A.J. Moulé.; K. Meerholz. “Intensity-dependent photocurrent generation at the anode in bulk-heterojunction solar cells.” *Applied Physics B: Lasers and Optics* 2008, 92, (2), 209-218.
- A.J. Ferguson; N. Kopidakis; S.E. Shaheen; G. Rumbles. “Quenching of Excitons by Holes in Poly(3-hexylthiophene) Films.” *J. Phys. Chem.* C 2008, 112, (26), 9865-9871.

University of California, San Diego

- D. Derkacs; W.V. Chen; P.M. Matheu; S.H. Lim; P.K.L. Yu; E.T. Yu. “Nanoparticle-induced light scattering for improved performance of quantum-well solar cells,” *Appl. Phys. Lett.* 93, 091107 (2008).
- D. Derkacs; W.V. Chen; P. Matheu; S.H. Lim; P.K.L. Yu; E.T. Yu. “Coupling of light scattered by nanoparticles into waveguide modes in quantum-well solar cells,” SPIE Proceedings 7047-1 (2008). [Invited]
- E.T. Yu; D. Derkacs; S.H. Lim; P. Matheu; D.M. Schaadt. “Plasmonic nanoparticle scattering for enhanced performance of photovoltaic and photodetector devices,” SPIE Proceedings 7033-66 (2008). [Invited]

University of Colorado

- J. Michl; J.C. Johnson; A. Akdag; A.E. Schwerin; M. Smith; Z. Havlas; A.J. Nozik. “Singlet Fission - Can It Be Harnessed?”, 22nd IUPAC Symposium on Photochemistry, July 27 - Aug. 1, 2008, Gothenburg, Sweden.

University of Florida

- J. Xue. “Effect of Heterojunction Structure on Performance of Vacuum-deposited Organic Photovoltaic Cells,” 2008 International Materials Research Conference, June 9–12, Chongqing, China, 2008.
- J. Xue; Y. Zheng; J.D. Myers; J. Ouyang. “Morphology Study of Vacuum-Deposited Pentacene:C60 Mixed Thin Films for Photovoltaic Applications”, AVS 55th International Symposium & Exhibition, Boston, Massachusetts, Oct. 19-24, 2008.

University of Illinois

- J. Yoon; A.J. Baca; S.I. Park; P. Elvikis; J.B. Geddes III; L. Li; R.H. Kim; J. Xiao S. Wang; T.H. Kim; M.J. Motala; B.Y. Ahn; E. Duoss; J.A. Lewis; R.G. Nuzzo; P.M. Ferreira; Y.Y. Huang; A. Rockett; J.A. Rogers. “Ultrathin silicon solar microcells for semitransparent, mechanically flexible and microconcentrator module designs,” *Nature Materials,* 7, 907 - 915 (2008).

University of Washington

- Yip, Hau, Baek, Ma, and Jen, “Polymer Solar Cells That Use Self Assembled-Monolayer-Modified ZnO/Metals as Cathodes” Adv. Mater. (2008), 20, 2376.
- Yip, Hau, Baek, Jen. “Self-Assembled Monolayer Modified ZnO/Metal Bilayer Cathodes for Polymer:Fullerene Bulk-Heterojunction Solar Cells” Appl. Phys. Lett., (2008), 92, 193313.
- Baek, Hau, Yip, Chen, Acton and Jen. “High Performance Amorphous Metallated π-Conjugated Polymers for Field-Effect Transistors and Polymer Solar Cells,” *Chem. Mater.*, (2008), 20, 5734.
- Park, Munro, and Ginger. ”Controlling Film Morphology in Conjugated Polymer:Fullerene Blends with Surface Patterning,” *J. Am. Chem. Soc.,* (2008), 130 (47), 15916.

University and Exploratory Research

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Fannie Posey Eddy (NREL), 303-384-6773, Fannie_Eddy@nrel.gov

DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@ee.doe.gov

FY 2008 Budgets: $494K (NREL), $1,047K (subcontracts)

Objectives

- Explore ultimate performance limits of PV technologies, approximately doubling their sunlight-to-electricity conversion efficiencies during its course.
- Improve research and development (R&D) on crystalline silicon cell efficiencies and fabrication methods to reduce manufacturing costs. This work is leveraged by the Center of Excellence.
- Perform leading edge research in thin-film materials and solar cells. The R&D activities include device fabrication, device analysis, film growth, materials characterizations, and modeling.
- Develop thin-film tandem cells and modules toward 25% and 20% efficiencies.
- Develop multi-junction, pre-commercial concentrator modules able to convert more than one third of the sun's energy to electricity.
- Develop high-risk/high-payoff third-generation (3G) photovoltaic (PV) technologies beyond 2015, including high-efficiency and exciton-based solar cells.
- Target emerging state of the art, high efficiency concepts relative to advanced super high-efficiency cells to allow cost effective generation of electricity and hydrogen.
- Offer scientific and technical research opportunities for minority undergraduate and graduate students in solar technologies via the Minority University Research Associates (MURA) project.

Accomplishments

- Completing and phasing out University and Exploratory Research (UER) Project sub contracts.
- Demonstrated inverted MM 3-junction terrestrial concentrator cells with AlGaInAs transparent graded buffer layers by Spectrolab.
- Built 1 m^2 sub module and installed the high efficiency cells (from Spectrolab) by Amonix.
- Completed internships; seven undergraduate students participated in NREL MURA Internship Program. Posters were presented by NREL-MURA interns at the 18th Workshop on Crystalline Silicon Solar Cells: Materials and Processes, August 3- 6, 2008, in Vail, Colorado.
- Presented MURA and student research findings at the Renewable Academic Partnership (REAP)/ Sustainable Energy from Solar hydrogen NSF/IGERT Workshop, University of Delaware, July 20-22, 2008.

Future Directions

- Phase out UER Project, since sub contracts have ended with the exception of MURA project.
- Continue to address key R&D issues in support of the Solar America Initiative (SAI) through remaining projects.
- Continue to assist DOE Golden Field Office (DOE/GO) in monitoring MURA project.
- Close out UER subcontracts, since project is in final phase.

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1. Introduction

The University and Exploratory Research (UER) project aims to explore the ultimate performance limits of PV technologies, approximately doubling their sunlight-to-electricity conversion efficiencies during its course. R&D is directed toward advancing the progress of high efficiency technologies and their demonstration in commercial prototype products. To accomplish this, a wide range of complex issues are investigated to provide initial modeling and baseline experiments involving several advanced concepts. The project includes both sub contract and NREL in-house activities being executed in parallel to reach long-term beyond 2015 goals. To ensure the success of SAI, NREL is assisting in this effort as well as with the SAI university and industry activities.

Sub contracted research include the following areas: (1) polycrystalline thin-film tandems; (2) research in III-V multijunction concentrators; (3) future generation research; and (4) research collaboration with minority universities in the MURA Project.

2. Technical Approach

The UER project consists of six separate programs with research sub contracted through industry and university partners. All of the sub contracts have been completed and are being phased out. One exception is the MURA project which will continue in fiscal year (FY) 2009.

The MURA task provides scientific and technical research opportunities for minority undergraduate students to work on various solar energy technology projects. NREL will assist GO in the management of these sub contracts and the solicitation/award process.

UER Agreement Tasks	FY 2008 Budget ($K)
Polycrystalline Thin-Film Tandems	*
III-V Multijunction Concentrators	*
Future Generation Project	156
MURA	291
Crystalline Si Universities	*
University Center of Excellence	600
Total**	**1,541**

*Forward (FY07) Funding ending in FY08.
**Includes NREL Exploratory Research $494.

3. Major FY 2008 Publications

- V.I. Polyakov; A.I. Rukovishnikov; B.M. Garin; V.P. Varnin; J.M. Dutta. “Point defects in undoped CVD diamond and high-purity semi-insulating SiC.” Accepted for publication in *IEEE Transaction* (May 2009 issue).

- S.K. Estreicher; M. Sanati; N. Gonzalez Szwacki. “Fundamental Interactions of Fe in silicon: First-Principles Theory.” *Solid State Phenomena*, 131-133, 233-240 (2008).

- S.K. Estreicher; M. Sanati; N. Gonzalez Szwacki. “Iron in silicon: interactions with radiation defects, carbon, and oxygen.” *Physical Review*, B 77, 125214/1-9 (2008).

- S. Jin; Y. Yang; J.E. Medvedeva; L. Wang; S. Li; N. Cortes; J.R. Ireland; A.W. Metz; J. Ni; M.C. Hersam; A.J. Freeman; T.J. Marks. “Tuning the Properties of Transparent Oxide Conductors. Dopant Ion Size and Electronic Structure Effects on CdO-Based Transparent Conducting Oxides. Ga- and In-doped CdO Thin Films Grown by MOCVD,” *Chem. Mater.*, 20, 220 (2008).

- S.P. Harvey; T.O. Mason; D.B. Buchholz; R. P.H. Chang; C. Koerber; A. Klein. “Carrier Generation and Inherent Off-Stoichiometry in Zn,Sn Codoped Indium Oxide (ZITO) Bulk and Thin-Film Specimens,” *J. Am. Ceram. Soc.*, 91, 467 (2008).

- W.C. Sheets; E.S. Stampler; M.I. Bertoni; M. Sasaki; T.J. Marks; T.O. Mason; K.R. Poeppelmeier. “Silver Delafossite Oxides.” *Inorg. Chem.*, 47, 2696 (2008).

- J.H. Song; T. Akiyama; A.J. Freeman. “Stabilizing mechanism of the dipolar structure and its effects on formation of carriers in wurtzite films: InN and ZnO.” *Phys. Rev. B*, 77, Art. No. 035332 (2008).

- J. Li; J. Liu; J.G. Evmenenko; P. Dutta; T.J. Marks. “Characterization of Transparent Conducting Oxide Surfaces Using Self-Assembled Electroactive Monolayer Probes.” *Langmuir*, 24, 5755 (2008).

- D. Zubía; L. Romo; M. Rodríguez; B. Aguirre; R. Ordóñez; Ivan Coronado; José Cruz-Campa; Gregory Lush; Stella Quiñónez; John McClure. "Deposition and Doping of ZnTe and ZnCdTe Alloys. Presented at the International Materials Congress, Cancun, Mexico, August 21, 2008.

Industrial CRADAs

Performing Organization: National Renewable Energy Laboratory

Key Technical Contact: John Benner (NREL), 303-384-6496, john_benner@nrel.gov

DOE HQ Technology Manager: Marie Mapes, 202-586-0565, marie.mapes@ee.doe.gov

2008 Budget: $2,100K (NREL)

Objectives

- Accelerate growth of partnerships with industry to move more NREL-developed technology into production faster.
- Lower administrative and financials barriers to partnerships for both NREL scientist and prospective industry at all phases of engagement from finding, forming, funding, and expanding collaborative development of products and processes.

Accomplishments

- Completed two solicitations for proposals.
- Selected twelve projects for funding.
- Stimulated nine new industry partnerships.

Future Directions

- Stimulate at least five new Cooperative Research and Development Agreements (CRADAs) that grow to large, multi-investigator levels.

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1. Introduction

Transferring our technologies to industry is the culmination of years of research. This is also perhaps the most difficult stage of development. While NREL can point to numerous examples of successful tech transfer, including many patents that have been licensed, the majority of our contributions are not publicized. Vast amounts of knowhow, measurements, data, sample exchange, and joint experiments have transformed industry processes and products without visible agreements. This has contributed to blunders from both sides of the partnership. Our planning has instances of terminating support for research tied to a partner's interest as well as collaborations with industry scientists that evaporated as resources were redirected. The remedy is to raise the visibility of the interaction through formalizing the agreement in a Technical Service Agreement (TSA) or Cooperative Research and Development Agreement (CRADA). The attention of management of the partnering companies is particularly enhanced when they have their own resources committed to the agreement.

The commercialization CRADAs project accelerates growth of partnerships with industry to move more NREL-developed technology into production faster. The project lowers administrative and financial barriers to partnerships for both the NREL scientist and prospective industry at all phases of engagement from finding, forming, funding, and expanding the collaborative development of products and processes that incorporate NREL technology.

2. Technical Approach

The nature of the photovoltaic (PV) business has fundamentally changed the way that NREL must interact with industry. As private funding has rocketed past federal support and the total private sector investments approach $2 billion annually, companies have become much more concerned and savvy in their approach to collaborating to gain outside help. Moreover, there are many more companies seeking access to NREL's resources. This change drives us toward use of a coordinated process to select partners and manage the success of each partnership.

Industry collaborations are grouped into four phases of maturity.

- Phase 0 covers technologies where no discussions have started with potential industry partners. This may be due to research needs to be completed or patent applications filed.
- Phase 1 collaborations describe interactions where NREL is working informally with a scientist from industry partner, perhaps exchanging samples and data, but no funds change hands and management involvement is minimal.
- Phase 2 interactions include TSAs or CRADAs funded at levels of up to $100,000. This provides the company with an introduction to NREL's business practices and ensures that the management of the company has engaged in the agreement.
- Phase 3 CRADAs are major collaborations with NREL's work is an integral part of the company's development efforts. Our largest CRADA today supports $2.8 million of work at NREL over 3 years.

The project supports developing relationships is many ways that are adjusted relative to the maturity of the interaction.

- Funding is awarded through internal competition to enable and encourage NREL scientists to initiate and deliver research. Funding also lowers barriers for the participating companies.
- Outreach to increase industry's awareness of NREL's capabilities and assistance in forming initial interactions.
- Interface with NREL technology transfer office and legal office to improve execution of partnership agreements, intellectual property (IP) protection, and related business activity.

3. Results and Accomplishments

This is a new project that will test the business model presented in the technical approach. During the first year, we created and executed two solicitations for proposals. The proposal briefly described the technical plan, industry partner, exit strategy, and anticipated peripheral benefit to NREL for engaging in the work. Reviewers assess the commercialization potential, the strength of the technical plan, and benefits to the Solar Energy Technologies Program. Twelve projects were awarded. These covered a wide range of technologies, such as transparent conducting oxides aimed for application by the glass industry, ink jet-printed contact technology, high performance multiple junction cells, evaluation of commercial substrates for thin-film solar cells, and moisture barrier coatings. In most instances, the name of the corporate partner is business sensitive or CRADA protected information. Thus, the specific agreements are not included in this report.

4. Planned FY 2009 Activities

Adaptability will be the hallmark of the industrial CRADAs project as it must fulfill the needs of a rapidly changing industry. During FY 2009, we will observe the effectiveness of the project in achieving its objectives. At present, most CRADAs are tightly focused on a single aspect of the development challenge, typically engaging only a single NREL investigator. In order to achieve the long-term targets of stimulating at least five new CRADAs that grow to large, multi-investigator levels, it already appears likely that the project will need to create a more effective process to generate partnerships encompassing multiple components of the technology under development.

Seed Fund Projects

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Sarah Kurtz (NREL, Primary Contact), 303-384-6475, sarah_kurtz@nrel.gov
Jeff Nelson (SNL), 505-284-1715, jsnelso@sandia.gov

DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@hq.doe.gov

FY 2008 Budgets: $1,870K (NREL), $483K (SNL)

Objectives

- Provide temporary funding for exploration of new ideas, including new materials, devices, or processes that have not reached the proof-of-concept stage
- Facilitate the Solar Energy Technologies Program (SETP) mission of transitioning exploratory/discovery-stage research to applied research and development (R&D), thereby providing a stream of next-generation photovoltaic (PV) technology options.

Accomplishments

- Synthesized n- and p-type organic semiconductor materials
- Developed capability of spraying at least 3 in. x 4 in. uniform carbon nanotube films
- Demonstrated increased photovoltage and blue photocurrent after addition of cadmium selenide (CdSe) quantum dots (QDs), demonstrating that QDs can be incorporated into an organic photovoltaic (OPV) device and show enhancements
- Produced lead selenide (PbSe) nanocrystalline solar cell with 2.2% efficiency and > 22 mA/cm^2
- Demonstrated liftoff of silicon (Si) cell with ~ 1% efficiency
- Investigated Si dot-dot interaction as a function of dot-dot distance and dot size
- Deposited and characterized zinc-copper-oxygen (ZnCuO) alloys over a range of copper-zinc (CuZn) compositions.

Future Directions

- Investigate copper-zinc-tin-sulfide/selenide as a new absorber material
- Explore flexible organic (OPV) made by lamination and inorganic hole transport layers for excitonic solar cells.

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1. Approach and Planned Activities

<u>Task #1: Doped Polymeric Molecular Semiconductor p-n Junction OPV</u>
Purpose: Investigate new approach to creating a stable OPV cell by using a class of materials that has been engineered for use as automobile paints. This approach is qualitatively different from other approaches in that it adds specific functional groups to create both n- and p-type material.

Milestone:
• By 12/08, synthesize gram quantities of n-type and p-type polymers and prepare first functional solar cells from the new materials.

Accomplishments:
• The synthesis/purification is proceeding well and the project is on track for evaluating the first solar cells by the end of 2008.

<u>Task #2: Carbon Nanotube Architectures for Low-Cost and High-Efficiency PV</u>
Purpose: Leverage the expertise already developed at NREL in synthesizing carbon nanotubes (CNTs) to determine their utility for use in PV devices. CNTs have the potential to be low cost, can be applied with high-speed solution phase processing at low temperatures, have high thermal stability, and may have performance (conduction and transmission) properties competitive with conventional transparent conductors.

Milestones:
• By 12/08, spray deposit bulk CNT electrode with area >10 cm^2, T>80%, and R_S<50 Ω/□.
• By 12/08, utilize sprayed SWCNT films as electrodes in PV devices and evaluate system performance (e.g., efficiency) relative to conventional transparent conductive oxides (TCOs). Publish results in journal.

Accomplishments:
• Developed capability of spraying at least 3 in. x 4 in. uniform CNT films.
• Participated in two invited talks – J. Blackburn at ECS 2008 and T. Barnes at OPV 2008.
• Achieved sprayed CNT electrodes with >10 cm^2, T>78%, and R_S<50 Ω/□.
• Determined that poly 3-hexylthiophene (P3HT)/PCBM OPV devices on single-walled carbon nanotubes (SWNT) electrodes with hole injection layer are nearly equivalent to control cells on indium tin oxide (ITO) (~3.8% efficiency on ITO vs. 3.5% on SWNTs); OPV cells on SWNT electrodes with no hole injection layer with efficiencies higher than 3%.

Task #3: Incorporation of Third-Generation Mechanisms into OPV Devices
Purpose: Explore the use of third-generation concepts such as QDs, other quantum-confined structures and multijunction approaches integrated with electroactive, conjugated polymers (P3HT) to develop a path to creation of solar cells with higher efficiencies. This work will focus specifically on implementation of a multijunction polymer solar cell, incorporating colloidal semiconductors into conjugated oligomers, polymers, and dendrimers.

Milestone:
• Demonstrate an initial single-junction QD/polymer device with publication.

Accomplishments:
• Demonstrated increased photovoltage (from 0.35 V to 0.6 V) and an increase in blue photocurrent after addition of CdSe QDs (quantum efficiency increased from 65% to 95% at 450 nm), clearly showing that QDs can create enhancements in an OPV device.
• CdSe QDs were capped with pyridine, NMA* N-phenyl-N'-methyldithiocarbamate and DPA* N,N'-diphenyldithiocarbamate, and then time-resolved microwave conductivity (TRMC) was used to evaluate the lifetime of the carriers in a P3HT blend. Surprisingly, the NMA showed much longer lifetimes (desirable) than the other caps. This implies better charge-carrier separation, which can lead to improved efficiency (manuscript in preparation).

Task #4: Thin III-V Solar Cells
Purpose: Epitaxial liftoff (ELO) has been explored for a number of years as a means to reduce the cost of multijunction III-V cells. Challenges have been identified in both handling the lifted-off layers and avoiding the creation of inter-layer cracks. We are exploring ELO and other liftoff techniques to create small area cells (<1 cm^2).

Milestone:
• Explore techniques to lift off III-V PV cells.

Accomplishments:
• Chose epitaxial liftoff over other liftoff techniques.

Task #5: Novel Nanocrystal-Based Solar Cell to Exploit MEG
Purpose: Demonstrate that multiple excitons can be collected within a solar cell. Specifically, if QDs are used to enhance the probability that multiple excitons are generated from absorption of a single high-energy photon (this has already been demonstrated), can multiple electrons/photons be collected in an external circuit?

Milestones:
• Optimize band gaps for PbSe/lead sulfide (PbS) system; increase Jsc to 25 mA/cm^2; double the field-effect mobility; publish results in two journals.
• Achieve 2% efficiency (AM1.5G); quantitative assessment of cell stability; and identification of degradation mechanisms, reliable and reproducible equivalent quantum efficiency (EQE) characterization, and spectroscopic demonstration of MEG within device quality.

Accomplishments:
• Produced solar cell with 2.2% efficiency and > 22 mA/cm^2 based upon forming a Schottky contact between PbSe NCs and the back metal electrode. The active layer of the solar cell consists entirely of PbSe NCs (2/08).
• Developed an optical model that, used in conjunction with total reflectance measurements and accurate EQE measurements, can determine the internal quantum efficiency (IQE). The IQE can be used as a tool for understanding and optimizing solar cell performance and to accurately determine whether multiple excitons are successfully collected from the solar cell (6/08).

Task #6: Si

Purpose: This project seeks to develop a method that allows the creation of crystalline silicon (c-Si) cells on a standard c-Si substrate and then allows the lifting-off of the c-Si cells, which are 10 to 20 microns thick, from the remaining substrate. The substrate is then reused to create additional layers of cells. These cells have a small area (<1 cm^2), which allows for further system-level cost savings.

Milestone:
• Demonstrate liftoff of thin c-Si chips and cells, as well as reuse of substrate.

Accomplishments:
• Demonstrated liftoff of Si cell with ~1% efficiency.

Task #7: Multifunctional Transparent Conducting and Self-Healing Impermeable Barriers

Purpose: Develop a multilayer coating grown at low-temperature (<80°C), resulting in a highly transparent coating with high electrical conductance, low water-vapor transmission, and lower cost than indium tin oxide.

Milestone:
• Demonstrate multilayer films with 80% transmission, <10 Ω/sq, and 0.01 g/m^2/day O_2/H_2O impermeability.

Accomplishments:
• Measured films with water vapor transport rates < 0.01 g/m^2/day.
• Measured films with < 10Ω/sq and >80% transmission.

Task #8: Si Quantum Dot Solar Cells

Purpose: Explore use of Si QDs in solar cells as a way of tuning the optical properties while retaining use of an abundant, high-performance material (silicon).

Milestones:
• Create simulations package to calculate the electronic and optical properties of Si QDs embedded in foreign matrix. Select and specify the most promising growth method of quantum dot structure.

Accomplishments:
• Selected University of Minnesota, with its dual-reactor plasma-enhanced chemical vapor deposition (PECVD) method, as best partner for growth of Si QD materials.
• Set up the atomistic calculation model for Si dot-array and investigated the dot-dot interaction as a function of dot-dot distance and dot size.

Task #9: Amorphous Oxide Semiconductors for Ambient Temperature Deposited PV

Purpose: Demonstrate a metal-oxide-based, thin-film heterojunction solar cell that can be deposited at ambient temperature.

Milestones:
• Deposit and characterize initial Zn-Cu-O material libraries.
• Demonstrate amorphous metal oxide p-n diode with photoactive response.

Accomplishments:
• Deposited and characterized Zn-Cu-O alloys over a range of Cu-Zn compositions, identifying conditions for growth of amorphous material.
• Identified the (unwanted) (+2) oxidation state of the Cu and reoptimized the growth conditions to obtain the desired (+1) oxidation state.

2. FY 2008 Patent Application

L. Simpson, “Thin Film Electronic Devices with Conductive and Transparent Gas and Moisture Permeation Barriers” (submitted).

3. Major FY 2008 Publications

Barnes, T.; Blackburn, J.; Tenent, R.; Morfa, A.; Heben, M.; Coutts, T. “Optimizing Carbon Nanotube Contacts for Use in Organic PV.” *IEEE PVSC 33*, IEEE: San Diego, CA, 2008, NREL/CP-520-42550. Golden, CO: National Renewable Energy Laboratory.

Tenent, R.; Barnes, T.; Heben, M.; To, B.; Gedvilas, L.; Blackburn, J. “Ultrasonic Spraying of Highly Conductive Transparent Single-Walled Carbon Nanotube Films for PV.” *Adv. Mat.*, submitted.

Luther, J.M.; Law, M.; Beard, M.C.; Song, Q.; Reese, M.O.; Ellingson, R.J.; Nozik, A.J. “Schottky Solar Cells Based on Colloidal Nanocrystal Films.” *NL*, 8, 3488 (2008).

Law, M.; Beard, M.C.; Choi, S.; Luther, J.M.; Hanna, M.C.; Nozik, A.J. “Determining the Internal Quantum Efficiency of PbSe Nanocrystal Solar Cells with the Aid of an Optical Model.” *NL*, ASAP (2008).

Wafer Silicon

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Qi Wang (NREL), 303-384-6681, qi_wang@nrel.gov

DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@hq.doe.gov

FY 2008 Budget: $1,912K (NREL)

Objectives

- Develop low-cost and high-efficiency cell process to meet the U.S. Department of Energy's (DOE's) goal of levelized cost of energy (LCOE).
- Conduct scientific research on silicon (Si) materials and energy devices.
- Collaborate and leverage partnerships with U.S. solar companies on wafer-Si research efforts.

Accomplishments

- Achieved 19.3% on FZ and 18.8% on CZ a-Si/c-Si heterojunction (SHJ) solar cells on p-type wafer.
- Achieved high open circuit voltage of more than 700 mV, which was a first at NREL, on a finished SHJ solar cell.
- Completed the installation of Si-cluster tool in NREL's Process Development and Integration Laboratory (PDIL), which can easily handle SHJ solar cells.
- Completed the purchase of Czochralski (CZ) crystal grower.
- Achieved narrower conductive line using ink-jet printing.

Future Directions

- Establish quicker evaluation of solar Si feedstock.
- Develop high-efficiency SHJ solar cells on thin wafers (< 100 μm).
- Develop novel materials for better surface passivation.
- Install and operate CZ-crystal grower
- Develop 5-inch heterojunction solar cells
- Study the surface and bulk passivation
- Develop interdigitated solar cell using heterojunction a-Si:H layer
- Further develop black-Si solar cells.
- Further develop direct writing contact
- Develop efficient furnace and fire-through metal contact.

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1. Results and Accomplishments

In April 2008, a CZ-crystal Si grower was ordered. This system can grow a Si ingot that is 3 to 4 inches in diameter and up to 10 inch in length, or 4.9 kilogram (kg) per load. It also has the capability of vacuum bake-out at 10^{-6} Torr. This CZ grower will be a vital tool to start evaluating solar graded Si feedstock. After completing the installation, we will be able to study solar grade Si from raw Si to solar cells and help solar industry partners. The system is expected to arrive at NREL in early February 2009 and begin operating in March 2009. The milestone for this task will be delayed because of the pending arrival of the CZ grower.

The Si-heterojunction solar cell task continually made progress this fiscal year (FY). The task was focused on moving toward 2 by 2 cm^2-size cell from 1 by 1 cm^2. The larger area cell minimizes the effect of perimeter loss. We have achieved high open circuit voltage of more than 700 mV on p-type wafer using the larger size. It was a first at NREL – the first time reaching more than 700 mV, using a cell with a heterojunction structure. We also worked on using normal CZ p-type wafer and achieved the conversion efficiency of 18.8%. This cell shows little light induced degradation, and the results were presented at the 33rd PV Specialists Conference. Our goal is to aim for more than 20% efficiency.

Wafer-size Si-heterojunction solar cell will be developed in newly installed Si-cluster tool in PDIL. The system was in operation in the final month of FY 2008, and the Si-cluster tool is in its tune-up phase.

In FY 2009, we will start developing wafer-Si heterojunction solar cell. While waiting for the Si-cluster tool to complete its tune up, the team has worked on wafer-Si texturing and cleaning, screen printing contact, and larger area e-beam metal deposition. Most periphery tasks of wafer-size SHJ process have been tested. SHJ solar cell and passivation of mc-Si in Si cluster tool will fully begin in FY 2009.

The black Si task made the most progress and met the milestone of 13% efficiency. The best cell performance has 14.9% efficiency with V_{oc} of 0.609 V, 78.5% FF, and 31.3 mA/cm^2 current density. The black Si process uses novel metal particles to modify the c-Si surface and creates a nano-structure that makes the reflection from c-Si near to zero, which gives it a black appearance. Figure 1 shows the results.

Untreated bare c-Si has about 30% reflectance. The process only takes a few minutes. If it works, it can speed up the texturing process in c-Si cell manufacturing. Cell development was standard diffused junction process. Challenges are to completely remove the metal that is associated with the black-Si process and improve cell process steps to enhance Jsc. This will be a focus in FY 2009.

Direct writing contact uses an inkjet printer to make fine conductive lines on c-Si cells. In FY 2008, we achieved 80 µm Ag line width with 10 µm tall printed at 180°C on an Evergreen solar c-Si solar cell, and 13% efficiency was reached. In FY 2009, we will continue to narrow the line width and increase the thickness.

In August 2008, 18th c-Si workshop was held in Vail, Colorado. Participants included professionals from universities, national labs, and the solar industry. The conference proceedings will be published in 2009.

2. FY 2008 Special Recognitions and Patents

V. Yost; H.M. Branz, "Anti-reflection etching of silicon surfaces catalyzed with ionic metal solutions," NREL ROI 07-17, patent filed August 2008.

H.M. Branz; A. Duda; D.S. Ginley; V. Yost; D.L. Meier; S. Ward. "Nanoparticle-based etching of silicon surfaces," NREL ROI 07-10, patent filed March 2008.

3. Major FY 2008 Publications

Q. Wang; M.R. Page; E. Iwaniczko; Y.Q. Xu; L. Roybal; R. Bauer; B. To; H.C. Yuan; A. Duda; Y.F. Yan. *"Crystal Silicon Heterojunction Solar Cells by Hot-Wire CVD: Preprint."* NREL/CP-520-42554. Golden, CO: National Renewable Energy Laboratory, 2008.

H.M. Branz; C.W. Teplin; D.L. Young; M.R. Page; E. Iwaniczko; L. Roybal; R. Bauer; A.H. Mahan; Y. Xu; P. Stradins; T. Wang; Q. Wang. "Recent Advances in Hot-Wire CVD R&D at NREL: From 18% Silicon Heterojunction Cells to Silicon Epitaxy at Glass-Compatible Temperatures." *Thin Solid Films.* Vol. 516(5), 15 January 2008, pp. 743-746, NREL Report No. JA-520-40835 (2008).

H.-C. Yuan; M.R. Page; E. Iwaniczko; Y. Xu; L. Roybal; Q. Wang; H.M. Branz; D.L. Meier. *"Silicon Solar Cells with Front Hetero-Contact and Aluminum Alloy Back Junction: Preprint."* NREL/CP-520-42566. Golden, CO: National Renewable Energy Laboratory, 2008.

M.R. Page; E. Iwaniczko; Y. Xu; L. Roybal; R. Bauer; H.-C.Yan; Q. Wang; D.L. Meier. *"Photoconductive Decay Lifetime and Suns-Voc Diagnostics of Efficient Heterojunction Solar Cells: Preprint."* NREL/CP-520-42564. Golden, CO: National Renewable Energy Laboratory, 2008.

Proceedings of 18th Workshop on Crystalline Silicon Solar Cells & Modules: Materials and Processes, editor Bhushan Sopori.

S. Bhushan, et al. "Mechanisms of Front Contact Formation in Si Solar Cells fire-through theory." Presented at the TMS 2008 Meeting, March 2008, New Orleans, Louisiana.

Film Silicon

Performing Organization: National Renewable Energy Laboratory (NREL)

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DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@ee.doe.gov

FY 2008 Budget: $3,307K

Objectives

- Develop photovoltaic (PV)-quality crystal silicon (Si) layers through low thermal budget epitaxial growth.
- Develop film crystal Si PV on inexpensive substrates with seed layer coatings.
- Develop baseline amorphous and nanocrystalline Si capability in PDIL cluster tool.

Accomplishments

- Demonstrated epitaxial Si growth by scalable hot-wire chemical vapor deposition (HWCVD) at 300 nm/min at glass-compatible temperature on wafer substrates.
- Grew HWCVD epitaxial Si at low temperature with dislocation density below 10^6 cm^{-2}.
- Doped HWCVD epitaxial Si n-type to 5 x 10^{15} cm^{-3} and produced active PV device on wafer.
- Collaborated with industrial partners to demonstrate epitaxial growth on inexpensive seed layers.
- Crystallized a-Si to oriented crystallites, using novel millimeter-wave annealing technique.
- Published 'cone kinetics' model of nanocrystalline and protocrystalline Si morphology.
- Demonstrated uniform 156-mm square a-Si:H deposition in PDIL cluster tool.

Future Directions

- Improve high-rate low-temperature epitaxy for crystal Si on glass and other substrates.
- Deposit efficient epitaxial Si PV devices on wafers and seed layers on glass.
- Collaborate with U.S. industry partners that provide seed layers for epitaxial growth.
- Improve quality of high growth-rate nanocrystalline and a-Si.

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1. Introduction

Silicon (Si) remains the material of choice for terrestrial PV because SI is abundant, non-toxic, and accepted in the marketplace. There is a well-developed industrial base in all forms of Si, and an enormous, rapidly growing, Si scientific literature. However Si PV costs must be reduced to reach the DOE 2020 goal of $0.06/kWh PV electricity. This requires module costs well below $1/W. Today, the Si feedstock cost alone is above $0.60/W. Though the feedstock cost will fall, it is unlikely that wafer Si can reach the 2020 Roadmap goals of about $0.50/W. However, films of crystalline Si could reach this goal by leveraging the existing crystal Si infrastructure but circumventing the need for high-cost wafers. This film Si project proposal addresses key research problems toward the mid-term creation of a wafer-replacement crystalline film Si technology and near-term expansion of thin-film SI industry.

2. Technical Approach

Our main goal was to develop the science and technology required for high-quality film crystal SI on glass or another low-cost substrate. It has been demonstrated by CSG Corp. that a 1.85-micron c-Si film solar cell can provide nearly 30 mA/cm^2 of current with effective light trapping. Our approach is to make high-quality c-Si by rapidly thickening a seed layer of large well-oriented crystalline grains by scalable hot-wire chemical vapor deposition (HWCVD). Our laboratory research, therefore, centered on improvement of low-thermal budget Si epitaxy, development of a doping capability, and first solar cell fabrications on the model system of epitaxial layers on wafers. The seed layer can be extremely thin, but must be deposited by some inexpensive technique. We have strong collaborations with three industry partners who believe they have technologies capable of depositing thin c-Si seed layers and three experimental projects to develop our own novel seed-layer approaches. Finally, we have also installed and made first depositions in a new cluster tool for 156-mm-square thin-film a-Si:H and nc-Si:H depositions, with a goal of improving the quality of high-rate films for thin-film Si solar cells.

3. Results and Accomplishments

We deposited HWCVD epitaxial layers at about 700°C with recombination-active dislocation density of about $2x10^5$ cm^{-2} (Fig. 1). This corresponds to a spacing of about 22 μm between dislocations --- consistent with efficient PV cells up to about 5-μm thick. This 40-μm n-type layer was deposited at about 120 nm/min. We have also deposited high-quality epitaxial layers on Si-on-insulator layers and on Si layers fabricated on borosilicate glass by several methods.

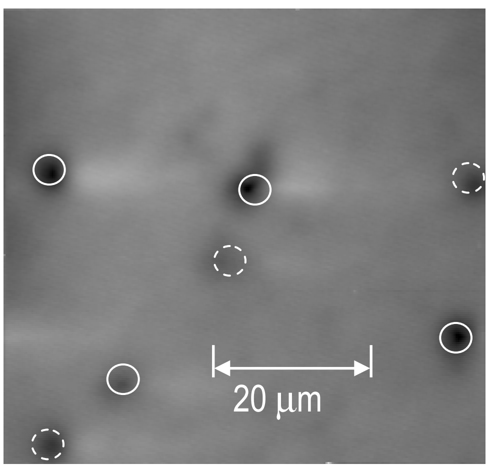

Fig.1 Cathodoluminescence scan of 40-μm-thick HWCVD epitaxial layer on wafer Si showing about $2x10^5$ cm^{-2} recombination-active defects that reduce the luminescence.

We installed flow-controllers able to meter tiny proportions of B_2H_6 and PH_3 dopant gases into the SiH_4 deposition gas and established the capability of doping of our epitaxial layers both n-and p-type. We can dope n-type layers to a Hall carrier concentration of $5x10^{15}$ cm^{-3}. By comparing Hall and secondary ion mass spectrometry level, we demonstrated dopant activation near 100% across a wide range of both n- and p-type doping densities. Fig. 2 shows the measured Hall mobilities of n-type films; these are very near the mobilities calculated for ideal c-Si crystals and measured in the best n-type wafers. Of course, minority carriers are more critical to PV, and long lifetimes must be established. Near the end of FY 2008, we grew our first 1% active PV devices epitaxially on highly-doped (dead) Si wafers.

High deposition rate is critical to low capital costs in manufacturing. We modeled the deposition rates of the HWCVD epitaxial layers and can clearly distinguish two key deposition regimes. Low reactant flow rates does limit the deposition rate. But at high flow rates, the rate becomes limited instead by reactant pressure, hot-wire geometry, and wire current (temperature). By increasing the pressure and using 2 tungsten filaments instead of one, we increased the deposition rate to 300 nm/minute, which mean a 2-μm layer is deposited in about 7 minutes. We have not yet discovered any barrier to even faster epitaxial rates, and our models of the epitaxial mechanism suggest that rates above 1 μm/minute should be possible with different wire geometries.

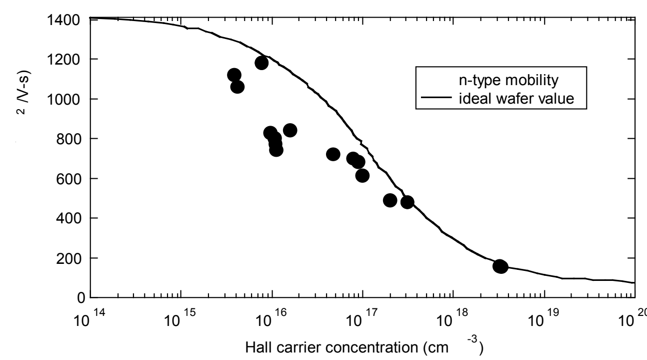

Fig. 2 Hall mobilities of n-type HWCVD epitaxial films approach ideal wafer values, indicating excellent majority-carrier properties.

4. Planned FY 2009 Activities

- Demonstrate epitaxial growth on candidate Si seed layers with low defect densities.
- Deposit efficient PV devices on both wafers and seed layers and establish T-dependence of HWCVD epitaxial quality.
- Develop hydrogenation methods for defective c-Si film and devices.
- Baseline efficient a-Si and nc-Si PV devices at large area in cluster tool.

5. FY 2008 Patents

- Five records of invention filed for crystal Si film PV, ranging from heteroepitaxy on novel seed materials to new contacting approaches.
- D.L. Young, B. Egaas, P. Stradins, "An ultra-fast method for measuring the quantum efficiency of solar cells," filed Sept 2008.

6. Major FY 2008 Publications

P. Stradins; C.W. Teplin; H.M. Branz., "Phase evolution in nanocrystalline silicon films: hydrogen dilution and the cone kinetics model," invited manuscript, submitted to *Phil. Mag. B.*

D.L. Young; H.M. Branz; F. Liu; R. Reedy; Q. Wang. "Electron transport and structure in highly-conducting P-doped polycrystalline Si thin films." *J. Appl. Phys.,* in press.

I.T. Martin; H.M. Branz; P. Stradins; D.L. Young; K.M. Jones; R.C. Reedy; C.W. Teplin. "Doping of high-quality epitaxial silicon grown by hot-wire chemical vapor deposition near 700°C." *Thin Solid Films,* in press.

F. Liu; K.M. Jones; Y. Xu; W. Nemeth; J. Lohr; J. Neilson; M.J. Romero; M. Al-Jassim; D.L. Young. "Ultra-high crystalline-quality silicon pillars formed by millimeter-wave annealing of amorphous silicon on glass." Submitted to Nature Materials.

H.M. Branz; C.W. Teplin; D.L. Young; M.R. Page; E. Iwaniczko; L. Roybal; R. Bauer; A.H. Mahan; Y. Xu; P. Stradins; T. Wang; Q. Wang. "Recent advances in hot-wire CVD R&D at NREL: From 18% silicon heterojunction cells to silicon epitaxy at glass-compatible temperatures." *Thin Solid Films;* vol. 516; 743-746; 2007.

J.D. Cohen; S. Datta; K. Palinginis; A.H. Mahan; E. Iwaniczko; Y. Xu; H.M. Branz. "Defect analysis of thin film Si-based alloys deposited by hot-wire CVD using junction capacitance methods." *Thin Solid Films;* vol. 216; 663-669; 2007.

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V. Gowrishankar; S.R. Scully; A.T. Chan; Q. Wang; H. M. Branz; M. McGehee. "Exciton harvesting, charge transfer and charge-carrier transport in amorphous-silicon nanopillar/polymer hybrid solar cells." *J. Applied Physics;* vol. 103; 64511-8; 2008.

P.C. Taylor; H.M. Branz; R.W. Collins; E.A. Schiff. "Preface to Proceedings of the 22nd International Conference on Amorphous and Nanocrystalline Semiconductors." *J. Non-Crystalline Solids*; vol. 354; vii-viii; 2008.

S. Datta; J.D. Cohen; Y. Xu; A.H. Mahan; H.M. Branz. "Junction capacitance study of an oxygen impurity defect exhibiting configuration relaxation in amorphous silicon-germanium alloys deposited by hot-wire CVD." *J. Non-Crystalline Solids;* vol. 354; 2126-30; 2008.

J.R. Doyle; Y. Xu; R. Reedy; H.M. Branz; A.H. Mahan. "Film Stoichiometry and Gas Phase Chemistry in HWCVD of a-SiGe:H," *Thin Solid Films;* vol. 516; 526-528; 2008.

H.M. Branz; P. Stradins; C.W. Teplin. "Cone kinetics model: Insights into the morphologies of mixed-phase silicon film growth." *Materials Research Symposium Proceedings;* vol. 1066; A01-03.

S. Datta; J.D. Cohen; Y. Xu; H.M. Branz. "Two-Step Capacitance Transients from an Oxygen Impurity Defect." *Materials Research Symposium Proceedings*; vol. 1066; A10-03.

C.W. Teplin; I.T. Martin; K.M. Jones; D. Young; M.J. Romero; R.C. Reedy; H.M. Branz; P. Stradins. "Quality and Growth Rate of Hot-wire Chemical Vapor Deposition Epitaxial Si Layers." *Materials Research Symposium Proceedings*; vol. 1066, A11-06.

I.T. Martin; C.W. Teplin; K.M. Jones; M.J. Romero; B. To; H.M. Branz; P. Stradins. "Mechanism of hot-wire chemical vapor deposition epitaxial silicon growth at 600 to 800°C." Presented at 5th HWCVD International Conference, Cambridge, Massachusetts, Sept. 2008.

H.M. Branz; K. Jones; M. Romero; C.-S. Jiang; P. Stradins; C.W. Teplin. "Film Silicon for Photovoltaics: Low-Temperature Hot-Wire CVD Epitaxy and Nanocrystalline Silicon Growth." Invited talk at 4th *Workshop on the Future of Photovoltaics*, Japan Association for Advancement of Science, Tokyo, Japan, March 2008.

Copper Indium Gallium diSelenide Research

Performing Organization: National Renewable Energy Laboratory (NREL)

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DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@ee.doe.gov

FY 2008 Budget: $1,750K

Objectives

- Receive initial components of copper indium gallium diselenide (CIGS) platform and finalize design of cadmium telluride (CdTe) platform for the Process Development and Integration Laboratory (PDIL).
- Expand intellectual property (patents) related to design of novel transparent conducting oxides or use in thin-film CIGS photovoltaic (PV).
- Assist with development of goals and metrics associated with CIGS technology roadmaps including coordination of PDIL platform designs.

Accomplishments

- Installed first component, the CIGS ultra high vacuum chamber. Other components (central transfer chamber and three sputtering chambers) will be delivered in 2009.
- Produced new world efficiency record of 20.0% for CIGS thin-film PV device.

Future Directions

- Complete environment, safety, and health (ES&H) and facilities requirements for full functionality of equipment in remainder of STF laboratories.
- Finish installation of CIGS platform and bring into full compliance with NREL ES&H regulations.
- Develop sensors for CIGS and assess strategies that establish key metric for ultimate device performance immediately following CIGS deposition.

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1. Introduction

The research undertaken by the Polycrystalline Thin-Film Devices Group is directed at thin-film semiconductor materials, device properties, and fabrication processes to improve the efficiency, stability, and cost of PV solar energy conversion. This research can be broadly placed into three categories: application of capabilities to assist industry in addressing current problems; exploration of specific techniques and processes to develop and transfer technology improvements that industry will soon need; and providing understanding that builds a solid technical foundation for continuing improvement of thin-film PV products. Within this framework, the project supported thin-film technologies related to Molybdenum, CIGS, and transparent conductive oxide (TCO) thin-film technologies. Activities and time frames are consistent with those identified in the *DOE Solar Program Multi-Year Technical Plan* and related *Technology Roadmaps.*

NRELs CIGS technologies lead the world in demonstrated cell performance while our innovations related to high-quality TCO technologies are being rapidly assimilated into the thin-film industry. Because thin-film PV can generate lower cost PV electricity than many historical alternatives (in $/watt), thin-film PV is the fastest growing segment of the PV market. Providing new innovations and a technical foundation for this rapidly expanding industry is at the heart of the efforts of the NREL Polycrystalline Thin-Film Group.

2. Technical Approach

The project focuses on research associated with CIGS device development. Activities related to TCO research were also funded through the CIGS device activity and partly through the NREL Fellows Research Grant to provide a full-time graduate student. Tasks are detailed below:

CIGS Research

- Conduct baseline cell research, including advanced TCO development for substrate devices.
- Examine device performance in progressively thinner absorber layers.
- Improve processes for larger-scale manufacture of CIS with high-performance.
- Examine CIGS intrinsic device stability modes.

3. Results and Accomplishments

The project objectives support near-term manufacturing, build the knowledge and technology base for future manufacturing improvements, allows for training of the next generation of CIGS PV device technologists, and sustains innovation that supports progress toward the future and the long-term Solar Energy Technologies Program goal of 15%-efficient commercial modules. We have steadily improved the quality of the layers in the CIGS device and achieved a world-record efficiency of 20.0%.

Efforts continued to be impacted by significant efforts to re-establishing the research equipment of the CIGS technology area from locations in the Solar Energy Research Facility (SERF) to new locations in the Science and Technology Facility (S&TF) at NREL. By the beginning of FY 2008, all equipment had been moved to the S&TF, all SERF laboratories had been evacuated as per ES&H requirements, and approximately 50% of the STF-located equipment was operational as per ES&H requirements. It is estimated activities associated with re-establishment of equipment consumed 20%-30% of the technical staff's time. All systems are being re-established as quickly as possible to meet rapidly expanding workload.

In August 2007, a CIGS device was fabricated that that was confirmed at 19.88% efficiency. Because of a change in spectral conditions, this result has since been re-certified at 20.0%. Both results exceed the previous world-record efficiency of 19.52% by a noticeable margin and have indicated a pathway toward even higher efficiency. A publication describing the process improvements that yielded these results was published. The result also confirms the equipment and procedures used for our CIGS research have survived the rigors and design modifications associated with the move and can again be relied upon to produce the high baseline performance that has placed NREL at the forefront of CIGS research.

Activities related to development of novel TCOs for CIGS incorporation was completed. This involved the development of a Al-doped ZnO (ZnO:Al) material that was designed to achieve higher infrared (IR) transmission. Unlike "standard" ZnO:Al that contains ~2 wt.% Al_2O_3 and is sputter deposited in pure argon, our research determined that if a hydrogen/argon sputtering ambient is used, the Al_2O_3 content can be reduced to ~0.05 wt.% to provide significantly improved electron mobility and higher carrier activation. Because fewer free carriers (electrons) are required to produce a low resistivity film, higher IR transparency results. Preliminary incorporation of this new composition of ZnO:Al into CIGS devices has yielded quantum efficiencies higher than achieved on world record CIGS devices, and so further testing was actively proceeding at the end of FY07. The second TCO project involves development of a ZnO + MgO alloy (ZnMgO) that may afford the ability to control the valance-band discontinuity at the Zn(Mg)O/CdS interface, thereby allowing higher V_{oc} at higher gallium concentrations. The material may also have higher resistance to environmental corrosion compared to ZnO. Initial analysis of ZnMgO fabricated by r.f. sputter deposition has been encouraging, and results related to incorporation of the layer into CIGS devices have been published.

The project related to sensor development proceeded exceptionally well. Through collaborative efforts with the measurements and characterization team, several important observations were made and published. First, it was re-confirmed that the minority carrier lifetime of the CIGS layer after CdS treatment is a strong indicator of ultimate device performance. Second, observed for the first time, the time between CIGS layer fabrication and CIGS deposition strongly affects the minority carrier lifetime, and therefore, the ultimate device performance. These observations have significant implications for industrial partners. First, it is important that the CIGS and CdS process sequences be conducted in a timely manner. Second, it is very difficult to assess carrier lifetime of the CIGS layer, unless appropriate equipment is at the facility where the CIGS is produced. Third, and most importantly, it is possible to develop an in-line diagnostic tool based on time-resolved photoluminescence that could be used to assess the quality of the CIGS layer prior to ultimate device fabrication.

The final highlighted accomplishment relates to receiving the first of the three orders related to the

CIGS PDIL platform. This first component will allow for CIGS deposition within the boundaries of the PDIL design guidance (i.e., 6"x6" format, multiple runs per chamber service (up to 100), 1.1 meter transfer height, pod transfer, cassette loading, and robot-compatible). After arrival, considerable effort was invested to fit up the system. Initial operation of this first phase of the CIGS system is expected in early FY 2009. This marks a significant step toward the establishment of the first of the PDIL platforms that are being designed by the Polycrystalline Thin- Films Group. Orders for the remaining two phases of the CIGS have also been placed.

4. Planned FY 2009 Activities

Efforts will continue to shift from the CIGS STF laboratories used to produce small devices and thin films toward efforts related to installation of the equipment required to establish operations in the CIGS PDIL. Efforts will also be expanded for CIGS-related cooperative research and development agreements (CRADAs). This and other planned activities are outlined below.

- Complete remaining fit-up of STF laboratories to attain functionality of previous SERF labs.
- Finalize specification and engineering for solution-growth CdS component.
- Fit up remaining CIGS PDIL components.
- Establish key metric for device performance immediately following CIGS deposition.
- Expand research of alternative processes for CIGS layer deposition.

5. FY 2008 Special Recognitions and Awards

- M.A. Contreras won the 2008 HENAAC outstanding technical achievement award for his contributions to the field of solar energy. (www.henaac.org)
- M.A. Contreras' publication in *Progress in Photovoltaics* journal was recognized as the most cited paper in the field of Energy and Fuels. He is one of the top 10 most cited scientists in this field. (http://sciencewatch.com/ana/fea/08novdecFea/)

6. Major FY 2008 Publications

- I. Repins; M.A. Contreas; B. Egaas; C. DeHart; J. Scharf; C.L. Perkins; B. To; R. Noufi. "19.9%-Efficient ZnO/CdS/CuInGaSe_2 Solar Cell with 81.2% Fill Factor," Prog. in Photovolt.: Res. and App. 16 235-239 (2008).
- M.A. Contreras; I. Repins; W. Metzger; M. Romero; D. Abou-Ras. "Se Activity and its Effect on Cu(In,GaSe_2 Photovoltaic Thin Films," Proc. 16th Int. Conf. on Ternary and Multernary Compounds (ICTMC-16), Technical university of Berlin, Berlin, Germany Sep. 16-19, 2008.
- D. Abou-Ras; C.T. Koch; V. Küstner; P.A. van Aken; U. Jahn; M.A. Contreras; R. Caballero; C.A. Kaufmann; R. Scheer; T. Unold; H.-W. Schock. "Grain-boundary types in chalcopyrite-type thin films and their correlations with film texture and electrical properties", E-MRS 2008 Spring Meeting, Symposium L, Strasbourg, France, May 26–30, 2008.
- W.K. Metzger; I.L. Repins; M.A. Contreras. "Long lifetimes in High-efficiency Cu„In,GaSe_2 Solar Cells", Appl. Phys. Lett. 93, 022110, 2008.
- X. Li; H. Ray; C.L. Perkins; R. Noufi. "Effects of Mg Content on $Zn_{1-x}Mg_xO$:Al Transparent Conducting Films," Proc. of Spring MRS San Francisco, March 24-28, 2008.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Optony Inc.	Sunnyvale, CA	Development of thin film CIGS solar cells for concentrator applications	250	250
JLN Solar	Mill Valley, CA	Development of the monolithic interconnection in minimodules	100	

Cadmium Telluride

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Timothy Gessert, 303-384-6451, tim_gessert@nrel.gov

DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@ee.doe.gov

FY 2008 Budget: $880K

Objectives

- Re-establish cadmium telluride (CdTe) research at Science and Technology Facility (S&TF).
- Expand intellectual property (IP) for design of novel transparent conducting oxides in thin-film CdTe photovoltaic (PV).
- Develop goals and metrics associated with CdTe Technology Roadmaps including coordination of Process Development and Integration Laboratory (PDIL) platform designs.

Accomplishments

- Made CdTe absorber laboratories in S&TF nearly 100% operational.
- Made CdTe contact laboratories in S&TF more than 70% operational.
- Made user-characterization labs and cell reliability labs 100% operational in STF.
- Established role of Cu on improving minority carrier lifetime in CdTe PV devices.

Future Directions

- Complete requirements for full functionality of equipment in remainder of S&TF laboratories.
- Complete initial procurement stage of CdTe PDIL equipment.
- Expand minority-carrier studies to CdTe materials produced by multiple sources.
- Establish ZnTe:Cu/Ti contact process using NREL CdTe absorber materials.
- Accelerate research on high-bandgap absorber layers for tandem-junction polycrystalline thin-film PV devices.
- Foster partnerships with commercial glass companies to develop PV-specific products.

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1. FY 2008 Special Recognitions and Patents

- T.A. Gessert, co-organizer, "New Concepts in Polycrystalline PV," 2008 European Materials Research Society meeting.
- T.A. Gessert, chair, Vacuum Technology Division. Becomes program chair in October 2008 for 2009 AVS National Symposium.
- T.A. Gessert; J. Duenow; T. Barnes; T.J. Coutts. Patent Filed. IR 07-42, High Quality Transparent Conducting Oxide Thin Films.
- Record of Invention filed with DOE, IR 08-28, X. Li and T.A. Gessert.
- Patent published. T.A. Gessert; Y. Yoshida; T.J. Coutts. IR 04-32. Transparent Conducting Oxides with Controlled Dielectric Permittivity.

2. Major FY 2008 Publications

- T.A. Gessert; W.K. Metzger; P. Dippo; S.E. Asher; R.G. Dhere; M.R. Young. "Dependence of Carrier Lifetime on Cu-Contacting Temperature and ZnTe:Cu Thickness in CdS/CdTe Thin Film Solar Cells," 2009 EMRS Meeting, Strassbourg, France. Accepted for Pub. *Thin Solid Films*.
- R.G. Dhere; Y. Zhang; M.J. Romero; S.E. Asher; M. Young; B. To; R. Noufi; T.A. Gessert. "Investigation of Junction Properties of CdS/CdTe Solar Cells and Their Correlation to Device Properties." *33rd IEEE PVSC Proceedings.*
- X. Li; J. Pankow; B. To; T. Gessert. "Comparison Between Research-Grade and Commercially Available SnO_2 for Thin-Film CdTe Solar Cells." 33rd IEEE PVSC Proceedings.
- L. Zhang; J.L.F. Da Silva; J. Li; Y. Yan; T.A. Gessert; S-H. Wei."Effect of Co-Passivation of Cl and Cu on CdTe Grain Boundaries," Accepted for Pub. *Physical Review Letters*, LU12095 (9/08).

Concentrating Photovoltaics

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Daniel Friedman (NREL), 303-384-6472, daniel_friedman@nrel.gov

DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@hq.doe.gov

FY 2008 Budget: $2,114K (NREL)

Objectives

- Demonstrate inverted lattice mismatched (iLMM) device with concentrator performance peak above 100 suns.
- Demonstrate iLMM cell with optimized second- and third-junction band gaps.
- Improve theoretical understanding of misfit and threading dislocations in III-V materials.
- Study the effect of growth parameters on strain relaxation and defect properties.
- Initiate development of 4-junction 2.0/1.6/1/2/0.9-eV IMM cell for efficiency approaching 50%.
- Evaluate degradation mechanisms of multijunction / iLMM cells; plan for mitigation.
- Develop computational tools capability to simulate the electrical, optical and thermal behavior of high efficiency multijunction solar cells in two and three dimensions.
- Investigate barriers to creation of a mature concentrating photovoltaics (CPV) industry.

Accomplishments

- Demonstrated record-setting IMM cell with 40.8% peak efficiency at 326 suns using optimized 1.83, 1.34, and 0.89 eV bandgaps.
- Developed new dislocation core structure model for InN/GaN misfit dislocations.
- Developed InGaAs growth capabilities on MBE; demonstrated metamorphic InGaAs cell.
- Developed top two subcells (2.0/1.6 eV) and demonstrated tandem incorporating them.
- Determined oxidation rate of AlInP window in various testing environments and vs. dopants.
- Acquired suite of software tools and adapted them to calculate behavior of MJ cells.
- Developed and published report on status of the CPV industry and barriers to its maturity.

Future Directions

- Improve grades for mismatched junctions; reduce resistance for higher concentration operation; high temperature operation and improve heat management.
- Evaluate performance of different alloys in the graded layers, including AlGaInAs and AlGaAsSb; comparative investigation of mismatch with both tensile and compressive strain.
- Assess stability and degradation mechanisms of metamorphic cells; study effect of encapsulants, AR coat, and metallization on AlInP window layer.
- Model effects of real-world problems, develop mitigation paths, and optimize device performance, for effects including non-uniform irradiance and high series resistance.

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1. Introduction

This activity develops advanced multijunction concentrator cells with improved performance, reliability, and cost-effectiveness. We transfer the resulting technology to the CPV industry through licensing and cooperative research and development agreements (CRADAs) with industrial partners. The CPV approach leverages the high output of the multijunction cells, while minimizing the cell cost as a fraction of the system cost, targeting low LCOE for installations at the large-rooftop to utility scales. A study by the Prometheus Institute ("Concentrating Solar Power – Technology, Costs, and Markets", Grama et al, 2008, p.6) projects CPV to become competitive at utility scale within the next decade. Ultimately the goal for CPV is lower LCOE than flat plate for commercial rooftop and utility markets.

No. (in AOP)	Agreement Title	FY 2008 Budget ($K)
1.1	High concentration operation of ILMM cell	410
1.2	Variable band gap ILMM	282
1.4	Theory of dislocations	95
1.5	LMM materials by MBE	190
1.6	50% ILMM cell	230
2.1	Reliability of cell components	297
5.3	Advanced cell modeling	475
6.2	Mature CPV Industry Study	135

2. Results and Accomplishments

Task 1.1 and 1.2: High-concentration, optimized-bandgap IMM cells

Significant improvements were made to the three-junction inverted lattice mismatched (iLMM) solar cell. We fabricated an inverted device with two compositionally graded buffer layers to achieve a world record 40.8% efficiency under concentration. Defect densities were only $1x10^5$ and $2x10^6$ cm^{-2} in the middle and bottom lattice-mismatched junctions respectively.

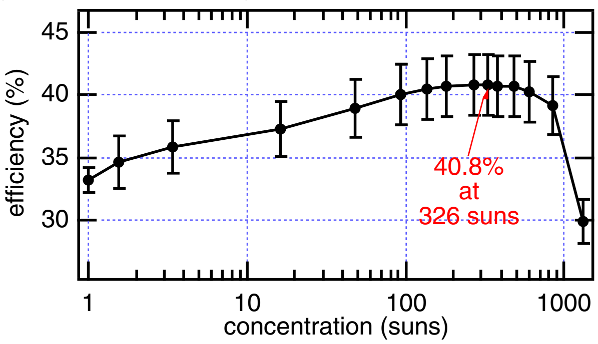

Fig. 1.1. Efficiency of record IMM three-junction device as a function of concentration.

Task 1.4: Dislocations Theory

We studied misfit dislocations at the InN/GaN interface, a useful model system whose understanding will help with the study of the arsenide-phosphides used in the IMM cell. We found that the InN/GaN interface is composed of three sets of 90º partial dislocations which strongly interact with each other within the two-dimensional interface plane to exhibit long-range order.

Based upon this initial study, odeling was then extended to include partial dislocations in GaAs. Two of these reconstructions are shown in Fig. 1.4. Calculations show the As core prefers the "double period" (DP) structure and is an electron donor, whereas the Ga core prefers the "single period" (SP) structure and is an electron acceptor. The two dislocations will therefore behave differently in p-type and n-type environments. This may help explain some of the puzzles related to the interaction between dislocations and doping.

Task 1.5: Lattice mismatched materials by MBE

Experiments to test the effect of dopants, temperature, and surfactants on strain relaxation and device characteristics were performed.

- Gross changes in morphology and strain relaxation indicate a dislocation pile-up at low growth temperatures.
- Use of bismuth as a surfactant during mismatched growth was studied. Local changes in luminescence energies indicate the creation of point defects in the graded layer, which adds to the series resistance.
- The addition of silicon in graded layers increases the defect density. Changing the beryllium doping in the graded layers of solar cells affects the position of the junction–possibly implying an n-type contribution to the carrier concentration by defects.
- High quality MBE-grown metamorphic InGaAs solar cells were developed as a foundation for further LMM studies.
- Acquisition and installation of a MOSS system on the MBE growth reactor will allow the stress of future metamorphic growths to be studied *in-situ*.

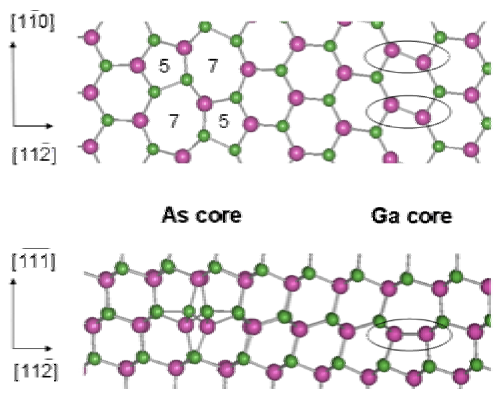

Fig. 1.4. Top and side views of 60° partial dislocations in GaAs. A "double period" As-core dislocation structure is shown with a "single period" Ga-core structure (right).

Task 1.6: 4-Junction IMM cell

Initially, 1.6-eV, n/p GaAsP solar cells were grown upright on GaAs substrates, using intervening GaAsP step-graded layers. A baseline cell structure without 2-eV GaInP minority-carrier barrier layers was first fabricated and evaluated. Next, barrier layers were added to the structure selectively (front and back surfaces) to assess performance improvements. Spectral absolute external quantum efficiency (AEQE) measurements showed the barrier layers reduced substantially non-radiative recombination at both the front and back interfaces, when compared to data for the baseline cell. With both barrier layers included in the cell structure, the AEQE exhibited a “box-car” characteristic for photon energies less than 2 eV. Furthermore, the internal quantum efficiency for the double-heterostructure (DH) GaAsP/GaInP cells approaches unity in this range. Current density (voltage) (J-V) data under standard one-sun conditions were also taken for the same set of 1.6-eV GaAsP cells. The baseline cell gave an efficiency of 9.4%, which improved to 12.2% for the DH cell incorporating barrier layers.

Task 2.1: Cell Reliability
Both experimental design of reliability testing and testing of individual cell components of LMM cells were performed. The quality and integrity of the AlInP window of a GaInP top cell is very important for high efficiency. Potentially very sensitive to oxidation, the damp-heat oxidation rate of AlInP was studied at various temperatures and humidities and found to be less significant than initial concerns. Upon the introduction of light, the oxidation rate increases by over 300%, a potentially important degradation mechanism for solar cells. Selenium and zinc doping of AlInP was also determined to increase the oxidation rate.

Experimental design of reliability testing on lattice-mismatched cells was completed. Performing EBIC or OBIC while forward biasing or irradiating a device will provide information about the change in defect density during device operation. Accelerated testing conditions including forward biasing, temperature, and weathering with intermittent cell characterizations will give information about failure modes and frequency.

Task 5.3: Advanced Cell Modeling
SPICE circuit analysis: We developed a full three-dimensional circuit model of a multijunction solar cell. The code can also calculate IV curves for non-uniform illumination, including cases in which the current mismatch between junction varies spatially across the cell.

Simulation of heat flow in a concentrator module under non-uniform illumination: We developed a model to study heat flow in a concentrator solar cell bonded to a heat sink. It consists of a 250μm-thick cell bonded to a Cu heat sink with a layer of thermal epoxy. The cell is non-uniformly illuminated with a peak concentration of ~10,000X and an average concentration of 1000X.

Simulation of III-V Multijunction solar cells: We developed 1-D and 2-D numerical models for single and multijunction solar cells of GaInP, GaAs and Ge. Validation of the results is on going.

Task 6.2: Mature CPV Industry Study
A study was completed on the status of the CPV industry and the remaining barriers to large-scale growth. Shared with dozens, the study has consistently generated positive feedback, including requests for invited talks or interviews.

5. FY 2008 Special Recognitions and Patents

- R&D 100 Award: Inverted Metamorphic Multijunction cell; M.W. Wanlass and Emcore.
- Friedman, D.J.; Geisz, J.F., U.S. Patent No. 7,309,832 B2, "Multi-Junction Solar Cell Device", December 18, 2007.

6. Major FY 2008 Publications

- J.F. Geisz; D.J. Friedman; J.S. Ward; A. Duda; W.J. Olavarria; T.E. Moriarty; J.T. Kiehl; M.J. Romero; A.G. Norman; K.M. Jones. "40.8% efficient inverted triple-junction solar cell with two independently metamorphic junctions." *Appl. Phys. Lett.*; 93, 123505, (2008).
- J.F. Geisz; A.X. Levander, A.G. Norman; K.M. Jones; M.J. Romero. "In-situ stress measurement for MOVPE growth of high efficiency lattice-mismatched solar cells." *J. Cryst.Growth*, 310, 2339 (2008).
- J.F. Geisz; S. Kurtz; M.W. Wanlass; J.S. Ward; A. Duda; D.J. Friedman; J.M. Olson; W.E. McMahon; T.E. Moriarty; J.T. Kiehl; M.J. Romero; A.G. Norman; K.M. Jones. "Inverted GaInP/(In)GaAs/InGaAs triple-junction solar cells with low-stress metamorphic bottom junctions." 33rd IEEE Photovoltaic Specialists Conference Proceedings, San Diego, 2008.
- M.A. Steiner; J.F. Geisz; R.C. Reedy; S.R. Kurtz. "A direct comparison of inverted and non-inverted growths of GaInP solar cells", Proceedings of the 33rd IEEE Photovoltaic Specialist Conference, San Diego, (2008).
- S.R. Kurtz. “Opportunities and Challenges for Development of a Mature Concentrating Photovoltaic Power Industry,” www.nrel.gov/docs/fy08osti/43208.pdf.
- S.R. Kurtz. “Current status of the CPV industry.” PV International 1, 121, (2008).

Organic Photovoltaics and Advanced Materials

Performing Organization: National Renewable Energy Laboratory (NREL)

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DOE HQ Technology Manager: Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2008 Budget: $2,241K

Objectives

- Develop organic-based thin film photovoltaics (OPV).
- Apply combinatorial methods to develop improved transparent conducting oxides (TCOs).
- Develop novel solution-based processes for PV including metallization and copper indium gallium diselenide (CIGS).
- Develop laser processing facility and apply to laser nucleation of amorphous Silicon (Si).
- Support cooperative research and development agreements (CRADAs) (e.g., HelioVolt, Evergreen Solar, BP, Konarka, TDA, Plextronics, XJET, and others).

Accomplishments

- Developed OPV device technology of organic and inorganic modifying layers for improved efficiency with promising initial results on scalability for spray and inkjet approaches.
- Hosted first international workshop on OPV lifetime, stability, and efficiency measurements with Plextronics and DOE. Initiated activities in efficiency and stability round robins internationally.
- Progressed in combinatorial tool set and ability to translate combinatorial results to state-of-art uniform films in ZnO, InZnO and CuZnO.
- Received R&D 100 award and FLC Technology Transfer Award for hybrid CIGS with Heliovolt. Developed new ink set and ink supplier for ink-based technologies.
- Made state-of-the-art quad-band laser process station operational with promising initial results on Si nucleation.

Future Directions

- Increase polymer synthesis effort to develop optimized materials for interfacial modification, active layer, and encapsulant for OPV. Hired senior polymer chemist and second post doc.
- Transfer ink-based technology to partners and develop commercial supplier of NREL-based inks; develop use of laser processing to develop large grain template layers for thin film Si on glass.
- Continue productive partnership with Solar America Initiative (SAI) and PV Incubator partners.
- Show controlled nucleation for amorphous Si recrystallization.
- Focus on processing to larger areas and addressing reliability and packaging issues; hold second International Summit on OPV lifetime, which was instrumental in revising OPV roadmap.
- Develop new TCOs with focus on very high performance, stability, interfacial chemistry, and work function. Continue examination of amorphous systems and development of ink-based approaches to high performance TCOs.

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1. Results and Accomplishments

1.1 Jointly with Sandia National Laboratories (SNL), develop next-generation OPV devices and begin to look at issues of scalability and lifetime.
Our OPV program has gained national and international attention due to our integrated approach to new acceptor and donor development coupled to our developments in new process technology, new characterization tools specific to OPV, and our initial results to address the lifetime (intrinsic and extrinsic) of OPV devices.

OPV devices with 4.2% efficiency have been made and measured using polymer/fullerene blends and ITO/PEDOT:PSS & Ca/Al electrodes. The open circuit voltage (V_{OC}), short circuit current (J_{SC}), and fill factor (FF) for 0.11 cm^2 devices were measured to be 609 mV, 10.9 mA/cm^2, and 63%, respectively. Scaling up the device area resulted in a reduction in the fill factor of the JV data, which is due to an increase in the series resistance due to the sheet resistance of the ITO electrode material. Present work on the revision of the electrode geometry and the reduction of the series resistance via a metal grid has demonstrated promising results on improving device performance for large area devices.

In an effort to initiate discussion and development of standard testing procedures for OPV device lifetimes and the degradation mechanisms in these devices, we helped to organize the first annual International Summit on OPV Stability. This successful event was designed to encourage the OPV community to come to an agreement on the proper testing protocols for OPV devices.

Initial studies on OPV device lifetime and stability are underway. The construction of two parallel combinatorial degradation simulators will allow for careful study and control of the effects of light soaking, light intensity, UV absorption, temperature, and inert, oxygen-free, and moisture-free atmospheric conditions on device lifetime and degradation. These degradation setups along with other OPV-specific characterization techniques will allow for the study of the degradation mechanisms at work in OPV devices. Data indicates that efforts to improve encapsulation technologies are of great importance for improved OPV device lifetimes.

The introduction of new device architectures, in particular inverted bulk heterojunction devices, can lead to the elimination of unstable low work function metal electrodes. This in turn has already led to much improved device shelf life in air compared to the traditional devices that employ air-sensitive Ca/Al electrodes. Such devices use a sol-gel ZnO layer to change the ITO electrode from a hole-collecting electrode to an electron-collecting electrode.

In order to improve the overlap between the absorption of the electron donor material and the solar spectrum, we have synthesized conjugated dendrimers with band gaps down to 1.8 eV and conjugated polymers with band gaps down to 1.5 eV. The dendrimer materials have been incorporated into bulk heterojunction devices and have already achieved power conversion efficiencies greater than 1% and have demonstrated V_{OC}'s greater than 900 mV despite having a lower band gap than P3HT, our standard donor material. This indicates the flexibility that organic synthesis allows for in the development of OPV materials.

The optimization of contacts in OPV devices is of great importance. This is further complicated by the necessity to re-optimize when change active layer materials due to changes in the electronic energy levels in these materials in order to efficiently extract charge. A comparison of several different metal electrodes for traditional bulk heterojunction devices proves calcium to be the best electrode material in terms of both performance and stability.

Additionally, we have investigated the effects of interface modification of P3HT/ZnO bilayers with amorphous TiO_2 deposited via atomic layer deposition (ALD), pulsed laser deposition (PLD) and solution to better understand charge generation and recombination processes at this interface. The TiO_2 layer dramatically improves the V_{OC} as a result of passivation of ZnO surface states and charge generation & lifetime as seen in Figure 6. In addition, a gradient in carrier concentration in the ZnO acceptor has also been shown to dramatically enhance current extraction.

We have investigated ink-jet printing and ultrasonic spray deposition as methods for materials deposition. There is little change in device performance when the PEDOT hole transport layer is deposited via traditional spin coating compared to ink-jet and ultrasonic spray.

Finally, we have been able to ultrasonic spray the active layer itself in air with efficiencies greater than 2%, and more recently efficiencies greater than 3% have been achieved using the same parameters when sprayed in a nitrogen atmosphere. This technique has been used to spray large area devices and appears to be an excellent method for high-throughput, large area deposition of organic materials in manufacturing.

1.2 Develop combinatorial materials science deposition, diagnostics, and data analysis tools for applications to TCO materials, applying to Si, CIS, cadmium telluride (CdTe), and OPV.

The combinatorial tool development has continued with the addition of new tools for mapping work function, optical properties and conductivity. We have now automated many of the tools and the associated data collection to move toward an integrated data management system. These have been applied to an increasingly broad range of problems with a focus on transparent conducting oxides. A key focus has been the continued investigation of amorphous TCO materials because of their excellent conductivity, transparency, smoothness, processability and low temperature deposition.

1.3 Develop ink-jet processing of electronic materials for application to metallization and semiconductor materials for Si, CIS, and OPV.
This work focuses on using liquid precursors to produce materials, such as metal contacts and absorber materials. These materials can either be deposited using inkjet printing or spray deposition. In the field of metal contacts a lot of progress has been made and our capabilities have expanded significantly. We have used inkjet printing for contacts on organic PV devices as well as CIGS devices. For OPV the results are not perfect yet, since the temperature at which the contacts can be printed is lower than the ideal temperature for the inks we have developed, leading to reduced conductivity of the metal and poor cell performance. Current effort is to develop an ink that will be compatible with OPV contact formation. In the area of contacts for CIGS, the effort has been very successful. When using a bilayer contact of nickel and silver efficiencies of more than 12.5% were achieved. A reference cell finished in a conventional fashion resulted in a cell with efficiency slightly above 13%. Considering the difference in shadow losses and the reduced cost of inkjet printing, makes inkjet printing very competitive with conventional evaporative contact.

In the area of contact for Si PV, large steps forward have been taken as well. First of all the burn-through contact printing has improved significantly and we now have an ink that could reduce processing temperatures of Si-based cells by more than 100ºC. Using inkjet printed contact cell efficiencies of over 13% were achieved on material that would get 13-14% efficiency with conventionally screen printed contacts. Also inks have been developed to form self-doping contacts. Work is shifting to develop inkjet printed contacts in other contact schemes. Currently we are working with industry to transfer the metallization technology. In order to do this we are working with industry to develop inkjet printing equipment as well as selecting an ink manufacturer for the inks developed at NREL.
Our effort in depositing a CIGS absorber layer from liquid precursor materials had good results. Using the inks developed at NREL has resulted in the formation of CIGS films that have large CIGS grains. Cells with reasonable efficiencies have been made using this large grain material. It can be made from bilayer films as well as mixed material films. Films are deposited using spray deposition. We are improving device performance and developing alternative inks that will have less expensive ingredients in order to reduce the ink cost. We are actively transferring this technology to one of our industrial partners.

Another absorber layer material that is under development for deposition by a liquid precursor is CdTe, developed as a nanoparticulate-based ink. Spray deposition is used to form a film. We have been successful in making optically dense thick films (up to 10µm with no cracks) of pure CdTe and are finishing these devices into cells.

Since many PV devices contain a TCO, there is also an effort in developing a liquid precursor-based TCO, indium-zinc-oxide (IZO). An ink has been developed that can be deposited using spray deposition in order to form an IZO film. Films with good optical properties and minimal cracking have been deposited. The best conductivity achieved using the developed ink is about 60S/cm. A typical TCO has a conductivity of 1000-6000 S/cm, so improvement is needed in order for a liquid precursor-based TCO to be a replacement for conventionally deposited TCOs.

Also, we are developing inks for an atmospheric processing platform (APP) for the NREL Process Development and Integration Laboratory (PDIL). This system will be located in bay 2 of the PDIL. The APP will have capabilities for inkjet printing, spray deposition, rapid thermal processing, XRD, XRF, sputter deposition, and evaporation. It will be capable of handling substrates up to 6”x6” in size. Everything will be located in an inert or vacuum atmosphere. Substrates can be moved around through the system without exposure to air by means of a linear motion system and a vacuum robot. The components of the system should arrive by December 2008, and completion of the system is expected in the first quarter of 2009.

1.4 Develop advanced laser process station for laser scribing, laser annealing, and laser recrystallization of PV device structures.
Crystallization of a-Si:H as a template layer for subsequent hot-wire chemical vapor deposition (HWCVD) epi Si growth is proceeding on three fronts, which are described below.

Seeding a-Si:H with very small crystals and have them grow into large crystals by thermal annealing before native crystallization sites nucleate (Collaboration with University of Minnesota/Uwe Korthagen)
Using a two chamber deposition system, consisting of a 'seed' chamber attached to a traditional plasma enhanced CVD (PECVD) a-Si:H deposition system, crystalline seeds (diameter ~ 5 nm) have been controllably introduced into an a-Si:H film, resulting in a crystalline volume fraction (v_f) varying from 0.24 to < 0.01. The resultant films were annealed at 600C and the v_f's were compared versus anneal time to an a-Si:H film containing no crystallite 'seeds'. For a v_f < 0.02, the film incubation time (time before the onset of crystallization) was shortened compared to that of an a-Si:H film, and TEM analysis showed no native nucleation during this time period.

This suggests that the 'sparsely introduced seeds' can indeed grow large without any interference from the native nucleation sites, thus providing proof of concept of this idea. Work is in progress to examine which initial v_f and which annealing temperature can produce the largest grains in the completely crystallized films.

Laser crystallization of NREL a-Si:H films (Collaboration with Sharp Corporation of America/Steven Droes)
Sharp has a well established crystallization process for a-Si:H, where they pulse the samples with a 4μm x 10mm laser beam spot which is then rastered across the entire sample, enabling full sample crystallization. They have examined many types of a-Si:H, and while the resultant sample crystallization is roughly similar, the sample electronic properties are vastly different. To date, they have laser annealed HWCVD samples containing 10-12 at % H, but which have been pre-annealed to evolve the majority of the bonded H (see Fig. 2). On the other hand, they were unable to crystallize a-Si:H films containing 2-3 at.% H (no pre-annealing), suggesting that evolution of this (smaller) H content is still significant enough to disrupt the crystallization process. Work is in progress to examine if films initially containing < 1 at.% H (no pre-annealing) can be crystallized, thus eliminating the (energy intensive) pre-annealing step altogether. Work will then be initiated to examine the electronic properties of these films.

Creation of 'artificial' nucleation center site by laser processing (NREL)
Utilizing the concepts of a critical crystallite size and local film inhomogeneity, a model for a nucleation center has been advanced which shows that nucleation in thermally annealed a-Si:H occurs in the more well ordered spatial regions in the network, which are defined by the initial inhomogeneous H distributions in the as grown films. Based upon this model, we propose to create 'artificial' nucleation centers by laser processing, which will then grow into large crystallites byy thermal annealing. To date, thin (200-300 nm) a-Si:H samples have been laser illuminated in an area (3mm x 3mm) large enough to enable characterization by XRD and/or reflection and transmission. Initial results in this area yielded illuminated areas that were already crystalline, suggesting that the laser power needs to be reduced. Having shown that no crystallinity has been achieved upon laser processing (illumination), we next plan to thermally anneal these films to compare the structure of the film areas, which have been laser processed to those which have not been processed.

2. Special Recognitions and Patents

- R&D 100 award and FLC Technology Transfer Award for Hybrid CIGS with Heliovolt.

3. Major FY 2008 Publications

- M.F.A.M van Hest; C.J. Curtis; A. Miedaner; R.M. Pasquarelli; T. Kaydanova; P. Hersh; D.S. Ginley. "Direct-Write Contacts: Metalization and Contact Formation." 33rd IEEE Photovoltaic Specialist Conference Proceedings; 2008.
- C.J. Curtis; M.F.A.M. van Hest; A. Miedaner; J. Nekuda; P. Hersh; J. Leisch; D.S. Ginley. "Spray Deposition of High Quality CuInSe2 and CdTe Films." 33rd IEEE Photovoltaic Specialist Conference Proceedings; 2008.
- B. Sang; F. Adurodija; M. Taylor; A. Lim; J. Taylor; S. McWilliams; R. Oswald; B.J. Stanbery; M.F.A.M. van Hest; J. Nekuda; A. Miedaner; C.J. Curtis; D.S. Ginley. "Low Cost Copper Indium Gallium Selenide by the FASST Process." 33rd IEEE Photovoltaic Specialist Conference Proceedings; 2008.
- M.F.A.M. van Hest; David Ginley. "Future Directions for Solution-Based Processing of Inorganic Materials," chapter in *"Solution-Based Processing of Inorganic Films."*

Sensitized Solar Cells

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Arthur J. Frank (NREL), 303-384-6262, Arthur_Frank@nrel.gov

DOE HQ Technology Manager: Jeffery A. Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2008 Budget: $698K (NREL)

Objectives

- Develop next-generation sensitizers, architectures, and charge-conducting phases for improved device stability and performance.
- Identify promising cell materials and configurations for highest device durability and efficiency.
- Develop assembly procedures and cell-sealing techniques to increase device stability.
- Obtain detailed understanding of fundamental processes that affect stability and device performance in collaboration with DOE's Office of Science Basic Energy Sciences program.

Accomplishments

- Demonstrated >95% device stability over 1,000 h under continuous light soaking.
- Demonstrated 19% improved device efficiency in dye-sensitized NT arrays having increased architectural order.
- Developed first general synthetic method for growing ordered inorganic p-type semiconductor as a charge-conducting phase in NT arrays.
- Synthesized ionic-based liquid electrolyte, delivering improved device stability.

Future Directions

- Continue to improve photoelectrode architectures, charge-conducting phases, and assembly/sealing techniques for enhancing device stability at increasing efficiency levels.
- Develop molecular and/or inorganic sensitizers with improved absorption across solar spectrum.
- Demonstrate device(s) incorporating the above mentioned cell components.

FY 2009 Planned Activities:

- Demonstrate ordered nanostructured materials with improved electrical and/or optical properties.
- Demonstrate device(s) with charge-conducting phases and/or nanostructured architecture; report preliminary device performance and durability results.
- Demonstrate 5% efficient device with <10% efficiency loss over 1,000 h.
- Synthesize and characterize low-volatile, liquid/quasi-solid and/or solid-state organic, and inorganic charge-conducting phases.

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1. Introduction

The Sensitized Solar Cell Agreement applies to bulk heterojunction devices, featuring nanoscale, interpenetrating liquid/solid and solid/solid networks of electron- and hole-conducting materials. Typically, a light-harvesting molecular or inorganic sensitizer is located at the interface between these two materials. The primary objectives are to evaluate laboratory cell stability at different performance levels, to identify the cause of efficiency loss, and to develop next-generation cell materials and configurations for improved device durability and efficiency.

Agreement Title	FY 2008 Budget ($K)
Photoelectrode architecture and device assembly & characterization	402
Design/develop charge conducting phases	296

2. Results and Accomplishments

Activities centered on designing and developing photoelectrode architectures, charge-conducting phases, and assembly/sealing techniques for improving cell stability and performance.

- Demonstrated a baseline level of device efficiency and stability for 1000 h. (09/08)

We built the first apparatus at NREL that is capable of performing long-term stability testing (>10000 h) under continuous simulated solar light illumination. We conducted preliminary stability tests on TiO_2 nanoparticle-based dye-sensitized solar cells involving (1) a reported stable new sensitizer and (2) an improved ionic liquid electrolyte in collaboration with M. Grätzel, Ecole Polytechnique Federale de Lausanne. The results demonstrated >95% device stability over 1000 h under continuous light soaking. The initial results are encouraging. They provided a baseline for comparing the stability and performance of devices incorporating other sensitizers, charge-conducting phases, and/or nanostructure architectures.

- Demonstrated ordered electrode architecture with enhanced electrical and light-harvesting properties. (01/08)

We identified the capillary stress created during evaporation of water from the mesopores of densely packed TiO_2 nanotube arrays was of sufficient magnitude to induce bundling and microcrack formation. We developed a methodology involving the supercritical CO_2 drying technique to prevent such architectural disorder. We also demonstrated higher photocurrent density and solar conversion efficiency in dye-sensitized cells incorporating films with the more aligned nanotube arrays.

- Developed knowledge base to synthesize solid-state inorganic p-type hole conducting phase. (09/08)

We identified key factors controlling the spatial profile of the growth of p-type inorganic hole conducting materials in the nanopores (< 100 nm) of n-type electron conducting materials. We simulated the synthetic conditions for electrodepositing hole conductors from the bottom of the nanoporous film upward toward the top of the film. The information from the simulations will guide the synthetic effort (FY 2009) to fill the entire pore network with an inorganic hole conducting material.

- Synthesized a liquid electrolyte with improved stability. (09/08)

We synthesized an ionic liquid based on an imidazole derivative for dye-sensitized solar cells. This liquid electrolyte is expected to improve the device stability. The initial results of performance and stability tests are encouraging.

3. FY 2008 Special Recognitions and Patents

- A.J. Frank, recipient of NREL's Director Award for achievements in dye-sensitized solar cells.
- K. Zhu, N.R. Neale, A. Miedaner, and A.J. Frank *Nano Lett.* 2007, 7, 69 was the most cited 2007 Nano Letters article as of September 2008.

4. Major FY 2008 Publications

A. J. Frank. "Science, Technology, and the Future of Sensitized Solar Cells." Presented workshop on High Efficiency Photoconversion of Solar Energy to Electricity and Fuels: Tutorial and Critical Research Directions at University of Colorado at Boulder, Colorado, August 13-15, 2008.

A.J. Frank. "Science, Technology and the Future of Sensitized Solar Cells." *Photovoltaics Beyond Conventional Silicon*, June 17-18, 2008, Denver, Colorado.

A.J. Frank. "Interfacial Photochemical Processes in Sensitized Nanostructured Electrodes." *30th DOE Solar Photochemistry Research Conference,* June 1-4, 2008, Charlottesville, Virginia.

A.J. Frank. "Materials R&D Opportunities in Sensitized Nanostructured Solar Cells." Presented at Materials Day 2008, Pennsylvania State University State College, April 14-15, 2008.

A.J. Frank. "PV Conversion Technologies, Session: OPV, Sensitized, Seed." Presented at Solar Annual Review Meeting, April 22-23, 2008, Austin, Texas.

J. Van de Lagemaat; K. Zhu; K.D. Benkstein; A.J. Frank. "Temporal Evolution of the Electron Diffusion Coefficient in Electrolyte-Filled Mesoporous Nanocrystalline TiO_2 Films." *Inorganica Chimica Acta.* 361, 620 (2008).

K. Zhu; T.B. Vinzant; N.R. Neale; A.J. Frank. "Removing Structural Disorder from Oriented TiO_2 Nanotube Arrays: Reducing the Dimensionality of Transport and Recombination in Dye-Sensitized Solar Cells." *Nano Letters* 7, 3739 (2007).

Measurements and Characterization

The Measurements and Characterization (M&C) project supports the Solar Energy Technology Program (SETP) through the development and application of measurement and analysis techniques to solve scientific and technical problems that arise in the development and commercialization of photovoltaic (PV) technologies. Our expertise and capabilities facilitate research, development, and test and evaluation (T&E) in support of each of the PV technology roadmaps.

The M&C project consists of four closely integrated core competency groups: Cell and Module Performance, Analytical Microscopy, Electro-Optical Characterization, and Surface Analysis. Each group utilizes a wide array of state-of-the-art measurements and characterization techniques and has highly trained staff with a combined total of more than 450 years of experience in PV materials and device characterization. This extensive PV experience base, coupled with the breadth of our capabilities, sets us apart from other organizations throughout the world (a summary of our analytical capabilities can be found at *www.nrel.gov/pv/measurements*).

The M&C project focuses its efforts in three complementary areas: support, collaborative R&D, and technique development, as shown in Figure 1. M&C Support focuses on providing routine and specialized measurement and characterization support for the PV community through rapid and direct response to requests. M&C support also includes test and evaluation (T&E) and stage-gate review activities in support of the Solar America Initiative (SAI). Collaborative R&D focuses on contributing to and leading collaborative research projects to address critical issues and problems in PV technologies. Technique and Diagnostic Development focuses on developing and implementing new and specialized measurement techniques in response to specific needs in PV R&D and manufacturing. This work is done within the context of supporting all DOE-supported technologies and technology partners.

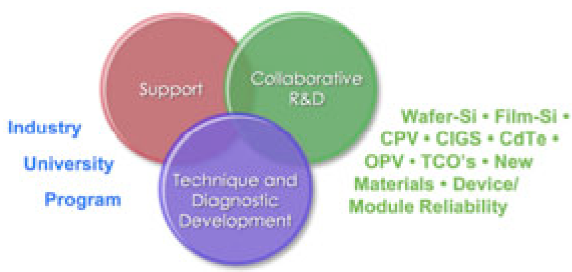

Fig. 1. Schematic showing Measurements and Characterization research areas of emphasis.

The M&C project is designed to help SETP meet its SAI 2015 targets, so the activities span a broad range of tasks that are focused on addressing technology-specific priorities. A summary includes:

- T&E services in support of the subcontracted program and stage-gate reviews
- Rapid-turnaround manufacturing process and device problem solving R&D
- Process development and device optimization R&D
- Cell failure analysis R&D
- Module failure analysis R&D
- New measurement techniques that address challenging material and device problems for mature and emerging PV technologies
- T&E protocols to accurately measure the performance of novel cell and module structures
- Measurements and characterization consulting for industry and university partners.

In FY 2008, this project assisted customers with the test and analysis of tens of thousands of materials and device samples, helping them direct their research and commercial product development. The M&C project has a long history of working with the PV community to solve material, device, manufacturing, packaging, and reliability issues. We strive to develop a solid scientific foundation to help our customers advance their manufacturing process development, research, and reliability R&D to a higher level.

Analytical Microscopy

Performing Organization: National Renewable Energy Laboratory (NREL)

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DOE HQ Technology Manager: Marie Mapes, 202-586-000, marie.mapes@hq.doe.gov

FY 2008 Budget: $2,660K

Objectives

- Provide routine and specialized measurement and characterization support for photovoltaic (PV) program research and industry teams.
- Lead and contribute to collaborative research that addresses critical issues in PV technologies.
- Develop and implement novel measurement techniques that enhance the ability to understand and advance fundamental PV research and development.

Accomplishments

- Provided extensive analytical microscopy support to Solar America Initiative (SAI) partners. Maintained cutting-edge support and acceptable turnaround time despite a nearly 50% increase in sample volume.
- Developed two-dimensional p-n junction mapping in multicrystalline silicon (Si(solar cells and applied that technique to help CaliSolar optimize their junction formation process in highly textured Si cells.
- Investigated carrier depletion behavior and grain misorientation in grain boundaries in polycrystalline Si thin films, in collaboration with in-house thin-film Si project.
- Designed, procured, commissioned, and tested new scanning probe microscope (AFM) and new scanning electron microscope (SEM) with environmental control and pod compatibility, in support of Process Development and Integration Laboratory (PDIL).
- Investigated uniformity of ultrathin electron injection layers for organic solar cells, in collaboration with Konarka.
- Expanded capabilities of WaferScan to better support SAI's industrial wafer Si projects.
- Investigated structural and electronic properties of nanocrystalline Si:H films and devices with nanometer-scale resolution to help United Solar optimize their multi-junction cells.
- Investigated microstructure and compositional profile of new world record copper indium gallium diselinide (CIGS) solar cell.

Future Directions

- Provide priority analytical microscopy support to SAI partners.
- Investigate recombination and electron transport in c-Si low-angle grain boundaries to establish critical misorientation degrading device performance.
- Complete establishment of environmentally-controlled AFM and vacuum-SEM systems, ensure readiness for PDIL applications; complete measurement of III-V device potential profile, and investigate GB potential behavior on a polycrystalline thin film.
- Provide better understanding of the role of grain boundaries and intra-grain defects in affecting transport properties of cadium telluride (CdTe) films.
- Evaluate effects of Ga flow on structure and chemistry of grain boundaries in CIGS thin films, including Ga concentration profile across grain boundaries.

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1. Introduction

The Analytical microscopy task supports all PV material technologies and involves broad collaborations with external research partners in university and industry laboratories, PV manufacturers, and internal research groups. Each year this project assists clients with the analysis of thousands of materials and device samples, helping them to understand and direct work on their research and commercial product development. We also serve as one of the SAI test and evaluation facilities used to evaluate subcontract stage gate deliverables.

These activities address one or more of the three areas crucial to meeting the goal of reducing the levelized cost of energy for PV to $0.06/kWh by 2015. The three areas are (1) improving device and module performance, (2) reducing manufacturing costs, and (3) improving device/module reliability.

2. Results and Accomplishments

Supporting SAI

The highest priority was supporting SAI projects. Considerable resources were devoted to supporting both Technology Pathway Partnerships and PV Incubator projects. Such projects resulted in a nearly 50% increase in our workload from the previous year. Despite this dramatic increase, we were able to provide state-of-the-art measurements at an acceptable turnaround time. The SAI work falls into three categories: measurement support, verification of deliverables, and research support. Three examples of the latter are given in this section.

Mapping in multi-crystalline Si solar cells

In support of CaliSolar's Incubator project, a technique for two-dimensional mapping of the p-n junction in textured Si cells was developed and applied. The technique is based on scanning Kelvin probe force microscopy (SKPFM) and was further supported by device simulation.

To get reliable potential measurements using SKPFM, we developed a special cross-sectional technique for textured, multi-crysalline Si (mc-Si) solar cells. A bias voltage (Vb) was applied to induce potential changes that were measured. Therefore, the V-b induced electric fielded on the surface, as deduced from the measured potential changes, can represent the electric field changes in the bulk, and the location at the maximum values of the electric field corresponds to the p-n junctions. This junction identification was further supported by device simulation using PC1D which corroborated our experimental findings. The most significant aspect of junction identification by this technique is its two-dimensional capability. To our knowledge, junction identification using SKPFM is the only method that can determine that.

Carrier depletion behavior and grain misorientation

Grain boundaries (GBs) are believed to be the main cause for efficiency loss in polycrystalline Si thin-film devices. In collaboration with NREL's Si group, the structural and the microelectrical properties of GBs in polycrystalline Si thin films were investigated by electron backscattering diffraction (EBSD) and scanning capacitance microscopy (SCM). The SCM measurements revealed highly non-uniform carrier depletion among the GBs, indicating the variety of electrical activities are due to the complicated GB structures. The carrier depletion on the GBs can be a measure of the charged deep levels or impurities, and thus an indicator of the carrier recombination behavior.

Comparison of SCM and EBSD measurements led us to the following conclusions: (1) $\Sigma 3$ GBs do not exhibit carrier depletion and thus do not have charged deep levels; (2) some $\Sigma 9$ GBs exhibit carrier depletion and some do not, indicating that the intrinsic $\Sigma 9$ GBs do not have charged deep levels and the carrier depletion is due to impurity gettering at the GBs; (3) no close relationship between the carrier depletion behavior and grain misorientation angles and directions was found on random GBs; and (4) carrier depletion behavior does not depend only on the grain misorientation, but also on the facet plan where the GB is taken. These studies are expected to significantly impact GB passivation and material optimization.

New scanning probe microscope

We installed scanning probe microscopy (SPM) capabilities for large-area samples and environmentally-controlled measurements. Electrical measurement techniques based on SPM have the advantage of providing information such as surface potential, electrical conductivity, and doping with spatial resolution second to none. However, the results of these measurements are strongly affected by the condition of the sample surface. The new SPM installed in the PDIL is connected to a glove box, and will operated in an inert ambient with less than 0.1 ppm of H2O and O2, allowing for analysis of clean surfaces.
The SPM has been installed, tested, and in operation. The sample transfer station had several problems, and most of them have been fixed.

Scanning electron microscopes

In support of the PDIL, two new scanning electron microscopes (SEM) were purchased. One microscope is an environmental tungsten-filament SEM, which is connected to a sample transfer/flipping station, and will be able to receive samples from deposition, processing, and analytical equipment in vacuum. The other system is a field-emission gun SEM that is suitable for high-resolution analysis.

<u>Uniformity of ultrathin electron injection layers</u>
In support of Konarka's SAI project, we have set up tunneling current measurements based on intermittent contact AFM to support the development of ultrathin (5-20 nm) Electron Injection Layers (EIL) in Konarka's PowerPlastic. Ultrathin EILs are critical in achieving high efficiency and, therefore, nanoscale inhomogeneities in the EIL represents a top priority in Konarka's PowerPlastic development. Because the roughness of the underlying transparent electrode is similar to that of the EIL, the thickness of the EIL is difficult to assess. Our tunneling current AFM, specifically developed to address the uniformity of Konarka's EILs, is based on measuring tunneling current pulses seen during the oscillation of a tuning fork (TF) sensor, driven by an external bias applied to the metallic ultrasharp tip attached to the TF.

<u>Expand the capabilities of WaferScan</u>
Our NREL-developed *WaferScan* enables luminescence spectrum imaging measurements (spectrum-per-pixel) over a lateral scanning range of 3" × 3" (to be extended up to 6" × 6" in the PDIL) in combination with high resolution cathodoluminescence. We have expanded the capabilities of *WaferScan* by adding measurements of the local reflectivity (R) and diffusion length (L), both based on luminescence. These measurements of the diffusion length can be performed at any processing stage and, therefore, do not require fully processed Si solar cells. Furthermore, the estimates of the diffusion length are free of the artifacts resulting from trapping or caused by local transients in capacitance common to other methods. In addition, we have added an input channel to perform electron-beam-induced current (EBIC) measurements, which can be performed simultaneously with spectrum imaging.

<u>Properties of nanocrystalline Si:H films and devices with nanometer-scale resolution:</u>
We found that the shape and density of the nanocrystalline Si (nc-Si:H) nc-Si:H materials can be controlled by the P concentration and H dilution ratio during the growth. The results provided critical information for United Solar to synthesize mixed a-Si:H and nc-Si:H with desired parameters. Bright field (BF) TEM images revealed the formation of con-shape nc-Si regions. The electrical properties of the nc-Si:H films were examined by scanning probe microscopy. The data we provided United Solar proved critical in optimizing their deposition process. .

3. Major FY 2008 Publications

- A.G. Norman. "A Critical Review of Intermediate Band Solar Cell Experimental Results." invited paper presented at the *Materials Research Society 2008 Spring Meeting*, San Francisco, March 2008.
- F. Liu; M.J. Romero; K.M. Jones; A.G. Norman; M.M. Al-Jassim; D. Inns; A.G. Aberle. "Intragrain Defects in Polycrystalline Silicon Thin-Film Solar Cells on Glass by Aluminum-Induced Crystallization and Subsequent Epitaxy." *Thin Solid Films*; 516 (2008) 6409.
- C.-S. Jiang; A. Ptak; B. Yan; H.R. Moutinho; J.V. Li; M.M. Al-Jassim. "Microelectrical Characterizations of Junction in Solar Cell Devices by Scanning Kelvin Probe Force Microscopy." *Ultramicroscopy*, in press.
- C.-S. Jiang; H.R.Moutinho; R. Reedy; M.M. Al-Jassim; A. Blosse. "Two-Dimensional Junction Identification in Multicrystalline Si Solar cells." *J. Appl. Phys.*, in press.
- C.-S. Jiang; B. Yan; Y. Yan; C.W. Teplin; R. Reedy; H.R. Moutinho; M.M. Al-Jassim; J. Yang; S. Guha. "P-Induced Nanocrystallite Dispersion in Hydrogenated Mixed-Phase Nanacrystalline Silicon Thin Films." *J. Appl. Phys.;* 103, 063515 (2008).
- H.R. Moutinho; R.G. Dhere; M.J. Romero; C.-S. Jiang; B. To; M.M. Al-Jassim. "Electron Backscatter Diffraction of CdTe Thin Films: Effects of CdCl2 Treatment." *J. Vac. Sci. Technol.;* A26, 1068 (2008).
- Y. Yan; C.-S. Jiang; R. Noufi; S.-H. Wei; H.R. Moutinho; M.M. Al-Jassim. "Electrically Benign Behavior of Grain Boundaries in Polycrystalline CuInSe2 films." *Phys. Rev. Lett.*; 99, 235504 (2007).
- Y. Yan; K.M. Jones; C.-S. Jiang; X.Z. Wu; R. Noufi; M.M. Al-Jassim. "Understanding the Defect Physics in Polycrystalline Photovoltaic Materials." *Physica B*; 401-402, 25 (2007).
- H.R. Moutinho; R.G. Dhere; M.J. Romero; C.-S. Jiang; B. To; M.M. Al-Jassim. "Recrystallization of PVD CdTe Thin Films Induced by CdCl2 Treatment." *33rd IEEE Photovoltaics Specialists Conference Proceedings*; May 2008, San Diego.

Electro-Optical Characterization

Performing Organization: National Renewable Energy Laboratory (NREL)

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FY 2008 Budget: $2,468K (NREL)

Objectives

- Help Solar America Initiative (SAI) subcontractors succeed by supporting collaborative research and development (R&D) projects, technique development, and standard measurements.
- Design, procure, and build seven new Process Development and Integration Laboratory (PDIL) tools: Semilab tool, spectroscopic ellipsometry tool, minority carrier lifetime tool, photoluminescence imaging tool, reflectometer, optical processing furnace, and wafer processing station.
- Continue advancing measurement techniques for minority carrier lifetime, minority carrier diffusion length, thin film optical properties, and fundamental photovoltaic (PV) device properties.
- Help NREL in-house PV technology projects succeed through collaborative R&D projects, technique development, and standard measurements.

Accomplishments

- Supported numerous SAI Technology Pathway Partnerships (TPPs) and incubator companies including: BP Solar, GE Energy, Nanosolar, United Solar, Konarka, AVA Solar, Blue Square Energy, CaliSolar, MicroLink, PrimeStar, and Solaria.
- Developed and demonstrated functional prototypes for measurement of minority carrier lifetime (RCPCD and uw-PCD), carrier density imaging (CDI), and photoluminescence imaging (PLI) on 6”x6” samples for incorporation into PDIL vacuum tools in fiscal (FY) 2009.
- Developed capability for one-sun SPV measurement of minority carrier diffusion length in silicon wafers. Also developed ability to measure the injection-level dependence of the MCDL.
- Significantly advanced the understanding and potential application of time-resolved photoluminescence (TRPL) for on-line materials quality diagnostics for CIGS and CdTe. This includes a break-through in measurement of 250 nanosecond carrier lifetimes in CIGS films and discovery of rapid degradation of CIGS films in air.
- Published computational study of the effects of grain boundaries and lifetime fluctuations on solar cell performance, minority carrier lifetime measurements, and their correlations for multi-crystalline silicon (Si) solar cells.
- Developed an integrated capacitive characterization technique to simultaneously conduct steady-state capacitive measurements (CV, AS, DLCP) to obtain rapid extraction of physical parameters.

Future Directions

- Provide top priority support for SAI subcontractors through collaborative R&D projects, technique development, and standard measurements.
- Bring six new PDIL tools to full operational capability: spectroscopic ellipsometry tool, minority carrier lifetime tool, photoluminescence imaging tool, reflectometer, optical processing furnace, and wafer processing station.
- Continue ongoing advancement of measurement techniques for minority carrier lifetime, minority carrier diffusion length, thin film optical properties, and fundamental PV device properties.
- Determine viability of TRPL as an online diagnostic for PV manufacturing. (contingent on capital equipment funding)
- Develop robust computational models for double and triple junction PV devices.
- Support NREL in-house PV technology projects through collaborative R&D projects, technique development, and standard measurements.

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1. Introduction

The Electro-Optical Characterization team consists of six scientists and three technicians with more than 100 years of combined experience in the development and application of advanced electro-optical measurement techniques. Our goal is to help partners in industry, universities, and in-house NREL teams succeed in increasing efficiency, reducing cost, and enhancing reliability.

2. Technical Approach

A priority is development and application of methods for measurement of minority carrier lifetime (MCL) and diffusion length. Experimental techniques for characterizing MCL include TRPL, resonantly coupled photoconductivity decay (RCPCD), microwave photoconductive decay (uw-PCD), infrared free-carrier absorption (FCA), photoluminescence imaging (PLI), and infrared carrier density imaging (CDI). We are developing advanced capabilities in surface photovoltage (SPV) for measurement of minority carrier diffusion length. We apply a number of spectroscopic techniques including photoluminescence spectroscopy, spectroscopic ellipsometry, near, mid, and far-infrared spectroscopy, and diffuse reflectance spectroscopy. A number of electrical device characterization methods are used to determine defect properties and fundamental junction parameters including deep level transient spectroscopy (DLTS), capacitance-voltage (C-V), admittance spectroscopy (AS), drive-level capacitance (DLCP), and in-plane impedance spectroscopy.

3. FY 2008 Special Recognitions and Patents

Invited talks

- Wyatt Metzger, "Recombination Kinetics in Polycrystalline $Cu(In,Ga)Se_2$ solar cells." EMRS Spring Meeting, May 25-29, 2008, Strasbourg, France.
- Steve Johnston, "Lifetime and diffusion length mapping and imaging techniques for silicon solar cells" 18th c-Si Workshop, Aug. 3-6, 2008, Vail, Colorado.
- Bhushan Sopori, "Wafer breakage in the silicon photovoltaic industry", SPIE Optics + Photonics, Aug. 10-14, 2008, San Diego, CA.
- Bhushan Sopori. "Recent Advances in Silicon Solar Cells: Device Design and Processing", Conference on Emerging Trends in Photovoltaics, March 2008, IIT Kanpur, India.
- Bhushan Sopori. "Engineered Interfaces for Si Solar Cell Applications", TMS Annual Meeting & Exhibition, Mar. 9-13, 2008, New Orleans.

Awards

- Wyatt Metzger and Dean Levi. Overall Best Poster Runner-Up Award. "Device Physics of Nanoscale Interdigitated Solar Cells". 33rd IEEE Photovoltaics Specialists Conference, May 11-16, 2008, San Diego, CA.

Patents

- Bhushan Sopori and Artak Hambarian, Optical Probe for Semiconductor Characterization, US Patent 7,420,669, Issued Sept. 2, 2008.
- Bhushan Sopori, Optical Cavity Furnace for Semiconductor Wafer Processing, Provisional filed, March 10, 2008.

Media Coverage

- AIP issued a press release based on the CIGS time-resolved studies published in APL [1]. www.aip.org/isns/reports/2008/046.html

4. Major FY 2008 Publications

- W.K. Metzger; I.L. Repins; M.A. Contreras., "Long Recombination Lifetimes in High-Efficiency $Cu(In,Ga)se_2$ Solar Cells." Applied Physics Letters; **93**, 022110(2008).
- R.K.Ahrenkiel; S.W. Johnston. "Lifetime Analysis of Silicon Solar Cells by Microwave Reflection." *Solar Energy Materials and Solar Cells*; **92**, 2008, pp. 830-835.
- W.K. Metzger. "The Potential and Device Physics of Interdigitated Thin-Film Solar Cells, *Journal Applied Physics*; **103**, 094515 (2008).
- R.K. Ahrenkiel; S.W. Johnston; W.K. Metzger; P. Dippo. "Relationship of Band Edge Luminescence to Recombination Lifetime in Silicon Wafers." *J. of Electronic Materials*; **37**, 396-402 (2008).
- W.K. Metzger. "How Lifetime Fluctuations, Grain-Boundary Recombination, and Junctions, Affect Lifetime Measurements and Their Correlation to Silicon Solar Cell Performance." *Solar Energy Materials and Solar Cells*; **92**, 1123(2008).
- B. Sopori; P. Rupnowski; J. Appel; V. Mehta; C. Li; S. Johnston. "Wafer Preparation and Iodine-Ethanol Passivation Procedure for Reproducible Minority-Carrier Lifetime Measurement." *33rd IEEE PVSC*, San Diego, May 2008.
- P. Rupnowski; B. Sopori. "Strength of Si Wafers with Microcracks: A Theoretical Model," *33rd IEEE PVSC*, San Diego, 2008.

Surface Analysis

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Sally Asher (NREL, Primary Contact), 303-384-6450, sally_asher@nrel.gov
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DOE HQ Technology Manager: Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2008 Budget: $1,767K (NREL)

Objectives

- Provide routine and specialized measurements of surfaces and interfaces to support advancement of photovoltaic (PV) program research and industry partners.
- Lead and contribute to collaborative research that addresses critical issues in understanding surfaces and interfaces in PV technologies.
- Develop and implement novel measurement techniques that enhance the ability to understand surface chemistry and physics of materials to advance fundamental PV research and development (R&D).

Accomplishments

- Provided surface analysis measurement support to more than 50 different U.S. PV companies and researchers in all areas of the DOE Solar Energy Technologies Program (SETP).
- Worked extensively with DCA Instruments to ensure the Process Development and Integration Laboratory (PDIL) Auger tool will meet specifications when completed.
- Monitored X-ray photoelectron spectroscopy (XPS) and flipping station construction, both tools to be delivered in December 2008.
- Used QCM flow cell to study CdS reaction kinetics, showed how these conditions can be used to tune and control film morphology, thickness, and chemical reagent utilization.
- Completed conceptual design and specifications for plasma/sputter/etch tool. Obtained budgetary numbers from vendors to refine design.
- Procured a new state-of-the-art dynamic secondary ion mass spectrometer (SIMS) instrument to replace 30-yr-old, first generation equipment. Delivery of new system by end of March 2009.
- Completed conceptual design and specifications of plasma-enhanced chemical vapor deposition (PECVD) tool.
- In collaboration with reliability researchers, improved barrier adhesion and performance leading to a successful patent application.

Future Directions

- Continue to provide high level of surface analysis research and support to Solar America Initiative (SAI) contractors and SETP researchers. Introduce new capabilities of XPS and SIMS instruments to researchers.
- Install, demonstrate functionality, and integrate large-platen PDIL Auger system.
- Install, demonstrate functionality, and integrate new small-spot XPS in PDIL.
- Conduct tests to assess cleanliness of PDIL transfer pod and affect of pod ambient on sample surface chemistry.
- Install, demonstrate functionality, and integrate new dynamic SIMS instrument.
- Complete ordering process and PDIL physical plant modifications for PECVD and sputter/plasma/etch tools.

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1. Introduction

Surfaces and interfaces play critical roles in controlling the properties of materials and in the operation and reliability of devices. The Surface Analysis project advances the understanding of PV materials and devices by employing surface science practices and techniques to investigate surface and interfacial properties of materials. Project scientists are active in three main areas: (1) analytical support to SAI research participants, conversion technology researchers, and researchers in reliability, (2) collaborate and lead research on the chemistry and physics of surfaces and interfaces of PV materials, and (3) advance the utility and understanding of our measurements by improving analytical methodology and by developing new tools for *in-situ* study of surface and interface properties. The Surface Analysis team contributes to and leads SETP activities involving surface chemistry and physics.

2. Technical Approach

This project uses best practices to obtain information about surfaces and interfaces of PV materials and devices. The specifications for the major pieces of analytical equipment currently utilized in our work are detailed at www.nrel.gov/pv/measurements/surface_analysis. html. The group is awaiting three new pieces of equipment that will add significant new capabilities to our analytical suite: small-spot XPS/UPS, large-platen Auger, and low-energy depth profiling dynamic SIMS.

During FY 2008, the group had priority activities in several areas. An important focus was on activities related to supporting SAI partners and collaborations with PV conversion technology researchers. We also worked with manufacturers of our new tools to ensure they would arrive in as timely a fashion as possible, while still meeting the performance specifications deemed important for the project's success. Finally, we worked to improve the accuracy of our results through internal and external collaborations.

3. FY 2008 Special Recognitions and Patents

Pankow, J.W.; Glick, S.W. Submitted NREL ROI IR 08-19 “Moisture barrier package consisting of flexible polymer sheet, atomic layer deposition interfacial layer, and PECVD moisture barrier overcoat layer.”

4. Major FY 2008 Publications

C.L. Perkins; X. Li. “A Liquid-Phase Quartz Crystal Microbalance for Photovoltaics Research,” *33rd IEEE Photovoltaics Specialists Conference Proceedings;* May 11-16, 2008, San Diego, California.

I. Repins; M.A. Contreras; B. Egaas; C. DeHart; J. Scharf; C.L. Perkins; B. To; R. Noufi. “19.9%-Efficient ZnO/CdS/CuInGaSe2 Solar Cell with 81.2% Fill Factor,” *Prog. Photovolt: Res. Appl.* **16** (2008) 235–239.

J.M. Luther; M. Law; Q. Song; C.L. Perkins; M.C. Beard; A.J. Nozik. “The Structural, Optical, and Electrical Properties of Self-Assembled Films of PbSe Nanocrystals Treated with 1,2-Ethanedithiol,” *ACS Nano,* **2** (2008) 271-280.

G. Teeter; S.E. Asher. “Modeling Copper Migration in Cadmium-Telluride Solar Cells Under Device-Processing and Field-Deployed Conditions,” *Proceedings of the 33rd IEEE PVSC Proceedings;* May 11-16, 2008, San Diego, California.

A.J. Ptak; R. France; C.S. Jiang; R.C. Reedy. “Effects of Bismuth on Wide-Depletion-Width GaInNAs Solar Cells,” *J. Vac. Sci. Techn.*, Part B, Vol. 26, 3 (2008).

J.R. Doyle; Y. Xu; R.C. Reedy; H.M. Branz; A.H. Mahan. “Film Stoichiometry and Gas Dissociation Kinetics in Hot-Wire Chemical Vapor Deposition of a-SiGe:H,” *Thin Solid Films*, Vol. 516, 5 (2008).

M. Sheoran; D.S. Kim; A. Rohatgi; H.F.W. Dekkers; G. Beaucarne; M. Young; S. Asher. "Hydrogen Diffusion in Silicon from Plasma-Enhanced Chemical Vapor Deposited Silicon Nitride Film at High Temperature,” *Appl. Phys. Lett.* Vol. 92, (172107), 2008

X. Li; J. Pankow; B. To; T. Gessert. “Comparison Between Research Grade and Commercially Available SnO2 for Thin-Film CdTe Solar Cells,” *33rd IEEE Photovoltaic Specialists Conference,* May 11-16, 2008, San Diego, California.

Cell and Module Performance

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Keith Emery (NREL), 303-880-2913, keith_emery@nrel.gov

DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@hq.doe.gov

FY 2008 Budget: $2,125K (NREL)

Objectives

- Support contact technical monitors, Solar America Initiative (SAI) partners and the photovoltaic (PV) industry by providing accurate traceable efficiency, peak watt, quantum efficiency (QE), and I-V measurements with respect to standard reporting conditions.
- Maintain ISO 17025 accreditation for cell and module calibrations.
- Maintain primary reference cell calibrations.
- Transfer I-V and QE measurement technology to SAI partners and the PV community.
- Maintain and advance the state-of-the-art in I-V and QE cell and module measurements.
- Continue with International Electrotechnical Commission (IEC) and American Society for Testing and Materials (ASTM) standards development.

Accomplishments

- Provided measurement support in the areas of cell and module performance to more than 70 PV research partners in industry, academia, and NREL.
- Performed 6,174 I-V and QE measurements on 1,898 cells and modules for 249 groups. There were 5,638 cell I-V, QE and linearity measurements on 1,564 samples, and 2,361 I-V measurements on 618 modules. The prototype concentrator module test bed took 84,448 I-V curves on 9 modules including the SAI partners Boeing, Solfocus, Spectrolab, and Enfocus. Multijunction prototype concentrator modules were also evaluated from Greenvolts, Daido Steel, and Fraunhofer ISE.
- Maintained ISO 17025 accreditation for primary and secondary cell and module calibrations. Completed periodic audits, maintenance of quality systems, calibrations, software, and documentation to meet A2LA requirements.
- Ordered multi-source concentrator cell solar simulator with a spectrally adjustable simulator in at least 10 bands to accommodate all of the conceivable high efficiency concentrator cell designs during the next 10 years.
- Installed large-area module solar simulator system and brought unit to operational status compliant with teams ISO 17025 quality system. The new simulator is capable of measuring modules as large as 137 centimeters by 200 centimeters.
- Completed construction and fit-up of NREL's Outdoor Test Facility expansion.
- Reduced measurement time and uncertainty of evaluating multi-junction devices at 1-sun, allowing spectral sensitivity of multi-junction cells to be addressed in terms of energy production as a function of spectral irradiance, total irradiance and temperature and not just their performance with respect to fixed reference conditions.

Future Directions

- Continue to support SAI partners at the highest possible priority and level.
- Continue to support the U.S. terrestrial PV community by transferring performance measurement technology and providing cell and module performance measurements and calibrations.
- Enhance capabilities to determine the energy part of the levelized cost of energy for PV technologies from flat-plate to low-X to high concentration.
- Bring newly procured simulators to an operational status and use them to determine energy delivered with respect to a reference year and spectral sensitivity of multi-junction technologies
- Maintain ISO 17025 accreditation for primary and secondary cell and module calibrations.

1. Major FY 2008 Publications

Emery, K. “Comment on "Roles of Donor and Acceptor Nanodomains in 6% Efficient Thermally Annealed Polymer Photovoltaics," *Appl. Phys. Lett*. **90**, 163511 (2007)], *Appl. Phys. Lett*. **91**, 266101 (2007).

Kurtz, S.; Moriarty, T.; Kiehl, J.; Emery, K.; et. al. “Status and Issues in High Efficiency III-V Solar Cells,” Proc. 17th International Photovoltaic Science and Engineering Conference, Japan, December 3-7, 2007.

Green, M.A.; Emery, K.; King, M.A.; Hishikawa, Y.; Warta, W. “Solar Cell Efficiency Tables (version 31),” *Progress in PV*, vol. 16, 61 (2008).

McMahon, W.E.; Emery, K.E.; Ottoson, L.; et. al. “Fill Factor as a Probe of Current-Matching for GaInP2/ GaAs Tandem Cells in a Concentrator System During Outdoor Operation,“ *Progress in PV*, 16, 213 (2008).

Barnett, A.; Emery, K.; et. al. ”Initial Test Bed For Very High Efficiency Solar Cells, Proc. 33 IEEE PVSC, San Diego, CA, 2008.

Rüther, R.; Rummel, S.; Anderberg, A.; et. al. “Performance Test of Amorphous Silicon Modules in Different Climate – Year Four: Progress in Understanding Exposure History Stabilization Effects,” Proc. 33 IEEE PVSC, San Diego, CA, 2008.

Del Cueto, J.A.; Rummel, S.; Kroposki, B.; Osterwald, C.; Anderberg, A. ”Stability of CIS/CIGS Modules at the Outdoor Test Facility Over the Years,” Proc. 33 IEEE PVSC, San Diego, CA, 2008.

Geisz, J.F.; Moriarty, T.E.; Kiehl, J.T.; et. al. “Inverted GaInP/(In)GaAs/InGaAs Triple-Junction Solar Cells with Low Stress Metamorphic Bottom Junctions,” Proc. 33 IEEE PVSC, San Diego, CA, 2008.

Gessert, T.A.; Moriarty, T.; et. al. "Effects of Cu Diffusion from ZnTe:Cu/Ti Contacts on Carrier Lifetime of CdS/CdTe Thin Film Solar Cells," Proc. 33 IEEE PVSC, San Diego, CA , 2008.

Emery, K. “Photovoltaic Test Performance,” *Photonics Spectra*, p. 76, June 2008.

Emery, K.; Moriarty, T.A. “Accurate Measurement of Organic Solar Cell Efficiency,” Proc. SPIE Optics + Photonics, session 7052-12, San Diego, CA, 2008.

Emery, K. “PV Reliability Determination from I-V Measurement and Analysis,“ Proc. SPIE Optics + Photonics, session 7048-1, San Diego, CA, 2008.

Del Cueto, T.A.; Rummel, S.; Kroposki, B.; Anderberg, A. ”Long-Term Performance Data and Analysis of CIS/CIGS Modules Deployed Outdoors,” *Proc. SPIE Optics + Photonics*, session 7048-1, San Diego, CA, 2008.

Green, M.A.; Emery, K.; King, D.L.; Hishikawa, Y.; Warta, W. “Solar Cell Efficiency Tables (version 32),” *Progress in PV*, **16**, 435 (2008).

Barnett, A.; Emery, K.; et al. “Very High Efficiency Solar Cell Modules,” *Progress in PV*, **16**, 852 (2008).

Geisz, J.F.; Moriarty, T.E.; Kiehl, J.T.; et. al. "40.8% Efficient Inverted Triple-Junction Solar Cell with Two Independently Metamorphic Junctions," *Appl. Phys. Lett*., 93, 123505 (2008).

2. University and Industry Partners

The group partnered with more than 250 groups, including measurement technology transfer and PV cell and module calibration services.

PDIL Infrastructure, Engineering, and Integration

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)
DOE Golden Field Office (DOE/GO)

Key Technical Contacts: Brent Nelson (NREL, Primary Contact), 303-384-6407, brent_nelson@nrel.gov,
Steve Robbins (NREL), 303-384-6400, steven_robbins@nrel.gov,
Robert White (NREL), 303-384-7802, robert_white@nrel.gov

DOE HQ Technology Manager: Marie Mapes, 202-586-3765, marie.mapes@hq.doe.gov

FY 2008 Budget: $1,830K (NREL)

Objectives

- Develop, improve, and implement process integration standards.
- Provide project management to secure capital equipment for the Process Development and Integration Laboratory (PDIL).
- Provide infrastructure development of facilities and equipment installation.
- Develop an integrated software infrastructure within the PDIL that enables secure data access for the National Center for Photovoltaics (NCPV) personnel and research partners.
- Work with core research teams to develop research partnerships with external collaborators, including advertising the PDIL to the PV industry via a Web site and other means.
- Provide engineering support to design custom- or high-risk tools that would otherwise be beyond the reach of our research groups.

Accomplishments

- Made PDIL equipment, including the silicon thin-film workstation, the photothermal deflection spectroscopy (PDS), n&k spectrometer, and SemiLab, fully operational and moved the transparent conducting oxide (TCO) sputtering tool.
- Delivered and installing the scanning electron microscope (SEM), atomic force microscopy (AFM), wafer wet etching station, and the copper-indium-galium-diselinide (CIGS) chamber of the CIGS workstation.
- Placed orders, with equipment being fabricated at the vendor location, for the atmospheric processing workstation, X-ray photoemission spectroscopy (XPS), centralized robotic transfer chamber for the integrated measurement and characterization (M&C) techniques, Auger electron spectrometer (AES), photoluminescence (PL), minority carrier lifetime, ellipsometer chamber, and the remainder of the CIGS workstation.
- Completed equipment designs for the cadmium-telluride (CdTe) workstation, silicon wafer replacement platform, plasma-enhanced chemical vapor deposition process diagnostic chamber, integrated plasma etch/sputter deposition chamber, reflectance spectroscopy tool, optical thermal annealing station, and the chemical bath deposition (CBD) of cadmium-sulfide (CdS),
- Designed and implemented database architecture and ordered file and database archive hardware and central server for PDIL.
- Designed networking hardware for the PDIL, which is being installed.
- Constructed initial harvester systems to move data from tools into file archives.
- Constructed initial data extraction system to translate tool data products into database files.
- Implemented a project-management database tool for tracking finances, project-management phases, research proposals, staffing, and industrial contacts.

Future Directions

- Finish installations of the SEM, AFM, wafer wet-etching station, CIGS workstation, atmospheric processing workstation, XPS, centralized robotic transfer chamber for the integrated M&C

techniques, AES, PL, minority carrier lifetime, reflectance spectroscopy tool, optical thermal annealing station, and ellipsometer chamber.

- Complete equipment designs and substantively complete the acquisition of CdTe workstation, silicon wafer replacement workstation, plasma-enhanced chemical vapor deposition process diagnostic chamber, integrated plasma etch/sputter deposition chamber, and CBD of CdS.
- Continue integrating research equipment into the PDIL data tools, developing and improving the user interface and working with scientific computing to develop data analysis tools.

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1. Technical Approach

The first step in integrating various techniques within, and between, platforms was developing standards for the common interface and transport elements as described in the abstract.

To integrate a diverse tool set requires a “universal” maximum substrate size and shape to be held in a platen. The platen size and shape drives the requirements for the entire design. The various core activities within the NCPV have set, by consensus, the maximum substrate size the platen can handle to be approximately 6” by 6”. This size supports the silicon (Si) PV industry that has both a “6-inch square” protocol in multi-crystalline Si and a “6-inch round” protocol in single crystalline Si. It also more than adequately supports the other technological areas studied by the NCPV with a commercially viable area.

Samples can be moved between workstations either via intra-tool or inter-tool sample transport. Intra-tool transport is the movement of samples between techniques on the same platform. The actual transfer mechanism will typically be robotic in a central chamber but it could be a linear track. The intra-tool transfer height is the Semiconductor Equipment and Materials International (SEMI) standard of 1.1 m above the floor.

Inter-tool transport is the movement of samples between techniques where those techniques do not share direct connection. These techniques could be in a stand-alone tool or a part of a larger platform. The sample is moved from one platform into the pod, which is sealed and disconnected from that platform before being wheeled to another platform, where the process is reversed. The transfer ambient within the pod can be either an atmosphere of ultra-high-purity inert gas or high vacuum. The use of inter-tool transport in a high vacuum ambient on such a large sample is a unique capability.

Another integration mode is to make some of our techniques modular, such that they can be moved between platforms. Since all chambers connecting to platforms will use a standard 10” metal sealed Conflat® vacuum flange, centered at 1.1 m above the floor, it allows for a modular deposition, processing, or characterization technique to be docked on any given platform, based on project needs, strategic priorities, and available space. Not all techniques can be modular as size, sensitivity, complexity, and safety issues must be taken into account.

Because there are very few techniques that are commercially available which are integrated onto a platform—and none using our standard sample size or inter-tool integration scheme—participating core activities within the NCPV develop their own workstations. They are in consultation with their industrial and university collaborators with regard to the specific techniques built into each platform. NCPV management oversees these plans within the scope of the NCPV strategic vision and available resources. The process-integration project works tactically to implement these plans according to the integration standards. Within the hardware agreement the group assists in equipment acquisition (prototyping, designing, specifying, etc.), leads in equipment installations (vacuum, gases, electrical, cooling, etc.), and provides PDIL infrastructure preparedness (common tools, support equipment, etc.). Within the software agreement, the group has established a PDIL network (fully cyber secure, databases, etc.) that integrates workstations into that network (IP protection), and develops user interfaces and data analysis tools. Within the project management agreement, the group assists projects with budgeting and scope management, develops communication tools, such as the Web site, and provides first-contact support for the PV community to propose collaborative work within the PDIL.

Technology Pathway Partnership (TPP)

Performing Organizations: Amonix; Boeing Company; BP Solar; Dow Chemical Company; GE Global Research; GreenRay; Konarka Technologies; Nanosolar; Soliant Energy; SunPower; United Solar Ovonic; National Renewable Energy Laboratory (NREL); Sandia National Laboratories (SNL)

Key Technical Contacts: Carolyn Elam, DOE Golden Field Office (DOE/GO), 303-275-4953, carolyn.elam@go.doe.gov
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Holly Thomas, DOE/GO, 303-275-4818, holly.thomas@go.doe.gov

DOE HQ Technology Manager: Scott Stephens, 202-586-0565, Scott.Stephens@ee.doe.gov

FY 2008 Budgets: $35,500K (TPP Recipients), $665K (NREL), $225K (SNL)

Objectives

- Bring better products to market and enable new applications. Develop modular, turnkey photovoltaic (PV) systems that provide residential and commercial customers with a complete solution and attractive value proposition such as enabling building-integrated PV (BIPV) and zero-energy homes. Develop designs and supply chains for large-field PV installations to service commercial and utility renewable portfolio standard (RPS)-generating requirements. Help U.S. companies to leapfrog global competition by providing best designed, lowest-cost solar solutions.
- Foster development of domestic PV industry. Catalyze collaboration across value chain to: (1) squeeze out costs; (2) better optimize PV-system design; and (3) assure superior performance and reliability. Demonstrate novel manufacturing processes that provide U.S. industry with cost advantage and that facilitate manufacturing scale-up.
- Increase impact of PV on U.S. energy economy and accelerate development of U.S.-produced PV systems, so solar electricity reaches parity with cost of electricity in grid-tied markets across the nation by 2015. Enable expansion of annual U.S. production capacity of PV systems from 240 megawatts (MW) in 2005 to as much as 2,850 MW by 2010, representing 10-fold increase. Foster research that will lower cost of PV-generated electricity to $0.05 to $0.10 per kilowatt hour (kWh) by 2015 in residential, commercial, and utility markets.

Accomplishments

- Initiated 11 TPP awards.
- Established roles and responsibilities, including technical monitor support by NREL and SNL.
- Completed key stage-gate reviews for five projects. Completion of remaining reviews anticipated for early fiscal year (FY) 2009.

Future Directions

- Develop PV systems that will enable solar electricity to reach grid parity by 2015.
- Expand U.S.-installed domestic capacity of PV systems to 5 to 10 gigawatts (GW).

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1. Introduction

The Technology Pathway Partnerships (TPPs) are an integral part of the DOE Solar America Initiative (SAI) and a significant enhancement of DOE’s business strategy of partnering with the industry to accelerate commercialization of PV R&D to meet ambitious cost and installed-capacity goals.

TPPs will accelerate commercialization of solar PV systems by 2015. The goal is to have PV electricity generation that is competitive with conventional electricity sources in all domestic grid-tied markets.

The specific goals of the 9-year TPP mission are:

- Accelerate development of U.S.-produced PV systems substantively, so PV-produced electricity reaches parity with cost of electricity in select grid-tied target markets.
- Expand U.S.-installed domestic capacity of PV systems to 5 to 10 gigawatts (GW).

The cost basis of electric energy in these markets is the kilowatt hour (kwh), therefore the SAI TPP program uses targets for PV systems based on the levelized cost of energy (LCOE) delivered by these systems. This key metric is defined as the measure of total lifetime costs of a PV system divided by expected lifetime energy output, with appropriate adjustments for such factors as time value of money. The overall cost goals for the SAI TPP projects are shown in Table 1.

Table 1. Cost Targets for Grid-Connected PV Systems in Key Market Sectors

Market Sector	Current U.S. Market Range (c/kWh)[1,2]	Solar Electricity Cost—Current and Projected (c/kWh)[1]		
		Benchmark	Target	
		2005	2010	2015
Residential[3]	5.8–16.7	23–32	13–18	8–10
Commercial[3]	5.4–15.0	16–22	9–12	6–8
Utility[4]	4.0–7.6	13–22	10–15	5-7

[1] Costs are based on constant 2005 dollars.
[2] Current costs are based on electric-generation with conventional sources.
[3] Cost to customer (customer side of meter).
[4] Cost of generation (utility side of meter).

2. Program/Technical Approach

The TPP efforts are focused on developing new and better PV solutions for the grid-tied electric power markets including:

- **Residential rooftop market.** Systems are typically mounted on rooftops and range from less than 1 kW to 10 kW, most commonly 3 to 4 kW. These systems are connected to the grid on the retail (customer) side of the utility meter and can be retrofitted for existing homes or integrated into new construction through BIPV designs.
- **Commercial rooftop market.** Systems are typically mounted on the large flat roofs of commercial, institutional, and industrial buildings, and range in size from less than 10 kW to 500 kW and connected on the retail side of the utility meter. Retrofits and BIPV are possible applications in this market as well.
- **Utility market.** These are large-scale (multi-megawatt) systems displacing conventional utility-generated intermediate load electricity (e.g., natural gas, Clean Coal Technology plants) for wholesale. Utility systems typically are ground-mounted and range in size from 1 MW to 10 MW, although much larger systems are in development. Designs include both fixed and tracking configurations.

The following approaches are designed to address goals for these markets.

- <u>Industry-led:</u> All technical details regarding approach, timelines, milestones, and system integration are formulated by applicants. The national laboratories provide critical support to DOE in monitoring technical progress, conducting tests and evaluations and directly supporting TPPs on specific R&D tasks.
- <u>Near- and mid-term results</u>: Emphasis is on technologies with the greatest potential for cost competitiveness leading up to 2015.
- <u>System focus:</u> The primary metric for SAI is LCOE, based upon the complete PV system rather than any component. SAI is working toward novel, integrated PV systems.
- <u>Partnerships:</u> Industry participants are strongly encouraged to formulate partnerships to address the spectrum of possible technical improvements in the PV-system value chain.
- <u>Market-based</u>. Market-oriented goals for cost, penetration, and job creation. All technical objectives established through SAI directly impact these market-based goals.

Each SAI TPP project planned in three 3-year phases to progressively reduce the cost of commercially available PV systems and components to yield commercial products and production processes to achieve the LCOE goals and support installed capacity targets by 2015.

- Phase 1. Demonstrate pilot production of lower-cost systems. R&D project duration of 3 years (2007–2010) allows companies the flexibility to align projects with their targeted business model, technical capabilities, and product/process maturity.
- Phase 2. Demonstrate replication of low-cost pilot production. Project duration of 3 years (2010–2012), with new entrants eligible.
- Phase 3. Develop supply chain and distribution infrastructure. Reduce capital expenditure of manufacturing scale-up through targeted investments in areas such as equipment and feedstock suppliers and distribution channels.

The awards must demonstrate the benefits of their project based upon LCOE and installed capacity measures. Each award also falls into a class of either systems or subsystems defined as follows:

- Systems-class projects (integrated systems): focus on multiple technology improvements in PV component and system design, integration, and installation.
- Subsystems-class projects (component-based): focus on component-level technology developments for system improvements.

DOE funding available for systems-class awards is limited to $20 million, and subsystems-class awards are limited to $8 million per 3-year period and require a 50% cost share of the total project.

The awards began in FY 2007. They are funded through (approximately) annual budget periods, which conclude with a stage-gate review scheduled around major technical milestone(s) or decision point(s). At the completion of each stage-gate review, a determination is made about the continuation of the project into the next year.

2.1. Stage-Gate Reviews:

A stage-gate management approach facilitates rigorous project management and supports continuous assessment of the awards. Deliverables must demonstrate the ability of each recipient to meet the LCOE cost targets for their technology. LCOE values are dependent on system performance and manufacturing costs, therefore these quantities are evaluated independently (performance evaluated by NREL/SNL, and cost evaluated by an independent contractor to DOE) to assure that they are sufficient to demonstrate the stage-gate criteria have been met. DOE conducts a programmatic review and decision to continue to the next phase as proposed, continue to the next phase with modifications, or to discontinue the project.

2.2. TPP Project Management Approach

Project monitoring and technical oversight are conducted by a team from the DOE Golden Field Office, which manages and administers the cooperative agreements; DOE headquarters; and technical monitoring support from NREL and SNL.

This management approach utilizes a technical monitor that is cognizant of the technology being developed. Technical monitors are from one of the DOE national laboratories (NREL or SNL).

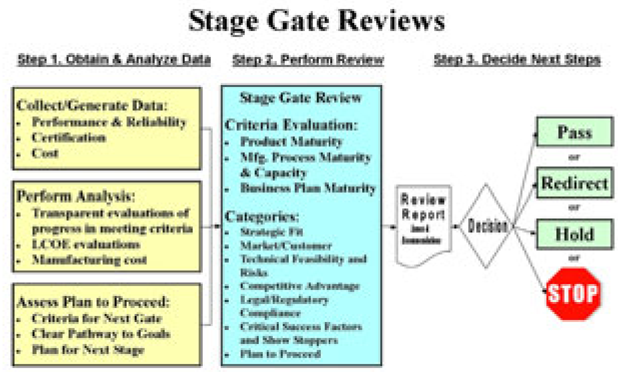

Figure 1. Steps of the Stage-Gate Process

Assignments are made based on the alignment between the skills and experiences of lab personnel and the R&D activities of the project. The technical monitors are an integral part of the project management team and assist DOE in overseeing and assessing the TPP's progress.

In this capacity, they provide substantial technical assistance and guidance, facilitate interactions with additional technical experts, as needed, and assure timely access to DOE-funded laboratory resources when required for the project (e.g., test facilities). The technical monitors also provide evaluations during the stage-gate reviews and evaluations of technical progress against milestones, consult on the go/no-go decision points and critical success factors, and provide recommendations from the stage-gate reviews.

3. Results and Accomplishments

3.1. DOE Program Review

DOE program review showcased the activities of the SAI TPP recipients in May 2008.

3.2. Project Kickoff Meetings

Following completion of the awards, kickoff meetings were held at each recipient's facility to review their technology baseline and plans.

3.3 Stage-Gate Reviews

Results from the five stage-gate reviews follow:

- Greenray Inc. (6/18/2008):
  Pass to Phase 2; continue to fund project at an increased funding level with required continuation conditions.
- Amonix Inc. (6/24/2008):
  Pass to Phase 2; continue to fund project at a reduced funding level with continuation recommendations.

- Boeing Co. (6/26/2008):
  Pass to Phase 2; continue to fund project at a reduced funding level with continuation recommendations.
- United Solar Ovonics LLC (8/27/2008):
  Results Pending.
- Konarka Technologies (9/4/2008):
  Results Pending.

3.4 TPP Awardee Progress.
Progress for each TPP awardee follows.

4. Planned FY 2009 Activities

Stage gates anticipated are shown in Table 2 (below).

5. Major FY 2008 Publications

Solar Program Peer Review Agenda Overview (April 2008). www.energy.gov/public.

Table 2. TPP Award Recipients, FY2008 Funding, Stage-Gate Schedule

SAI TPP Recipient	FY 2008 Obligation	Start Date	First Stage-Gate Date
Amonix Inc.	$3,295,288	14 May 2007	6/24/2008
The Boeing Co.	$8,025,670	1 July 2007	6/26/2008
BP Solar Inc.	$4,089,000	1 Sept. 2007	1/27/2009
Dow Chemical Co.	$1,241,296	1 Aug. 2007	11/06/2008
GE Global Research .Inc.	$4,972,000	1 Sept. 2007	11/19/2008
Greenray Inc.	$735,000	1 Jan. 2007	6/18/2008
Konarka Technology Inc.	$768,000	1 July 2007	9/4/2008
Nanosolar Inc.	$3,580,000	1 Sept. 2007	11/29/2008
Soliant Energy Inc.	$2,098,991	1 Sept. 2007	2/10/2009
SunPower Corp.	$4,173,000	1 Sept. 2007	11/30/2008
United Solar Ovonics LLC	$5,808,247	30 Apr. 2007	8/27/2008

TPP Awardee: Amonix, Inc.

“Low Cost High Concentration Photovoltaic Systems for Utility Power Generation”

Total Award Amount: $33,635K, DOE/Recipient Share $15,605K/$18,029K

Objectives

- Develop high-volume (25 MW/year), low-cost manufacturing facility in 3 years.
- Redesign components of high concentration PV system for high-volume, low-cost manufacture and installation.
- Conduct reliability testing of redesigned system components
- Incorporate multijunction solar cells into redesigned system.

Accomplishments

- Redesigned and tested key system components including the MegaModule.
- Opened pilot manufacturing facility in Seal Beach, California.
- Manufactured five redesigned MegaModules.

Future Directions

- Complete IEC 62108 qualification and type approval of Amonix product.
- Demonstrate 25 MW per year manufacturing facility.
- Confirm Amonix system and project costs meet DOE LCOE targets for 2010 and 2015.

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1. Introduction

The principal objective is to step up to high-volume production for Amonix’s high concentration PV (CPV) systems. The project implements DOE’s strategy of partnering with companies to accelerate commercialization and meet aggressive cost goals. The Amonix CPV system incorporates the world’s highest efficiency solar cells.

2. Technical Approach

Amonix plans to expand its manufacturing capacity to 25 MW/year by equipping a foundry dedicated to the production of redesigned multi-junction cells and building a production line for automated manufacturing of all components of the MegaModule, including the cell packages, the receiver plate, and the module structure. Components of the MegaModule are being redesigned for low-cost and high-volume manufacturing, and the MegaModule depth was reduced to lower material costs. Fast-cure adhesives for lens attachment have been tested to reduce manufacturing time. High-volume vendors for the pedestal, drive, and torque tube will be sought. The drive, controls, and installation processes will be improved for high-volume installation and lower cost. Multi-junction cells are being developed and cell packages will be adapted to accommodate these cells. Amonix will fabricate and test 25 kW Si, 35 kW Si, and 50 kW mJ concentrators.

3. Results and Accomplishments

- Plant and equipment plan for 7-MW/year production facility. (4/08)
- Qualification tests at Arizona State University of key MegaModule components. (4/08)
- Redesigned 16” MegaModule maintains or improves performance compared with baseline 21” MegaModule. (4/08)
- Conduct manufacturing cost study for DOE analysis and verification. (submitted 6/08)
- Demonstrate progress toward DOE’s LCOE goals for 2010 using Solar Advisor Model. (submitted 6/08)

The first deliverable was a detailed design plan for the Amonix manufacturing plant and its equipment. The manufacturing plant is located in Seal Beach, and Amonix took occupancy in 2008 after obtaining National Environmental Protection Act approval through DOE. Unlike manufacturing of other PV technologies (crystalline silicon, thin films, and organic cells) there will be minimal wastes and emissions.

The second deliverable was the qualification of a new process for MegaModule component assembly. The qualification, test 10.8 for humidity freeze, is part of the International Electrotechnical Commission (IEC) 62108 standard for “concentrator photovoltaic (CPV) modules and assemblies. IEC 62108, published in December 2007, is the first international CPV standard.

The third deliverable required support from SNL to conduct a performance comparison between the 16” MegaModule scheduled for production and the baseline 21” MegaModule constituting Amonix’s previous fifth generation design. The dimension refers to the thickness (also focal length) of the MegaModule shown in Figure 2; a 16” MegaModule requires 35% less steel (with corresponding less cost) than the 21” does. Testing was completed in 4/2008 and confirmed the new 16” MegaModule design performed better than the 21” MegaModule.

Fig. 2 Three 16” MegaModules and two 21” MegaModules ready for comparison testing at University of Nevada Las Vegas with small multijunction module attached to center right portion of last MegaModule for reliability testing.

Amonix submitted the fourth deliverable, a manufacturing cost study, and fifth deliverable, calculation of the levelized cost of electricity (LCOE) using DOE’s Solar Advisor Model (SAM), as part of the stage-gate review convened by DOE in June 2008. Manufacturing cost and LCOE analyses conducted by Amonix confirm that Amonix is on track to meet the DOE LCOE cost targets in 2010 and 2015.

In addition to the above activities, Amonix has been central to two important collaborative CPV activities. Amonix has been active in the development of CPV standards since 1997, first within the IEEE working group that had a U.S. focus and later with the IEC Working Group 7 (WG7--CPV) of Technical Committee 82 (PV) whose work encompasses international CPV standards. The organization of ICSC5 is the second important collaborative activity led by Amonix in 2008. Amonix co-sponsored the first ICSC1 in 2002, followed by three more conferences since then. ICSC5 is scheduled for November 2008 in Palm Desert, California, followed by a WG7 meeting. ICSC5 is co-sponsored by numerous CPV companies and is acknowledged as the only conference organized by the CPV industry for the CPV industry.

Amonix is transitioning to manufacturing a mature, high-concentration technology with the 16” MegaModule, the 6th generation CPV system, and increasing Amonix’ manufacturing capacity.

Amonix installed 10 MW of Amonix MegaModule systems in 2007. This is the first time that 10 MW of any high concentration PV technology have been manufactured, installed, and operated.

4. Planned FY 2009 Activities

- Demonstrate progress toward DOE’s LCOE goals for 2010.
- Commence operation of 7 MW/year production facility in Seal Beach.
- Qualify 16”-MegaModule system to IEC 62108.
- Demonstrate successful operation and qualify 7-MegaModules drive.
- Complete installation of two 5-MegaModule and 7-MegaModule systems.
- Procure MJ cells with 35% average efficiency, optimized for the concentration and spectrum required by the Amonix system.

5. FY 2008 Special Recognitions and Patents

Amonix was inducted into the Environmental Hall of Fame on June 8, 2008 (See Figure 5).

6. Major FY 2008 Publications

V. Garboushian; K. Stone; R. Gordon; A. Slade. "Performance of the Amonix High Concentration PV System in Southern Nevada." *Power-Gen Conference 2008 Proceedings*; Las Vegas, Nevada, (February, 2008).

R. McConnell. “CPV Reliability—Reliability in an Expanding Technology,” *Accelerated Aging Testing in PV Workshop Proceedings*; April 2008, Lakewood, Colorado.

V. Garboushian; R. McConnell; K. Stone; R. Gordon; G. Kinsey; C. Crawford. “Reliable Deployment of High Concentration PV Systems.” *SPIE Optic and Photonics Conference Proceedings*; August 2008, San Diego, California.

7. University and Industry Partners

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)
University of Nevada, Las Vegas Robert Boehm	Las Vegas, NV	Installation and testing of Amonix MegaModules	245*
Arizona State University	Tempe, AZ	IEC 62108 Qualification Testing	35*
Spectrolab Inc.	Sylmar, CA	High Efficiency Multijunction Solar Cells	50*
NREL	Golden, CO	Cooperative R&D Agreement	75*
Cyro Industries	NH	Plastic Lamination R&D	TBD**

*Funded with prior year (FY 2007) funds. ** Award pending

TPP Awardee: The Boeing Co.

"Concentrator Photovoltaic Power System"

Total Award Amount: $45,315K, DOE/Recipient Share: $19,981K/$25,334K

Objectives

- Develop new concentrating photovoltaic (CPV) system, incorporating high-efficiency multi-junction cells, for utility-scale PV power market.
- Employ novel non-imaging optical design to optimally utilize the cells while addressing reliability and cost of the tracker and balance of systems equipment.
- Increase efficiency of production multijunction solar cells for high-concentration terrestrial applications from 36% to 40% by 2010.
- Reduce cost of cells by over 50% and increase cell production capacity to 1 GW/year by 2015.
- Achieve a $0.15/kWh LCOE by 2010 and $0.07/$kWh by 2015.

Accomplishments

- Produced 37.8% average production efficiency cells.
- Demonstrated 5-MW/yr automated cell manufacturing throughput rate.
- Constructed prototypes of three CPV module designs, including one complete array.
- Demonstrated over 27% module active-area efficiency.
- Established path to meeting $0.15/kWh LCOE target.
- Completed preliminary factory design.
- Completed qualification of PV Powered 100-kW inverter with an industry-best, 10-year warranty.

Future Directions

- Investigate manufacturability of 4-junction cells.
- Investigate costs and benefits of moving to very high concentration ratio optics.
- Investigate protective coatings for first surface mirror and antireflective coatings for cover glass and secondary lens.

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1. Introduction

Boeing has long been a leader is solar cell technology through its wholly-owned subsidiary, Spectrolab. This concentrator PV project is intended to leverage that technical leadership and to expand Spectrolab's market in terrestrial solar power. Spectrolab's leadership is in multi-junction (III-IV) gallium arsenide solar cells. This project has a dual focus: (1) increase the efficiency of Spectrolab's cells while reducing cost and (2) develop the concentrator system that uses those cells to produce power.

2. Technical Approach

Spectrolab addressed manufacturing cost by demonstrated automated manufacturing equipment and addressed cell value by continuing to improve cell efficiency. Spectrolab issued a subcontract to Caltech for multijunction cell research (see Section 7).

The Boeing Phantom Works team completed its selection of a preferred optical configuration (off-axis) and built various prototypes to advance the CPV product design. This team also pursued system engineering approaches to drive down LCOE in a verifiable manner. Team member PV Powered improved the reliability of its next generation inverter and validated its operation through UL certification.

3. Results and Accomplishments

- Produced 37.8% average production efficiency cells during engineering confidence run for the production C2MJ cell design and completed that generation's final design review.
- Implemented automated tooling at Spectrolab for cell manufacturing and demonstrated annualized production rate of 5 MW/year.
- Completed construction and evaluation of CPV modules of three different designs and one complete array.
- Investigated various performance and environmental issues and incorporated lessons-learned into subsequent designs.

- Demonstrated module acceptance angle of greater than 1.7° and active area efficiency of more than 27% with prototype C configuration.

Two-axis array trackers were purchased and evaluated. A new tracker control algorithm was implemented and demonstrated.

Team member PV Powered obtained certification of their new 100-kW inverter. Reliability improvements have allowed PV Powered to offer the first 10-year standard warranty in the industry.

- Completed preliminary power plant system design. Brought on engineering, procurement, and construction company to assist with system optimization.
- Created detailed LCOE model and established path to meet the $0.15/kWh LCOE target.
- Participated in IEC WG7 standards committees, particularly CPV tracker and system energy rating committees.

4. Planned FY 2009 Activities

- Demonstrate production mean cell efficiency of at least 38.5%.
- Perform module environmental test using C2MJ cells and using criteria consistent with IEC 62108.
- Demonstrate CPV array with power output >250 W/m^2 peak, produced with pre-production tooling.
- Demonstrate pilot production of inverter/tracker.
- Deploy system to evaluate system performance and LCOE model cost inputs.

5. FY 2008 Special Recognitions and Patents

- U.S. Patent No. 61/091,284, Flexible Thermal Cycle Test Equipment for Concentrator Solar Cells (provisional).
- U.S. Patent No. 12/258,321, Flexible Thermal Cycle Test Equipment for Concentrator Solar Cells.

6. Major FY 2008 Publications

M.J. Archer; D.C. Law; S. Mesropian; A. Boca; M. Haddad, R.R. King; H.A. Atwater. “GaInP/GaAs Dual Junction Solar Cells on Ge/Si Epitaxial Templates”; *33rd Photovoltaic Systems Conference Proceedings*; May 11-16, 2008, San Diego, California.

D.C. Law; R.R. King; H. Yoon; M.J. Archerb; A. Boca; C.M. Fetzer; S. Mesropian; T. Isshiki; M. Haddad; K.M. Edmondson; D. Bhusari; J. Yen; R.A. Sherif; H.A. Atwater; N.H. Karam. “Future technology pathways of terrestrial III–V multijunction solar cells for concentrator photovoltaic systems”, *Sol. Energy Mater. Sol. Cells* (2008),

R.R. King; P. Pien; R. Jones; A. Boca; K.M. Edmondson; D.C. Law; C.M. Fetzer; W. Hong; D. Bhusari; P. Hebert; M. Lau; R. Brandt; J. Ermer; N.H. Karam. “High-Efficiency Terrestrial Concentrator Multijunction Solar Cells – Research to Manufacturing at Spectrolab”, *5th International Conference on Solar Concentrators for the Generation of Electricity Proceedings*; November 16-19, 2008, Palm Desert, California.

A. Plesniak; R. Jones; J. Schwartz; G. Martins; J. Hall, D. Whelan; P. Benítez; J.C. Miñano; A. Cvetkovíc. "Successful Rapid Development of a High Performance Concentrating Photovoltaic System for Utility Scale Power Generation." Poster presented at 5th International Conference on Solar Concentrators for the Generation of Electricity, Palm Desert, California, November 2008.

A. Boca; K. Edmondson; R. King. “Concentrator Solar Cell Performance Enhancement by Way of Prismatic Covers.” Poster presented at 5th International Conference on Solar Concentrators for the Generation of Electricity, Palm Desert, California, November 2008.

7. University and Industry Partners

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Light Prescription Innovators	Los Angeles, CA/Madrid, Spain	Optics design support	1,756	362
PV Powered	Bend, OR	Qualify 250-kW inverter	3,921	3,371
Comau	Detroit, MI	Contract manufacturer	185	0

TPP Awardee: BP Solar International, Inc.

"Reaching Grid Parity Using BP Solar Crystalline Silicon Technology"

Total Award Amount: $39,693K, DOE/Recipient Share: $19,431K/$20,262K

Objectives

- Reduce module cost to 67% of 2006 costs by 2010 and to 50% of 2006 costs by 2015.
- Develop process for fabrication of solar grade silicon (Si).
- Optimize and implement Mono^{2TM} casting technology to improve material quality.
- Reduce wafer thickness from 220 µm in 2006 to 160 µm in 2010 and 100 µm in 2015.

Accomplishments

- Completed initial commercial demonstration of Mono^{2TM}.
- Commercial introduction of modules with U.S. produced AR-coated glass.
- Development of rapid method for determining cure level in EVA modules.
- Demonstrated wafering of 160 µm thick wafers using 120 µm diameter wire.
- Developed accelerated test sequence to assess potential damage and power loss due to cell breakage.
- Identified improvements necessary to reduce module manufacturing costs by 25% and verified technologies in the laboratory.

Future Directions

- Demonstrate 16% cell efficiency using Si cast with at least 50% solar grade material.
- Implement Mono^{2TM} in production.
- Complete development of roof-integrated PV module and submit for certification.
- Complete PV charge controller design, test through HALTS, and certify to UL 1741.
- Verify residential and commercial systems under development will meet LCOE 2010 target goals.

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1. Introduction

BP Solar's TPP program is based on accelerated development of multicrystalline Si technology for use in the residential and commercial markets, using products specifically designed for these applications. The goals of this program are to achieve grid parity and increase production volume. To meet these goals, our objectives are to substantially reduce 1) module cost to 67% of today's cost by 2010 and to 50% of today's costs by 2015; and 2) system costs to 60% of today's cost by 2010 and to 36% of today's costs by 2015. These are projected to result in levelized cost of electricity of 8 to 10¢/kWh for residential systems and 6 to 8¢/kWh for commercial systems by 2015.

2. Technical Approach

The BP Solar program addresses all aspects of the PV product chain from raw materials including Si through installation of the systems at the customer site. To achieve parity with the grid and growth to gigawatt levels of production requires involvement of the entire product chain. Partners in this effort include:

- Materials vendors (Dow Corning for Si, encapsulants and pottants, Ceradyne for crucibles, STR for EVA and AGC Flat Glass North America for glass) to lower cost, improve quality and performance, and assure material is available in the volume necessary.
- Equipment vendors (Komax and ATS) to develop next generation of equipment for automated production at high volumes.
- Vendors of balance of systems equipment (Xantrex for inverters. Comverge for energy dispatchablity) to improve reliability, increase lifetime, increase volume and lower cost.
- Universities (Georgia Tech, Arizona State University, North Carolina State University and University of Central Florida) and a research laboratory (Palo Alto Research Center) to provide research support.
- Utility (SMUD) will provide customer interface, demonstration sites, and utility prospective on the value of PV electricity.

Key components of the program include:

- Si purification process development of solar grade Si to increase availability of Si feedstock for PV industry.

- Casting: implementation of Mono$^{2™}$ technology (single crystal quality at multi cost);
- Wafering: thinner wafers down to 150 µm in 2010 and to 100 µm in 2015; thinner wire; improved slurry and slurry recycling; and automated demounting and singulation of wafers.
- Cell process: optimized design and processing for ultra-thin Mono$^{2™}$ to achieve cell efficiency of 18% in 2010 and 20% in 2015.
- Module: lower material costs, products designed for integration into specific roof types, and safe operation at high voltages.
- Automation and process control to transition from hundreds of cells per hour to hundreds of cells per minute.
- Higher efficiency, increased reliability inverters.
- Improved low cost systems monitoring.
- Reduced indirect costs through organized deployment channels and integrated solutions.

3. Results and Accomplishments

3.1 Silicon Feedstock
Partner Dow Corning successfully produced 60 kg of Si with <4 ppmw B, <5 ppmw of P, and <10 ppmw of metals. They also reported the production of over 1,200 kg of SGS with 4 ppmw of B, 5 ppmw of P, and <10 ppmw of metals. Dow also conducted a smelting trial at the National Energy Technology Labs (NETL) in Albany, Oregon. The trial confirmed the ability to use the trial produced ~95 kg Si of Si with an average boron and phosphorous content of 1.6 and 7.5 ppmw, respectively, confirming that carbonaceous binder in the silica briquette formulation will not affect the reactivity of the quartz.

3.2 Casting
Lower-tier Ceradyne completed development of a SiN hard coat process for PV crucibles, and nine casting stations have been qualified for production of Mono^{2TM} Si. A pre-production run of more than a megawatt of materials has begun.

3.3 Wafering
BP Solar completed the milestone to develop <180 micron wafer technology and made a decision not to implement in BP Solar wafering at this time due to equipment limitations.

A trial of 10 cuts with 120 µm diameter wire to cut 160 µm wafers indicated that cutting performance on current equipment is unacceptable at either 160- or 180-µm wafer thickness.

3.4 Cell Process
Dow developed an Iso-chemical texturing process and made a decision to implement on new cell lines. They also qualified low-bow Al-B paste BSF to be implemented for wafer thicknesses below 200 µm. Dow completed a preliminary evaluation and selected an approach for back-contact cells. Efforts are underway to use advanced emitters, advanced metallization, and laser firing to increase thin-cell efficiencies.

3.5 Module Development
BP designed a residential BIPV product and is finalizing ordering the mold. Tests verify that the ethylene-vinyl acetate (EVA) can be laminated to the thermoplastic polyolefin (TPO)-roofing membrane but discolored in damp heat tests. A generation 2 AR-coated glass was developed that transmits 0.8% more power than generation 1. BP has deployed new, higher-energy module designs for test at five outdoor sites worldwide. BP also developed a rapid method for testing the cure levels in EVA and is evaluating the procedure for possible use in all factories.

3.6 Manufacturing
BP completed development of a monitoring and control unit for printed line width and implemented it in production. A second improvement is a monitoring and control unit for sheet resistance.

3.7 Inverter
Partner Xantrex designed a charge controller for high voltage PV systems with battery storage. The full prototype design was completed, and circuit boards, sheet metal chassis, magnetics, and other electronic parts were procured for 5 units. The complete set of circuit boards was fabricated and all parts installed, and one complete unit was assembled to support the start of the functional testing of the circuitry.

3.8 Monitoring and Control
An initial monitoring installation was completed at the SMUD House of the Future. The system is operational, and initial local dispatch and recharge tests have been performed. BP also completed connector evaluation and test and selected one for use.

3.9 System Engineering
BIPV residential roofing product installation and aesthetic issues discussed with channel partner.

3.10 Deployment
BP prepared a report documenting third party approval requirements for the installation of PV systems. Also, the performance model was updated to include diffuse light and AR-coated glass.

3.11 Collaboration
BP participated in Solar ABCs efforts in standards and codes development.

4. Planned FY 2009 Activities

- Produce 600 kg of SoG Si with <0.5 ppmw B, <1.5 ppmw P and <1 ppmw metals at a throughput rate of at least 60 kg/hour.
- Design, construct, and demonstrate commercial-solar grade Si pilot line facility.
- Demonstrate cast ingots with mix of solar grade Si to achieve 16% cell efficiency.
- Complete evaluation/development of integrated demounting and cleaning system.
- Develop process and evaluate implementation of 160μm wafers and cells at average efficiency of 17% in production,
- Demonstrate and evaluate implementation of EVA cure-level monitoring.
- Demonstrate qualification and evaluate implementation of faster cure encapsulant.
- Complete development of roof-integrated PV module and submit for certification (UL and CEC).
- Complete redesign of module for improved safety and reliability.
- Complete development and evaluate implementation of membrane roofing product.
- Optimize operation of new screen printer and evaluate implementation strategy.
- Complete design of PV charge controller, test through HALTS, and submit for certification to UL 1741.
- Complete arc monitor and suppression system evaluation/selection.
- Complete design, fabrication, and test of prototype PV system monitor units.
- Complete membrane-roofing product system design.
- Install first prototype residential system.
- Verify residential and commercial systems under development to meet DOE LCOE 2010 target goals.

5. FY 2008 Special Recognitions and Patents

Six disclosures related to this program have been submitted. Three patent applications are being prepared, but none were submitted in FY 2008.

6. Major FY 2008 Publications

J.H. Wohlgemuth. “Field observations and product returns – What can we learn?” *Accelerated Aging Test & Reliability in PV Workshop II Proceedings,*” Denver, CO, 2008.

J.H. Wohlgemuth; D.W. Cunningham; N.V. Placer; G.J. Kelly; A.M. Nguyen. “The effect of cell thickness on module reliability.” *33rd IEEE PV Specialist Conference Proceedings,* May*,* 2008.

J.H. Wohlgemuth; D.W. Cunningham; R.F. Clark; J.P. Posbic; J.M. Zahler; P. Garvison; D.E. Carlson; M. Gleaton. “Reaching grid parity using BP Solar crystalline silicon technology.” *33rd IEEE PV Specialist Conference Proceedings,* May 2008.

J.H. Wohlgemuth; D.W. Cunningham; D. Amin; J. Shaner; Z. Xia; J. Miller. “Using accelerated tests and field data to predict module reliability and lifetime.” *23rd European PV Solar Energy Conference Proceedings*, Sept. 2008.

D.W. Cunningham; A. Parr; J. Posbic; W. Poulin. “Performance comparison between BP Solar Mono^{2TM} and traditional multicrystalline modules.” *23rd European PV Solar Energy Conference Proceedings*, Sept. 2008.

J.H. Wohlgemuth. “Reliability of PV Systems.” *SPIE Conference on Optics & Photonics Proceedings, Solar Energy + Applications”,* San Diego, August, 2008.

N.G. Stoddard; B. Wu; L. Maisano; R. Russell; J. Creager; R. Clark; J.M. Fernandez. "The Leading Edge of Silicon Casting Technology and BP Solar's Mono^2 Wafers", *18th Workshop on Crystalline Silicon Solar Cells and Modules*, Vail, CO, August, 2008.

7. University and Industry Partners

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Dow Corning Gary Burns Haroula Reitz	Midland, MI	Solar-grade Si feedstock for the casting process. Develop alternative silicone encapsulation system.	745	745
AGC Flat Glass NA Jean-Francois Oudard	Kingsport, TN	Develop solar glass with AR coatings.	74	94
ATS-Ohio David Kelly	Lewis Center, OH	Develop automated thin wafers and cells handling equipment	*	0
Arizona State University G. Tamizhmani Raja Ayyanar Harvey Bryan	Tempe and Mesa, AZ	Evaluate PV module and array performance; monitor residential PV system; Model power distribution system and advanced power converters; design BIPV products.	44	0
Ceradyne Thermo Materials Scott Higgenbottom	Clarkston, GA	Develop large area, high purity crucibles for Si Casting	150	150
Georgia institute of Technology Ajeet Rohatgi	Atlanta, GA	Design, optimize, and fabricate high-efficiency solar cells on BP Solar cast Si wafers	161	0
Komax Systems York Brian Micciche	York, PA	Develop screen print and tabbing/stringing equipment for thin PV cells.	*	*
PARC Dave Duff	Palo Alto, CA	Develop, qualify of a gridline printing system.	*	*
Recticel Dirk Daems	Auburn Hills, MI	Design, develop residential BIPV molded module frames.	*	*
Sacramento Municipal Utility District Cliff Murley	Sacramento, CA	Provide utility prospective to and demonstrations sites for residential and commercial PV systems.	*	*
STR Ryan Tucker	Enfield, CT	Develop of low cost, high performance encapsulants.	80	80
University of Central Florida Neelkanth Dhere	Coco, FL	Study module energy collection, PV connector performance and module leakage current.	80	0
Xantrex Technology Inc. Mark Edmunds	Burnaby, BC	Develop hi-reliability, battery-backed grid-tie inverter power conversion system	0	268
North Carolina State University George Rozgonyi	Raliegh, NC	Evaluate BP cast multi-crystalline and mono^2 Si.	100	0

*No invoices received as of 9/30/2008.

TPP Awardee: Dow Chemical Co., Inc.

"Fully Integrated Building Science Solutions for Residential and Commercial Photovoltaic Energy Generation"

Total Award Amount: $19,649K, DOE/Recipient Share $9,824K/$9,825K

Objectives

- Reduce total systems cost by revolutionizing design, incorporating mass production module fabrication, and developing solutions that are driven by targeted applications.
- Reduce LCOE for residential BIPV to $3.85/watt installed by 2010.

Accomplishments

- Validated shingle design concepts with respect to decreasing installation costs.
- Determined materials needed in robust, long term packaging components.
- Met minimum cell efficiency requirements for roadmap to meeting LCOE targets.

Future Directions

- Scale up pilot line for low cost manufacturing of shingle.
- Transfer residential shingle developments to commercial roofing product concepts.

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1. Introduction

Dow is working to develop modular, turnkey PV systems that provide residential and commercial customers with a complete solution and attractive value proposition. Dow's approach to a complete solution is to reduce the total systems cost by revolutionizing the design; incorporating mass production module fabrication; and developing solutions that are driven by the targeted applications as opposed to reconfiguring or modifying modules that had been designed for alternative purposes (e.g., ground mounted solar farms and other rigid applications). Dow is addressing all components of a turnkey system through existing channels with the building, construction, and infrastructure markets. Dow has partnerships with home builders (Pulte Homes and Lennar Homes), access to balance of system components through Dow Wire and Cable, and channels to the roofing industry through the wholly owned subsidiary Dow Roofing Systems.

2. Technical Approach

Dow developed a shingle design ready for pilot scale production. A smaller version was designed to test interconnects, packaging materials and installation techniques. Several design issues were identified through this approach to be made in the full size shingle.

Shingle design was impacted by a change in cell supplier. We were able to rapidly qualify another copper indium gallium diselenide (CIGS) manufacturer to aid our development. This manufacturer, Global Solar, Inc., operates two large scale CIGS PV manufacturing sites in Tucson, Arizona, and Berlin, Germany.

Dow expended significant effort on materials characterization and development to design a CIGS PV cell package that was suitable for the shingle functional format. This was accomplished utilizing both external products and internal technology under development.

3. Results and Accomplishments

Milestones achieved:

- Secured cell supply for prototype development.
- Produced working prototype shingles with packaging material.
- Produced full scale shingle.
- Reviewed cost model with Navigant.

Competitive Benchmarking, Cell Supply, and Shingle Development

Dow worked to set a baseline for performance of competitive products in the market both from a PV cell perspective and a packaging materials perspective.

System Engineering and Integration

Dow is new to solar product development and spent a considerable amount of time developing a BIPV material test plan to qualify the needed materials to provide cell stability and long shingle life. In addition to an integrated test plan, a test lab, which is now fully functional, was needed to be acquired and equipment qualified.

Dow is developing the BIPV product materials structure using a multi-generation plan to ensure continuous progress in terms of cost reduction while at the same time maintaining successful product performance. Many different approaches to achieving adequate barrier performance that will enable CIGS based PV shingles to perform more than 20 years were experimented with, tested, and in some cases, taken to development. Dow evaluates all the materials of construction with the total solution in mind.

Dow is working towards a simple yet rugged and reliable interconnection design for the Dow Solar Shingle, which totally eliminates all on-the-roof wiring and therefore the necessity of having an electrician or licensed solar installer do the installation. As part of addressing installation costs, Dow validated their design with a test build using standard roofing contractors.

4. Planned FY 2009 Activities

- Develop equipment modifications to fit product design with Global Solar Energy. (Q1)
- Build pilot line and start-up. (Q1)
- Install and collect data on turnkey systems. (Q2)
- Develop commercial roofing analog product. (Q1)

5. FY 2008 Special Recognitions and Patents

U.S. Provisional Patent Application No.61/098941, connector device for building-integrated PV device.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)
Global Solar Energy Jeffery Britt	Tuscon, AZ	Cell supplier	3
Prost Construction Vaughn Prost	Columbia, MO	Install demo unit with Columbia Water and Light to initiate rate structure study for solar PV electricity production.	35

TPP Awardee: General Electric (GE) Global Research, Inc.

"A Value Chain Partnership to Accelerate U.S. PV Industry Growth"

Total Award Amount: $46,217K, DOE/Recipient Share $20,000K/$26,217K

Objectives

- Investigate multiple technical pathways for producing modules and system components that will meet SAI LCOE goals and be successful in U.S. marketplace.
- Address segments of U.S. PV market where GE's technical and system integration competencies can have largest impact on PV system cost and performance.
- Deliver into residential and commercial markets complete system of components consisting of module array, dc-ac inverter, and energy monitor.
- Meet LCOE targets of $0.13/kWh to $0.18/kWh by 2010 and $0.08/kWh to $0.10/kWh by 2015.

Accomplishments

- Demonstrated 18% efficiency small area, single crystal Si solar cell.
- Demonstrated continuous carbothermic process to convert SiO_2 to high purity Si.
- Demonstrated solar cells from molded wafers with efficiencies 2% (absolute) above baseline.
- Developed life-time model for encapsulated CIGS cells.
- Developed model comparing interconnect schemes for flexible thin film modules.
- Constructed and demonstrated lab prototype residential architecture.
- Designed and constructed inverter test bed capable of reproducing CEC measurement protocol.

Future Directions

- Increase reaction efficiency in solar grade Si process by 2x.
- Increase for molded wafer solar cells of 1% (absolute) efficiency.
- Develop prototype encapsulated, flexible thin film module.
- Demonstrate high-reliability and high-efficiency residential and commercial inverter prototypes.

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1. Introduction

GE and its partners are investigating three PV pathways: (1) bifacial high-efficiency Si cells and modules; (2) low-cost multicrystalline Si cells; and (3) modules and flexible thin film modules. The balance of system for residential and commercial installations is also being investigated. Innovative system installation strategies are being pursed as an additional avenue for cost reduction.

2. Technical Approach

GE focused on three distinct technical pathways for the module and a technical pathway for the inverter/balance of system and installation. Each pathway is self-contained, spans the value chain to include materials, solar device, and system, and includes critical technologies and partners.

2.1 Bifacial High-Efficiency Silicon Module

GE is developing a 20%+ efficient solar cell based on a graded a-Si on crystalline Si hybrid technology using a scalable fabrication process. The bifacial nature of this solar cell presents an opportunity for the fabrication of a highly effective 2-5x concentrator module to reduce Si area while maintaining the form factor of a standard one-sun design.

2.2 Low-Cost Multicrystalline Silicon Module

GE is developing a solar cell based on a molded Si wafer in a continuous casting process that eliminates the waste associated with conventional sawing, resulting in a wafer that is 2x less expensive to produce. GE is working to improve the quality of the molded Si wafers to approach that of conventional polycrystalline cast wafers. GE has demonstrated capability for cell efficiencies of 12%–14% when fabricated using conventional cell manufacturing techniques. GE is also developing process using a low-cost Si feedstock based on a carbothermic-reduction process that will be less costly to scale than other processes currently in use. This process takes advantage of GE's knowledge of high quality quartz manufacturing and will allow the production of an abundant supply of Si feedstock.

2.3 Flexible Thin Film Module

GE is working with vendors who are developing technology for CIGS on flexible substrates as a source of flexible solar cells. This technology has great potential for low cost and the creation of unique building integrated products. GE has developed a set of packaging technologies for flexible organic light emitting diodes (OLEDs) that will be directly applied to the CIGS material. A novel multilayer SiN/organic film that can be directly deposited onto the solar cell or a polycarbonate sheet is the basis for a moisture-tight package that provides significantly better protection than the Teflon-based materials being used. In addition to moisture protection, thin film packages require UV protection. GE will leverage its extensive experience in the area of UV protection of polymer films to realize a fully encapsulated thin film product.

2.4 Balance of System (BOS)

GE and partner Xantrex are working to lower inverter cost and improve performance by developing innovative new circuit designs, utilizing high performance components, and by taking advantage of higher volume component pricing made possible by market growth. A large element of the cost is embedded in the system engineering and integration functions and in the installation. GE will be working with top PV installers to identify internally driven cost elements related to time and materials, identify external factors such as local codes and regulations that influence costs non-uniformly, and develop a streamlined process flow.

3. Results and Accomplishments

3.1 Bifacial High-Efficiency Silicon Module

GE achieved a number of key milestones, including 18%-cell efficiency on small area laboratory devices based on a graded a-Si/c-Si heterojunction design. This efficiency was the result of a significant amount of process development around surface passivation of the crystalline Si surface for high Voc and surface texturing for high Jsc. The GE team also developed a model to study the performance of these heterostructures. With this model, the team was able to study the affect of surface states at the a-Si/c-Si interface as well as the relationship between doping levels, wafer resistivity, and layer thickness on conversion efficiency.

Based on business considerations, GE has terminated efforts for the bifacial high-efficiency Si module for this project and will focus future project efforts on low cost multi-crystalline Si modules, flexible thin film module, and balance of systems.

3.2 Low-cost Multicrystalline Silicon Module

Multicrystalline Si has been produced via carbothermic reduction processes with boron and phosphorous concentrations below 0.3 ppma. Furthermore, a 20% process efficiency has been demonstrated, as well as a pathway towards higher process efficiency moving forward.

The molded wafer was initially commercialized by AstroPower in 2001, and GE acquired the assets of AstroPower. The benefit of the molded wafer process is that wafers are easy to handle and there are no costly Si-recycle loops required by today's conventional casting. The critical figures of merit for the process are the minority carrier lifetime (driving efficiency) and wafer thickness. GE is altering the wafer thickness by changing the Si powder spreading apparatus and by optimizing the thermal profile. This thickness, combined with modest improvements in efficiencies will generate Si utilization numbers equal to casting.

Wafers produced by the single wafer casting process have been processed into solar cells on a conventional, high volume solar cell production line. Cell thickness has been reduced by about 50%, and cell efficiency increased by as much as 50% relative to the original Astropower process.

3.3 Flexible Thin Film Module

GE reviewed three interconnect strategies: tabbed/stringed cells, shingled cells, and monolithically integrated cells. GE developed a model to predict the electrical performance, using input from measured contact and sheet resistances for the three different interconnect strategies under consideration. The model is being used to determine optimum geometric and materials configurations.

CIGS cells are known to be sensitive to moisture, thus some type of barrier layer is needed for flexible modules where glass is replaced by permeable plastic. GE has data that indicate the damp heat test is a valid acceleration of real-world conditions, and has developed data and models to allow prediction of real-world lifetime for various packaging options. These allow GE to compute acceleration factors from the damp heat test.

GE is testing packages based on laminating cells with encapsulant and barrier-coated plastic films. GE identified two fundamentally different stabilization schemes for transparent, but not inherently stable, polymer films. The first approach uses coatings with high-performance UV stabilizers, where such thin coatings are relatively low-absorbance and degradation is governed by initial absorbance and stability of UV screener molecule. The second UV-stabilization scheme uses thermoplastic cap layers on base film. Such thick layers are very high absorbance, and degradation is governed by physical erosion of the surface in microns/year. GE is performing accelerated weathering on variations of these two schemes, and initial data indicate there are several options to achieve 25-year lifetime.

3.4 Balance of System (BOS)

The GE team is developing a 4.8-kW residential inverter with dual array inputs and developed a lab high efficiency prototype. Preliminary reliability calculations show that this inverter will have significantly longer life than conventional designs.

An automated test setup has been built to fully exercise the residential inverter. The setup consists of power supplies to simulate the PV arrays, AC loads, a computer, and oscilloscope. This allows GE to perform one week of testing in 30 minutes. The full CEC test protocol can be easily implemented using this setup in addition to measuring anti-islanding capability and maximum power point tracking (MPPT) accuracy.

4. Planned FY 2009 Activities

Milestones include:

4.1 Low-cost Multicrystalline Silicon Module

- Increase by 2x solar grade silicon process reaction efficiency.
- Increase of 1% (absolute) in molded wafer solar cell efficiency.

4.2 Flexible Thin Film Module

- Fabricate an encapsulated, flexible thin film module prototype.

4.3 Balance of System (BOS)

- Demonstrate beta prototype of high-reliability and high-efficiency residential inverter.

5. Major FY 2008 Publications

X. Zhang; J. Fronheiser; B. Korevaar; T. Tolliver. "Post-treatment of a-Si/c-Si interface resulting in optimized passivation properties," Poster presentation at the *33rd IEEE PVs Specialists Conference, May 11–16, San Diego, CA, 2008.*

X. Zhang; J. Fronheiser; B. Korevaar; T. Tolliver. "Post-treatment of a-Si/c-Si interface resulting in optimized passivation properties," Extended abstract for the *33rd IEEE PVs Specialists Conference, May 11–16, San Diego, CA, 2008.*

B. Korevaar; X. Zhang; J. Fronheiser; T. Tolliver. "Influence of annealing on performance for hetero-junction a-Si/c-Si devices," Poster presentation at the 2*3rd European PV Solar Energy Conference, Sept. 1–5, 2008, Valencia, Spain.*

B. Korevaar; X. Zhang; J. Fronheiser; and T. Tolliver. "Influence of annealing on performance for hetero-junction a-Si/c-Si devices," Extended abstract for the 2*3rd European PV Solar Energy Conference, Sept. 1–5, 2008, Valencia, Spain.*

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Xantrex Technology, Inc. RD Merritt	Burnaby, BC Canada	Develop low-cost, high-reliability inverter technology.	1,300	775
Institute of Energy Conversion Steven Hegedus	Newark, DE	Qualification testing of vendor-supplied devices, assist in specification of test devices, conditions, and requirements for environmental and stress testing, performance and environmental testing of flexible-packaged modules.	156	0
Georgia Institute of Technology Ajeet Rohatgi	Atlanta, GA	Si solar cell fabrication using multicrystalline and single crystal wafers.	100	0
North Carolina State University George Rozgonyi	Raleigh, NC	Detailed material characterization to understand the lifetime limiting defects and mechanisms in Si wafers.	100	0

TPP Awardee: Greenray, Inc.

"Development of an AC Module System"

Total Award Amount: $5,044K, DOE/Recipient Share: $2,522K/$2,522K

Objectives

- Develop fully-integrated plug-and-play PV system through integration of power electronics with high efficiency PV module.
- Reduce PV system installation labor cost by half.
- Increase system reliability and reduce system maintenance costs by 75%.
- Increase system safety for installers and users.
- Lower lifecycle cost of PV energy to meet DOE goals.

Accomplishments

- Demonstrated prototype of inverter.
- Demonstrated prototype of residential mounting system.
- Demonstrated prototype of data system.

Future Directions

- Complete thorough testing of inverter, including final safety certification.
- Deploy AC module system prototypes with key partners for evaluation.

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1. Introduction

The market for PV systems on the roofs of homes and commercial buildings is growing rapidly in the United States. Expectations are high that growth will continue for the foreseeable future. To help foster the widespread adoption of PV, GreenRay is aiming to create a true plug-and-play AC system, with advantages in simplicity, safety, performance, and cost. GreenRay is focused on driving cost out of PV through evolution of the balance-of-systems and levels of integration.

2. Technical Approach

GreenRay is developing three elements for the AC module system: high-reliability inverter, simple residential mounting system, and data acquisition system. To achieve an integrated PV system that simplifies installation, GreenRay is eliminating many of the redundant structural elements in today's systems. Prototypes of the mounting system were developed and evaluated by an experienced PV installer.

The inverter has been designed to achieve a 20-year lifetime, improve system reliability, and reduce maintenance. Consultants have provided reviews of the inverter design to help GreenRay achieve its goals. The integrated data system is designed to take advantage of the distributed intelligence in the AC module system to provide module-level information.

3. Results and Accomplishments

Major results and accomplishments of the project are listed below:

- Demonstrated operation of alpha version of inverter at full power with THD below 5%. (4/08)
- Reliability analysis predicted greater than 20-year life for inverter. (4/08)
- Completed preliminary cost projections of AC module system show potential to achieve targeted lifecycle cost of energy. (5/08)

GreenRay completed the design of its novel inverter in a form factor optimized for integration with a PV module. The alpha prototype of the inverter operated successfully. Consultants reviewed the design and suggested several improvements. The reliability analysis was completed using standard tools and methods to model the circuit. Results indicate the potential to achieve the targeted lifetime and reliability.

Key design innovations make it possible to remove some mounting elements found in today's PV systems. The installation labor cost savings were validated, and the GreenRay AC module system will be roughly half that of conventional systems.

Imbedded data acquisition and communication capability was tested and demonstrated. The user interface features were reviewed with key stakeholders and refined.

4. Planned FY 2009 Activities

- Complete stress and performance testing of AC module using in-house facilities and outside test labs. (06/09)
- Submit AC module for final safety certification. (06/09)

5. FY 2008 Special Recognitions and Patents

Two patents were filed in FY 2008:
- High reliability inverter for an AC module.
- AC module wiring method.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Coal Creek Design	Lafayette, CO	Inverter design and development	\$65	\$0
SANYO Energy	Dallas, TX	PV modules to support inverter and AC Module development	\$106	\$106

TPP Awardee: Konarka Technologies, Inc.

"**Low Cost, Lightweight Solar Modules Based on Organic Photovoltaic Technology"**

Total Award Amount: $8,585K; DOE/Recipient Share: $3,656K/$4,929K

Objectives

- Improve stability by imparting oxygen and water vapor barrier properties to laminating adhesives.
- Improve performance by creating new n-type carriers for PV active layer.
- Improve performance and lower cost by substituting printed metal grid for high cost, vacuum deposited transparent semi-conductor.
- Performance objective of cell efficiency ~10% with module efficiency 7%-8%.
- Rooftop module lifetime objective is 10 years; cost objective $\leq$\$0.2/kWh.

Accomplishments

- Increased stability:
  - Demonstrated effectiveness of plate-like particles on water vapor and oxygen barrier properties of several classes of laminating adhesives.
  - Demonstrated that clay fillers retain high percentage of barrier properties at 60^{o}C.
  - Identified water and oxygen degradation mechanisms, along with solutions.
- Improved performance of n-Type Carriers:
  - Demonstrated control of lowest unoccupied molecular levels of fullerene derivatives; several of these derivatives exhibit electron mobility greater than PCBM.
- Improved performance of printed metal grids:
  - Demonstrated metal grids with >80%T, <10ohms/cm^2 can be printed at 100ft/min.
  - Demonstrated functioning cells using grid electrodes.
- Reduced cost: none of these accomplishments will increase costs, and the ability to print grids at high speed will ultimately lower cost. However, cost was not part of the first year objectives.

Future Directions

- Continue to develop clay-filled adhesives and conduct module tests.
- Develop solution-coatable barriers to replace high cost vacuum deposited barriers. (NREL)
- Optimize active layers with new fullerene derivatives and new low band gap polymer donors.
- Continue to investigate n-type polymers as replacements for fullerenes in active layer.
- Continue to optimize silver formulations and printing processes with goal of replacing ITO.
- Fabricate large area modules in our recently announced, 1-GW capacity manufacturing plant.

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1. Introduction

Since opening in 2001, Konarka Technologies has been dedicated to producing solar modules at low cost. The latter will be achieved by using organic materials that can be coated or printed on flexible substrates from solution using low cost, high speed processes. The objectives of this project, which can be divided into stability and performance, are centered on making these goals a reality.

2. Technical Approach

The program started by determining the factors and conditions that have the greatest affect on stability and then proceeded to investigate creative, practical approaches to solving the problems. These approaches centered on utilizing commercial barriers with improved properties as they became available and developing adhesives that add to the barrier properties.

To address performance, Konarka recognized that most of the available polymer donors and fullerene acceptors need improvement (e.g., extinction coefficient of the materials to incident radiation). This also meant that as the p-type polymer donors were improved, the properties of n-type component would also have to be modified to match the properties of the new polymers. In addition, the conductivity and transparency properties of the transparent electrode had to be improved, and since ITO on plastic substrates is one of the most costly components of the cell, it had to be replaced, if cost goals are to be achieved.

3. Results and Accomplishments

For the first 14 months, Konarka focused on improving the stability of the modules by improving the barrier properties of the laminating adhesive. Major degradation mechanisms were identified. These include oxygen complexation (reversible), oxygen degradation (irreversible), and water swelling which causes interface delamination. The initial approach to mitigating these effects was to incorporate inert, plate-like clay particles into the adhesive and increase the mean free path of water and oxygen molecules. Overall reductions of water/oxygen transmission rates have been realized by this approach. However, overall cell stability has been achieved with another approach, the use of commercially available film barriers. Also, in order to reduce barrier film costs, a new approach using solution coatable barriers was developed. Stability can be further improved by using the clay-filled adhesives on the edge barrier of the module.

To improve cell performance, several fullerene derivatives have been developed that exhibit improved properties. One set has shallow LUMO levels to match with high band gap polymer donors and raise the cell voltage. Another set has deep LUMOs to match with low band gap polymers. Cells have been fabricated that demonstrate moderate efficiency. The two types of fullerene derivatives are presently being produced to a quantity that allows optimization of cell performance. A second approach to improved cell performance involves the use of printed grids for increased junction illumination and decreased cell series resistance. Printed metallic grids have been demonstrated that have the desired properties of conductivity and transmissivity, and along with formulating highly conductive hole injecting layer, the grids can be used to replace ITO as the transparent electrode.

4. Planned FY 2009 Activities

- Introduce first product at recently-acquired 250,000-ft^2 manufacturing plant in New Bedford, Massachusetts. When fully operational, the coating/printing line will be able to produce modules capable of >1 GW (5% module efficiency).
- Improve module stability and performance.
- Improve over-laminate barriers to achieve 5-year rooftop stability for the initial products (2009).
- Replace currently used PET substrates with more stable materials.
- Create and develop new p- and n-type materials for the active layer and by replacing expensive ITO transparent electrode with a printed silver grid to achieve 5%–7% cell and module efficiency.

5. FY 2008 Special Recognitions and Patents

United States Issued Patents (2008)

Six patents were filed: US 7,407,831: Method for producing organic solar cells or photo detectors; US 7,413,997: Nanostructured electrode; US 7,329,709: Photoactive materials and related compounds, devices, and methods; US 7,351,907: Displays with integrated photovoltaic cells; US 7,414,188: Co-sensitizers for dye sensitized solar cells; US 7,407,831: Method for producing organic solar cells or photo detectors.

6. Major FY 2008 Publications

- M. Morana; M. Wegscheider; A. Bonanni; N. Kopidakis; S. Shaheen; M. Scharber; Z. Zhu; D. Waller; R. Gaudiana; C. Brabec. “Bipolar charge transport in PCPDTBT-PCBM bulk-heterojunctions for PV applications.” *Advanced Functional Materials* (2008), 18(12), 1757-1766.
- A. Welte; C. Waldauf; C. Brabec; P.J. Wellmann. “Application of optical absorbance for the investigation of electronic and structural properties of sol-gel processed TiO2 films.” *Thin Solid Films* (2008), 516(20), 7256-7259.
- R. Gaudiana; C. Brabec. “Fantastic plastic.” *Nature Photonics* (2008), 2(5), 287-289.
- J.A. Hauch; P. Schilinsky; S.A. Choulis; S. Rajoelson; C.J. Brabec. “The impact of water vapor transmission rate on the lifetime of flexible polymer solar cells.” *Applied Physics Letters* (2008), 93(10), 103306/1-103306/3. CODEN: APPLAB ISSN:0003-6951.
- C.J. Brabec; J.R. Durrant. ”Solution-processed organic solar cells.” *MRS Bulletin* (2008), 33(7), 670-675.
- C.N. Hoth; P. Schilinsky; S.A. Choulis; C.J. Brabec. “Printing Highly Efficient Organic Solar Cells.” *Nano Letters* (2008), 8(9), 2806-2813.
- K. Forberich; G. Dennler; M.C. Scharber; K. Hingerl; T. Fromherz; C.J. Brabec. “Performance improvement of organic solar cells with moth eye anti-reflection coating.” *Thin Solid Films* (2008), 516(20), 7167-7170.

- G. Dennler; N.S. Sariciftci; C.J. Brabec. “Conjugated polymer-based organic solar cells.” *Semiconducting Polymers* (2nd Edition) (2007), 2 455-530.
- A.J. Moule; A. Tsami; T.W. Buennagel; M. Forster; N.M. Kronenberg; M. Scharber; M. Koppe; M. Morana; C.J. Brabec; K. Meerholz; U. Scherf. “Two Novel Cyclopentadithiophene-Based Alternating Copolymers as Potential Donor Components for High-Efficiency Bulk-Heterojunction-Type Solar Cells.” Chemistry of Materials (2008), 20(12), 4045-4050. CODEN
- T. Ameri; G. Dennler; C. Waldauf; P. Denk; K. Forberich; M.C. Scharber; C.J. Brabec; K. Hingerl. „Realization, characterization, and optical modeling of inverted bulk-heterojunction organic solar cells.” *Journal of Applied Physics* (2008), 103(8), 084506/1-084506/6.
- G. Dennler; M.C. Scharber; T. Ameri; P. Denk; K. Forberich; C. Waldauf; C.J. Brabec. “Design rules for donors in bulk-heterojunction tandem solar cells-towards 15% energy-conversion efficiency.” *Advanced Materials* (Weinheim, Germany) (2008), 20(3), 579-583.
- J.A. Hauch; P. Schilinsky; S.A. Choulis; R. Childers; M. Biele; C.J. Brabec. “Flexible organic P3HT:PCBM bulk-heterojunction modules with more than 1 year outdoor lifetime.” *Solar Energy Materials & Solar Cells*; (2008), 92(7), 727-731.
- J.K. Lee; W.L. Ma; C.J. Brabec; J. Yuen; J.S. Moon; J.Y. Kim; K. Lee; G.C. Bazan; A.J. Heeger. “Processing Additives for Improved Efficiency from Bulk Heterojunction Solar Cells.” *Journal of the American Chemical Society* (2008), 130(11), 3619-3623.
- J. Ramier; N. Da Costa; C.J.G. Plummer; Y. Leterrier; J.A.E. Manson; R. Eckert; R. Gaudiana. “Cohesion and adhesion of nanoporous TiO2 coatings on titanium wires for PV applications.” *Thin Solid Films* (2008), 516(8), 1913-1919.
- R. Mosurkal; L.A. Samuelson; J. Kumar; D. Waller; R. Gaudiana. “Synthesis of a Soluble Pentacene Derivative: 6,13-bis(m-trifluoromethyl phenyl ethenyl) Pentacene.” *Journal of Macromolecular Science, Part A: Pure and Applied Chemistry* (2008), 45(11), 948-951.

7. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Institute for Energy Conversion University of Delaware R. Birkmire	Newark, DE	Determine stability of modules under various conditions of temperature, humidity, and light. Investigate instability mechanism.	105	76
NREL David Ginley	Golden, CO	Improve barrier properties of perimeter seals by means of adding rod-like fillers to adhesives. Year 2, converted to solution coatable barriers.	450	-

TPP Recipient: Nanosolar, Inc.

"Delivering Grid-Parity Solar Electricity for the Commercial Market"

Total Award Amount: $42,616K, DOE/Recipient Share $20,000K/$22,626K

Objectives

- Achieve grid-parity economics for commercial market based on an integrated suite of innovations in module, inverter, and mounting technology.
- Reach 2010 levelized cost of energy (LCOE) target of 6.3¢/kWh and 2015 LCOE target of 5.5¢/kWh.

Accomplishments

- Demonstrated successful achievement of all technical milestones for Phase I including:
  - Achieved ~95% Indium materials utilization efficiency (MUE).
  - Optimized wide-web, roll-to-roll, high-MUE coating deposition methods scalable to multiple MW/year module manufacturing.
  - Demonstrated prototype modules with >80% of component cell efficiency.
  - Validated cell/module design through prototype testing.
  - Demonstrated cell and module temperature cycling stability of CIGS thin-film cells within PV modules per test IEC6164 10.11.
  - Demonstrated cell and module UV stability of CIGS thin-film cells within PV modules per tests IEC61646 10.8 and IEC61646 10.10.
  - Develop, optimize, and qualify low-cost wiring strategies for CIGS thin-film PV modules per tests IEC61730 and IEC61646 10.0.
  - Substantially exceeded power conversion efficiency (PCE) requirement for prototype modules at conclusion of Phase I, and with very tight PCE distribution.
- Validated cost inputs enabling LCOE targets as calculated by DOE Solar Advisor Model (SAM).

Future Directions

- Demonstrate successful achievement of all technical milestones for Phase II of the project.
- Demonstrate pilot deployment with Nanosolar modules (Phase III).

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1. Introduction

Nanosolar's technology is based on a printed semiconductor, which permits substantially improved cost efficiency. To implement this technology at grid parity, the entire system requires improvement and some redesigned for a systems-optimized perspective. Nanosolar is accomplishing this by developing an integrated suite of system components and designs based on innovations in module, inverter, and mounting technology and informed by real-world performance feedback.

2. Technical Approach

Solar Cell Technology

Nanosolar has developed proprietary technology based on Copper-Indium-Gallium-diSelenide (CIGS) absorber technology that allows the printing of this semiconductor material using a high-speed, high-throughput roll-to-roll manufacturing process. A central challenge in cost effectively constructing an efficient, large-area CIGS-based solar cell or module is that the elements of the CIGS layer must be within a narrow stoichiometric ratio on nano-, meso-, and macroscopic length scale in all three dimensions. Achieving precise stoichiometric composition over relatively large substrate areas is difficult using traditional vacuum-based deposition processes. To address this, Nanosolar prints nanoparticulate CIGS precursor materials onto low-cost metal foil substrates and performs rapid thermal processing to convert the nanoparticulate coating into a CIGS absorber layer. This locks in the appropriate stochiometry into the nanoparticulate precursor material and ensures the required spatial uniformity, while permitting high speed throughput to minimize cost.

Mounting System

Optimal design of mounting structures for PV arrays requires the balance of several opposing design constraints. Specifically, such mounting structures need to support the inclination of the module at near latitude tilt to provide maximum electrical output, be aerodynamic with regard to the wind so that the loads imposed on the structure by wind are minimal and minimal ballast or connections to the structure are necessary, and be relatively light weight so that the structure does not add significantly to the weight the roof must bear. Nanosolar is designing the mechanical structures of modules within the context of potential mounting systems and system reference designs. They are identifying the minimal application-specific structural requirements through wind-tunnel and other tests, and developing a novel low-cost kWh-optimal mounting and deployment system.

Inverter technology

In this project, we will systematically tune the kWh-performance of the system, focusing in particular at the module-inverter interface, to achieve the system performance required for our LCOE targets. For example, minimizing operations and maintenance cost at the system level requires long inverter life, enabled by high performance components, while minimal upfront inverter cost is enabled by low-cost. Balancing cost and performance in the inverter design is a key aspect of the inverter technology development.

System Design

A system reference design is being developed based on standardized system blocks with kWh-optimized performance, minimal site-specific engineering and permitting, and rapid installation. Our approach is based on the definition of a "standard" system block within which we apply our product design and technology innovations and streamline deployment with respect to the major application segment.

3. Results and Accomplishments

See accomplishments section above.

4. Planned FY 2009 Activities

- Demonstrate achievement of all technical milestones for Phase II.
- Demonstrate pilot deployment with Nanosolar modules (Phase III).

5. FY 2008 Special Recognitions and Patents

Nanosolar developed and protected this technology as a combined set of trade secrets and three patent applications. Four additional applications are being prepared.

6. University and Industry Partners

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)	FY 2008 Cost Share ($K)
SunLink, LLC	San Rafaal, CA info@sunlink.com	Development low cost mounting solution thin-film module	0	104

TPP Recipient: Soliant, Inc.

"Concentrating Solar Panels: Bringing the Highest Power and Lowest Cost to the Rooftop"

Total Award Amount: $13,660K; DOE/Recipient Share $4,887K/$8,7723K

Objectives

- Develop tracking/concentrating solar module that has the same geometric form factor as a conventional flat, roof mounted PV panel.
- Target LCOE of $0.79/kWh in 2010.
- Target efficiency of 26% in 2010 (22% for 2008 prototype, 24% for 2009 pilot).
- Target performance equivalent to 600Wp in 2010 (490W for 2008 prototype, 540W for 2009 pilot).

Accomplishments

- Delivered prototype tracking/concentrating solar module that mounts to standard racking systems on commercial rooftops, with standard output electrical connections.
- Developed prototype unit equivalent to 414W per SNL evaluation; 23% collector efficiency, 17.6% total area efficiency.
- Buildup pilot manufacturing line to deliver pilot units October 2008.

Future Directions

- Continue to improve efficiency and power output.
- Deliver pilot and volume manufactured units establishing path to goal of LCOE.

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1. Introduction

Soliant Energy is a venture capital-backed startup focused on bringing advanced concentrating solar panels to market. They are the first company to integrate tracking solar concentrators into the form factor of conventional flat solar panels for rooftop applications. The Soliant design breakthrough will enable Soliant to put more solar power on a rooftop than any other solution. On any given roof, Soliant's high-efficiency panels can double a system's annual output relative to that of traditional panels. Equally important, since most commercial installations fill the entire roof, these high-efficiency panels will increase the size (in kW) of the average system, providing a further boost to the SAI's objective to rapidly roll out US capacity.

Soliant's strategy is to sell directly into the existing distribution channel of installers. Soliant's focus on scaling a panel manufacturing business is intended to minimize risk and rapidly deploy large capacity of new technology into the solar market.

2. Technical Approach

Soliant's effort is intended to produce capital equipment with high reliability under harsh conditions. During the 1st phase (9/07-3/08) the goal was engineering validation (EV) to demonstrate a working product design. This phase was completed with delivery of our prototype unit, validated by SNL, to meet all key objectives.

The second phase is design validation (DV) which further refines the design and readies it for manufacturing. Soliant made substantial progress toward completing this phase by establishing a pilot manufacturing line in Monrovia, California. This phase is expected to be completed in December 2008.

The third phase will be production validation (PV) and will culminate in the first large-scale deliveries of our product to customers by the end of 2009.

3. Results and Accomplishments

- Delivered prototype concentrating solar panel for SNL test and evaluation.
- Made substantial progress toward completion of pilot manufacturing line.
- Signed long-term agreement with cell supplier and made progress toward long-term agreements with other key suppliers.

The major focus of the effort in FY 2008 was to specify the market-entry concentrating solar panel, produce a working prototype for SNL's test and evaluation, and make progress on completing the manufacturing pilot plant. Soliant specified, designed, produced, and validated concentrating solar panel that produces annual power equivalent to 414Wp flat plate. The panel has a 23% collector efficiency and a 17.3% total area efficiency. These results are slightly poorer than outlined in the negotiated project objectives but the reasons are understood. In addition, detailed models produced during this fiscal year suggest that space/power tradeoffs in the current module design may result in a lower LCOE and higher return on investment than originally expected because of improvements in shade tolerance and spacing parameters.

Figure 1 shows the prototype panel in a photograph taken at SNL during initial testing.

Soliant began building their pilot manufacturing line in March 2008. The tooling was kicked off and contracts for long lead-time equipment let in April 2008. They moved to the new facilities in Monrovia in July 2008. By the end of the FY 2008, all the machinery for the pilot line had been received, and tuning and debugging was begun.

Figure 1. Soliant Prototype Panel at SNL

Soliant also developed an in-house testing capability for a variety of environmental tests on panel components, paving the way for UL listing in 2009.

Planned activities for Soliant also included developing a receiver packaging capability. We have developed this capability and have submitted a report for evaluation as a stage-gate deliverable. Two subcontract research initiatives have been kicked off with MIT. Professor Jung-Hoon Chun is studying the manufacturing impacts of various alternatives in a multi-echelon supply chain. The other, directed by Professor Martin Culpepper, is investigating mechanisms for three-dimensional articulation of the optical element. These activities were delayed due to staffing complications at MIT and are still in the early stages of conceptual design.

4. Planned FY 2009 Activities

Early in FY 2009, Soliant expects to deliver the first panels produced from the pilot manufacturing line together with a roadmap to the projected LCOE. The rest of the year will be devoted to customer “beta” installations, obtaining UL listing for the product, and setting up full-scale manufacturing capability for delivery of UL-listed commercial product to paying customers in fourth quarter 2009.

5. FY 2008 Special Recognitions and Patents

Two U.S. patents were filed.

6. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2008.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)
Spectrolab, Inc. Jeff Peacock	Sylmar, CA	Development and supply of III-V concentrator PV cells	26
MIT Prof. Jung-Hoon Chun Prof. Martin Culpepper	Cambridge, MA	Advanced research in manufacturing engineering	59
SunEdison, Inc. Steve Voss	Beltsville, MD	Customer-perspective review of proposed panel specification	0

TPP Awardee: SunPower, Inc.

"Grid-Competitive Residential and Commercial Fully Automated PV Systems Technology"

Total Award Amount: $52,647K, DOE/Recipient Share $24,700K/$27,947K

Objectives:

- Develop high-efficiency, turn-key PV systems for residential and commercial markets to deliver electricity at grid parity by 2010–2015.
- Lower LCOE thru optimization of complete supply chain.
- Create U.S.-based jobs.

Accomplishments:

- Developed solar cell with 23.8% efficiency, measured by NREL.
- Developed prototype laminate for class A fire rating, delivered to NREL.
- Manufactured continuous CZ-ingot growth with high lifetime materials.
- Developed baseline pilot line equipment for unitary product manufacturing for commercial applications.
- Developed state-of-the-art Engineer to Order software and implemented design software capabilities.
- Verified modeling programs for systems performance to be within 1% of actual system performance.

Future Directions:

- Continue high efficiency, low cost cell development.
- Begin to implement U.S.-based module manufacturing.
- Develop low cost modules with fire rating and for use in bifacial applications.
- Test and validate kerf free Si 'slicing' methods.

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1. Introduction

Sunpower Corporation assembled a diverse team of leading companies, including several small businesses, to form their TPP and believe that, through the combined efforts, the program's Levelized Cost of Energy (LCOE) goals for 2010 and 2015 can be met. SunPower is developing turn-key, high-efficiency residential, commercial, and large ground-mounted systems that are designed to be cost effective in delivering electricity at grid parity. This systems-class TPP program addresses technology from Si crystal growth to systems installed in the field. Partners include SunPower, as the prime recipient, and Solaicx, SiGen, Dow Corning, Xantrex, Silicon Ribbon, and NREL, as sub-recipient partners.

2. Technical Approach

The technical approach includes tasks for the development of improved crystal growth processes (Solaicx), innovative wafer fabrication (SiGen), higher efficiency cells, better modules (Dow Corning), automated in-line cell and module production equipment development, product refinement in modules and systems, and more reliable inverters (Xantrex). The program involves development of new processes, the identification and evaluation of alternative, reduced cost materials, increased productivity in fabrication of products and reduced waste. System development includes inverters, monitoring, and overall streamlining of system deployment. Figure 1 shows the value chain covered in the award.

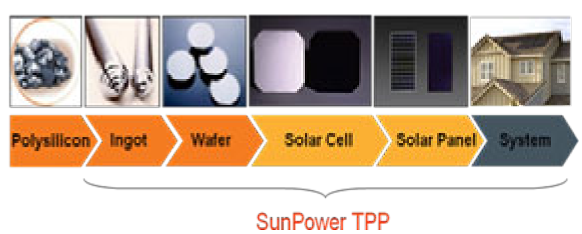

Figure 1. SunPower SAI TPP

SunPower will develop turn-key, high-efficiency residential systems that are both attractive and cost effective and deliver electricity at grid parity. Key system attributes are LCOE competitive with grid power by 2015, module efficiency over 20%, and reduced installation time and cost. Sunpower intends to reduce system costs from present levels by over 50% by 2015.

3. Results and Accomplishments

SunPower increased cell conversion efficiency, leveraging costs across the value chain from raw polysilicon to installation. High efficiency cells reduce area-related BOS costs, module conversion costs, and installation labor. Additionally, higher efficiency systems are required to provide enough power for the large portion of residential rooftops which are space constrained. Higher efficiency modules allow for higher capacity PV arrays to be mounted within the roof area constraints of a home, thereby amortizing fixed installation and sales costs over more total system watts. For a given system power, higher efficiency often permits optimized positioning of the array, thereby maximizing total value of energy produced (including factoring in increased time-of-day pricing). As cost per watt of PV is reduced, the total system size will be increasingly limited by space instead of total system costs, making increased efficiency a strong lever for reducing the end user LCOE.

SunPower manufactures 21% efficient solar cells in its 100 MW/year manufacturing facility. SunPower modules typically generate 40% more power than a similar sized standard crystalline module. In addition SunPower cells have a low temperature coefficient of -0.38%/C. SunPower modules have demonstrated up to 5% higher energy harvest than traditional modules with an the identical power rating due to their superior temperature coefficient and reduced sensitivity to spectral variation, angle of incidence, and light intensity. SunPower plans to continue to improve both conversion efficiency and cell temperature coefficient. Figure 2 shows the continuing progress toward high efficiency cells.

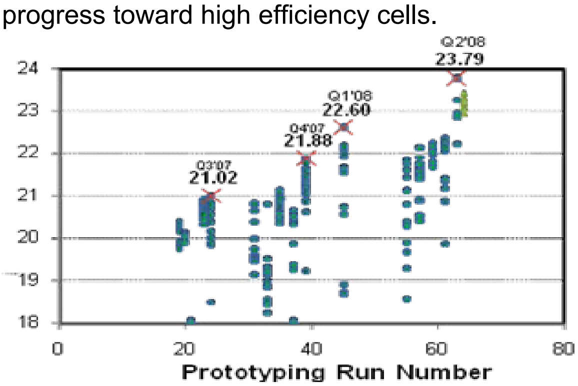

Figure 2: Cell Efficiency accomplishments under SunPower's SAI program

Cell efficiencies between 21% and 22% have been verified by NREL and are being manufactured.

An analysis of diffusion pitch dimensions and a simulation model to look at efficiency losses due to lateral transfer of electrons indicates that decreasing the diffusion pitch has an efficiency effect greater than 0.5% absolute. Additional increases in efficiency have been seen with the new pattern design with less dark-space loss and smaller recombination losses. The new pitch and pattern design has had a net efficiency gain of nearly 2%. The new pattern has produced a narrower distribution which is more predictable for module builds of different wattage rating.

This new pattern design has been implemented in the factory lines. All future production lines will include this upgrade and as SunPower increases production volume, this represents the major fraction of our production product. These new cells have enabled SunPower to produce a >20% efficient module (SNL-verified).

Reduced Silicon, Solar Cell & Module Cost

Solaicx has developed a high-throughput, high-lifetime growth method. SiGen is working on a kerf-free process to produce high quality Si wafers. This process is expected to improve Si utilization by several multiples.

SunPower has successfully incorporated 145-micron cells in the factory, and full conversion is expected by the end of the year to this new thickness.

Bifacial Modules: Another key focus area in the past year was bifacial module development. Prototype modules were produced with 16.8% front side and 10% backside efficiency. Seven test units were measured for bifacial performance. The amount of frontside Irradiance measured on the backside is typically about 10%-20% of the total irradiance. A demonstrated kWh/kWp increase of 7.5% with T20 Tracker compared to SPR-AR modules was achieved. Further gains in the bifacial modules are possible by reducing module mismatch, optimizing cell, and increasing backside irradiance.

Integrated Residential System Solution to Reduce Installation Costs: Because the grid-tied residential system installation cost is more than 25% of the total system costs, the SunPower team is also working to reduce these costs.

SunPower has implemented systematic design changes to reduce system installation time, training, and standardization to reduce the skill level required for installation (from skilled electrical trades to semiskilled for example), and software and field tool development to automate procedures. The streamlined installation process allows installers to leverage their substantial fixed costs over a greater volume of installations, further reducing the overall customer LCOE.

SunPower deployed streamlined installation approaches during Phase 1. Figure 3 shows the Nellis AFB 14-MW project, the largest in North America, which used some preliminary approaches to streamlined deployment. Up to 1 MW per day was installed at this site.

Attractive System Design: SunPower's product design features superior appearance with its all black back-contact solar cell as well as visually appealing module packaging. For mainstream adoption of solar systems, appearance will be important. New integrated system designs are necessary to facilitate the adoption of solar by a wider audience. SunPower developed appealing integrated residential systems in cooperation with its design partners, homebuilder advisors, and an architectural review board.

Figure 3. Nellis AFB PV Installation

Long-Term Reliability: It is critical to the success of the PV market. SunPower focused efforts on performing accelerated testing of new cell, module, and system technologies. Testing labs were established in California and the Philippines, closely monitoring field systems for long-term performance data. Si solar cells and modules have proven long-term performance, but innovations such as residential integrated roof systems must be carefully designed to avoid potentially higher operating temperatures as well as address fire and safety aspects unique to an integrated approach.

In the residential market, inverter reliability in particular must be improved to reduce the cost and trouble to the homeowner of PV system ownership. SunPower is working with Xantrex to extend the field life of the inverter. Additionally, internet-connected system monitoring and even modules are proposed to enhance reliability testing and allowing installer partners to deliver proactive customer support.

System Monitoring: SunPower is working to refine system modeling software under this program and is making significant improvements in the ability to predict system performance. The average actual kW-hr compared to the predicted kW-hr energy production is over 99%. Continued statistical analysis and program refinement are planned.

4. Planned FY 2009 Activities

- Develop 5 cells with target efficiency of 23%.
- Develop 5 cells produced with autoline-compatible processes with efficiency greater than 20%.
- Produce laminate for class A fire rating.
- Develop next-generation prototype laminate for residential applications.
- Manufacture prototype modules in U.S.
- Implement streamlined tools and processes to reduce LCOE in installer network.

5. Major FY 2008 Publications

F. Henley; A. Lamm; S. Kang; Z Liu; L. Tian. "Direct Film Transfer (DFT) Technology for Kerf-Free Silicon Wafering." *23rd European PV Conference Proceedings*; September, 2008, Valencia, Spain.

F. Henley; A. Brailove; A. Lamm; T. Heerwagen; E. Sauar; M. Nese; R. Steeman; B. Hammel. "Kerf-Free Silicon Wafering Equipment Configuration Using Beam-Induced Cleave." *23rd European PV Conference Proceedings*; September, 2008, Valencia, Spain.

"Solar America Initiative Grid Competitive Systems Technology A Systems Driven Approach to Cost Reduction." *33rd IEEE PVSC Proceedings*; May 11–16, 2008, San Diego, California.

"Solar America Initiative Grid Competitive Systems Technology A Systems Driven Approach to Cost

Reduction." *PVs Summit 2008 Proceedings*; June 18-20, 2008, San Diego, California.

"Solar America Initiative Grid Competitive Systems Technology A Systems Driven Approach to Cost Reduction." 17th Workshop on Crystalline Silicon Solar Cells & Modules: Materials and Processes Proceedings; August 5-8, 2007, Vail Cascade Resort, Vail, Colorado.

6. Industry Partners

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Solaicx Peter Bostok	San Jose, CA	Develop continuous CZ Si ingot growing technique	2,092	1,046
SiGen Philip Ong	San Jose, CA	Develop 2MeV proton implant system for fabrication of 50µm thin films	498	298
Dow Corning Becky Laur	Midland, MI	Development of advanced polymers for solar modules	43	21
Xantrex R Merritt	Burnaby, BC	15-Year Inverters, identify reliability mechanisms	680	0
NREL John Benner	Golden, CO	Solar cell measurement support	48	0
RibbonTechnology Arik Donde	San Jose, CA	Develop float Si	429	0

TPP Awardee: United Solar Ovonics, Inc.

"Low Cost Thin Film Building-Integrated PV Systems"

Total Award Amount: $39,849K, DOE/Recipient Share $19,339K/$20,510K

Objectives

- Address commercial BIPV market and reduce LCOE to 12.8¢/kWh in 2010 to meet DOE's short-term goal.
- Reduce LCOE for commercial BIPV further to 7.6¢/kWh in 2015 to meet DOE's 2015 goal.

Accomplishments

- Obtained NREL confirmed ~9.8% stable total-area (0.268 cm^2) efficiency on multi-junction device incorporating nc-Si, using small-area modified very high frequency (MVHF) batch reactor on Al/ZnO back reflector with production condition constraints.
- Attained thickness uniformity ≥90% for a-Si:H, a-SiGe:H, and nc-Si:H layers deposited over large area (450 cm^2) using MVHF batch machine (NREL verified).
- Deposited nc-Si:H films over 50" wide cathode at 0.6 nm/sec and achieved uniformity better than 80% over 42" wide area, with photoconductivity and morphology similar to small area VHF research samples (NREL-verified).
- Increased power rating for our product from 136 W to 140 W.
- Attained ~9.3% stable total-area (0.268 cm^2) efficiency on a-Si:H/a-SiGe:H/a-SiGe:H triple-junction device, using small-area MVHF batch reactor on Al/ZnO back reflector with a-Si:H and a-SiGe:H cells deposited at ≥ 0.6 nm/s. Efficiency results were measured at NREL.
- Succeeded in depositing 2-3 micron thick ZnO films over 2"x2" area at ~8 nm/s and prepared on both Al/ZnO and Ag/ZnO back reflectors.
- Completed preliminary test and analysis of several important passive components of PV laminates.
- Developed prototypes of advanced in-line device monitoring techniques in roll to roll deposition machines.
- Designed new cost-effective detachable solar module for easy installation.

Future Directions

- Advance state-of-the-art technology for nc-Si:H materials and solar cells for both small area and large area deposition and attain higher conversion efficiency with production-compatible parameters.
- Insert new deposition technology and increase power rating of prototype laminate with increased power rating.
- Scale up MVHF technology and explore feasibility of incorporating it in roll-to-roll production deposition machines.
- Investigate new module designs, assembly processes, and materials in order to reduce module, installation, and systems level costs.
- Advance cutting edge technology for in-line diagnostic tools for in-situ monitoring of device parameters.

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1. Introduction

United Solar Ovonic (Uni-Solar) is working to develop a low cost solution for the commercial BIPV market. The goal of this program is to reduce the cost of various cost centers including modules, inverters and other balance of systems (BOS), and installation, such that the LCOE will be reduced by 15%-20% by 2010, consistent with DOE's 2010 goal. In addition, they plan to develop new materials and new manufacturing processes for even higher module efficiency and lower cost production processes to address DOE's 2015 LCOE goal. The Uni-Solar team includes experts from universities, NREL, and industry.

2. Technical Approach

Based on the analysis of cost centers and cost reductions in each process of the product, the company divided the project into five tasks: solar module improvement, inverter and balance of systems, system engineering and integration, deployment, project management, and TPP collaborative activity.

Work on the module represents the largest portion of the project and underscores a multi-pronged thrust to reduce module cost. One subtask focuses on materials and process optimization of the current manufacturing lines to improve the manufacturing process to increase the efficiency of the product and throughput. A second subtask addresses the need to improve the solar cell device efficiency. Higher cell efficiency directly translates to higher product rating for the same footprint and thereby lower cost. One way to attain higher efficiency cells is to use nc-Si:H material as a potential replacement for a-SiGe:H alloys in the multijunction cell. In conjunction, the high-rate MVHF technology will be developed for deposition of a-Si:H, a-SiGe:H, and nc-Si:H materials and cells in order to obtain higher efficiency and reduce capex. The MVHF technology will be developed for up to production-size area deposition.

Another effort is directed towards bringing down the cost of stainless steel substrate, wires, and encapsulant materials. Innovative detachable module solutions will be developed that will reduce installation cost.

Within the Inverter and Balance of System (BOS) area, the work focuses on new designs and better integration of inverters for building integrated applications. In the area of system engineering and integration tier, the work focuses on inexpensive installation designs for different types of roofs. For deployment facilitation, the work focuses on demonstrating cost reductions by installing, monitoring, and using lessons learned from test arrays in different locations on different types of roofs.

This project coordinates the efforts of several partners including equipment manufacturers, academia, national labs, inverter companies, and engineering design companies. The entities were selected on the basis of their competence and relevance to our flexible BIPV product.

3. Results and Accomplishments

Uni-Solar achieved target performance with both potential device designs and processes as listed under the Accomplishments section above.

Another goal was the performance against target LCOE (for 2010). Uni-Solar's average module selling price was ~$3.00/W for the fiscal year ended 6/30/08. The long-term goal is $1.10/W, which corresponds to a selling price of $1.83/W, assuming a gross margin ~40%. Using projected costs of inverter and balance of systems, Uni-Solar is on track to achieve their LCOE targets for 2010 and 2015.

Several other goals were achieved in miscellaneous areas, ranging from the small area high rate VHF a-Si:H, a-SiGe:H multi-junction solar cells, to backend process improvement and material reduction. A key achievement was the improvement of the power rating of the current product. Before Phase I, the current product was rated at 136 W and 128 W. Under Phase 1, the product rating increased to >140 W.

4. Planned FY 2009 Activities

- Improve small area nc-Si:H based cells at high deposition rates with MVHF glow discharge to achieve stable total-area efficiency ~11.0%.
- Achieve stable aperture-area efficiency ~10.0% for large-area a-Si:H/nc-Si:H based multi-junction solar cells.
- Improve light-trapping in cells, possibly using Ag/ZnO back reflector in a roll-to-roll machine. Conduct appropriate reliability tests before qualifying Ag/ZnO back reflector for product.
- Accelerate use of MVHF high rate deposition in the roll-to-roll deposition system, including a feasibility study of roll-to-roll VHF machines.
- Continue to work with academia and NREL for better understanding of a-Si:H, a-SiGe:H, and nc-Si:H layers made by MVHF and explore new back reflectors.
- Continue to work on cost reduction of stainless steel substrate, grid wire for current collection, and alternative encapsulant materials.
- Conduct systems engineering and integration to develop detachable BIPV solution.
- Continue to advance in-line diagnostic technology for *in-situ* monitoring device parameters.
- Work with inverter companies to bring down cost.
- Install two BIPV systems.

5. Major FY 2008 Publications

Several other papers were submitted to journals and conferences, and the following are published papers.

P.G. Hugger; J.D. Cohen; B. Yan; G. Yue; X. Xu; J. Yang; S. Guha. "Electronic properties of nanocrystalline Si deposited with different crystallite fractions and growth rates." *Mater. Res. Soc. Symp. Proc.*; 1066 (2008), 149.

B. Yan; G. Yue; Y. Yan; C.S. Jiang; C.W. Teplin; J. Yang; S. Guha. "Correlation of hydrogen dilution profiling to material structure and device performance of hydrogenated nanocrystalline silicon solar cells." *Mater. Res. Soc. Symp. Proc.*; 1066 (2008), 61.

B. Yan; G. Yue; C.S. Jiang; Y. Yan; J.M. Owens; J. Yang; S. Guha. "Optical enhancement by textured back reflector in amorphous and nanocrystalline silicon based solar cells." *Mater. Res. Soc. Symp. Proc.*; 1100E (2008) at www.mrs.org.

T. Su; T. Ju; B. Yan; J. Yang; S. Guha; P.C. Taylor. "Magnetic resonance in hydrogenated nanocrystalline silicon thin films," *Mater. Res. Soc. Symp. Proc.* 1066 (2008), 273.

G. Yue; B. Yan; J. Yang; S. Guha. "Hydrogenated amorphous silicon and silicon germanium triple junction solar cells at high rate using RF and VHF glow discharges." *33rd IEEE PVSC Proceedings*; May 2008, San Diego, California, in press.

B. Yan; G. Yue; J. Yang; S. Guha. "Correlation of current mismatch and fill factor in amorphous and nanocrystalline silicon based high efficiency multi-junction solar cells." *33rd IEEE PVSC Proceedings*; May 2008, San Diego, California, in press.

X. Xu; K. Lord; G. Pietka; F. Liu; K. Beernink; B. Yan; C. Worrel; G. DeMaggio; A. Banerjee; J. Yang; S. Guha. "High efficiency ultra lightweight a-Si:H/a-SiGe:H/a-SiGe:H Triple-junction solar cells on polymer substrate using roll-to-roll technology." *33rd IEEE PVSC Proceedings*; May 2008, San Diego, California, in press.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008* ($K)	Cost Share * ($K)
University of Oregon Dr. J. David Cohen	Eugen, OR	Electronic and Optical characterization of materials for a-Si:H, a-SiGe:H, and nc-Si:H materials and solar cells	142	0
Syracuse University Dr. Eric Schiff	Syracuse, NY	Diagnostic development of mobility characterization tool for a-Si:H, a-SiGe:H and nc-Si:H solar cells and optical modeling studies for light trapping in a-Si:H, a-SiGe:H and nc-Si:H solar cells	149	37
Colorado School of Mines Dr. P. Craig Taylor	Golden, CO	Defect characterization of materials and devices using NMR, ESR, and PL	150	29
NREL Dr. Pauls Stradins	Golden, CO	Full material characterization and modeling of high rate materials using various characterization methods	145	0

*SAI Phase 1 awarded amounts.

University Partnerships

Performing Organizations:	Arizona State University (ASU); California Institute of Technology (Caltech); Georgia Tech Research Corporation (GIT); Massachusetts Institute of Technology (MIT); North Carolina State University (NCSU); Pennsylvania State University (Penn State); University of Delaware (UD); University of Florida (UF); University of Toledo (UT)
Key Technical Contacts:	Carolyn Elam (DOE/GO, Primary Contact), 303-275-4953, carolyn.elam@go.doe.gov Joe Lucas (DOE/GO), 303-275-4849, joe.lucas@go.doe.gov Jim Payne (DOE/GO), 303-275-4756, jim.payne@go.doe.gov Holly Thomas (DOE/GO), 303-275-4818, holly.thomas@go.doe.gov
DOE HQ Technology Manager:	Marie Mapes, 202-586-3765, marie.mapes@hq.doe.gov
FY 2008 Budget:	$3,500K (DOE/GO)

Objectives

- Leverage university understanding and experience to improve photovoltaic (PV) products and process development.
- Develop projects offering direct, near-term improvements in PV products and development processes.

Accomplishments

- Developed multidimensional model to establish design for 20%-efficient cells with passivated back contact and developed structure meeting the model. (GIT)
- Found suitable SS substrate base for Cu(InGa)Se2 PV devices and achieved small area device efficiency of 11%. (UD-Eser)
- Determined reaction pathway for synthesis of CuGaSe2, CuInSe2, and CuInxGa1-xSe from basic precursor structures. (UF)
- Produced several superlattice structures with 15% In and 68% P with fair results, and researchers are approaching a closely balanced superlattice.(NCSU)

Future Directions

- Evaluate engineering of receivers. (ASU)
- Identify best dielectric system with reduced shunting and good optical properties. (GIT)
- Develop Bragg reflector with reflectivity of > 80% and a working cell (< 1.2--1.3 eV). (NCSU)
- Demonstrate 12% device on SS/SBR with evaporative and selenized $Cu(InGa)Se_2$ films less than 1.5 µm thick (09/09).(UD-Eser)
- Fabricate and characterize InP/Si templates on 100-mm Si substrates. (CalTech)
- Synthesize low-bandgap, high-mobility acene-based organic semiconductors with improved stability. (PennState)

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1. Introduction

Universities hold a fundamental understanding of materials and device physics as well as experience with lab-scale processes and prototype production. This experience uniquely positions universities in transitioning PV technology from lab to marketplace. Market-oriented research exposes students to PV-related commercialization.

2. Technical Approach

University PV Process and Product Development Support awarded 11 projects in six topic areas: cadium telluride (CdTe)/1 award, copper indium gallium diselenide (CIGS)/2 awards, concentrating PV (CPV)/3 awards, thin silicon (Si)/1 award, organic PV/1 award, and wafer Si/3 awards.

Agreement Title	FY 2008 Budget ($K)
ASU – G. Tamizhmani *Reliability Evaluation of Concentrator Photovoltaic Modules per IEC Qualification Specifications*	250
Caltech – H.A. Atwater *100 mm Engineered InP-on-Si Laminate Substrates for InP-based Multijunction Solar Cells*	355
GIT – A. Rohatgi *Development of Rear Contact Technologies for Next Generation High Efficiency Commercial Si Solar Cells*	356
MIT – A. Buonassisi *Defect Engineering, Cell Processing, and Modeling for High-Perfomance, Low-Cost Crystalline Si PV*	TBD
NCSU – S.M. Bedair *Tunable Narrow Band Gap Absorbers for Ultra High Efficiency Multi-junction Solar Cells*	361
Penn State – C.A. Grimes *TiO2 Nanotube Array-Organic Semiconductor Heterojunction Solar Cells for Efficient, Low Cost, Large Area Scalable Solar Energy Conversion*	499
UD – E. Eser *Development of a Low Cost Insulated Foil Substrate for Cu(InGa)Se2 PV*	497
UD – U. Das *High Efficiency Back Contact Si Heterojunction Solar Cells*	357
UF – T. Anderson *Routes for Rapid Synthesis of CuGaxIn1-xSe2 Absorbers*	194
UT – X. Deng *High-Rate Fabrication of a-Si-Based Thin-Film Solar Cells Using Large Area VHF PECVD Processes*	340
UT – R. Collins *Improved CdTe PV Modules by Atmospheric Pressure Vapor Deposition*	290

3. Results and Accomplishments

3.1 Reliability Evaluation of Concentrator Photovoltaic Modules per IEC Qualification Specifications (ASU)
In this collaborative project, the testing cost and time for the concentrator photovoltaics (CPV) partners will be reduced by as much as 65%. Overall, the faster qualification/reliability testing and certification strategy planned will benefit the entire CPV community and allow the CPV manufacturers/technology to effectively compete with the flat-plate PV manufacturers/technology in the marketplace with independently demonstrated performance reliability/qualification and comparable testing duration. This cooperative project is expected to increase the production capacity of CPV products.

3.2 100-mm Engineered InP-on-Si Laminate Substrates for InP-based Multijunction Solar Cells (Caltech)
This grant expands upon recent advances in III-V laminate substrate development for multijunction solar cell technology to achieve low-cost, high efficiency multijunction solar cells fabricated on 100-mm InP/Si laminate substrates. The approach is to scale-up Caltech's previously developed InP/Si laminate substrate process for III-V multijunction cell fabrication to 100 mm diameter InP/Si substrates, developing a robust process for fabrication of 100-mm InP/Si substrates, and a cost-mode for high volume manufacturing. Wafer specification sfor an InP/Si substrate that is commercially manufacturable at high volumes will be established and validation from prototype fabrication of InGaAsP/InGaAs and InAlAs/InGaAsP/InGaAs multijunction solar cells.

3.3 Development of Rear Contact Technologies for Next Generation High Efficiency Commercial Si Solar Cells (GIT)
The objective is to develop low-cost high-quality rear contacts and fabricate production-ready high-efficiency monocrystalline (~20%) and multicrystalline (17%-18%) Si solar cells.

- Developed multidimensional model to establish design for 20%-efficient cells with passivated back contact.
- Modeled and optimized rear contact geometry as function of contact spacing and surface recombination velocity.
- Developed thermally stable dielectric for passivated rear contact structure that exceeds requirements of our model and reduces SRV to <100 cm/s prior to contact formation.

3.4 Defect Engineering, Cell Processing, and Modeling for High-Perfomance, Low-Cost Crystalline Si PV (MIT)
The objective is to close the efficiency gap between industrial multicrystalline Si (mc-Si) and monocrystalline Si solar cells, while conserving the economic advantage of low-cost, high-volume substrates inherent to mc-Si. The project objective will be supported by the following: (1) Identify and decouple the impacts of primary lifetime-limiting defects; and (2) Develop low-cost defect engineering technologies to achieve homogeneous and high bulk minority carrier

lifetimes, approaching the 100 μs range, in low-cost crystalline Si substrates; and (3) Develop defect-tolerant device processing technology, capable of supporting high-efficiency solar cells at low cost.

3.5 Tunable Narrow Band Gap Absorbers for Ultra High Efficiency Multi-junction Solar Cells (NCSU)
The objective is to reduce LCOE by improving the efficiency of III-V multi-junction solar cell and lead to a practical and achievable efficiency >45% through a four-junction cell. Using organometallic chemical vapor deposition at 600ºC and 625ºC, super lattice structures have successfully been grown with periods consisting of approximately 15% In and 68% P with GaAs transition layers between each In and P layer, as confirmed by various measurements including SEM.

Several superlattice structures with 15% In, 68% P have been produced with fair results and researchers are approaching a closely balanced superlattice.

3.6 TiO2 Nanotube Array-Organic Semiconductor Heterojunction Solar Cells for Efficient, Low Cost, Large Area Scalable Solar Energy Conversion (Penn State)
This project aims to reliably produce scalable and highly efficient solid state solar cells, using a heterojunction of TiO_2 nanotube arrays and an organic semiconductor with a goal to manufacture low-cost, large-area air-stable solar cells with photoconversion efficiencies of 6%-8%.Four major technical objectives are:

- Optimize performance of transparent TiO2 nanotube array-P3HT-PCBM blend double heterojunction solar cells.
- Synthesize functionalized pentacene derivatives and incorporate them into TiO2 nanotube array hybrid solar cells in order to decrease band gap, increase stability, and improve compatibility with oxide surfaces.
- Explore high-throughput fabrication techniques for formation of active layer organic semiconductor films on TiO2.
- Quantify limiting parameters affecting solar cell performance.

3.7 Development of a Low Cost Insulated Foil Substrate for Cu(InGa)Se2 PV (UD-Eser)
The goal is to develop low cost stainless-steel (SS) flexible-substrate coated with high-temperature silicone-based resin (SBR) dielectric for use in the processing of Cu(InGa)Se2-based PV.

- Found suitable SS substrate base for Cu(InGa)Se_2 PV devices.
- Achieved small area device efficiency of 11%.
- Tested Web-transport mechanism of R2R system; SS-foil substrate up to 18 inch/min speed.

3.8 High Efficiency Back Contact Si Heterojunction Solar Cells (UD-Das)
The objective is to implement an interdigitated back contact (IBC) Si solar cell using low temperature heterojunction (HJ) depositions. The use of Si HJs allows a simpler design of rear contact solar cells and higher performance at lower deposition temperatures.

- Demonstrated bi-layer c-Si front surface passivation structure of 2 nm a-Si:H / 80 nm SiNX with surface recombination velocity < 10 cm/s and good antireflection properties.
- Incorporated intrinsic a-Si:H (i. a-Si:H) buffer layer at the rear surface. A detailed device characterization and optimization of a-Si:H buffer layer provided pathways to improve fill factor in IBC-SHJ cells.

3.9 Routes for Rapid Synthesis of CuGaxIn1-xSe2 Absorbers (UF)
The objective is to develop predictive models that quantitatively describe reaction pathways to synthesize CIGS for increased throughput from the shortened reaction time for absorber synthesis. Additional cost reductions due to process scale-up will be realized by providing quantitative rate data. The target is a synthesis time 2 minutes or faster.

- Determined reaction pathway for synthesis of CuGaSe2, CuInSe2, and CuInxGa1-xSe from basic precursor structures.
- Developed thermodynamic model describing contained Cu-In-Ga-Se ternary phase diagrams.
- Built diffusion mobility database to quantitatively predict absorber synthesis rates.

3.10 High-Rate Fabrication of a-Si-Based Thin-Film Solar Cells Using Large Area VHF PECVD (Very High Frequency Plasma-Enhanced Chemical Vapor Deposition) Processes (UT-Anderson)
Two objectives of this effort are (1) to develop and improve a large area (3 ft × 3 ft) VHF-PECVD system for high rate fabrication of 8 Å/s a-Si and 20 Å/s nc-Si absorber layers with high uniformity in film thicknesses and in material structures, and (2) develop and optimize large-area VHF PECVD

processes to achieve high-performance a-Si/nc-Si tandem-junction solar cells with 10% stable efficiency.

3.11 Improved CdTe PV Modules by Atmospheric Pressure Vapor Deposition (UT-Deng)

This project will advance an atmospheric pressure vapor deposition (APVD) process for CdTe modules and to achieve module performance comparable to competing CdTe technologies while retaining the significant manufacturing cost advantages of APVD. Steps include:

- Incorporate glass optimized for PV applications into the production line for improved module efficiency greater than 10%.
- Apply spectroscopic ellipsometry in spatially scanning mode in on-line and other optical probes for real-time for process monitoring.
- Develop APVD-compatible activation process.
- Develop hi-performance back contact that does not require vacuum processing and is compatible with monolithic cell integration on glass by laser scribing.
- Improve module monolithic integration process for greater scribe process latitude.
- Verify less than 1% decay of module performance per year.

4. Planned FY 2009 Activities

ASU

- Procure, install, and commission humidity-freeze chamber and damp-heat chamber; conduct engineering evaluation of receivers and systems (thermal cycling of receivers; outdoor exposure testing of systems)

GIT

- Develop spin-on dielectrics with low fixed charge density (< $\pm 10^{11} cm^{-2}$). (01/09, GIT)
- Identify best dielectric system with reduced shunting and good optical properties. (01/09)
- Evaluate recombination in contact window and assess its impact on cell performance. (04/09)
- Deposit SiCx using silane-free solid source and evaluate surface recombination velocity on p-type surfaces.
- Optimize design of a-Si/doped a-Si passivation including thickness and doping concentration of each a-Si layer. (07/09)
- Demonstrate screen-printed passivated, local back contact structure can reduce or eliminate warping of thin wafers. (10/09)
- Demonstrate a back surface recombination velocity below 200 cm/s and a back surface BSR of 90%-97% on crystalline Si solar cells. (10/09)

NCSU

- Develop $In_xGa_{(1-x)}As$ x>0.3 $GaAs_{(1-y)}P_y$ y>0.8 and carrier concentration less than $10^{16}/cm^3$. (11/08)
- Optimize t_{In}, t_P, x, and y to achieve strain for matched structure and avoid relaxation. (01/09)
- Design necessary masks. (07/09)
- Develop Bragg reflector with reflectivity of > 80%. (08/09). And a working cell (< 1.2--1.3 eV). (10/09)

UD-Eser

- Demonstrate pinhole-free Si-based resin (SBR) coating. (03/09)
- Demonstrate 12% device on SS/SBR with evaporative and selenized $Cu(InGa)Se_2$ films less than 1.5 μm thick (09/09).
- Start deposition of Na-doped $Cu(InGa)Se_2$ films on 5- to 10-ft. rolls with 10% device efficiency.

CalTech

- Fabricate and characterize InP/Si templates on 100-mm Si substrates. (09/09)

Penn State-Grimes

- Optimize nanotube pore size, wall thickness, and length in existing device configuration consisting of P3HTPCBM blend infiltrated into TiO2 nanotube arrays.
- Optimize polymer blend ratio and film thickness.
- Synthesize low-bandgap high mobility acene based organic semiconductors with improved stability.
- Understand configuration of polymer chains inside pores and determine penetration of polymer into nanotubes.

UD–Das

- Investigate inorganic and organic passivation layers for front illuminating side of IBC-SHJ structure to further reduce optical losses.
- Optimize plasma process for rear-side passivation, emitter, and contact-layer deposition, guided by two-dimensional numerical simulations.

University of Florida

- Design and prepare base-CIGS thin films, based on (a) elemental layers, (b) selenization of precursor, and (c) bilayer precursor.
- Complete assessment of Cu-Ga-Se and Cu-Ga-In ternary phase diagram.
- Implement DICTRA modeling of binary metal couples to extract diffusion mobilities of Cu-In, Cu-Ga, and Ga-In and modeling of binary Se

couples to extract diffusion mobilities: Cu-Se, In-Se, and Ga-Se.

UT–Deng

- Complete numerical simulation of stable uniform plasma for large-area VHF-PECVD chamber.
- Complete detailed engineering design and installation of VHF.
- Modify PECVD electrode hardware, gas delivering system, and cathode and gas shower configuration to improve uniformity.
- Demonstrate large area VHF PECVD processes for high-rate ≥(8 Å/s) a -Si deposition with thickness non-uniformity of <±10%.

UT–Collins

- Determine minimum CdTe thickness and optimum thickness for CdS.
- Determine optimum optical configuration for on-line scanning.
- Develop scribes fabrication processes.

5. Major FY 2008 Publications

UD-Das

U.K. Das; D. Xu; O. Jani; M. Lu; S. Bowden; R.W. Birkmire. "Designing rear surface for carrier transport in all back contact silicon heterojunction solar cells."

Caltech

G.M. Kimball; N.S. Lewis; H.A. Atwater. *Proceedings of 33rd IEEE Photovoltaic Specialists Conference*; May 11-16, 2008, San Diego, California.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
ASU/G. Tamizhmani Solfocus/Warren Nishikawa Soliant Energy/Brad Hines	Mountain View, CA Pasadena, CA	Provide CPV receivers and one assembly for Thermal Cycling testing and Outdoor Exposure testing	0 0	50 50
Caltech/H.A. Atwater Spectrolab/Daniel C. Law	Sylmar, CA	Provide assistance with cell processing, GaAS cell fabrication	375	0
GIT/A. Rohatgi SiXtron Advanced Materials, Inc.	Varennes, Quebec Canada	Provide silane-free solid source for SiN-/SiC-bsed AR-coatings and passivation layers for Si cells	454	0
NCSU/S.M. Bedair Spectrolab/Ken Edmondson	Sylmar, CA	Support integration of NCSU subcell into multi-junction cell	75	0
Penn State/C.A. Grimes University of Kentucky	Lexington, KY	Assist in design and synthesis of organic semiconductors	499	99
UD/E. Eser Dow Corning/Elizabeth McQuiston	Midland, MI	Develop silicone-based dielectric coated SS foils	497	99
UD/U. Das SunPower/Richard Swanson	Sunnyvale, CA	Provide high-performance IBC cells	361	92
UT/X. Deng Xunlight Corp./X. Deng	Toledo, OH	Provide materials, labor, and equipment for Xunlight's roll-to-roll production line	340	68
UT/R. Collins Solar Fields/Norm Johnston University of Nevada, Las Vegas/Clemens Heske University of Michigan	Perrysburg, OH Las Vegas, NV Ann Arbor, MI	Supply large area thin film deposition processing Provide electron and photon spectroscopies Provide high resolution electron microscopy	72 25 14	37 6

Photovoltaic Technology Incubator

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Martha Symko-Davies (NREL), 303-384-6528, Martha_symko_davies@nrel.gov

DOE HQ Technology Manager: Scott Stephens, 202-586-0565, scott.stephens@ee.doe.gov

FY 2008 Budget: $10,127K (NREL)

Objectives

- Shorten the timeline for companies to transition prototype and pre-commercial photovoltaic (PV) technologies into pilot and full-scale manufacture.
- Move companies into commercial production quickly and successfully.
- Position companies to be competitive for Technology Pathway Partnership (TPP) funding opportunities.
- Focus the efforts of subcontractors to a limited number of high-impact module technology improvement opportunities (TIOs) that are on the critical path to scaling-up their technology to full manufacture.

Accomplishments

- Completed merit criteria and analysis to select negotiations for second round of Incubator subcontracts in June 2008.
- Down-selected subcontracts via Stage gate to seven subcontracts in August 2008.

Future Directions

- Issue a third letter of interest (LOI) for the Solar America Initiative (SAI) PV Incubator in fiscal year (FY) 2009.
- Complete merit review for responses to the LOI.
- Complete stage-gate review of individual progress versus deliverables by late summer 2009.
- Begin negotiations with the companies selected under the second Incubator solicitation, which include: 1366 Technologies, Skyline Solar, Solexel, Solasta, Innovalight, and Spire Corp.
- Issue a LOI for the SAI PV PRE-Incubator in FY 2009.

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1. Introduction

The primary objective of the SAI PV Technology Incubator project is to shorten the timeline for companies to transition PV technologies into pilot and full-scale manufacture. The incubator concept generally applies to companies that are not far enough along in technology and product development pathways to be positioned to qualify for the first of the SAI's Technology Pathway Partnership (TPP) awards. Successful participation in the SAI PV Technology Incubator project will quickly move companies into commercial production and position those companies to be competitive for the next TPP funding opportunity, which is expected to be issued in 2010.

SAI provides significant opportunities for collaboration and partnership among industry and university researchers to develop and improve solar energy technologies. This SAI PV Technology Incubator project targets research and development on PV cell and module prototypes with demonstrated functionality in either large-area cell/module form or, preferably, prototypes produced in pilot-scale operations. The emphasis on proposed activities should be focused on the barriers to manufacturing scale-up and 2010 commercialization.

Advances are needed to achieve prototype modules and pilot production, which will be facilitated through projects funded under this LOI. It is expected that the subcontract duration will be

18 months for each award made under this solicitation. Entrance opportunities for the Incubator project are anticipated every 9 months as funding opportunities become available. The entrance criterion is demonstrated PV cells or process lab devices or modules. A successful demonstration for the entrance criterion is a quantifiable and verifiable baseline measurement. The successful exit criterion would be for prototype modules and pilot production demonstration greater than 3 megawatts per year (mW/year). These entry and exit criteria are provided to applicants as general guidelines for maturity of technology that the U.S. Department of Energy (DOE) intends to fund through this LOI, but the guidelines are flexible. Applicants may be more advanced than the stated entrance criteria at the time of application and may plan to be more advanced than ~3mW/year pilot production at the completion of their "incubator" project.

2. Technical Approach

2.1. SAI PV Incubator Management

The Project Management and Support subtask addresses: (1) management of the Incubator project; (2) management of subcontracts awarded; and (3) coordination of NREL in-house activities in support of the small businesses.

Table 1. PV Incubator Project Tasks and Budget

Task Title	FY 2008 Budget ($K)
PV Technology Incubator Management	11,384
PV Technology Incubator Subcontracts	2,500

2.2. SAI PV Incubator Scope

NREL solicited LOIs from individual U.S. small businesses and small business-led teams that were working on research and development of demonstrated PV cell and module prototypes. The LOI emphasized overcoming the barriers to manufacturing scale-up and 2010 commercialization.

Topic Areas include:

- Novel wafer-based silicon (Si) modules
- Polycrystalline thin films
- Film silicon on a foreign substrate
- High-efficiency cells, including multijunction, and concentrating PV (CPV) module concepts
- Organic PV, dye-sensitized solar cells, or other polymer-based solar cells
- Low-X concentration CPV systems with limited or 1-axis tracking module designs
- Low-X Si modules, 3-10X.

Table 2. FY 2008 PV Incubator Subcontractors

Subcontractor	Title of Subcontract
AVA Solar	Advanced CdTe PV Technology
Blue Square Energy	Silicon Solar Cells on Low Cost Substrates
EnFocus Engineering	Pilot Manufacturing of Rooftop-Ready Solar Panels Using High Concentration PVs
CaliSolar	New Metallization Technique Suitable for 6-mW Pilot Production of Efficient Multicrystalline Solar Cells Using Upgraded Metallurgical Si
MicroLink	Epitaxial Liftoff Fabrication of Low-Cost, High-Efficiency, GaAs-Based, Dual-Junction Solar Cells for Concentrator Applications
Plextronics	Economic On-Grid Solar Energy via Organic Thin Film Technology
PrimeStar Solar	Production Scale-up of World Record CdTe/CdS Cell
Solaria	Development of a Wafer-Si Solar Cell Based Low-Concentration PV Module
SolFocus	Reflective Optics CPV Panels Enabling Large-scale, Reliable Generation of Solar Energy Cost-competitive with Fossil Fuels
SoloPower	CIGS Technology based on Electroplating

3. Results and Accomplishments

AVA Solar has demonstrated consistent and uniform thin-film solar cell performance, a manufacturing friendly process capable of fabricating thin-film solar cell efficiency of more than 11% conversion efficiency (verified by NREL) deposited on 16.5 inch x 16.5 inch low-cost, soda-lime glass substrates. Also demonstrated was a reliable thin-film CdTe module performance that passed the hot and humid test of 1000 hours at 85 degree C and 85% relative humidity. Manufacturing consistency has been demonstrated with 5-day production runs with a throughput for 1 module for the absorber layer deposition done every 2 minutes. Thin-film CdTe module aperture-area conversion efficiency of more than 8.0% for 16.5 inch x 16.5 inch size substrates has been fabricated and verified by NREL. In addition, material utilization of the semiconductor layers in excess of 90% has been demonstrated in the pilot line. AVA Solar has developed a robust, industrial scale process for fabricating thin-film CdTe modules at a potential cost of less than $1/watt, which will significantly reduce the cost of generating solar electricity.

The primary effort of Primestar Solar is to accelerate the commercialization of the highly efficient thin film PV technology for various applications such as commercial rooftop and grid-tied applications. The research involves developing high performance prototype mini-modules (6 inch x 6 inch), as well as designing and commissioning a pilot line for full-size commercial thin film power modules. The project involves qualifying thin-film CdTe record performance advanced window layers films (CTO, ZTO, CdS:O) for commercial low-cost manufacturing with films deposited uniformly across the mini-module glass substrates. In addition, film deposition rates for the window layers are adapted for large-scale production. Research was also performed to optimize the thin-film CdTe mini-modules using the advanced window layers developed in this subcontract. A full-sized power module pilot line equipment design and cost estimates have also been done as part of the research activity. Prototype thin-film CdTe power modules will be fabricated in the next several months.

The SolFocus effort is developing a 500x concentrating PV module with a folded reflective design in a compact frame. The design can be manufactured in volume and is scalable to gigawatt (gW) capacity. Major highlights of the effort include the design and construction of a concentration power unit with an efficiency of 25.5% and a full-sized module constructed with these units that exhibited an NREL-verified efficiency in excess of 20%.

SoloPower, Inc., improved their CIGS roll-to-roll processing and demonstrated control of their composition ratios to 0.94 for Cu/(In+Ga) and 0.26 for Ga/(In+Ga). This was well within the targeted average ranges of a Cu/(In+Ga) ratio of 0.94 +0.09/-0.07 and a Ga/(Ga+In) ratio of 0.26 +0.03/-0.02. They have also demonstrated NREL-verified 100-cm2 solar cell efficiencies of 12% and an NREL-verified 1-m2 aperture area module efficiency of 8.96%.

CaliSolar, Inc., developed their cell processing using shadow mask electroplated front contacts and best known conditions resulting in the demonstration of twelve NREL-verified multi-Si cell efficiencies of 15%. They have also demonstrated their process capability for laser grooving of Si wafers at as low as 17µm, as well as masking/plating on Si wafer with electroplated line widths of as low as 32µm. This was well below the 30µm laser grooves and 50-µm line widths required under this subcontract.

4. Planned FY 2009 Activities

The subcontracts from the second solicitation will be awarded in December 2008. These subcontracts will then undergo a Stage-Gate review during the summer of 2009. At that time an evaluation of progress will occur and a determination to continue with the second 9-month phase of the subcontract will be made.

A third PV Incubator Solicitation will be released in 2009. It is anticipated that the new round of subcontracts will be finalized in late summer of 2009.

Additionally, the Pre-Incubator will be released in January of 2009. This project would be for the R&D of an early stage idea/application that would grow into a prototype and be a year-long effort.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
AVA Solar, Inc. Pascal Noronha	Fort Collins, CO Pnoronha@avasolar.com	Advanced CdTe PV Technology	571.9	290.7
Blue Square Energy, Inc. Jerry Culik	North East, MD jculik@bluesquareenergy.com	Silicon Solar Cells on Low Cost Substrates	390.3	201.1
EnFocus Engineering Corp. Jason Lu	Sunnyvale, CA jason.lu@enfocuscorp.com	Pilot Manufacturing of Rooftop-Ready Solar Panels Using High Concentration PVs	541.3	200.2
CaliSolar, Inc. Alain Blosse	Sunnyvale, CA alain@calisolar.com	New Metallization Technique Suitable for 6-MW Pilot Production of Efficient Multicrystalline Solar Cells Using Upgraded Metallurgical Si	651.0	968.4
MicroLink Devices Noren Pan	Niles, IL npan@mldevices.com	Epitaxial Liftoff Fabrication of Low-Cost, High-Efficiency, GaAs-Based, Dual-Junction Solar Cells for Concentrator Applications	533.3	235.2
Plextronics Shawn Williams	Pittsburgh, PA swilliams@plextronics.com	Economic On-Grid Solar Energy via Organic Thin Film Technology	1050.0	262.5
PrimeStar Solar Fred Seymour	Golden, CO fred.seymour@primestarsolar.com	Production Scale-up of World Record CdTe/CdS Cell	1008.6	492.3
Solaria Corp. Kevin Gibson	Fremont, CA Kevin@solaria.com	Development of a Wafer-Si Solar Cell Based Low-Concentration PV Module	633.2	809.2
Sol Focus, Inc. Steve Horne	Palo Alto, CA steve_horne@solfocus.com	Reflective Optics CPV Panels Enabling Large-scale, Reliable Generation of Solar Energy Cost-competitive with Fossil Fuels	806.5	659.9
SoloPower, Inc. Bulent Basol	San Jose, CA bbasol@solopower.com	Commercialization of High Efficiency Low Cost CIGS Technology Based on Electroplating	70.7	250.8

Thin Film PV Partnership Program

Performing Organizations:	National Renewable Energy Laboratory (NREL) DOE Golden Field Office (DOE/GO)
Key Technical Contact:	Harin S. Ullal (NREL), 303-384-6486, harin_ullal@nrel.gov
DOE HQ Technology Manager:	Scott Stephens, 202-586-1201, scott.stephens@ee.doe.gov
FY 2008 Budget:	$2,266K (NREL)

Objectives

- Support the Solar America Initiative Technology Partnership Pathway project to achieve levelized cost of energy by 2015.
- Support the near-term transition to first-time manufacturing and commercial introduction of reliable thin-film amorphous silicon (a-Si), copper indium diselenide (CIS), cadmium telluride (CdTe), and film silicon modules.
- Build a technology base upon which these advanced photovoltaic (PV) technologies can continue to be successful in improving manufacturing and to progress in performance, reliability, and cost reductions, resulting in products that are able to compete in the PV marketplace.
- Sustain innovation to support progress toward ambitious long-term PV cost and performance goals (e.g., 15% efficient modules costing less than $50/m^2 and capable of lasting 30 years), which are appropriate for cost-competitive PV-generated electricity.

Accomplishments

- Met one important OMB/DOE/EERE/SET joule milestone. First Solar achieved a production cost of $1.14 per watt from $1.60 for thin film PV technology and then further reduced it to $1.08.
- Provided support to assist three technology partners, U.S. manufacturing facilities, to expand: First Solar, 144 MWp; Uni-Solar, 160 MWp; and Global Solar, 40 MWp.
- Supported industry growth, when possible, as the production of thin films in the United States grew from about 10 MWp in 2003 to an estimated more than 250 MWp in 2008.

Future Direction

- Phase out remaining subcontracts in the Thin Film PV Partnership Program. Of the 14 subcontracts in FY 2008, only three subcontracts remain in FY 2009: First Solar, Global Solar, and University of South Florida. 008.

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1. Introduction

Thin-film photovoltaic (PV) technologies have good potential to meet ambitious cost and performance goals, such as achieving long-term goals for a levelized cost of energy by 2015. The Thin Film PV Partnership Program is designed to accelerate progress toward meeting those goals. The partnership includes subcontracted research and development (R&D) in CIS, CdTe, a-Si, and new thin films, such as film silicon. The partnership members work closely with NREL's internal researchers, facilitating collaborative activities with academia and U.S. thin-film industry groups.

2. Major FY 2008 Presentations and Publications

We have published several subcontract reports and presentations. Other important publications and presentations include the following:

H.S. Ullal. "Recent Developments in Thin Film Solar Cell Technologies." Presented at the International Conference on Solar Cells, Cochin, Kerala, India. Jan. 21-23, 2008.

H.S. Ullal; B. Von Roedern. "Thin Film CIGS and CdTe PV Technologies: Commercialization, Critical Issues and Applications." *Solid State Technology*, February 2008.

B. Von Roedern; H.S. Ullal. “The Role of Polycrystalline Thin Film PV Technologies in Competitive PV Module Markets.” *33rd Photovoltaic Specialist Conference Proceedings;* May 11-16, 2008, San Diego, California.

H.S. Ullal. “Thin Film PV Technologies.” Moderator at the Inter Solar North America, San Francisco, California. July 15-17, 2008.

H.S. Ullal. “Overview and Challenges of Thin Film Solar Electric Technologies.” *World Renewable Energy Congress X Proceedings;* July19-25, 2008, Glasgow, Scotland, U.K.

H.S. Ullal. “The Great Thin Film Debate.” Panelist at Solar Power International 2008, Oct 13-16, 2008, San Diego, California.

3. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2008.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Colorado School of Mines Jim Sites	Ft. Collins, CO sites@lamar.colostate.edu	Characterization and analysis of CIS and CdTe devices	50	0
Colorado State University W.S. Sampath	Ft. Collins, CO sampath@engr.colostate.edu	Development of a robust in-line manufacturing approach for CdTe, and stability assurance	130	0
First Solar, LLC Peter Meyers	Perrysburg, OH pmeyers@firstsolar.com	Expanding the limits of CdTe PV performance	70	20
First Solar, LLC Roger Green	Perrysburg, OH rgreen@firstsolar.com	Development of robust high efficiency thin film CdTe PV modules	0	0
Global Solar Energy	Tucson, AZ swiedman@globalsolar.com	Cost and reliability improvements for CIGS based on flexible substrates	1,110	1,110
NanoSolar Chris Eberspacher	Palo Alto, CA chris@nanosolar.com	High-productivity annealing for thin film CIS PV	100	8
University of Nevada Clemens Heske	Las Vegas, NV heske@unlv.nevada.edu	Characterization of the electronic and chemical structure at the thin-film solar cell interfaces	157	0
University of Oregon Dave Cohen	Eugene, OR dcohen@oregon.uoregon.edu	Innovative characterization of amorphous and thin-film silicon for improved module performance	138	0
University of South Florida Chris Ferekides	Tampa, FL ferekide@eng.usf.edu	High-efficiency CdTe cells by CSS	200	14
University of Toledo Al Compaan	Toledo, OH ADC@physics.utoledo.edu	Fabrication and physics of CdTe devices by sputtering	245	75
University of Toledo Xunming Deng	Toledo, OH dengx@physics.utoledo.edu	Fabrication and characterization of advanced triple-junction amorphous-Si-based solar cells	270	78
University of Utah Craig Taylor	Salt Lake City, UT craig@physics.utah.edu	Innovative characterization of amorphous and thin-film silicon for improved module performance	79	0

PV Manufacturing R&D

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Richard Mitchell (NREL), 303-384-6479, richard_mitchell@nrel.gov

DOE HQ Technology Manager: Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2008 Budget: $3,032K (NREL)

Objectives

- Improve photovoltaic (PV) manufacturing processes and products for terrestrial applications.
- Accelerate PV manufacturing cost reductions.
- Increase commercial product performance and reliability.
- Lay the foundation for significantly increased production capacity.
- Achieve these goals in an environmentally safe manner.

Accomplishments

- Conducted a stage-gate evaluation, as part of the annual DOE Solar Energy Technologies Program (SETP) Review, of U.S. industry participants in the PV Manufacturing Research and Development (R&D) Project to assess continuation of manufacturing R&D and select areas for elimination or support.
- *Dow Corning* – Established protection-system processing on full-size module production line.
- *Evergreen Solar* – Completed initial operation of production system for in-situ ribbon-cutting system.
- *SolarWorld* – Demonstrated production of 18% efficient cells and 15% efficiency modules and production costs of less than $2/watt using processing developed under this subcontract.
- *Xantrex Technology* – Completed hardware optimization for 500-kilowatt (kW) inverter: bridge matrix; enclosure; power supply; and control board assembler.

Future Direction

- Complete remaining documentation of research under the PVMR&D Project.

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1. Introduction

The PV Manufacturing R&D (PVMR&D) Project was designed to assist the U.S. PV industry through a cost-shared manufacturing R&D partnership with the U.S. Department of Energy (DOE). Subcontracted research has focused on the U.S. PV industry's improvement of processes and products, resulting in (1) a substantial reduction in associated manufacturing costs; (2) a technology foundation that supports significant manufacturing scale-up of 500-megawatt (MW) total U.S. capacity; and (3) positioning the industry to meet rapidly emerging large-scale deployment opportunities. This focus has directly supported the DOE Solar Energy Technologies Program (SETP) Advanced Materials and Devices activities.

Each subcontractor has enhanced existing manufacturing technologies through cost-shared development efforts, geared toward achieving the overriding PVMR&D goals. Work areas have included (1) the improvement of module manufacturing processes to increase module reliability; (2) system and system-component packaging, system integration, manufacturing, and assembly; (3) product manufacturing flexibility; and (4) balance-of-systems (BOS) development, including storage and quality control.

2. Technical Approach

The PVMR&D Project is a government/industry partnership through cost-shared, subcontracted research in PV manufacturing technologies. The approach for the FY 2007 work effort was divided into two areas: (1) Project Management and Support subtask activities and (2) research subcontracts under the FY 2003 competitive solicitation for large-scale module and component yield, durability, and reliability (YDR).

During FY 2007, the focus of the PVMR&D Project was redirected to support the Technology Pathway Partnership (TPP) Funding Opportunity Agreement under the Solar America Initiative (SAI). As such, many of the subcontracted research activities under the YDR procurement were terminated early in order to transfer their research focus to newly awarded TPP research.

2.1 PV Manufacturing R&D Management

The Project Management and Support subtask addresses (1) management of the PVMR&D project; (2) management of subcontracts awarded under the YDR procurements; and (3) coordination of NREL's in-house activities in support of PVMR&D industrial partners. The task budget is detailed in Table 1.

Table 1. PVMR&D Project Tasks and Budget

Task Title	FY 2008 Budget ($K)
PV Manufacturing R&D Technical Coordination	203
Module Yield, Durability, and Reliability	3,032

2.2 Yield, Durability, and Reliability

The FY 2008 YDR subtask comprises the cost-shared PVMR&D subcontracts in Table 2, resulting from a competitive solicitation in FY 2003. The focus was on improving module manufacturing processes to increase module reliability, system and system-component packaging, system integration, manufacturing, and assembly; product manufacturing flexibility; and BOS development, including storage and quality control. The emphasis was on enhancing the reliability of the module, system components, and the complete system. Note that many of the subcontracts under this subtask were terminated early; therefore, the funding originally under this subtask was made available for use in the SAI TPP projects. The early termination of additional subcontracts has also been coordinated to address budget shortages due to increased emphasis on SAI projects.

3. Results and Accomplishments

3.1 Yield, Durability and Reliability

The Large-Scale Module and Component Yield, Durability, and Reliability letter of interest issued in FY 2003 focused on addressing needs in two categories. Category A, PV System and Component Technology, largely addresses the nonmodule aspects of PV systems component manufacturing processes. Category B, PV Module Manufacturing Technology, primarily addresses aspects of module manufacturing processes. Under this subtask, the significant achievements of remaining individual subcontractors in FY 2008 are described below.

Dow Corning Corporation
"High Performance Packaging Solutions for Low-Cost, Reliable PV Modules"
- Completed scale-up activities for pilot-scale, protective-system production line.
- Completed trials on new protective-system, demonstrating positive performance compared to results from previous processes.
- Established protection-system processing on full-size module production line.

Evergreen Solar, Inc.
"Low-Cost Manufacturing of High-Efficiency, High-Reliability String Ribbon Si PV Modules"
- Completed implementation of production system for in-situ ribbon-cutting system.
- Completed initial operation of production system for in-situ ribbon-cutting system.
- Completed modification of lamination process to accommodate for cells in the top 2% of the weight distribution.

First Solar
"Solar Cell Design for Manufacturability"
- Initiated design reviews of new sputter coater.
- Initiated early termination of subcontracted research to address budget shortages due to increased emphasis on SAI projects.

SolarWorld Industries America
"Manufacturing Improvements in CZ Silicon Module Production"
- Demonstrated prototype of 25% thinner cutting wire with no yield change at wafering.
- Demonstrate >90% mechanical yield of thin cells in production line.
- Demonstrated Cz-Silicon module manufacturing production costs of less than $2/watt.

- Demonstrated production of 18% efficient cells and 15% efficiency modules using processing developed under this subcontract.

Xantrex Technology
"Advanced, High Reliability, System Integrated 500-kW Photovoltaic Inverter Development"

- Completed design of inverter regulation and array tracker software.
- Completed hardware optimization for 500-kW inverter: bridge matrix; enclosure; power supply; and control board assembler.

4. Major FY 2008 Publications

T.L. Jester. *Manufacturing Improvements in Cz Silicon Module Production.* Annual Subcontract Report, July 2005 -- October 2006, NREL/SR-520-42418. Golden, CO: National Renewable Energy Laboratory, November 2007.

J. Botkin. *Accelerating PV Cost Effectiveness Through Systems Design, Engineering, and Quality Assurance.* Final Subcontract Report, NREL/SR-520-42420, June 2007. Golden, CO: National Renewable Energy Laboratory, December 2007.

J. Shingleton. *One-Axis Trackers – Improved Reliability, Durability, Performance, and Cost Reduction.* Final Subcontract Technical Status Report, 2 May 2006 – 31 August 2007, NREL/SR-520-42769. Golden, CO: National Renewable Energy Laboratory, February 2008.

J.A. Rand. *Solar Cell Design for Manufacturing.* Final Subcontract Report, October 2005 - September 2007, NREL/SR-520-43228. Golden, CO: National Renewable Energy Laboratory, May 2008.

R. West. *Advanced, High-Reliability, System-Integrated 500kW PV Inverter Development.* Final Subcontract Report, 29 September 2005 - 31 May 2008, NREL/SR-520-43839. Golden, CO: National Renewable Energy Laboratory, August 2008.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Dow Corning Corporation Barry Ketola	Midland, MI barry.ketola@dowcorning.com	High Performance Packaging Solutions for Low Cost, Reliable PV Modules	675	675
Evergreen Solar, Inc. Jack Hanoka	Marlboro, MA hanoka@evergreensolar.com	Low-Cost Manufacturing of High-Efficiency, High-Reliability String Ribbon Si PV Modules	321	321
First Solar, LLC Greg Helyer	Perrysburg, OH ghelyer@FIRSTSOLAR.COM	Implementation of Reliable Manufacturing of Higher Efficiency Module	0	0
SolarWorld Industries America Theresa Jester	Camarillo, CA Theresa.jester@shellsolar.com	Manufacturing Improvements in CZ Silicon Module Production	1,000	1,075
Xantrex Technology, Inc. Raymond Hudson	San Luis Obispo, CA Ray.Hudson@xantrex.com	Advanced, High Reliability, System Integrated 500-kW Photovoltaic Inverter Development	0	0

Systems Modeling

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL)
Key Technical Contacts:	Nate Blair (NREL, Primary Contact), 303-384-7426, nate_blair@nrel.gov Mark Mehos (NREL), 303-384-7458, mark_mehos@nrel.gov Chris Cameron (SNL), 505-844-8161, cpcamer@sandia.gov Craig Christensen (NREL), 303-384-7510, craig_christensen@nrel.gov
DOE HQ Technology Manager:	Dan Ton, 202-586-4618, dan.ton@ee.doe.gov
FY 2008 Budgets:	$1,140K (NREL), $730K (SNL)

Objectives

- Enhance DOE Solar Energy Technologies Program (SETP) Solar Advisor Model (SAM) to develop capabilities to calculate energy output, energy costs, and cash flows, using up-to-date component and system data while enabling parametric analysis.
- Validate SAM and other solar models for a variety of technologies, applications, and locations.
- Guide research and development (R&D) prioritization for industry and government use and to provide credible energy production and cost data, using a common platform for project development, evaluation, and due diligence.
- Provide additional tools to industry to meet their planning, R&D, siting, and other modeling needs to help accelerate market penetration.
- Support progress evaluation at stage-gate assessments for the Solar America Initiative (SAI).

Accomplishments

- Release new SAM versions with:
  - Improved PV performance algorithms (e.g., SNL inverter model and CEC module model) and use of latest databases for each model
  - Detailed operating and maintenance (O&M) inputs (e.g., annual $, $/MW, $/MWh)
  - Enhanced Graphical User Interface (GUI) and greater graphical output capability
  - Added time-of-use utility rates and automated Independent Power Producer (IPP) financing optimization to SAM.
- Made SAM finance model with incentives operational and externally-reviewed.
- Added/expanded module and inverter performance and weather databases.
- Conducted first annual SAM user forum at Solar 2008 conference.
- Made PVWATTS available as Web service for California Solar Initiative and others.
- Evaluated SAM and other PV performance models vs. 1-year of data for cSi systems.
- Conducted levelized cost of energy (LCOE) reviews for Technology Pathway Partnership stage gates.

Future Directions

- Acquire data on diverse PV systems and apply to model validation and evaluation, in collaboration with industry.
- Continue DOE and user support, including analysis for TPP stage-gate reviews, and hold a full-day user forum.
- Incorporate electrical storage (and necessary control logic) within SAM for PV systems to examine the impact on demand-control for residential and commercial systems.
- Incorporate PVWatts as an additional option with SAM.
- Examine modifying SAM backbone enable batch processing and uncertainty analysis.

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1. Introduction

The system modeling task consists of systems performance and LCOE modeling and validation projects. The primary function of SAM is to allow users to investigate the impact of variations in physical and financial parameters to better understand their impact on key figures of merit for solar power systems. Figures of merit related to the cost and performance of these solar power systems include, but are not limited to, system output, peak and annual system efficiency, LCOE, and system capital and O&M costs. SAM is used widely by DOE, laboratory management, research staff, and throughout the solar community. Its combination of robust performance models for multiple solar technologies with detailed financial models in a publicly available package is unique. The task also supports maintenance and continued development of PVWATTS, which is a very popular model for simple performance estimates for PV systems.

2. Results and Accomplishments

There were two major milestones for SAM development. The first was a release of the SAM Version 2.0, completed in June of 2008. It included a variety of small enhancements but focused on:

- Major update of user manual with documentation
- Improved PV performance algorithms
- Capability of using latest California Energy Commission (CEC) and SNL module and inverter databases
- Detailed O&M inputs (e.g., annual $, $/MW, $/MWh options).

The second milestone was the release of SAM Version 2.5. It includes:

- Dish Stirling CSP models
- Enhanced GUI and greater graphical output capability
- Time-of-use utility rates and automated IPP financing optimization.

This deliverable was due October 1 but has been delayed due to several bugs found in the code and waiting for feedback from the Dish Stirling industry on the pre-release version. It will be released during the first quarter of FY 2009. Other deliverables for this task focused on improved user support and model validation.

User forum and user interactivity
This was accomplished throughout the year via email user support, Google Group, a user survey, and our efforts to collect suggestions from all users into our list of future improvements. The first modeling workshop, held at Solar 2008 in San Diego, was well received.

Component Performance Databases
The PV component performance database in SAM has been expanded to include 421 modules for the SNL model, 128 modules for the CEC model, and 369 inverters. Performance parameters for the inverter database are derived from test data published by the California Energy Commission.

Stage Gate Support
SAM was employed by the SAI TPPs to project LCOE reductions for their technologies. Navigant Consulting provided additional cost projections. SNL used the TPP and NCI data as well as laboratory test data, where available, to analyze LCOE and provide summary reports to the TPP stage-gate review panels.

Performance Model Validation
A key effort begun in FY 2008 was to validate the performance models that use these data by comparing model predictions for systems output versus measured output using measured weather data as model input. Three crystalline-silicon systems installed at SNL were monitored for a year. The results of the model comparison were presented in an IEEE paper.

3. Planned FY 2009 Activities

Activities for SAM can be broken into two general groupings: core activities (jointly funded by PV and CSP funds) and PV-specific activities.

Core Activities

- Initiate or continue to create a communication pathway from the users to the SAM development team. These activities include:
  - Expanded user forum, building on 2008.
  - Managed Internet-based user discussion group
  - Implemented enhancements, rated highly via our SAM user survey in F 20Y08.
- Improve and augment the documentation in the user support area including:
  - Incorporate context-sensitive help system. Update growing list of existing documentation (e.g., user guide, technical reference manual, online help).

- Improve SAM Website
- Add case studies of interesting SAM runs

- Allow for system annual and/or hourly energy production to be an input.
- Continue to expand the number and type of weather files available to SAM.
- Enhance graphical capabilities through a variety of small activities, since it providing robust graphical results is a core capability.
- Develop capability to run SAM in batch mode, which would allow examination of a specific output metric across a very broad range of inputs (enhanced level of +80k).

Specific PV Activities

- Enhance National Center of Photovoltaics (NCPV) presence on the team. Either a single person through FY 2009 or a rotating position will allow SAM to more adequately address NCPV modeling needs as well as allow for greater communication of SAM capabilities within the NCPV.
- Annual 1-day workshop to focus on needs of TPP SAM users (enhanced level of +40k).
- Add PV-Watts as a PV option in SAM.
- Add module shading as an option to model.
- Add ability to model electric storage (either on or off grid), likely in the form of batteries.
- Consider impact of mounting methods.
- Investigate improvements for seasonal derate.
- Support the needs of the PV program by sponsoring university-level development of enhanced PV modeling capabilities relevant to the current systems.
- Add capability to sum different system outputs and do financial analysis at an aggregate level. (e.g., enhanced level of +100k).
- Develop weather and system performance data sets for additional climates and technologies. Apply the data to additional model validation.
- Continue to add components to the module and inverter databases.
- Perform cost and LCOE reviews at all SAI TPP stage gates, in collaboration with Navigant Consulting.

4. Major FY 2008 Publications

N. Blair; M. Mehos; C. Christensen. "Sensitivity of Concentrating Solar Power Trough Performance, Cost and Financing with Solar Advisor Model." *2008 14th Biennial CSP SolarPACES (Solar Power and Chemical Energy Systems) Symposium*; March 4-7, 2008, Las Vegas, Nevada (CD-ROM).

N. Blair; M. Mehos; C. Christensen; C. Cameron. "Modeling Photovoltaic and Concentrating Solar Power Trough Performance, Cost, and Financing with the Solar Advisor Model." *American Solar Energy Society Conference Solar 2008*; San Diego, California.

P. Gilman; N. Blair; M. Mehos; C. Christensen; S. Janzou; C. Cameron. "Solar Advisor Model User Guide for Version 2.0." 133 pp.

N. Blair; C. Cameron. "Solar Advisor Model." NREL SEAAC Seminar Series Presentation. *Strategic Energy Analysis Center On-line Seminar.*
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C. Cameron; W. Boyson; D. Riley. "Comparison of PV System Performance-Model Predictions with Measured PV System Performance." 33rd IEEE PVSC, San Diego, California, 2008.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)
Janzou Consulting Steve Janzou	Evergreen, CO Steve_janzou@nrel.gov	Program the front-end and basic engine of the Solar Advisor Model	180
University of Wisconsin-Madison Prof. Sanford Klein	Madison, WI Klein@engr.wisc.edu	e.g., Develop an advanced PV module model	100
Paul Gilman Paul Gilman	Chicago, IL PaulGilman@earthlink.net	Provides user support and technical writing support	60

Systems Analysis
Market, Value, and Policy Analysis

Performing Organizations: National Renewable Energy Laboratory (NREL)
Lawrence Berkeley National Laboratory (LBNL)

Key Technical Contacts: Robert Margolis (NREL), 202-488-2222, robert_margolis@nrel.gov
Selya Price (NREL), 202-488-2205, selya_price@nrel.gov
Ryan Wiser (LBNL), 510-486-5474, RHWiser@lbl.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2008 Budgets: $1,150K (NREL), $200K (LBNL)

Objectives

- Provide a broad range of analytical support to the U.S. Department of Energy's (DOE) Solar Energy Technologies Program (SETP).
- Anticipate and respond to the rapidly evolving analytical needs of SETP.
- Carry out detailed analysis of existing and emerging markets, including analysis to be included in the annual solar market trends report.
- Continue development of the Solar Deployment Systems (SolarDS) model—a PV market penetration model that will be compatible with broader model-development effort within the Solar Energy Technologies Program.
- Provide inputs to, support for, and review of the annual GPRA benefits analysis process. Develop methods and tools for improving the quantification of the benefits and costs of distributed PV in the National Energy Modeling System (NEMS) and other models.
- Evaluate policies and other factors that impact the value of solar energy technologies in a variety of markets.

Accomplishments

- Conducted a historical analysis of investment in solar energy technologies from 2000 to 2007.
- Published a comprehensive report on PV financing mechanisms for the state and local government sector as well as carried out analysis and research for additional reports on PV financing in other sectors (residential, Federal, commercial and industrial). Provided PV financing information to large numbers of stakeholders via presentations and webinars.
- Carried out analysis and compilation of data/information in preparation for publication of SETP's first annual report on solar technology market, cost, and performance trends.
- Continued development of the SolarDS market penetration model, including updating of financial incentives such as the recently passed Federal ITC and state incentive program budgets, as well as incorporation of additional financing options into the model.
- Provided short term analysis support to SETP to respond to information requests from Congress, the EERE corporate office, NREL, and other stakeholders.

Future Directions

- Publish an annual solar market trends report on solar market, cost, and performance trends.
- Support the annual Government Performance and Results Act (GPRA) benefits and Program Decision Support analysis efforts.
- Carry out solar market penetration modeling/analysis utilizing the SolarDS model.
- Continue research, publication, and report updating of PV financing information, including the State/Local, the Federal, the residential, and the Commercial and Industrial sectors.
- Produce topical reports and provide general analytic support that anticipates and responds to the emerging critical needs of the solar industry and SETP.

- Develop resources such as publications, data sources, and models to support the ongoing informational, decisional, and planning needs of SETP.

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1. Introduction

The primary objective of the market, value and policy analysis activity is to provide a broad range of analytical support to the Solar Program. The work carried out under this agreement anticipates and responds to the rapidly evolving analytical needs of the Solar Program. Thus while the set of activities to be funded under this agreement are outlined below, the priorities will likely change over the course of the year and the work plan will be adjusted accordingly.

Three broad types of analysis will be carried out under this project including:

- Market analysis: Carrying out detailed analysis of existing and emerging markets, conducting analysis and compiling data in preparation for publication of SETP's first annual report on solar market, cost, and performance trends, development of the Solar Deployment Systems (SolarDS) market penetration model.
- Value analysis: Providing inputs to, support for, and review of the annual GPRA benefits analysis process, developing methods and tools for improving the quantification of the benefits and costs of distributed PV, maintaining NREL's PV Value Clearinghouse.
- Policy analysis: Defining and carrying out analysis that meets the needs of the Solar Program in a timely fashion, for example related to issues such as the reliability, security and time-of-use value of PV, as well as the potential role of solar in the energy economy in the long-term. Policy analysis also involves analysis of potential policy initiatives/proposals at the federal and state levels. In other words, in addition to specific tasks (as discussed below) Policy Analysis includes providing general analytical support to the Solar Program.

2. Technical Approach

The market, value, and policy analysis activity relies on two main technical approaches.

The first approach is to use and improve existing models and to develop new tools that can be employed to develop long-term market-penetration projections for solar technologies. This effort involves examining both the system and policy drivers of solar technologies in various markets in both the short and long term, as well as improving the analytical basis for projecting the SETP's economic and environmental benefits. Here, the emphasis has been on models and modeling, for example, using existing models—such as the Energy Information Administration's NEMS, MARKAL, and others—to carry out analyses. These analyses examine the structure of various models and provide feedback on how to improve the representation of solar technologies in existing models to modelers. They also help to develop new models, such as SolarDS, that will help meet the needs of the SETP and solar community more broadly.

The second approach is to employ a range of policy analysis tools and techniques to evaluate policies and other factors that impact the value of PV technologies in a variety of markets. These tools and techniques include using existing models, spreadsheets, and other tools (such as surveys and gathering and synthesizing information from a wide range of sources). Here, the emphasis is on using analytical tools to quantify how changing policies, rate structures, system designs, and other factors have or will impact the value of solar technologies to consumers, utilities, governments, and other players.

3. Results and Accomplishments

Accomplishments resulting from market, policy, and value analysis activities in FY 2008 include:

- Research and publication of PV financing information for the state and local government sector and preparation of forthcoming papers on PV financing in the residential, Federal, and commercial and industrial sectors.
- A historical analysis of investment in solar energy technologies from 2000 to 2007, to be published in early FY09.
- Further development of the SolarDS market penetration model, including updating of financial incentives such as the recently passed Federal ITC and state incentive program budgets and incorporation of

additional financing options. The model will be ready for review in early FY09.
- Development of a model that allows estimation of the growth in manufacturing required to meet carbon reduction scenarios. The model evaluates different trajectories of carbon avoidance and also applies the CO2 emissions from manufacturing PV at the time the panels are produced. A draft paper has been written evaluating scenarios where PV provides 10-25% of U.S. electricity by 2050.
- Development of a solar financing model to compare the IRRs of PV systems with a capacity based incentive ($/kW) and a performance based incentive ($/kWh). The impact of these and other financing incentives and options will be evaluated further.
- Providing general analytical support to the SETP by responding to short term requests for information from Congress, EERE, and other stakeholders plus preparation of slides and material for presentations given by the SETP Program Manager and staff.
- Collection and analysis of data on installed on-grid PV system cost trends (partial cost share to fund LBNL).
- Research and drafting of paper on utility rate structures.
- Various analyses as captured in the reports and publications listed in Section 5.

4. Planned FY 2009 Activities

Over the next 5 years, as solar markets continue to grow at a record pace and solar technologies continue to evolve rapidly, the need for detailed, timely analysis will be critical for helping to guide policy decisions within the SETP. Thus, a number of ongoing analytical activities will be supported under this task. These ongoing activities include publishing an annual report on solar market, cost, and performance trends, developing a process for collection of on-grid PV installation data, producing and improving the annual GPRA benefits and Program Decision Support analysis, producing a series of topical policy reports, continuing to publish and update PV financing information, producing analyses based on recently developed models such as SolarDS, and carrying out analysis activities that anticipate and respond to the emerging critical needs of both the solar industry and the SETP.

5. Major FY 2008 Publications

M.H. Coddington; R.M. Margolis; Jørn Aabakken. *"Utility-Interconnected Photovoltaic Systems: Evaluating the Rationale for the Utility-Accessible External Disconnect Switch."* NREL Technical Report (NREL/TP-581-42675). January 2008.

K. Cory; J. Coughlin; C. Coggeshall. *"Solar Photovoltaic Financing: Deployment on Public Property by State and Local Governments."* NREL Technical Report (NREL/TP-670-43115). May 2008.

P. Denholm; R.M. Margolis. "Evaluating the Limits of Solar Photovoltaics (PV) in Electric Power Systems Utilizing Energy Storage and Other Enabling Technologies." *Energy Policy,* Vol. 35, pp. 4424-4433. 2007.

P. Denholm; R.M. Margolis. "Impacts of Array Configuration on Land-Use Requirements for Large-Scale Photovoltaic Deployment in the United States." Paper presented at SOLAR 2008 - American Solar Energy Society (ASES); May 3–8, 2008, San Diego, California.

P. Denholm; R.M. Margolis. "Land-use Requirements and the Per-capita Solar Footprint for Photovoltaic Generation in the United States." *Energy Policy*, Vol. 36, pp. 3531– 3543, 2008.

P. Denholm; R.M. Margolis; J. Milford. "Quantifying Avoided Fuel Use and Emissions from Solar Photovoltaic Generation in the Western United States." *Environmental Science & Technology*.

P. Denholm; R.M. Margolis. *"Supply Curves for Rooftop Solar PV Generated Electricity for the U.S."* NREL Technical Report (NREL/TP-670-44073).

S. Graham; R. Katofsky; L. Frantzis; H. Sawyer; R.M. Margolis. "Future of Grid-Tied PV Business Models: What Will Happen When PV Penetration on the Distribution Grid is Significant?" Paper presented at SOLAR 2008 (American Solar Energy Society); May 3–8, 2008, San Diego, California.

Grid Integration Support

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Ben Kroposki (NREL, Primary Contact), 303-384-2979, benjamin_kroposki@nrel.gov
Juan Torres (SNL, Primary Contact), 505-844-0809, jjtorre@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2008 Budgets: $400K (NREL), $400K (SNL)

Objectives

- Address both the technical and analytical challenges that need to be overcome in order to enable the penetration of high amounts of photovoltaics (PV) into the electrical power system.
- Develop grid integration tests and field demonstrations that implement high-penetration PV.
- Develop technical analysis, modeling, and simulation tools and economic modeling and policy analysis to evaluate high-penetration PV scenarios.
- Develop briefing materials for stakeholders, with a focus on utility operations and planning entities that help them quantify the benefits and impacts of large-scale PV grid integration.

Accomplishments

- Completed and published the Renewable Systems Interconnection (RSI) Study, a series of 14 reports on impacts, plans, and strategies to address high PV penetration on the electric grid.
- Revised the draft RSI multi-year research plan.
- Completed a white paper on energy storage for PV systems.
- Set up Cooperative Research and Development Agreements, or CRADAs, with Sacramento Municipal Utility District (SMUD), Xcel Energy, and SunEdison on access to data and monitoring for grid integration of PV systems. Completed the initial report on data collection and monitoring.
- Assisted islands of Hawaii (Kauai, Oahu, and Lanai) with planning, analysis, and engineering of PV systems into their electric power system.

Future Directions

- Continue collecting field data to verify early findings and steer technology research and development (R&D) in grid integration.
- Develop Critical Renewable Energy for Storage Technology (CREST) initiative.
- Support International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) Task 11 – PV Hybrid Systems and Microgrids.
- Develop lab-based test and development sites to provide leadership and early development for industry efforts in implementing high-penetration PV scenarios.

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1. Major FY 2008 Publications

- Achilles, S.; Schramm, S.; Bebic, J. GE Global Research, *Transmission System Performance Analysis for High-Penetration PV* (February 2008).
- Bebic, J. GE Global Research, *Power System Planning: Emerging Practices Suitable for Evaluating the Impact of High-Penetration PV* (February 2008).
- Contreras, J.L.; Frantzis, L.; Blazewicz, S.; Pinault, D.; Sawyer, H.; Navigant Consulting Inc., *PV Value Analysis* (February 2008).
- Denholm, P.; Margolis, R.; Milford, J.; *Production Cost Modeling for High Levels of PV Penetration* (February 2008).
- Frantzis, L.; Graham, S.; Katofsky, R.; Sawyer, H. Navigant Consulting Inc., *PV Business Models* (February 2008).
- Kroposki, B.; Margolis, R.; Kuswa, G., Torres, J.; Bower, W.; Key, T.; Ton, D. *Renewable Systems Interconnection: Executive Summary,*

NREL Technical Report (NREL/TP-581-42292) (February 2008).

- Liu, E.; Bebic, J. GE Global Research, *Distribution System Voltage Performance Analysis for High-Penetration PV* (February 2008).
- Manz, D.; Schelenz, O.; Chandra, R.; Bose, S.; de Rooij, M.; Bebic, J. GE Global Research, *Enhanced Reliability of Photovoltaic Systems with Energy Storage and Controls* (February 2008).
- McGranaghan, M.; Ortmeyer, T.; Crudele, D.; Key, T.; Smith, J. (EPRI); Barker, P. (NOVA Energy Specialists LLC). *Advanced Grid Planning and Operation* (February 2008).
- McIntyre, A. *Cyber Security Analysis* (February 2008).
- Ortmeyer, T.; Dugan, R.; Crudele, D. (EPRI); Barker, P. (NOVA Energy Specialists LLC). *Utility Models, Analysis, and Simulation Tools* (February 2008).
- Paidipati, J.; Frantzis, L.; Sawyer, H.; Kurrasch, A. (Navigant Consulting, Inc.). *Rooftop PV Market Penetration Scenarios* (February 2008).
- Renné, D.; George, R.; Wilcox, S.; Stoffel, T.; Myers, D.; Heimiller, D. *Solar Resource Assessment*, NREL (February 2008).
- Ton, D.; Kroposki, B.; Margolis, R.; Kuswa, G.; Torres, J.; Key, T. *Renewable Systems Interconnection Distributed Photovoltaic Study*, 17th PVSEC, Fukuoka, Japan, (December 2007).
- Ton, D.; Kroposki, B.; Margolis, R.; Kuswa, G.; Torres, J.; Bower, W.; Hanley, C.; Boyes, J. *Renewable Systems Interconnection Distributed PV Activities; Multi-Year Research Plan (MYRP) FY 2008-FY 2013* (2008).
- Ton, D.; Bower, W.; Cameron, C., *Solar Energy Grid Integration Systems (SEGIS); Concept Paper* (2008).
- Ton, D.; Kroposki, B.; Margolis, R.; Kuswa, G.; Torres, J; Key, T. *Renewable Systems Interconnection Distributed Photovoltaic Study*, 23rd European PV Solar Energy Conference and Exhibition, Valencia, Spain (September 2008).
- Whitaker, C.; Newmiller, J. (BEW Engineering); Ropp, M. (Northern Plains Power Technologies); Norris, B. (Norris Energy Consulting). *Distributed Photovoltaic Systems Design and Technology Requirements* (February 2008).
- Whitaker, C.; Newmiller, J. (BEW Engineering); Ropp, M. (Northern Plains Power Technologies); Norris, B. (Norris Energy Consulting). *Test and Demonstration Program Definition* (February 2008).

Inverter and Balance-of-Systems Project

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contacts: Sigifredo Gonzalez (SNL, Primary Contact), 505-845-8942, sgonza@sandia.gov
Ward Bower (SNL), 505-844-5206, wibower@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2008 Budget: $765K (SNL)

Objectives

- Develop a test platform and protocols to evaluate Solar America Initiative (SAI) state-gate deliverable and Solar Energy Grid Integration Systems (SEGIS) stage-gate deliverables.
- Develop a test platform to evaluate advanced control algorithms of micro-grid applications.
- Determine effects of long-term inverter operation after 2 years of outdoor operation (second set of inverters). These samples provide reliability information of a small grid-connected system and provide a platform to validate system modeling activities.
- Develop new photovoltaic (PV) inverters and balance-of-system (BOS) hardware that meet today's utility interconnect standards, performance requirements, and safety requirements.
- Provide the standards and codes committee with consensus information and requirements flow between the committees and the inverter industry. Enable PV inverter manufacturers to meet standard and code requirements.

Accomplishments

- Conducted SAI phase 1 stage-gate deliverable evaluation on GreenRay Micro-Inverter.
- Completed re-characterization evaluations on the second set of inverters undergoing long-term evaluations.
- Conducted preliminary evaluations on Xantrex 30-kilowatt (kW) transformerless inverter. Continue to provide beta site evaluations on performance of inverter utilizing PV as dc source.
- Determined inverter performance, power quality, and utility compatibility capabilities for one commercial inverter and two residential PV inverters.
- Conducted preliminary validation evaluations on a PV-system performance model.
- Reviewed National Electrical Code (NEC) 2011 proposed changes and participated in code revision process.

Future Directions

- Complete first round of long-term inverter operation evaluations and implement any significant inverter performance issues discovered in the long-term inverter operation evaluations and introduce them into the PV-system performance model.
- Determine development protocols and tools needed to validate SAI stage-gate deliverables that target individual PV system components and the complete PV system.
- Provide PV inverter manufacturers with a facility to enhance performance capabilities.
- Continue to develop enhanced laboratory capabilities to evaluate SEGIS stage-gate deliverables that include energy management capabilities, load shedding capacities, and voltage support.

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1. Major FY 2008 Publication

"Development of a MATLAB/Simulink Model of a Single-Phase Grid-Connected Photovoltaic System," IEEE submitted paper.

Solar Energy Grid Integration Systems

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contacts: Ward Bower (SNL, Primary Contact), 505-844-5206, wibower@sandia.gov
Scott Kuszmaul (SNL), 505-844-5401, sskuszm@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, Dan.Ton@hq.doe.gov

FY 2008 Budget: $3,200K (SNL)

Objectives

- Lay the groundwork for high levels of photovoltaic (PV) market and electrical grid penetration, or grid integration.
- Enable PV systems to meet the goal of making solar power cost competitive with conventional sources of electricity.
- Integrate systems to include energy management, energy storage, communications, and total system optimizations.
- Commercialize and deploy advanced, clean, PV-system technology that will enhance our energy security and confront the serious challenge of global climate change.

Accomplishments

- Completed and published Solar Energy Grid Integration Systems (SEGIS) concept paper, used for SEGIS solicitation.
- Completed an extremely aggressive schedule to launch the SEGIS solicitation, which was aimed at high PV penetration, value added, and meeting goals the Solar America Initiative (SAI) levelized cost of energy (LCOE):
  - Request for information
  - Request for proposals for 3-stage efforts
  - Evaluation criteria
  - Proposal receipts and evaluations (27)
  - Contractor selection
  - Placed 12 contracts
  - Kickoff meetings for 12 SEGIS contractors
  - Provided quarterly report templates
  - Received first quarterly reports.
- Completed evaluation criteria for stage 2.

Future Directions

- Complete stage 1 Conceptual Designs and Market Analysis with down select to stage 2 and draft a summary report for SEGIS stage 1.
- Select stage 2 contractors showing a high likelihood of success for prototype development for systems providing the best value to the U.S. Department of Energy (DOE) Solar Energy Technologies Program (SETP) and future grid integration.
- Initiate SEGIS energy storage (ES) efforts to include more aggressive energy management and energy storage to address intermittency mitigation, utility-grid support, and system optimization for grid integration.
- Summarize SEGIS contractor findings into future directions and prioritizations with “Status and Sequences” for future grid integration research and development (R&D).
- Analyze SEGIS deliverables to determine impacts on LCOE as well as value added that enables higher penetration and higher market shares.

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1. Results and Accomplishments

All milestones except placement of the SEGIS contracts were level 5. All milestones were met within 1 day of scheduled times. The placement of the contracts was a level 3 milestone and was completed on schedule on June 26, 2008.

Table 1: SEGIS Accomplishments

Milestone	*Action*	*Accomplishments*
Announce-ment Workshop	Completed April 19, '07	More than 80 participants. General program goals prioritized
Funding Opportunity Announce-ment (FOA)	FOA nearly completed SNL transfer Sep 29, '07	DOE FOA efforts abandoned and replaced with a new SNL RFP plan
SEGIS Concept Paper	Completed Oct '07	Provided SEGIS objectives and goals WRT "High Penetration"
SEGIS RFI	Completed Oct 30, '07	Request for Information provided technical input & a "Bidders List"
SNL/DOE Web Pages	Active Nov 2007	Provided solicitation and program information
SEGIS RFP	Completed Nov 28, '07	Provided all proposal requirements
Proposals (27)	Completed Feb 4, '08	27 Proposals received
Proposals Evaluated	Completed Mar 20, '08	Clarifications/financial denial questions continued
Contracts Placed	Completed Jun 26, '08	12 contracts placed to all contractors on same day
Kickoff Meetings	Completed Aug 4, '08	½ -Day meetings at contractor facilities
1st Quarterly Reports	Received Sep 19, '08	Reports per SNL Template

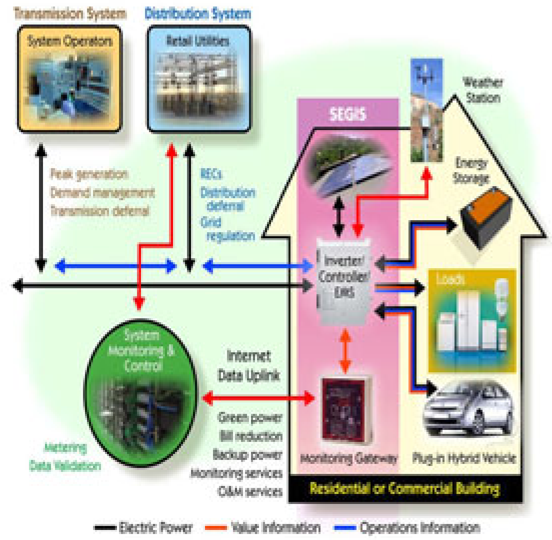

Figure 1. The SEGIS Concept

2. Major FY 2008 Publications

- Bower, W.; Ton, D.; Ropp, M.; Gonzalez, S.; Torres, J. "*Advanced Integrated Inverters and Energy Management Systems",* Proceedings of the 17th International PV Science and Engineering Conference, Fukuoka, Japan, Dec 3-7, 2007.
- Bower, W.; Ton, D. "Solar Energy Grid Integration Systems (SEGIS)", Proceedings of the 23rd EU PV Solar Energy Conference and Exhibition, Valencia, Spain, Oct 2008.
- Solar Energy Grid Integration Systems (SEGIS) Concept Paper, October 2007, Sandia National Laboratories, www.sandia.gov/SAI/files/SEGIS%20Concept%20Paper-071025.pdf.

3. University and Industry Partners

The following organizations were under contract for SEGIS research activities. Their subcontractors and team members are not listed.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)*	Cost Share ($K)*
Apollo Solar John Pfeifer	Bethel, CT John.Pfeifer@ApolloSolar.com	"An Advanced Grid-tied Inverter, Charge Controller, Energy Monitor and Internet Gateway". Advanced modular components for power conversion, energy storage, energy management and a portal for communications for residential size solar electric systems are being developed. The inverters, charge controllers, and energy management systems will be able to communicate with utility energy portals for implementation of two-way power flows of the future.	250	66

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)*	Cost Share ($K)*
EMTEC Jon VanDonkelaar	Delaware, OH jvandonkelaar@emtec.org	SEGIS – "An Emerson PV Inverter Development." Develop large, highly efficient, small footprint, power conversion, and energy storage and management for commercial PV systems. Includes integrated grid controllers with smart meter interface to provide more predictable economics for power distribution and to minimize fluctuations in supply and demand.	250*	66
EnPhase Ragu Belur	Petaluma, CA rbelur@Enphaseenergy.com	"Nano-inverters with VAr Control and Energy Management System." Develop a complete module-integrated solar electric solution controlled by an energy management system (EMS). The EMS also interfaces with utilities.	250	66
General Electric Rayette Fisher	Niskayuna, NY fisher@crd.ge.com	"Grid Integration of High-penetration Solar Energy." Develop concepts for integrating solar PV generation with the electrical grid in both commercial and residential applications. The residential setting improvements will focus on integrating energy storage, responsive loads, and utility demand side management.	250	66
NexTech Power Systems Paul Savage	Hauppauge, NY paul.savage@nextekpower.com	"Advanced PV Interface Providing Concurrent AC & DC Power and Network Support (the Bi-Directional Nextek Power Gateway)." Evolve a power gateway to incorporate bi-directional current flow capability, higher voltage, and added functionality including integrated communications and an energy management system for value-added PV-utility interconnection.	250	66
Petra Solar Adje Mensah	Somerset, NJ Adje.Mensah@petrasolar.com	"Development of Economically Viable, Highly Integrated, Highly Modular SEGIS Architecture." The development is for multi-layer control and communication with PV systems to achieve grid interconnectivity, cost reduction, system reliability, and safety resulting in a cost competitive, easy to install, modular and scalable system.	250	66
Premium Power Bill O'Donnell	North Andover, MA bodonnell@premiumpower.com	"Intelligent PV Inverter (Intelligent PV Inverter System w/energy Management and Optimized for use with Solar Energy)." Focus is on an inverter system that makes PV economically viable in terms of investment, operating costs, and system lifetime. The technical focus is an intelligent PV system for commercial- and utility-scale applications with an advanced inverter, energy management and optimization capabilities.	250	66
Princeton Power Mark Holveck	Princeton, NJ dhammell@princetonpower.com	"Demand Response Inverter." A complete design for a 100-kW "Demand Response Inverter" based on	250	66

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)*	Cost Share ($K)*
		proprietary technology. The design will be optimized for low-cost, high-quality manufacture and will integrate control capabilities including dynamic energy storage and demand-side load response.		
PVPowered Steve Hummel	Bend, OR stevehummel@pvpowered.com	"MPPT and EMS Advancements." Develop a suite of maximum power point tracking (MPPT) algorithms to optimize energy production from the full range of available and emerging PV module technologies. Two-way communications and integration with facility energy management and utility management networks are also being developed.	250	66
Smart Spark Pactrick Chapman	Champaign, IL p.chapman@smartsparkenergy.com	"Alternating Current PV Module with System Interface." Design, construct, test, and commercialize an alternating-current photovoltaic (ACPV) module with smart building system interfaces that provide system diagnostics, data logging, and an advanced utility interconnection.	250	66
University of Central Florida Robert Reedy (FSEC), Dr. Issa Batarseh (UCF) as co-Pi	Orlando, FL reedy@fsec.ucf.edu	"Grid-Smart Inverters." Develop grid integration concepts for PV that incorporate optional battery storage, utility control, communication, monitoring functions, and building energy management systems. Also will validate an "anti-islanding" strategy for PV inverters to allow PV generation to remain connected during some grid disturbances, while meeting safety operation requirements.	250	66
VPT Energy Systems Dr Glenn Skutt	Blacksburg, VA gskutt@vpt-inc.com	"Inverter Control Card (ICC), Bidirectional Power Converter (BPC), Power Hub Controller (PHC), and Integrated Power Hub (IPH) with vehicle-grid integration." Develop component circuits and an overall system design for an integrated energy system. The R&D will include inverter controllers that can be used with existing inverters to add sophisticated grid interoperability, active anti-islanding/intentional islanding control, and a bidirectional power converter for plug-connected vehicles	250	66
Total			**2,779**	**1,643**

* Exact amounts for each contractor are withheld at this time, since all contractors remain in competition for the next SEGIS Stage. Totals for unloaded DOE contract funds out and contractor cost share are shown in the **Totals** row. Note that total contractor cost share is **37%** of the total expenditures which is considerably more than the **20%** required per the RFP.

Module Screening and Field Evaluation

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Carl Osterwald (NREL), 303-384-6764, carl_osterwald@nrel.gov
Michael Quintana (SNL), 505-844-0474, maquint@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@hq.doe.gov

FY 2008 Budgets: $1,945K (NREL), $320K (SNL)

Objectives

- Provide reliability/durability stage-gate testing for Solar America Initiative (SAI) Technology Pathway Partnerships (TPPs) and Photovoltaic (PV) Incubators.
- Include objectives related to levelized cost of energy (LCOE), efficiency, dollar per peak watt, and other metrics associated with SAI goals (www.eere.energy.gov/solar/solar_america).
- Perform field evaluations of reliability of PV systems.

Accomplishments

- Completed reliability assessment of 1-megawatt (mW) system in Napa.
- Completed reliability assessments of module/inverter components for Advent Solar, Emcore, GreenRay, Xantrex, PV Powered, and Soliant.
- Completed installation of four new environmental test chambers.
- Completed thermal cycling or damp heat testing for SolFocus, DOW, GreenRay, Emcore, and Advent Solar.
- Measured degradation rates under high-voltage stress.
- Determined oxidation rate of AlInP window in various testing environments.

Future Directions

- Increase fielded system reliability assessments, linking to needs of the Service Life Prediction (SLP) project.
- Develop field-controlled long-term system exposure activity.
- Initiate a program specifically targeting acquisition of reliability data that will feed predictive model development with multiple partners and capture a variety of operating environments.
- Provide reliability assessments/testing for SAI TPP and Incubator partners.
- Continue SAI stage-gate reliability testing support.
- Monitor long-term performance of small grid-tied systems at NREL and report results to industry.
- Develop lab- and field-data acquisition tasks to support predictive model development efforts.
- Conduct reliability assessments on fielded systems of partners, supplying data for predictive model development.
- Facilitate and/or conduct baseline testing prior to fielding long-term exposure systems in collaboration with industry partners.
- Increase reliability testing in fields such as corrosion, metallurgy, mechanical vibration, and other non-destructive techniques.

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1. Introduction

This initial technology screening/testing element of the overall reliability program will position the DOE Reliability Project to directly support PV technologies while they are in development, as well as commercial products. Clients may be SAI TPPs, existing manufacturers, or new U.S. manufacturers engaged in design and development of PV products.

This work complements other projects that focus on accelerated testing of components, materials, and modules, diagnosis of failure modes and mechanisms, predictive modeling of reliability, and standards development.

2. Milestones

- Complete installation and fit-up of four new environmental chambers in the Outdoor Test Facility (OTF) high-bay (NREL, 10/14/2008).
- Complete qualification testing scheduled for first-year stage-gates for the TPPs (NREL, 9/30/2008).
- Summary report of industry support activities provided during FY 2008 including baseline testing results (NREL, 9/30/2008).
- Document hot-humid stress effects on interfacial adhesion of PV modules (NREL).
- Deliver system performance reports and analyses to module manufacturers (NREL, 9/30/2008).
- Complete installation of Sanyo HIT Si grid-tied system and begin long-term monitoring (NREL, 12/15/2007).
- Submit a journal article for publication that assesses the usefulness of high voltage stress testing (HVST) as an accelerated test used in predicting module lifetime and identifying and accelerating failure modes (NREL, 8/1/2008).
- Down select and initiate studies of cause and possible mitigation paths from among the degradation mechanisms listed in the CPV work plan or others identified as important (SNL, 9/4/2008).
- Negotiate partnership(s) and field commercially available modules and inverters for long term exposure (SNL, 9/30/2008).
- Field minimodules/coupons (TPP participants given priority) expecting commercialized or near-commercial products in FY 2008 (SNL, 6/30/2008).

3.1 New OTF Environmental Chambers (NREL)
Using $560,000 of general equipment funds allocated in mid-FY 2007, four new environmental chambers were procured and installed. These replaced a number of older units in the high-bay laboratory of the OTF, one more than 20 years old. With the larger building electrical transformer that was installed as part of the OTF expansion project, new capacity became available for two additional large chambers, bringing the total to six. This new capacity is for SAI stage-gate deliverables and the new module test-to-failure effort.

3.2 Stage-Gate Deliverable Testing (NREL/SNL)
SAI stage-gate testing activities at NREL included thermal cycling of a full-sized concentrator module for the SolFocus program and damp heat exposure of glass and flexible thin-film laminates for Dow. Both of these included current-voltage by the NREL Cell & Module Performance group and standard wet-and-dry insulation tests. The environmental chamber testing was performed despite utility and laboratory disruptions caused by the OTF expansion and the installation of new environmental chambers. SNL's stage-gate support of reliability testing included damp heat testing of GreenRay module scale inverter enclosures and a field based reliability assessment of the Soliant module.

3.3 Industry Support Activities (NREL/SNL)
A number of PV manufacturers were supported with testing activities, including Advent Solar, Sunpower, Dow, SolFocus, Uni-Solar, First Solar, AVA Solar, Soliant, Emcore, Xantrex, PVPowered, GreenRay, and Schott Solar. Activities included 1) thermal cycling, damp-heat, vibration, and UV exposure, 2) design assessment for reliability, and 3) side-by-side outdoor energy production of modules with anti-reflective glass.

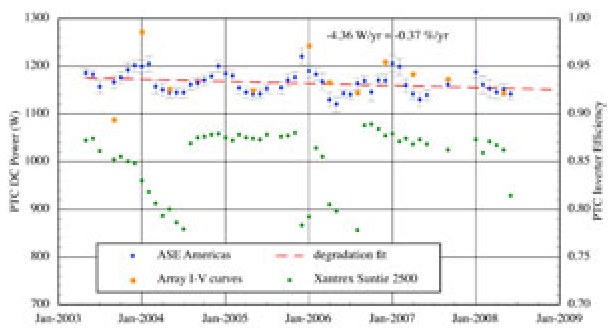

Fig. 1. Example of long-term small system performance monitoring at NREL for a Mobil Solar ribbon-Si array showing degradation rate and monthly average inverter efficiency.

3.4 Long-term Small Array Testing (NREL)
A number of small arrays (~1 kW) are operated at the OTF, using inverters to provide maximum power point loading with careful data logging of DC and AC electrical parameters to calculate performance over time. Monthly regressions of 15-minute average data provide ratings to performance test conditions (1000 W/m^2, 20°C ambient, 1 m/s wind speed), from which degradation rates can be calculated (see Fig. 1).

Periodic I-V curves of both the arrays and individual strings are also used to observe changes in performance. Test results are generated every 3 months and then reported to the respective manufacturers, which include Schott Solar, First Solar, Uni-Solar, and Sunpower. A new Sanyo amorphous-Silicon (a-Si)/Si heterostructure system was installed, using 200-watt modules.

3.5 High-Voltage Testing of CIGS Modules (NREL)

Large systems often require operation of modules at high bias voltages. Outdoor testing of modules under high voltage can uncover degradation or failure that may be observed in high-voltage systems and may accelerate degradation that occurs at lower voltages. After 3 years of exposure, degradation rates of 3.8-4.7%/yr and 2.5-2.8%/yr were observed for the negatively and positively connected modules.

3.6 CPV Cell Reliability (NREL)

(Note: this work was part of the cell-level reliability work and is described in more detail in the Concentrator Crystalline Cells part of the Annual Report. It will be funded 100% through that agreement in FY 2009.)

The quality and integrity of the AlInP window of a GaInP-top cell is very important for high efficiency in a GaAs-based multijunction solar cell. The AlInP is potentially very sensitive to oxidation. For this reason, the damp-heat oxidation rate of AlInP was studied at various temperatures and humidity levels and found to be less significant than initial concerns indicated. Upon the introduction of light, the oxidation rate increases by over 300%, a potentially important degradation mechanism for solar cells. Selenium and zinc doping of AlInP was also measured and determined to increase the oxidation rate. Results are shown in Fig. 2.

3.7 Fielded Systems Monitoring and Reliability Assessments (SNL)

A key input needed to build a reliability model is data from fielded-systems performance and O&M history. We developed an understanding of the model needs and the type of data that is available through our work with our initial partner and potential partners. This has enabled us to specify minimum data needs and a format. Another aspect of field assessment is failure-mode identification. Every field assessment seems to yield information regarding a degradation or failure within components or as a function of interactions of components. For example, we observed an inverter design that had multiple fan failures within 18 months of service, causing system outages and requiring maintenance intervention. We also observed failure of position feedback devices on tracking systems, causing suboptimal tracking. Finally, we have initiated system-long term exposure activity to understand state-of-the-art module degradation rates. This teamed effort includes a 60% contribution of product provided by SunPower as a fielded-system monitoring partner. The systems will include domestic and foreign-made modules with thin-film and crystalline technologies represented.

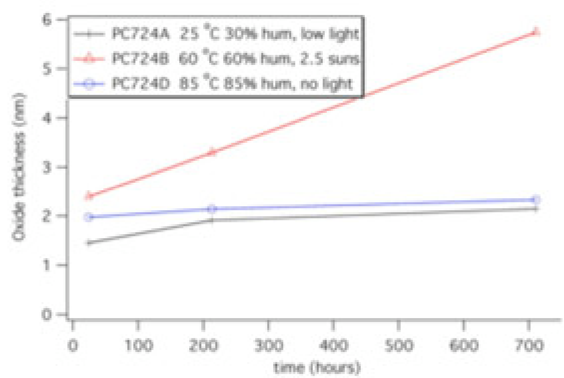

Fig. 2. Time evolution of AlInP oxide layer thickness under various temperature and humidity environments.

3. Major FY 2008 Publications

Osterwald, C.R. *Terrestrial Photovoltaic Module Test-to-Failure Protocol.* NREL/TP-520-42893. Golden, CO: National Renewable Energy Laboratory, March 2008.

Osterwald, C.R.; McMahon, T.J. "History of Accelerated and Qualification Testing of Terrestrial Photovoltaic Modules: a Literature Review." *Prog. Photovolt: Res. Appl. 2008.*

Del Cueto, J.A.; Rummel, S.; Kroposki, B.; Osterwald, C.; Anderberg, A. "Stability of CIS/CIGS Modules at the Outdoor Test Facility over Two Decades." Presented at the 33rd IEEE Photovoltaic Specialists Conference, 2008.

Del Cueto, J.A.; Kroposki, B.; Rummel, S.; Anderberg, A. "Long-Term Performance Data and Analysis of CIS/CIGS Modules Deployed Outdoors." Presented at SPIE, 2008.

Industry Reliability and Codes

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Sarah Kurtz (NREL, Primary Contact), 303-384-6475, sarah_kurtz@nrel.gov
Michael Quintana (SNL), 505-844-0474, maquint@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@hq.doe.gov

FY 2008 Budgets: $475K (NREL), $445K (SNL)

Objectives

- Work with photovoltaic (PV) industry to set objectives for Reliability Project by holding the Accelerated Aging Workshop II.
- Support community's development of standards for reliability and test and evaluation.

Accomplishments

- Facilitated the Accelerated Aging Testing and Reliability in PV II Workshop.
- Completed and posted a summary report of the workshop.
- Supported community's efforts, resulting in committee draft approval of IEC 61853-1 standard for a power-rating methodology.
- Multiple standards documents were drafted, reviewed, or revised.

Future Directions

- The third Accelerated Aging Workshop is planned to be held in Albuquerque, New Mexico.
- In fiscal year (FY) 2009, the PV community's priority for standards is development of the framework needed for energy model validation.

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1. Introduction

PV products require long lifetimes and low degradation rates to achieve desired cost goals and customer acceptance. These needs are changing rapidly as the PV industry evolves rapidly. The Accelerated Aging Testing and Reliability in PV Workshop II was held to reassess the PV industry's needs, priorities, and recommendations on accelerated aging and reliability research in light of recent growth and changes in both the PV industry and the DOE Solar Energy Technologies Program (SETP).

Historically, a highly valued role of the national laboratories has been support of standards development. Standards provide a foundation for growth of a healthy industry by providing common test methodologies and product specifications. These strengthen the industry by:

- Lowering testing costs by defining common international test methodologies, thus, avoiding the need to retest products for each market.
- Defining test methodologies that reflect product performance in the field, thereby encouraging healthy product development.
- Speeding customer acceptance by defining consistent product specifications and nomenclatures.

2. Major FY 2008 Publications

"*Accelerated Aging Testing and Reliability in Photovoltaics Workshop II Summary Report*." www.eere.energy.gov/solar/solar_america/pdfs/accelerated_aging_report_2008.pdf.

Granata, J. *"Role of the National Labs in Codes and Standards"*, private report submitted to Dan Ton (8/08).

Service Life Prediction

Performing Organizations:	Sandia National Laboratories (SNL) National Renewable Energy Laboratory (NREL)
Key Technical Contacts:	Michael Quintana (SNL), 505-844-0474, maquint@sandia.gov, Sarah Kurtz (NREL), 303-384-6475, sarah_kurtz@nrel.gov
DOE HQ Technology Manager:	Dan Ton, 202-586-4618, dan.ton@hq.doe.gov
FY 2008 Budgets:	$645K (SNL), $270K (NREL)

Objectives

- Develop and apply a process with data, methodology, and a model that industry and other stakeholders can use to predict reliability of photovoltaic (PV) systems and components.

Accomplishments

- Established a partnership with Reliasoft, a commercial reliability software vendor, to leverage expertise gained in applications in other industries.
- Established predictive model architecture for a typical crystalline silicon system based on one partner's multi-megawatt (mW) system with 5 years service.
- Secured initial data partner to populate model for development purposes. This includes mostly c-Si modules; some thin film data is also available from this system.
- Incorporated input from the Accelerated Aging and Reliability Workshop into the model development effort.
- Factored the complexity of how failure is defined in systems versus components, revealed in various studies, into continuing efforts.
- Demonstrated draft model NREL, U.S. Department of Energy (DOE), BP Solar, and SunEdison to get a variety of inputs on the model utility; reactions were positive and provided multiple levels of input.
- Developed minimum data needs required for continued model development. This has led to a better understanding of model potential and criteria for subsequent efforts.
- Generating interest in simulations that are beginning to produce parameters including reliability, availability, and design sensitivities for c-Si.

Future Directions

- Secure a minimum of three additional data partners.
- Increase model fidelity by developing inputs based on accelerated life tests correlated to field based technology assessments.
- Increase model capabilities to include basic level predictions for emerging technologies.
- Increase efforts to display model development and capabilities to a variety of audiences including utilities, integrators, manufacturers, and financial interests at scientific and business workshops and conferences.
- Increase modeling activity to generate greater information on inverter reliability.

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1. Major FY 2008 Publications

Quintana, M. (SNL) "DOE Photovoltaics Project." Presented at the Accelerated Aging Testing and Reliability in Photovoltaics Workshop II Summary Report. www.eere.energy.gov/solar/solar_america/pdfs/accelerated_aging_report_2008.pdf.

Carlson, C. (Reliasoft) "Best Practice for Achieving High Reliability PV Systems." Presented at the Accelerated Aging Testing and Reliability in Photovoltaics Workshop II Summary Report. www.eere.energy.gov/solar/solar_america/pdfs/accelerated_aging_report_2008.pdf.

Accelerated Lifetime Testing

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: David Albin (NREL, Primary Contact), 303-384-6550, david_albin@nrel.gov
Michael Quintana (SNL), 505-844-0474, maquint@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2008 Budgets: $1,935K (NREL), $630K (SNL)

Objectives

- Advance the development and use of accelerated lifetime test (ALT) protocols for photovoltaic (PV) modules, cells, materials, and components.
- Provide timely information on the fundamental stability of modules, exposed to real conditions.
- Develop new, highly accelerated tests that reduce the cycle time for product development.
- Develop understanding of failure and degradation mechanisms associated with PV technologies.

Accomplishments

- Identified two distinct degradation mechanisms (with activation energies of 0.6 eV and 2.9 eV) in NREL-made CdS/CdTe solar cells; the 2.9 eV mechanism is particularly significant as it appears responsible for a longer-term instability of CdTe cells stressed between 60 ºC and 80 ºC.
- Compared damp-heat-induced degradation of ZnO, $Zn_{1-x}Mg_xO$, ITO, and F:SnO_2, quantifying the relative instability of ZnO for thin-film solar cells.
- Improved, uncompromised by external leads, test methodology for quantifying the degradation of transparent conducting oxides (TCOs) in relevant, encapsulated configurations.
- Defined a test-to-failure protocol as a basis for comparison of reliability of modules.
- Demonstrated test methodology and measured acceleration factors for UV-induced adhesion loss.
- Prioritized work using failure-mode analyses performed under service-life prediction (SLP) models and failure analysis.
- Established strong collaborations with Solar America Initiative (SAI)-funded industrial partners.
- Failure modes and effects analyses were performed for c-Si, CIS, CdTe, and residential inverters.
- Conducted x-ray diagnostics to determine failure of conductive adhesive bonds post-damp heat tests; results of this work are being utilized in a Technology Commercialization Development Fund (TCDF) effort at SNL.
- Designed and built an accelerated test chamber at SNL that can be coupled to a solar simulator for testing of CIS TCOs and barrier coatings.
- Initiated efforts to develop accelerated tests at SNL that assess reliability of conductive foil tapes used in thin-film applications.

Future Directions

- Continue efforts to understand failure and degradation mechanisms and quantify degradation rates as a function of stress conditions.
- Continue support of SAI and the PV industry.
- Compare outdoor with accelerated stress on encapsulant adhesion.
- Expand conductive foil tape accelerated life test development.
- Develop ALT-based degradation model to incorporate into the SLP reliability predictive model.
- Elucidate the science of thermal cycling of the die attach for concentrator cells.
- Working with thin-film scientists, apply new technique to study the effects of humidity, temperature, and encapsulation on TCOs.

- Increase applications of ALTs to inverter development and service life prediction.

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1. Introduction

The Accelerated Lifetime Testing project supports the DOE Solar Energy Technologies Program Reliability Project by providing information about failure and degradation of PV technologies. Accelerated testing can provide a means for quickly identifying design or manufacturing flaws, facilitating their mitigation. Rapid product development benefits from highly accelerated tests. Quantitative accelerated tests can differentiate products before they are placed in the field.

PV products require long lifetimes and low degradation rates to achieve desired cost goals and customer acceptance. Today's PV industry is evolving rapidly and product development/testing must be completed in a time that is far shorter than the desired lifetime of products. Accelerated testing is essential for establishing some confidence in product reliability and durability. As the industry matures, it will become more important and practical to quantitatively predict degradation and failure rates. Careful comparison of accelerated and field-test results provides either the basis or validation of predictive models. Studies that quantify the effects of stress factors can be used to predict isolated failure/degradation rates as a function of stress conditions. Thus, accelerated testing is a key element of any reliability program.

Packaging and component issues are particularly important for module durability. For mature technologies, reliability is mainly affected by packaging. Reliability is determined by the effectiveness of packaging in reducing moisture and other external ingress, providing durable mechanical support and protection, and maintaining adequate electrical and optical performance quality. The introduction of thin-film products exacerbates failure due to the 1-2 order reduction in cell-to-packaging material volume. These latter structures are more sensitive to moisture, physical stresses, and deleterious environments both outside and within the package. Unlike more mature, silicon-based technologies, the processing, cell design, and cell interconnect strategies of thin-film products are rapidly evolving. Such an environment requires the development of ALT protocols that can effectively screen product design changes as well as provide statistically based inputs for detailed analysis of all potential failure mechanisms. SLP cannot be achieved quickly by field-testing. Well-designed ALTs, the identification of degradation mechanisms, and their corresponding reaction rates (e.g., activation energies) provide the basis for timely SLPs.

Inverter failures continue to be high on the list of reliability issues seen in PV systems. In part, this may be a result of lack of and/or less mature test standards for inverters. Additionally, rapidly evolving technology improvements provide a moving target for test standard development. Stresses and/or events experienced by inverters are not necessarily similar to modules, and especially can be influenced by the utility grid. This activity, along with the SLP task, will develop tests that adequately mirror the environments experienced by inverters in commercial, utility, and residential applications in varying use conditions.

2. Technical Approach

Numerous discussions with SNL, DOE, industrial partners, and internal NREL experts in different technology areas (CIGS, CdTe, etc.) contributed to the work plan. The Accelerated Aging and Reliability workshop provided critical industry feedback, identifying priorities and test needs. In the area of thin-film reliability, a common thread was the development of generalized tests and analysis procedures that were not specific to one technology or process. Specific needs included testing of materials, interconnects, window layers, and other cell components prior to module qualification testing. Many of the SAI partners funded in this area view flexible products as necessary to achieve DOE goals for levelized cost of electricity.

A result of this workshop was an initial analysis of both rigid (glass-glass) and flexible CIGS products. This analysis was used to define priorities for this project that included:

- Understanding degradation of flexible, thin-film products; specifically, understanding the role of TCO degradation.
- Accelerated testing of adhesion of encapsulant materials.

Another key aspect of our technical approach is active partnership with industry. These interactions are necessary for maintaining the relevancy of our research to SAI goals. CRADAs have been established with a CdTe manufacturer, a principal supplier of CdTe feedstock material, and a major supplier of packaging and coating materials. We have also established working relationships with flexible CIGS manufacturers to evaluate their packaging strategies using a newly developed ALT, specifically designed for that task.

This project leveraged expertise and equipment at NREL associated with CdTe and CIGS cell fabrication to develop ALTs to target critical needs identified through industrial feedback. Strong associations with both CdTe and CIGS manufacturers were leveraged to address thin-film reliability in a unique, dynamic, and industrially driven fashion. Work has begun on mini-module and cell ALTs, studying different edge seals, encapsulants, and back-contact materials. The convolution of traditional reliability processes (encapsulation) with thin-film group activities (TCO, film growth, and metallization) will be used to develop more relevant test coupons for ALT studies.

3. FY 2008 Special Recognitions, Awards, Patents, and Other Activities

- J. Pern and D. Albin, committee members, 2008 SPIE conference on "Reliability of PV Cells, Modules, Components, and Systems".
- D. Albin,presented an invited talk at the Univ. of Rochester "Process-related and Intrinsic Degradation in Polycrystalline, Thin-Film CdTe Solar Cells".
- J. Pern presented talks at both the 2008 SPIE conference and the Silicon workshop.
- APP PV Reliability Project: J. Pern, organization committee U.S. chair, working with T. James, S. Kurtz, J. Nelson, J. Granata, M. Quintana, and Prof. Cui of SJTU to organize the APP International PV Reliability Workshop, Dec. 4-5, 2008, in SJTU, Shanghai, China.
- Panosyan, Z.; Gippius, A.; Pern, F.J.; Touryan, K. "Methods and Apparatus for Making Diamond-Like Carbon Films," patent application.

4. Major FY 2008 Publications

D.S. Albin. *"Accelerated Stress Testing and Diagnostic Analysis of Degradation in CdTe Solar Cells."* 2008 SPIE Reliability of PV Cells, Modules, Components, and Systems, http://spie.org (2008).

F.J. Pern, et al. *"Degradation of ZnO Window Layer for CIGS by Damp-Heat Exposure."* 2008 SPIE Reliability of PV Cells, Modules, Components, and Systems, available online at http://spie.org. (2008).

G.J. Jorgensen; T.J. McMahon. "Accelerated and outdoor aging effects oh photovoltaic module interfacial adhesion properties." *Prog. in PV*; 16(6), p. 519 (2008).

T.J. McMahon. "Solar Cell/Module Degradation and Failure Diagnostics." *IEEE 46th Annual Intl. Reliability Phys. Symp. Proceedings*; p. 172 (2008).

M.D. Kempe; P. Thapa. "Low-Cost, Single-Layer Replacement for the Back-Sheet and Encapsulant Layers." SPIE Proceedings; 2008, San Diego, California.

M.D. Kempe, et al. "Ripping into CIGS Cells; Do Encapsulants Materially Impact Degradation Rates?" *Solar Industry*; **1(9)**, p 58-63, Oct. (2008).

M.D. Kempe. "Accelerated UV Test Methods and Selection Criteria for Encapsulants of Photovoltaic Modules." *Atlas Testing Services Corporate Newsletter*, Fall 2008.

C. Osterwald. *"Terrestrial Photovoltaic Module Accelerated Test-To-Failure Protocol."* NREL/TP-520-42893. Golden, CO: National Renewable Energy Laboratory, 2008.

J. Pern, et al. *"Damp-Heat Induced Degradation of Transparent Conducting Oxides for Thin-Film Solar Cells."* NREL/CP-520-42525. Golden, CO: National Renewable Energy Laboratory, 2008.

M.D. Kempe. "Accelerated UV Test Methods for Encapsulants of Photovoltaic Modules." Presented at 33rd IEEE PVSC, 2008.

M.D. Kempe, et al. "Stress Induced Degradation Modes in CIGS Mini-Modules." Presented at 33rd IEEE PVSC, 2008.

J.A. Del Cueto, et al. "Stability of CIS/CIGS Modules at the Outdoor Test Facility over Two Decades." Presented at 33rd IEEE PVSC, 2008.

Module, Array, and System Technology and Evaluation

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL)
Key Technical Contacts:	Bill Marion (NREL), 303-384-6793, bill_marion@nrel.gov Jennifer Granata (SNL), 505-844-8813, jegrana@sandia.gov
DOE HQ Technology Manager:	Dan Ton, 202-586-4618, Dan.Ton@ee.doe.gov
FY 2008 Budgets:	$1,575K (NREL), $890K (SNL)

Objectives

- Characterize performance and reliability of Technology Pathway Partnership (TPP) and other Solar America Initiative (SAI)-developed products during development and for stage-gate evaluations.
- Develop protocols and capabilities for test and evaluation of new components and systems, including systems-level technologies such as concentrating photovoltaics (CPV).
- Develop and maintain capabilities to define and conduct tests to provide information/data for validation and improvement of reliability and performance models.
- Conduct baseline testing of modules, minimodules, and/or coupons for the Long Term Exposure activities detailed in the Reliability Project.

Accomplishments

- Performed baseline and stage-gate testing and evaluation for SAI TPP participants. (NREL/SNL)
- Refurbished NREL outdoor module test facility with 45 module capacity and instrumentation upgraded to include global spectroradiometer. (NREL)
- Completed PV module/system performance assessments at SNL for seven non-SAI industry partners (Entech, Advent, Evergreen, Emcore, Xantrex, PVPowered, Recurrent Energy) on >150 samples, leading to product design optimizations. (SNL)
- Developed NREL two-axis tracking test bed for testing flat-plate and concentrating PV modules, with tracking-error monitor and direct-normal spectroradiometer. (NREL)
- Installed and analyzed data for a PV system from Open Energy to determine performance characteristics of a building integrated photovoltaics (BIPV) system. (NREL)
- Provided assistance with measurements for the performance assessment of a 8.2-megawatt (mW) PV system in Alamosa, Colorado. (NREL)
- Performed initial assessment of the Napa Valley College 1-mW PV system and created field electrical performance characterization plan. (SNL)
- Initiated the upgrade of the data acquisition system at SNL Photovoltaic Systems Evaluation Lab (PSEL) to double testing capacity (from 4 to 8 simultaneous tests). (SNL)
- Rebuilt one of SNL's two-axis trackers to improve tracking accuracy for flat-plate and CPV modules to improve baseline outdoor measurements and long-term exposure. (SNL)
- Achieved status as an SNL Primary Standards Laboratory satellite calibration center for spectral responsivity measurements. (SNL)

Future Directions

- Characterize the performance and reliability of SAI-developed products during development and for stage-gate evaluations with a focus on TPP and Incubator technologies that were not ready for evaluation in fiscal year (FY) 2008.
- Develop protocols and capabilities for test and evaluation of new components and systems, including systems-level technologies such as new CPV technologies and new BIPV technologies.
- Define and conduct tests to provide information/data for validation and improvement of systems-level models, including reliability, inverter, and other performance models.
- Transfer improved test procedures and methods to standards committees and industry.

1. Results and Accomplishments

The level 3 and 4 milestones and their date achieved are as follows:

- Completion of all stage-gate required tests and reports delivered for stage-gate reviews (9/30/2008).
- Technical report on building-integrated PV (BIPV) system performance (9/30/2008).

The following sections describe the major results and accomplishments of the agreement.

3.1 Stage-Gate Tests and Reporting

SAI TPP participants were supported by SNL through Stage Gate testing and evaluation (Amonix, Greenray), baseline testing (Soliant, SunPower, Boeing), and on-site product evaluations (Boeing). Solaria CPV modules underwent a 3-month test at NREL that compared their energy production to that for non-concentrating PV. Test reports were generated for Amonix, Greenray, Soliant and Sunpower in preparation for Stage Gate reviews. Baseline testing for Boeing continues, and a report will be generated upon testing completion. All other TPP participants and select incubator participants were contacted for baseline testing, and plans are underway to conduct testing for DOW, GE, AVA, BP Solar, and SolFocus.

3.2 BIPV System Performance Evaluation

To better understand the performance of production BIPV systems, in particular their operating temperatures, a BIPV system was installed at NREL, and its performance was measured. PV tiles, manufactured by Open Energy and that integrate with standard concrete roofing tiles, were used for the installation. At the request of the manufacturer, the PV tiles were installed using two different industry methods. The first method attaches the PV tiles directly to the roof sheathing with screws. The second method installs the PV tiles on counter battens that raise the PV modules an inch above the roof sheathing and permits additional air flow under the PV modules.

Compared to the direct-mount installation, the improved air flow for the counter batten installation reduced PV modules temperatures by as much as 10°C at midday, and overall energy production was increased by 3.4%. Both installations had temperature rise coefficients that were 5-6°C less than what we had expected based on minimum standoff height; perhaps a consequence of tile-roofing systems being somewhat porous for air flow.

3.3 T&E Capabilities Development

A spectroradiometer was added to NREL's Performance and Energy Rating Test Bed (PERT) for measuring global tilt spectral irradiance. PERT provides outdoor testing of 45 PV modules, with I-V curves measured every 15 minutes. Between I-V curve measurements, the PV modules are peak-power tracked, and average power is recorded. The addition of the spectral irradiance data will permit quantifying performance differences between technologies due to variations in solar spectrum. This is important for both energy rating standards and performance modeling. Software was also developed for reporting PV module performance, using IEC 61724 metrics and for quality assessment of PERT data.

A test bed is under development for evaluating the performance of two-axis tracking PV concentrator and flat-plate modules. An existing two-axis tracker at NREL has been modified to improve its tracking. A spectroradiometer for the measurement of direct normal spectra has been installed for evaluating CPV sensitivity to spectral distribution. A PERT-type data acquisition system for collection of meteorological data and I-V curve measurements has been procured and is undergoing fit-up and testing. It will allow power measurements of up to 600 watts. Performance measurements of CPV modules will begin in early FY 2009.

To expand outdoor module test capabilities, SNL is building a two-axis tracker with greater than 0.5 degree pointing accuracy to enhance testing of CPV module, optics, and other balance of systems components. The base was completed in FY 2008, with final construction and alignment to be completed in early FY 2009. This is of particular importance for the SAI baseline and stage gate testing for companies such as Boeing and SolFocus. In addition, SNL is doubling the data acquisition capacity to allow for eight modules to be tested simultaneously, which can be extremely valuable to understanding the differences between modules of differing technologies.

3.4 Field Evaluations

In December 2007, NREL provided assistance with measurements of solar radiation and meteorological parameters for Black and Veatch's performance assessment of the 8.2-mW PV system, constructed by SunEdison in Colorado.

In April 2008 in support of the Amonix SAI TPP stage-gate review, SNL performed simultaneous field testing of two Amonix MegaModules in Las Vegas, Nevada, allowing for a real-time comparison of two different generations of MegaModules. The MegaModules, nominally 5 kW, were located at two separate sites in Las Vegas. Performance and weather data were collected over a 2-day period, and SNL generated a report comparing the output of the two MegaModules in support of Amonix's first stage gate review. This comparison demonstrated the increase in power output in the next-generation MegaModule.

Also in April 2008, SNL visited a 1-mW SunPower (PowerLight) installed system in Napa, California. The system consisted of PowerLight modules on single-axis trackers. Yellowed areas near junction boxes of all modules indicated a possible design flaw, leaky diodes. Performance, often linked to reliability issues, was assessed. Tracking errors observed in several trackers have provided impetus to understand the threshold where tracking error significantly affects performance. Cooling-fan failures on inverters within 18 months of installation spurred questions regarding performance and reliability penalties, especially if immediate action is not taken to replace/repair the fans.

3.5 Improved Test Procedures and Methods

NREL's PERT data were used to develop and validate an accurate model for PV power that only requires three parameters: power at SRC, power temperature coefficient, and power at 200 W/m^2. (The ESTI lab has elected to evaluate this and other models for a benchmark paper on predictive models.) The use of the power at the 200 W/m^2 parameter allows a correction to be applied for PV modules that do not maintain their efficiency at low irradiance levels. Depending on PV module, this reduces the overall error in energy predictions by 0-2%.

In March, SNL completed 1 year of data collection on three, 1-kW grid-tied PV systems which were installed at SNL's PV Systems Optimization Laboratory, shown in Figure 1. Key system parameters, solar radiation, and weather data were collected at 2-minute intervals. This data set was used to validate performance models against measured data for the models used in the Solar Advisor Model, and the results were published at the PV Specialists Conference in May 2008.

Fig. 1. Systems installed at SNL's PV Systems Optimization Laboratory

Angle of Incidence (AOI) performance of flat-plate modules and off-axis tracking assessments of CPV modules are imperative to accurately model the yearly performance and calculate levelized cost of energy (LCOE). In 2008, SNL improved the precision of the outdoor module AOI test capability, which in turn improved the accuracy of the performance modeling output.

With the rapid increase in the number and size of fielded PV systems in the United States, the need for accurate and safe field testing has escalated. SNL hosted a team of field-test experts from NREL, Southwest Research Experiment Station (SWRES) at New Mexico State University, and Southeast Regional Experiment Station (SERES) at the Florida Solar Energy Center in March 2008 to discuss field-test protocols that need to be generated for the industry. SNL took the lead to generate a first draft of this protocol and work with the other experts to finalize a document that will be provided to industry at the end of FY 2009.

2. Major FY 2008 Publications

B. Marion. "Comparison of Predictive Models for Photovoltaic Module Performance." Presented at 2008 33rd IEEE Photovoltaic Specialists Conference; San Diego, California, May 11-16, 2008.

M. Muller; J. Rodriguez. *"Performance Comparison of a BIPV Roofing Tile System in Two Mounting Configurations."* Draft report, Golden, CO: National Renewable Energy Laboratory, September, 2008.

C. Cameron; W. Boyson; D. Riley. "Comparison of PV System Performance-Model Predictions with Measured PV System Performance." Presented at 2008 33rd IEEE Photovoltaic Specialists Conference; San Diego, California, May 11-16, 2008.

PV Module Database

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contacts: Dan Riley (SNL), 505-284-3152, driley@sandia.gov
Jennifer Granata (SNL), 505-844-8813, jegrana@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, Dan.Ton@ee.doe.gov

FY 2008 Budget: $180K

Objectives

- Create an algorithm to generate module performance parameters for new commercial modules that closely match existing modules for entry into module database, based on name plate and specification sheet data.
- Solicit and develop an external source for empirically developed module parameters for database.
- Provide external testing source with SNL-purchased modules for testing and inclusion into the module database.

Accomplishments

- Created algorithm to generate module performance parameters based on name plate and specification sheet data.
- Added 190 modules to the database using performance parameters generated by the algorithm.
- Added 10 modules to the database using test data gathered at SNL.
- Generated the initial solicitation to develop the external source to take over routine module testing and database maintenance.
- Documented key test parameters necessary for external source to take over routine module testing.
- Hosted Atonometrics to show them SNL's test procedures and methodologies and initiate test technology transfer for outdoor module performance measurements.
- Visited Arizona State University Photovoltaic (PV) Test Laboratory to assess the laboratory's capability to perform accurate PV module measurements and discuss future collaborative efforts.
- Converted database files from an older format to a newer format, allowing better integration with new database software and tools.

Future Directions

- Complete solicitation for external transfer of routine module testing and database maintenance.
- Develop the capabilities of the selected contractor to perform high-accuracy outdoor module measurements and properly analyze module measurements to attain parameters necessary for the SNL PV Array Performance Model.
- Verify the accuracy of the contractor by testing representative modules from many U.S.-based module manufacturers and comparing results with the same modules tested by the contractor.
- Transfer maintenance and control of the module database to the contractor.
- Provide funding to contractor for the purchase and testing of new PV modules for inclusion into database.

Energy Rating Method Validation

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Bill Marion (NREL), 303-384-6793, bill_marion@nrel.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, Dan.Ton@ee.doe.gov

FY 2008 Budget: $200K (NREL)

Objectives

- Develop models, methodologies, and procedures for predicting the energy production of photovoltaic (PV) modules and systems.
- Support the implementation of energy rating standards by evaluating and validating draft standards related to energy ratings.

Accomplishments

- Completed a 4-year experiment to assess the performance of amorphous silicon (a-Si) PV modules operating at three sites with different climates. Results published at 2008 IEEE PV Specialists Conference (PVSC). The purpose of the experiment was to determine light-induced degradation and stabilization characteristics of single- and multi-junction a-Si PV modules and the influence of climate and exposure history.
- Evaluated and continuously measured the outdoor performance of a PV module in order to achieve the irradiance-temperature test requirements of the draft energy rating standard, International Engineering Consortium (IEC) 61853-1.

Future Directions

- Validate and evaluate studies of the draft standard IEC 61853 Photovoltaic (PV) Module Performance and Energy Rating–Part 1, which focused on irradiance and temperature performance measurements and power rating.
- Develop and validate methods for correcting angle-of-incidence losses due to reflection and methods for accounting for variations in solar spectrum.

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1. Introduction

PV module manufacturers have typically supplied a module’s power rating at standard reporting conditions (SRC, 1000 W/m^2 irradiance, 25°C cell temperature, and AM1.5 spectrum). This is useful for comparing the performance of different modules at SRC, but is not necessarily a good predictor of performance in the field where irradiance, temperature, and spectrum may depart significantly from conditions at SRC, and the module’s response to these departures may be dependent on PV technology or manufacturer.

An international consensus document being developed on energy ratings is IEC 61853, “Photovoltaic Module Performance Testing and Energy Ratings.”

2. Major FY 2008 Publications

R. Rüther; J. del Cueto; G. Tamizh-Mani; A.A. Montenegro; S. Rummel; A. Anderberg; and B. von Roedern. ”Performance Test Of Amorphous Silicon Modules In Different Climates – Year Four: Progress In Understanding Exposure History Stabilization Effects.” Presented at the 2008 33rd IEEE Photovoltaic Specialists Conference, May 11-16, 2008.

J. del Cueto. *“On the Feasibility of Using PERT Data to Derive Module Performance as per IEC 61853-1,”* Test Report, Golden, Colorado: National Renewable Energy Laboratory, September 2008.

Regional Experiment Stations

Performing Organizations: Southwest Regional Energy Station (SWRES)
Southeast Regional Experiment Station (SERES)

Key Technical Contacts: Steve Palmeri (DOE Golden Field Office), 303-275-4832, steve.palmeri@go.doe.gov
Holly Thomas (DOE/GO), 303-275-4818, holly.thomas@go.doe.gov

HQ Technology Manager: Tom Kimbis, 202-586-7055, tom.kimbis@ee.doe.gov

FY 2008 Budgets: $1,136K (SWRES), $855K (SERES)

Objectives

- Ensure that education, training, outreach, and technical support required to accelerate rate of nation's photovoltaic (PV)-deployment efforts are available and effectively implemented to support growth of PV market.
- Provide leadership and support to industry and national labs for: (1) systems, module, and inverter testing; (2) creating and implementing procedures, codes, and standards for quality, safe, and cost-effective installed systems; (3) hardware certification; and (4) addressing system engineering issues observed in fielded systems.
- Provide technical support to DOE, national laboratories, Solar America Cites, Showcase Projects, and industry in execution and validation of stage gates for Technology Pathway Partnerships.

Accomplishments

- Completed second-period requirements of 3-year award and began the final period work.
- Conducted product testing, system evaluations, and research and development (R&D) activities that related to cutting levelized cost of energy (LCOE), increasing system efficiency, and cutting initial costs of PV systems, particularly as required by Solar America Initiative (SAI) participants.
- Provide technical outreach as member of Tiger Teams to Solar America Cities and Showcases.

Future Directions

- Continue to lead or serve as a member of Tiger Teams to Solar America Cities and Showcases.
- Continued testing and evaluation of fielded PV systems for TPP stage-gate testing, general system benchmarking, and characterization of PV systems and components for performance, cost, and reliability.
- Continue training and participate in development and dissemination of codes and standards.

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1. Introduction

The Regional Experiment Stations (RES) consist of two organizations: SERES and SWRES. These stations are affiliated with local universities, University of Central Florida for SERES and New Mexico State University for SWRES. RES provide support in such areas as:

- Module reliability R&D.
- Inverter and BOS development.
- PV systems engineering, analysis, evaluation, and optimization, especially for fielded systems.
- Education, advance codes, and standards.

2. Technical Approach

2.1. PV Systems Assistance Center

The Photovoltaic Systems Assistance Center (PVSAC) is a virtual laboratory comprised of engineers and staff from both SWRES and SERES. PVSAC is an independent third-party evaluator to evaluate TPP interim results during their stage-gate reviews.

2.2. Infrastructure Development

Training, design review and approval, and codes and standards development are conducted.

2.3. Long-Term Component Testing

RES provide unique and severe environments for long-term exposure (hot/dry and hot/humid) for stressing PV modules and inverters in outdoor system-like configurations.

3. Results and Accomplishments

SERES:

- Participated in 'Tiger Team' evaluation for Orange County Convention Center, Solar America Showcase. Provided extensive technical support through bid specification development and design review.
- Partnered with ETL-Intertek to conduct performance testing of PV modules in accordance to UL-1703 and IEC standards.
- Conducted comprehensive design reviews for 38 small-scale PV systems installed in Florida, which were evaluated for code compliance and basic performance criteria.
- Conducted week-long course, *Installing PV Systems,* at FSEC each month. The course was also modified to be taught at several locations around the United States, including Solar America Cities and for workforce development programs such as Employ Florida Banner Center. More than 350 individuals attended the courses.
- Created Solar Information Office to address demand for information and technical assistance from general public. The office is primarily staffed by students with SERES staff supervisors. During an average week, there are more than 100 public contacts via email, phone, and walk-ins.
- Evaluated module performance versus module nameplate for more than 75 PV modules, using data as basis for determining stabilized module performance information and long-term performance.
- Installed several PV systems in Florida for disaster relief applications. The systems were primarily installed at schools that serve as emergency shelters, and the PV systems help to provide power during grid outages. SERES support was provided for design review, acceptance testing, and performance monitoring.
- Continued data collection for side-by-side comparison of utility interactive inverters. Identical arrays were used, and performance was monitored continuously under real conditions in a hot-humid climate.
- Prepared design guide for application of existing structural codes to attachment of PV arrays to residential rooftops. The work was done in conjunction with various partners with Miami-Dade Building Code Compliance Office, Florida International University Hurricane Research Center, BP Solar, Miami-Dade County, District 8, BEW Engineering, and Solar ABCS.
- Provided support for Florida public policy regarding net-metering and resulted in an updated and industry-supportive role for the state.

SWRES:

- Served as Tiger Team lead or participant Solar America Cities and Showcases: Forest City (Oahu, HI); Tucson, AZ; Santa Rosa, CA; San Jose, CA; and Austin, TX.
- Collaborated with SNL to review solar modeling activities (PVSAM, PVWatts), joint field test exercises, reliability tests, benchmark data validation, accelerated life testing, and instrumentation requirements.
- Consulted with electrical inspectors nationwide on major code concerns.
- Evaluated prototype systems for several industry clients.
- Conducted Internet-based training and Webinar for more than 60 electricians, inspectors, and installers.
- Trained more than 1,140 designers, inspectors and installers in NEC workshops during 3-month reporting period.
- Monitored inverter performance, real-time performance at www.nmsu.edu/~tdi/iltf.

4. Planned FY 2009 Activities

- Continue to lead or as member of technical outreach Tiger Teams to Solar America Cities and Showcases.
- Continued testing and evaluation of fielded PV systems for TPP stage-gate testing, as well as general system benchmarking PV systems and component performance, cost, and reliability characterization.
- Continue training and participate in development and dissemination of codes and standards.
- Support market transformation activities with needs that capitalize on SERES research and technology transfer work.
- Increase capabilities in field-test and outdoor validation activities for hot-humid climates.

- Increase PV module testing capabilities for certification programs to help minimize test time and to reduce backlogs for industry for an expanding U.S. industry.
- Continue expanding small residential inverter testing facilities.
- Continue workforce development efforts through course offerings in PV-system design and installation.

5. Patents and Publications

<u>SERES</u>

- R.M. Reedy; P.E. and G.H. Atmaram. “Recent Activities on Wider Utilization of Photovoltaic Technology in Florida.” *33rd IEEE Photovoltaic Specialists Conference Proceedings*; May 11-16, 2008.
- G. Atmaram; et al. “Need for Uniform PV Module Performance Testing and Certification.” *33rd IEEE PV Specialist Conference Proceedings;* May 11-16, 2008, San Diego, California.

<u>SWRES</u>

- J. Wiles. "To Fuse or Not to Fuse." *Home Power;* #125, June/July 2008.

6. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/ Title of Research Activity	FY 2008 ($K)
University of Central Florida Florida Solar Energy Center Bob Reedy/Stephen Barkaszi	Cocoa, FL	PV System Research and Technical Assistance	855
Southwest Technology Development Institute Andrew Rosenthal	Las Cruces, NM	PV System Research	1,000

Solar Radiometry and Modeling

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Daryl R. Myers (NREL), 303-384-6768, daryl_myers@nrel.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2008 Budget: $800K (NREL)

Objectives

Accurate solar radiometric measurements and models reduce uncertainties associated with solar energy conversion systems, ultimately influencing the levelized cost of energy (LCOE). Project objectives include:

- Support Measurements and Characterization ISO 17025 (General Requirements for the Competence of Calibration and Testing Laboratories) accreditation scope.
- Provide ISO 17025-compliant broadband and spectral radiometric calibrations traceable to international and national reference standards.
- Participate in consensus standards development (American Society for Testing and Materials, International Lighting Commission) related to solar system testing.
- Reduce uncertainties in solar radiometric data and solar radiation models.
- Transfer optical and solar measurements-related technology to the solar conversion industry.

Accomplishments

- Verified NREL reference standard stability relative to World Radiometric Reference (WRR) at NREL Pyrheliometer Comparison (NPC), Sandia National Laboratories, and 19 other participating laboratories.
- Performed 30 spectral and 305 broadband solar broadband radiometer calibrations for NREL and solar industry partners.
- Classified five industrial partner and three NREL flash solar simulators according to ASTM E927.
- Transferred NREL Pulse Analysis Spectroradiometer System (PASS) technology to Spire Corporation through technical partnership agreement.
- Published NREL PASS technology in proceedings of the Society for Photo-Optical Instrumentation Engineers (SPIE) technical conference.
- Completed update of Commission Internationale de'Eclariage (CIE or International Lighting Commission) Publication 85 on Solar Simulation.
- Analyzed relative performance over 11 months of 1-minute radiometric data for 15 solar radiometer models; produced draft NREL technical report of results.
- Modified SEDES2 spectral model to convert hourly broadband solar data, referred to as TMY2, to hourly spectral distributions for all sky conditions; began validation process.
- Modified all-sky version of Bird Clear Sky broadband solar radiation model to include ground to cloud to ground reflection element.
- Installed new global latitude tilt and direct normal spectroradiometers at NREL's Outdoor Test Facility (OTF) and Solar Radiation Research Laboratory (SRRL); spectral data Web-accessible.
- Responded to 311 requests for technical information from industry, university, and DOE inquiries.

Future Directions

- Investigate short-term (submonthly) aerosol optical depth estimates to improve hourly broadband and spectral distribution models.
- Assess commercially available solar pyrheliometers to better characterize the accuracy of direct beam measurements for concentrating applications.
- Develop a new spectral irradiance calibration technique to reduce spectral measurement uncertainty by at least a factor of 2.
- Apply measured and modeled solar radiation data to validation of short-term (subhourly), medium-term (hourly), and long-term (daily) solar radiation forecasting approaches.

Solar Resource Assessment and Characterization

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Dave Renné (NREL), 303-384-7408, david_renne@nrel.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2008 Budget: $580K

Objectives

- Address system-level performance metrics by:
  - Improving the quality and reliability of domestic and international site-time-specific solar resource data sets and related meteorology to optimize solar energy system production and lower levelized cost of energy;
  - Developing solar resource data products that support efficient system design and increase investor confidence in system deployments;
  - Creating easy access to data and products for all consumers, solar developers, and planners.

Accomplishments

- Produced updated Typical Meteorological Year (TMY) database for the United States, using both the original 1961-1990 and 1991-2005 National Solar Radiation Database (NSRDB) data sets. The new data set, TMY3, is available at http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.
- Collaborated with NASA and others on technical results for the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 36 "Solar Resource Knowledge Management."
  - Released report on benchmarking methodologies through the MESoR Programme. These methodologies include not only root mean square error and mean bias error statistics but also a second-order benchmarking scheme using Kolmogorov-Smirnoff statistics.
  - Demonstrated the first prototype of a Web portal, jointly through activities with Project MESoR. This web portal is available at http://project.mesor.net.
  - Tested the National Digital Forecast Database (NDFD), two versions of the European Center for Midrange Weather Forecasting, and a version of the Weather Research Forecasting model (WRF), adjusted to the Global Forecast System, at three high quality ground-based solar measurement sites in the United States: Colorado, Nevada, and Mississippi.

Future Directions

- Conduct test and validations of solar resource forecasting schemes.
- Initiate steps to develop an in-house satellite-based solar resource assessment capability.
- Pursue further updates to the NSRDB, based on 2006 data.
- Investigate long-term influences on solar resources due to climate variability and trends.
- Continue operating agent support to IEA/SHC Task 36 and begin the development of key benchmarking studies.
- Continue to develop and publish Web-based tools and data sets to make solar resource information more readily accessible to users.

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1. Major FY 2008 Publications

D.S. Renné. "Renewable Energy Resource Data Provide the Foundation for Effective Clean Energy Programs Around the World." *World Renewable Energy Congress – X Proceedings; July 2008, Glasgow, Scotland.*

S. Wilcox; W. Marion. "Development of an Updated Typical Meteorological Year Data Set for the United States." *Solar 2008 Conference Proceedings; May 8-12, 2008, San Diego, California*.

Environmental Health and Safety

Performing Organization: Brookhaven National Laboratory (BNL)

Key Technical Contact: Vasilis Fthenakis (BNL), 631-344-2830, vmf@bnl.gov

DOE HQ Technology Manager: Alec Bulawka, 202-586-5633, alec.bulawka@ee.doe.gov

FY 2008 Budget: $470K

Objectives

- Assist in preserving the safe and environmentally friendly nature of photovoltaics (PV) and in minimizing environmental health and safety (EH&S) risks and associated costs to ensure the public support and economic viability of PV systems.
- Identify potential EH&S barriers of PV materials, processes, or applications and define strategies to overcome such barriers.
- Maintain EH&S Research Center as the world's best source on PV EH&S, providing accurate information related to EH&S issues and perceptions.

Accomplishments

- Featured in Environmental Science & Technology (ES&T) and Scientific American.
- Conducted a life cycle analysis of III/V and a multi-crystalline concentrator PV; presented the results at the 23nd European PV Solar Energy Conference, Barcelona, Italy.
- Conducted a study on lessons learnt in silane handling and presented the results at the IEEEPVSC, as well as a seminar, jointly with Air Products, on silane safety.
- Promoted international collaborations on life cycle assessment (LCA) of PV energy technologies.
- Led International Energy Agency Task 12; developed guidelines for LCA.
- Recycling CdTe spent modules and manufacturing waste; improved the separations and recovery of Cd in high Fe industrial streams.
- Assisted several companies on site-specific EH&S issues.
- Answered several requests for EH&S information from the public and the industry.

Future Directions

- Conduct LCA of near-commercialization PV technologies (e.g., a-Si/microcrystalline tandem and CIGS).
- Conduct preliminary LCA of 3rd generation PV technologies to guide the industry towards more environmentally friendly alternatives.
- Accurately define environmental profiles of solar in comparison to other energy technologies.
- Define cost of recycling spent modules and determining scenarios for cost reductions.
- Assist industry in preventing accidents and releases of hazardous materials to the environment, and guiding them towards environmentally friendly material and process options.
- Conducting LCA of integrated PV and storage systems.
- Answer industry, legislators', and public inquiries about EH&S issues in solar energy cycles.
- Identify and characterize EH&S hazards associated with emerging materials, including nano-material forms for the U.S. Department of Energy, its contractors, and the private sector.

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1. FY 2008 Special Recognitions

"Emissions from PV Life Cycles" was featured on the cover of the February issue of ES&T and broadcasted in the New York Times, IEEE Spectrum, Scientific American, and a Dutch paper.

"Prospects of solar energy in the U.S." was featured on the cover of Scientific American (published in 19 languages) and broadcasted by Spiegel, EnergyBiz, Sun & Wind Energy, and several radio and TV stations.

Solar America Board for Codes and Standards

Performing Organizations:	New Mexico State University (NMSU) Tucson Electric Power (TEP) Research Foundation of the State University of New York (SUNY–Albany)
Key Technical Contact:	Holly Thomas (DOE/GO), 303-275-4818, holly.thomas@go.doe.gov
DOE HQ Technology Manager:	Tom Kimbis, 202-586-7055, tom.kimbis@hq.doe.gov
FY 2008 Budget:	$780K (NMSU)

Objectives

- Establish consistent support for codes and standards development to enable solar technology deployment on a large scale. (NMSU)
- Improve the responsiveness, effectiveness, and accessibility of codes and standards in all markets, including federal, state, local, and utility. (NMSU)
- Establish utility photovoltaic (PV)-capacity credits models to reduce market barriers and promote solar energy technology acceptance. (NMSU)
- Develop a central repository for collection and dissemination of documents, regulations, and technical materials related to solar codes and standards. (NMSU)
- Describe and experimentally compare methodologies quantifying the effective capacity credit of non-dispatchable resources, such as PV, and build consensus for proposed methodologies. (SUNY)
- Develop, test, and verify method to accurately evaluate the capacity credit of time-variant PV generation and develop utility-based methods to evaluate the value of solar generation to electric utilities. (TEP)

Accomplishments

- Published three codes and standards study reports. (NMSU)
- Convened 13 stakeholder meetings to provide input on codes and standard issues. (NMSU)
- Identified major gaps in the current work on codes and standards and prioritized them for a strategic plan for future work. (NMSU)
- Modeled two methodologies to quantify the capacity credit of dispersed PV: (1) the Effective Load Carrying Capability (ELCC), based upon the concept of loss of load probability, and (2) the Solar Load Control Capacity (SLC), based on load control with a small amount of demand response and/or storage to firm PV capacity. (SUNY)
- Published a report, “Utility Solar Generation Valuation Methods.”(TEP)

Future Directions

- Publish four additional codes and standards study reports. Commence outreach to targeted audiences on report recommendations. (NMSU)
- Facilitate stakeholder involvement and communication on codes and standards issues through stakeholder meetings, electronic newsletters, and the Solar America Board for Codes and Standards (ABCs) Web site. (NMSU)
- Conduct fire safety research on rating of PV modules mounted on different roofing materials. (NMSU)
- Participate in the development of international and national standards through International Electrotechnical Commission (IEC) Technical Committee 82 and other standard making organizations. (NMSU)

PV Installer Certification

Performing Organization: North American Board of Certified Energy Practitioners (NABCEP)

Key Technical Contacts: Margie Bates (DOE/GO, Primary Contact), 303-275-4845, margie.bates@go.doe.gov
Kathleen Bolcar (DOE), 202-586-6646, kathleen.bolcar@hq.doe.gov

DOE HQ Technology Manager: Tom Kimbis, 202-586-7055, tom.kimbis@hq.doe.gov

FY 2008 Budget: $185K (DOE/GO)

Objectives

- Develop and implement quality credentialing and certification programs for renewable energy practitioners that include solar photovoltaic (PV) installer certification, solar thermal installer certification, recertification program, and entry-level Certificate of Knowledge of solar PV systems.
- Establish competency standards to assist in the smooth growth of a renewable energy workforce.

Accomplishments

- Continued to increase the number of individuals who have achieved NABCEP certifications and obtained its entry-level Certificate of Knowledge of solar PV systems:
  - 164 individuals received solar PV certification in FY08, representing an increase of 22% over FY 2007. Total NABCEP-certified solar PV installers to date: 587.
  - 525 individuals obtained PV entry-level Certificate of Knowledge of Solar PV systems in FY 2008, increase of more than 100% from 2007. Total NABCEP Entry-Level Certificates of Knowledge issued to date: 999.
  - 29 individuals obtained NABCEP solar thermal installer certification in FY 2008. Total NABCEP-certified solar thermal installers to date: 85
- With the help of NABCEP's volunteer pool of experts, updated the solar PV exam question bank and free study guide to reflect changes in the National Electric Code.

Future Directions

- Conduct an aggressive marketing and outreach campaign to ensure that there are significant increases in the number of test-takers pursuing NABCEP certification.
- Increase awareness within the business community, state and federal agencies, and consumer base about the benefits of NABCEP certification.
- Develop and announce a new family of certification programs that address the rapidly changing needs and roles in the renewable energy market.

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1. FY 2008 Special Recognitions and Awards

- Received prestigious ANSI/ISO/IEC 17024 accreditation.

2. Major FY 2008 Publications

- Bi-monthly NABCEP newsletters.
- Three new brochures: *Benefits of Certification*, *Benefits to the Nation,* and *Benefits to the States.*

3. University and Industry Partners

NABCEP works closely with companies and organizations, including Interstate Renewable Energy Council, National Electrical Contractors Association, Solar Rating Certification Corporation, National Renewable Energy Lab, Sandia National Lab, International Brotherhood of Electrical Workers, BP Solar, Sharp Solar, Powerlight, SunPower Corporation, SunEdison, Appalachian State University, Southwest Technology Development Institute, North Carolina Solar Center, and New York State Energy Research and Development Authority.

Solar Decathlon

Performing Organization:	National Renewable Energy Laboratory (NREL)
Key Technical Contact:	Cécile Warner (NREL), 303-384-6516, cecile_warner@nrel.gov
DOE HQ Technology Manager:	Richard King, 202-586-1693, richard.king@ee.doe.gov
FY 2008 Budget:	$3,237K (NREL)

Objectives

- Conduct next fiscal year (FY) 2009 Solar Decathlon university competition where exclusively solar-powered houses will demonstrate building-integrated photovoltaics (BIPV) and solar technologies in marketable residential applications
- Develop, release, and manage solicitations to produce FY 2009 event.
- Conduct post-Decathlon instrumentation and monitoring.

Accomplishments

- Concluded implementation of 2007 Solar Decathlon university competition, which included releasing final regulations; firming up sponsorships; supporting teams; scoring; monitoring; and carrying out all aspects of event. (October 2007)
- Held "Building Industry Day" for builders at 2007 Solar Decathlon. (October 2007)
- Orchestrated signing of a memorandum of understanding (MOU) between U.S. Department of Energy (DOE) and Spain's Housing Ministry to collaboratively develop 2010 Solar Decathlon Europe competition. (October 2007)
- Selected 20 teams for 2009 Solar Decathlon, awarding each team a 2-year, $100,000 contract. Launched activities leading toward execution of 2009 event. (January 2008)
- Garnered award of excellence for 2007 Solar Decathlon's communications efforts from 2008 International Association of Business Communicators (IABC) Southern Region Silver Quill Awards. (September 2008)

Future Directions

- Conduct 2009 Solar Decathlon in first quarter of FY 2010 and release solicitation for 2011 event.
- Replace "Getting Around" electric car contest with new "Net Metering" contest for 2009 contest.
- Assess performance of selected, occupied former Solar Decathlon houses to evaluate long-term implications of PV in buildings.
- Continue and expand productive interactions with building industry.

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1. Introduction

The Solar Decathlon fosters the widespread acceptance of PV-integrated buildings by overcoming technical and commercial barriers and by facilitating the integration of PV into the built environment through technology development, applications, and key partnerships. Through this project, PV will become a routinely accepted building technology in the 21st century.

2. Technical Approach

The Solar Decathlon's goal is to develop and facilitate widespread adoption of PV in the built environment, resulting in solar-powered homes and businesses that demonstrate building-integrated PV and solar technologies in marketable applications and partnerships that build on successes.

2.1 Conduct 2007 Solar Decathlon

The Solar Decathlon is an intercollegiate competition in which teams work to design, build, and operate the most attractive and energy-efficient solar-powered homes. Twenty teams of students from the United States, Canada, Germany, and Spain competed in the 2007 event. The teams, selected through a competitive procurement in 2005, worked on their projects over the intervening 2 years under NREL's supervision and guidance. They transported their houses to the National Mall in Washington, D.C., where they built a "solar village" and opened their homes to the visiting public from October 12 to October 20, 2007. Teams competed against each other in 10 contests—some of which were scored by measuring performance, while others were scored by jurors representing expertise in appropriate fields. The contests tested the teams' abilities to produce electricity and hot water from solar panels to perform all the functions of a home and provide power for an electric car. In addition to the energy-related contests, each house was judged on its architecture, livability, ease of construction, and replication of design. The teams provided their homes' designs and communicated with the public about their homes.

2.2 Develop and Release Solicitation for 2009 Solar Decathlon Event

NREL prepared and released a solicitation for the 2009 event at the start of the 2007 event. Each winning university proposal was set to receive $100K in research funding (over two years) to support the innovative development of BIPV technology in its entry.

2.3 Conduct Post-Decathlon Monitoring Program

A PV building benchmarking effort to assess long-term performance of occupied Solar Decathlon homes after the competition was developed in FY 2006 and the effort was continued in FY 2008. This comprehensive monitoring and instrumentation activity, together with a building simulation and modeling effort, works toward the goal of understanding and improving the design and performance of BIPV homes.

Task Title	FY 2008 Budget ($K)
Solar Decathlon (NREL)	3,237*

*Includes activities reported in Communications and Outreach section of annual report.

3. Results and Accomplishments

3.1 Major Accomplishment: Solar Decathlon 2007

NREL organizers and its subcontractors successfully carried out the 2007 Solar Decathlon held October 2 through October 22, 2008, on the National Mall in Washington, D.C. Tasks performed in order to achieve this goal included:

- Providing scores for the 10 contests.
- Performing expert judging for contests such as market viability, architecture engineering, Web sites, and house tours.
- Reviewing team designs for code and regulation compliance.
- Installing equipment.
- Performing instrumentation system development, acquisition, and shakedown.
- Distributing of communication materials (i.e., brochures, media kits, official program, Web site materials, and graphics).
- Coordinating teams, sponsors, and volunteers.
- Procuring stagecraft and assembly of solar village.
- Executing procedures for safe conduct during entire event.

In addition to hosting a Web site that informed visitors about the competition and scoring, we managed crowds of more than 200,000 visitors to the Solar Decathlon and a massive media interest in the future of solar energy and the next generation of solar practitioners and solar homes.

3.2 *Major Accomplishment: Held "Building Industry Day" for Builders at the 2007 Solar Decathlon*

On October 18, 2007, solar industry leaders conducted nine separate workshops for builders at the 2007 Solar Decathlon.

3.3 *Major Accomplishment: MOU for Solar Decathlon Europe 2010*

NREL organizers coordinated the signing of an MOU between DOE Assistant Secretary for Energy Efficiency and Renewable Energy Andy Karsner and Spain's Undersecretary of Housing Fernando Magro Fernández to collaborate in the development of a Solar Decathlon Europe competition in 2010.

3.4 Major Accomplishment: Received 2008 IABC Southern Region Silver Quill Award

NREL organizers of the 2007 Solar Decathlon event garnered an award of excellence for communications activities that resulted in 200,000 visitors to the National Mall, 400,000 unique visitors to the event Web site, more than 1,000 related media articles and stories, and nearly 650 million media impressions.

3.5 Major Accomplishment: Solicit and Select Teams for 2009 Solar Decathlon and Launch Activities Leading toward Execution of 2009 Event

NREL organizers selected 20 teams (from proposal responses to a solicitation) to participate in the 2009 Solar Decathlon (see list in Section 6). In FY 2008, competition organizers also worked on designing a village micro-grid to make the 2009 Solar Decathlon competition more consistent with the U.S. market for new and existing homes and more compatible with the Builders Challenge rating system. In 2009, each house will be grid-tied to a village-scale micro-grid and the new “Net Metering” contest will enable teams to earn points for exporting power to the micro-grid. The 2009 grid-connected solar village will advance the Solar Decathlon goals and expand the knowledge base for grid-connecting solar buildings.

Milestones Supported by DOE Funding

Milestone or Deliverable	Due Date	Status
Announce and release solicitation for 2009 event	10/12/07	Complete
Select and announce teams for 2009 event	1/20/08	Complete
Finalize and publish 2009 rules and building code	9/30/08	Complete

4. Planned FY 2009 Activities

- Convene workshop for 2009 Solar Decathlon Teams in second quarter of FY 2009.
- Continue activities leading toward execution of 2009 Solar Decathlon event.
- Design and prepare for installation, safe operation, and removal of temporary micro-grid that will interconnect all 20 Solar Decathlon 2009 homes and supply power for event organizers.

5. Major FY 2008 Publications

C. Anna, *Solar Decathlon: Building the Future,* U.S. Department of Energy (Brochure) www.nrel.gov/docs/fy08osti/43638.pdf.

U.S. DOE, *Solar Decathlon Web site,* www.solardecathlon.org.

M. Wassmer, *2009 Solar Decathlon Rules and Regulations,* www.solardecathlon.org/pdfs/sd2009_rules.pdf.

M. Wassmer, *2009 Solar Decathlon Building Code,* www.solardecathlon.org/pdfs/sd2009_building_code.pdf.

6. University and Industry Partners

Organization/ Principal Investigator or Contact	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)
Colorado Code Consulting, LLC Thomas Meyers	Berthoud, CO codeconsultant@gmail.com	Complete one plan review of 20 sets of drawings and specifications for the Solar Decathlon competition in preparation for on-site building inspections of the competition houses after they are installed on the National Mall in Fall 2009	20
Cornell University Matt Ulinski	Ithaca, NY mu25@cornell.edu	2009 Solar Decathlon team	50
Iowa State University Ulrike Passe	Ames, IA upasse@iastate.edu	2009 Solar Decathlon team	50
Penn State Jeffrey R. S. Brownson	University Park, PA nanomech@psu.edu	2009 Solar Decathlon team	50
Rice University John Casbarian	Houston, TX jjc@rice.edu	2009 Solar Decathlon team	50
Team Alberta (University of Calgary / SAIT Polytechnic / Alberta College of Art + Design / Mount Royal College) Warren Veale	Calgary, Alberta, Canada veale@ucalgary.ca	2009 Solar Decathlon team	50

Organization/ Principal Investigator or Contact	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)
Team Boston (Boston Architectural College / Tufts University) Jeff Stein	Boston, MA jeff.stein@the-bac.edu	2009 Solar Decathlon team	50
Team California (Santa Clara University / California College of the Arts) Timothy Hight	Santa Clara, CA THight@scu.edu	2009 Solar Decathlon team	50
Team Missouri (Missouri University of Science and Technology / University of Missouri) Katie Grantham Lough	Rolla, MO kag@umr.edu	2009 Solar Decathlon team	50
Team Ontario/BC (University of Waterloo / Ryerson University / Simon Fraser University) Geoffrey Thun	Cambridge, Ontario, Canada studio@velikovthun.com	2009 Solar Decathlon team	50
Technische Universität Darmstadt Manfred Hegger	Darmstadt, Hesse, Germany hegger@ee.tu-darmstadt.de	2009 Solar Decathlon team	50
The Ohio State University Mark E. Walter	Columbus, OH walter.80@osu.edu	2009 Solar Decathlon team	50
The University of Arizona Larry Medlin	Tuscon, AZ rlmedlin@email.arizona.edu	2009 Solar Decathlon team	50
Universidad de Puerto Rico Sonia M. Miranda-Palacios	San Juan, Puerto Rico mirandasonia@alum.mit.edu	2009 Solar Decathlon team	50
Universidad Politécnica de Madrid José Manuel Paéz Borrallo	Madrid, Spain vicerector.internacional@upm.es	2009 Solar Decathlon team	50
University of Illinois at Urbana, Champaign Patrick Chapman	Champaign, IL plchapman@uiuc.edu	2009 Solar Decathlon team	50
University of Kentucky Donald Colliver, Ph.D., PE	Lexington, KY colliver@bae.uky.edu	2009 Solar Decathlon team	50
University of Louisiana at Lafayette W. Geoff Gjertson	Lafayette, LA gjertson@louisiana.edu	2009 Solar Decathlon team	50
University of Minnesota Ann Johnson	Minneapolis, MN Johns421@umn.edu	2009 Solar Decathlon team	50
University of Wisconsin-Milwaukee Gregory Thomson and Chris Cornelius	Milwaukee, WI thomsong@uwm.edu	2009 Solar Decathlon team	50
Virginia Tech Joseph Wheeler	Blacksburg, VA joewheel@vt.edu	2009 Solar Decathlon team	50

Solar America Showcases

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL) New Mexico State University (NMSU) Florida Solar Energy Center (FSEC)
Key Technical Contacts:	Steven Palmeri (DOE/GO, Primary Contact), 303-275-4832, steve.palmeri@go.doe.gov Cecile Warner (NREL), 303-384-6516, cecile_warner@nrel.gov Vipin Gupta (SNL), 915-491-1158, vpgupta@sandia.gov Andy Rosenthal (NMSU), 505-646-1323, arosenthal@nmsu.edu Robert Reedy (FSEC), 321-638-1470, reedy@fsec.ucf.edu
DOE HQ Technology Manager:	Charlie Hemmeline, 202-586-6646, charles.hemmeline@ee.doe.gov
FY 2008 Budget:	$1,590K

Objectives

- Accelerate demand for solar technologies among key end-use sectors.
- Assist in creating high visibility solar projects that increase public awareness of solar power.
- Create replicable, large-scale projects that can become models for other U.S. entities.

Accomplishments

Forest City Military Communities Project

- Supported a real estate project that showcases the wider adoption of solar technology. This project is a public-private joint venture with the Department of Navy to build or refurbish 6,500 homes for military families on U.S. naval and marine bases in Hawaii.

Orange County Convention Center (OCCC) Project

- Provided assistance to the OCCC, in partnership with the Orlando Utilities Commission (OUC), to install a nominal 1-megawatt (MW) photovoltaic (PV) system on the roof of and in the area surrounding its North-South Building. The system will include a large rooftop system, as well as four experimental systems showcasing new technologies at ground-level for public viewing.

San Jose City Project

- Helped identify eight city-owned buildings that might be suitable for solar installations. These locations are highly visible in the San Jose downtown area and have the potential for up to 2 MW of total solar power.

Future Directions

- Continue to seek solar projects to support in fiscal year (FY) 2009 that accelerate demand for solar technologies.

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1. Introduction

The purpose of Solar America Showcases (SAS) is to accelerate demand for solar technologies among key end-use market sectors. Under this activity, DOE provides technical assistance to large-scale, high-visibility solar installation projects that have the ability to impact the market for solar technologies through large project size, use of a novel solar technology, and/or use of a novel application for a solar technology. In addition, it is desired that the project be replicable or have replicable components. Although it is not expected that projects meet all of these parameters, ideally projects reflect some or most of these qualities. Large-scale installations may include PV, concentrating solar power (CSP), and solar water heating (SWH) applications.

Regarding the *scale* of the project, DOE looks for projects with total capacity in excess of 100 kilowatt (kW). Projects may include multiple sites and do not have to be co-located. In addition to the initial installation, the kW total may also include planned follow-on activities (direct replication efforts). Examples include installations in residential subdivisions, shopping centers, office buildings or parks, big box retail locations, factories, and utility solar production.

2. Technical Approach

SAS awarded technical assistance to four organizations. These organizations represented a broad spectrum of applications with cross-cutting issues that allowed the Solar America Initiative (SAI) to work on several barriers. These barriers included:

- Addressing financing barriers for solar applications in a municipality.
- Creating a request for proposal (RFP) that municipalities can use for soliciting bids on solar installations.
- Developing an economically sound model for doing site surveys across a large housing complex.
- Researching inverter location and interconnection issues.
- Developing protocols for acceptance testing and commissioning processes on new solar installations.

3. Results and Accomplishments

3.1 Forest City Military Communities Project

- Provided technical assistance necessary for Forest City to install a 107-kW PV system on the Halsey Terrace Community Center, a project that could create 9 MW of power that will benefit over 6,500 Navy and Marine Corp families in Honolulu, Hawaii.
- Provided Forest City the know how to plan up to 3-kW PV systems on 759 housing units on Kaneohe Bay Marine Corps Base.

3.2 Orange County Convention Center (OCCC)

- Provided assistance in the development of the RFP document for the 1-MW PV system.
- Evaluated five pre-qualification bids were received in the first round, although as one arrived 10 minutes late, it was disqualified.
- After analyzing the capabilities of the companies, Ferreira Construction of NYC and Johnson Controls, Inc. (JCI) were invited to submit a final bid to part 2 of the RFP, and Orange County declared JCI the winner in late June.
- Participated in the first design meeting in mid-September to discuss data communication within the center and locations of the arrays around the site.

3.3 City of San Jose Project

The technical assistance team performed site evaluations, cost estimations, predicted energy savings, and performed cash flow analyses on the following buildings in the City of San Jose:

- City of San Jose Central Service Yard.
- 4^{th} Street Parking Garage.
- Children’s Discovery Museum.
- HP Pavilion.
- San Jose Convention Center.
- Story Road Landfill.
- Las Plumas EcoPark.
- San Jose/Santa Clara Water Pollution Control Plant.

3.4 New Showcase Projects Selected in FY 2008

- Mystic Seaport Museum in Mystic, Connecticut.
- District Department of the Environment/District of Columbia Energy Office.
- Zero Energy Solar PV Housing Development in Mesa del Sol, New Mexico.

4. Planned FY 2009 Activities

- Complete work with OCCC as well as each of the new projects selected in 2008.
- Develop new funding opportunity announcements (FOAs) for specialty projects such as zero energy homes, microgrid projects, and/or MW sized systems.

Solar America Cities

Performing Cities Awarded in 2007:	
	Ann Arbor, MI; Austin, TX, Berkeley, CA; Boston, MA; Madison, WI; New Orleans, LA; New York, NY; Pittsburgh, PA; Portland, OR; Salt Lake City, UT; San Diego, CA; San Francisco, CA; Tucson, AZ
Performing Cities Awarded in 2008:	
	Denver, CO; Houston, TX; Knoxville, TN; Milwaukee, WI; Orlando, FL; Philadelphia, PA; Sacramento, CA; San Antonio, TX San Jose, CA; Santa Rosa, CA; Seattle, WA; St. Paul-Minneapolis, MN
Key Technical Contacts:	Margie Bates, (DOE/GO), 303-275-4845, margie.bates@go.doe.gov Joe Lucas (DOE/GO), 303-275-4849, joe.lucas@go.doe.gov Steve Palmeri (DOE/GO), 303-275-4832, steve.palmeri@go.doe.gov
DOE HQ Activity Manager:	Thomas Kimbis, 202-586-8064, tom.kimbis@ee.doe.gov
FY 2008 Budgets:	$2,400K (DOE), $2,400K (Technical Assistance from National Labs)

Objectives

- Provide financial assistance awards, also called cooperative agreements, up to $200,000 to each of the 12 newly awarded cities under the Solar America Cities 2008 solicitation, in addition to 13 Solar America Cities awarded in 2007, with populations of 100,000 or more to propose activities that support the objectives of DOE and Solar America Initiative (SAI) market transformation activities.
- Provide up to $200,000 in tailored technical assistance from DOE national laboratories and contractors to each of the 2008 recipient cities to accomplish the project goals.

Accomplishments

- Issued a second round of competitive funding opportunity announcement (FOA) and awarded $2.4 million in financial assistance and $2.4 million in technical assistance to 12 additional U.S. cities to form strategic partnerships.
- Held the first annual Solar America Cities meeting in Tucson, Arizona, bringing together the 2007 and 2008 awardees to share best practices, share lessons learned, present new ideas, and engage in networking opportunities.
- Launched a Solar America Cities Web site http://solaramericacities.energy.gov/Home.aspx.
- Provided technical assistance for each of the 2007 and 2008 cities from National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), Oak Ridge National Laboratory (ORNL), Southwest Regional Experiment Station (SWRES) at New Mexico State University (NMSU), and Southeast Regional Experiment Station (SERES) at the Florida Solar Energy Center (FSEC).

Future Directions

- Integrate solar energy technologies into city energy planning and removal of market barriers to solar energy development that exist in urban planning charters, zoning regulations, building codes, permitting, and inspections procedures.
- Promote solar technology among residents and local businesses through outreach, curriculum development, incentive programs, and other innovative approaches.
- Develop a comprehensive city-government approach to solar implementation involving key stakeholders, utilities, and private partners.
- Widespread increase in the adoption of solar energy technologies across the cities in the residential, commercial, and public building sectors and at utilities.

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1. Technical Approach

The objective of the SAC 2008 funding opportunity announcement (FOA) was to support cities ready to take a comprehensive, systemic, city-wide approach to solar technology that facilitates mainstream adoption and provides a model for other cities. DOE selected 13 SAC in June 2007 and an additional 12 cities in March 2008 to help lay the foundation for a solar energy market that can serve as a model for cities around the nation.

Each of the new cities submitted a proposal outlining its plans to build a sustainable solar infrastructure, streamline city-level regulations, and promote the adoption of mainstream solar technology among residents and businesses.

Table 1. Winning Cities for 2008

Solar America Cities 2008	FY 2008 Budget ($K)
Denver, CO	200
Houston, TX	200
Knoxville, TN	200
Milwaukee, WI	200
Orlando, FL	199
Philadelphia, PA	200
Sacramento, CA	200
San Antonio, TX	200
San Jose, CA	200
Santa Rosa, CA	200
Seattle, WA	200
St. Paul & Minneapolis, MN	200

On-Site Technical Assistance

In their proposals, each city identified the technical assistance their projects might require in areas such as city planning, technology selection, project financing, building codes, architecture and community outreach. Similar with 2007 cities, DOE appointed a technical assistance lead, called a Tiger Team leader to each city. Members of the Tiger Team were drawn from the National Renewable Energy Laboratory (NREL) in Colorado, Sandia National Laboratories (SNL) in New Mexico, Oak Ridge National Lab (ORNL) in Tennessee, Southwest Regional Experiment Station (SWRES) at New Mexico State University, and Southeast, Regional Experiment Station (RES) at the Florida Solar Energy Center.

2. Results and Accomplishments

In April 2008, DOE held the first annual SAC meeting to share experiences, lessons learned and provide the 2007 and 2008 cities the opportunity to network.

DOE launched a Solar America Cities Web site at http://solaramericacities.energy.gov/Home.aspx to promote the goals and accomplishments.

Ann Arbor: completed an online database of solar access for Ann Arbor residences and a highly-visible 10-kilowatt (kW) photovoltaic (PV) installation.

Austin: identified areas where solar could be the vehicle for teaching basic science to students began incorporating this knowledge into a school curriculum.

Berkeley: developed an online project calculator and completed its marketing and outreach plan.

Boston: developed and launched the online solar energy map (http://gis.cityofboston.gov/solarboston) and hosted five solar energy events with a combined attendance of more than 700 participants.

Madison: developed a Web site with information about solar, permitting, and funding information and introduced an ordinance simplifying the permitting process for solar systems and removing restrictions into the legislative process.

New Orleans: established a Web site, www.solarpowernola.org, as a repository for solar technology information and established North American Board of Certified Energy Practitioners (NABCEP) solar installer training program at a local college.

New York: convened the third annual Solar Summit, a conference focused on implementing solar in New York City with leaders from utilities, industry, government, and academia attending and presenting.

Pittsburgh: conducted several solar workshops with SAI city partners.

Portland: generated Web, print, and electronic marketing materials, educating thousands of individuals throughout the region about the benefits of solar energy. Facilitated approximately 200 PV and solar thermal systems to residents and businesses (217 kW.)

Salt Lake: implemented Utah’s first solar PV installer course at Salt Lake Community College and hosted two solar and National Electric Code (NEC) code training sessions.

San Diego: developed the city Solar Map and completed an extensive survey, announced by the mayor, to all homes and businesses with solar installations, resulting in a 30% rate of return.

San Francisco: developed “GoSolarSF” city incentive program and addressed barriers to installing solar on multi-tenant buildings.

Tucson: helped develop solar installer training classes at Pima Community College and trained 75 inspectors on NEC and solar installations.

Denver: prepared presentation for the Zoning Code Task Force related to solar technologies and access laws in preparation for first major revision to city’s code in 50 years.

Houston: designed and launched the Solar Houston Initiative Web site and developed a Solar Technician Curriculum (23 Credit Hours) for Houston Community College, geared towards NABCEP certification.

Knoxville: launched a Website highlighting Knoxville’s SAC program at www.cityofknoxville.org/policy/solar.

Milwaukee: drafted initial energy plan and submitted it to project stakeholder stakeholders. Began talks with Madison to develop a regional solar plan.

Orlando: launched its new rebate program, which offers $200 per customer for installing a solar thermal system and receiving an energy audit.

Philadelphia: conducted first round of stakeholder meetings to solicit feedback from critical stakeholders for Philadelphia’s solar future.

Sacramento: identified 16 potential sites for solar PV, 10 existing sites, and six new construction sites.

San Antonio: conducted a press conference on groundbreaking of a Peak Performance House, a solar experimental lab.

San Jose: sponsored a Summer Solstice trade show with the mayor to highlight solar companies that offered 0% down financing for the residential sector and received approval from council to explore partnerships with utilities and solar generators regarding large scale solar installations (solar farms) on city vacant lands.

Santa Rosa: completed a site assessment and preliminary design for a 65-kW solar PV support structure for the parking lot at the city’s wastewater treatment plant.

Seattle: developed “Solar Works in Seattle!” workshops planned for educating City Light customers.

St. Paul and Minneapolis: completed planning for the installation of two solar charging systems for plug-in hybrid cars.

Government Solar Installation Program (GSIP)

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Steven Palmeri (DOE/GO, Primary Contact), 303-275-4832, steve.palmeri@go.doe.gov
Carolyn Elam (DOE/GO), 303-275-4953, carolyn.elam@go.doe.gov
Cecile Warner (NREL), 303-384-6516, cecile_warner@nrel.gov
Vipin Gupta (SNL), 915-491-1158, vpgupta@sandia.gov

DOE HQ Technology Manager: Charles Hemmeline, 202-586-6646, charles.hemmeline@ee.doe.gov

FY 2008 Budget: $280K

Objectives

- Support federal agencies to achieve commitment to purchasing 2 gigawatts (GW) of solar power at federal facilities and 1 GW at state and local facilities, with all transactions and installations to be completed by 2012 ahead of the final renewable energy purchase phase of the Energy Policy Act of 2005 (EPAct 2005).
- Lower production costs for solar components through a market-based approach of using governmental energy needs to build demand for solar products and increase production.
- Maximize installation of secure, on-site renewable energy projects at all DOE sites, optimize affordable purchases of renewable electricity by DOE facilities, or both.

Accomplishments

- Developed a model for a federal Photovoltaic (PV) request for proposals, vetted through financial and solar communities and the General Services Administration (GSA).
- Initiated development of a dynamic Government Solar Installation Program Web-enabled tool.
- Prepared a report technically defining the solar energy opportunities for federally-owned Congressional office buildings in Washington, D.C.
- Prepared a report providing technical assessment of the potential for using solar energy and other key energy efficiency features as part of the Elephant House renovation in progress at the National Zoological Park in Washington, D.C.
- Planned the federal PV standard offer contract/power purchase agreement with a standard lease model for release during fiscal year (FY) 2008.

Future Directions

- Continue assessments of governmental buildings and implementation of solar rooftop installations.
- Work with the DOE Federal Energy Management Program (FEMP) to identify the best federal buildings where solar makes the most sense.
- Begin a dialog with other federal agencies to help them identify locations where solar can be installed in a cost-effective manner on their buildings.

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1. Introduction

GSIP is a market-based challenge to public entities—federal agencies, states, cities, counties, and other local governments—to increase their use of solar energy power. GISP is carried out in partnership with DOE's Transformational Energy Action Management Initiative, a department-wide effort to reduce energy intensity across all DOE complexes by 30%. The major GSIP partners are the DOE Solar Energy Technologies Program, DOE Federal Energy Management Program, and General Services Administration.

State and Stakeholder Outreach

Performing Organization: Interstate Renewable Energy Council (IREC)

Key Technical Contacts: Margie Bates, (DOE/GO, Primary Contact), 303-275-4845, margie.bates@go.doe.gov
Kathleen Bolcar (DOE), 202-586-2820, kathleen.bolcar@hq.doe.gov

DOE HQ Technology Manager: Charles Hemmeline, 202-586-6646, charlie.hemmeline@hq.doe.gov

FY 2008 Budget: $1,500K (DOE/GO)

Objectives

IREC's 5-year plan is based on extensive outreach and education focused on the following activities:

- Encourage and coordinate quality training workshops and accessible learning opportunities, as well as provide assistance to educational providers through the Workforce Training and Quality Assessment Project.
- Connect experts with Solar America Initiative – Market Transformation (SAI-MT) stakeholders on key issues in a cost-effective and convenient format.
- Provide models and assistance on net metering and interconnection to lower both barriers and cost for the installation of solar electricity through the Connecting to the Grid Project.
- Monitor and participate, as appropriate, in public hearings/meetings and provide input that could impact solar barriers and/or commercialization through solar codes and standards public hearings.
- Manage and maintain a Web site that offers easily accessible news, information, tools, best practices, and materials.
- Prepare annual reports on solar market trends and impacts regarding interconnection and net metering, training and certification programs, state incentives, and other relevant issues.

Accomplishments

- Actively educated and supported information about net metering and interconnection in 18 states.
- Published "Best Practices and Recommendations" for renewable energy training.
- Published 26 issues of the IREC/SAI e-newsletter for more than 3,000 subscribers and posted on the IREC Web site.
- Published 12 issues of the Interconnection/Net Metering e-newsletter for more than 3,200 subscribers.
- Updated job trends and occupational profile reports.
- Published annual solar market trends report.

Future Directions

- Coordinate training workshops through the Workforce Training and Quality Assessment Project in conjunction with states, cities, and other SAI-MT stakeholders for code and building department officials.
- Disseminate 26 issues of the SAI-MT e-newsletter during the next year and coordinate six SAI telephone seminars.
- Disseminate 12 issues of Interconnection and Net Metering e-newsletters during the next year.
- Address the infrastructure barriers with the states through the Solar Codes and Standards Hearing Project that supports the objectives of SAI.
- Maintain the IREC Web site.

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1. Introduction

The Interstate Renewable Energy Council (IREC) promotes increased stakeholder communications and education under the Solar America Initiative – Market Transformation (SAI-MT) addresses infrastructure barriers to solar energy, and coordinates with industry, DOE, national laboratories, states, cities, and counties.

2. Technical Approach

IREC continued to promote better communications among stakeholders, addressed infrastructure barriers by promoting easy and fair hook-up rules to the utility grid, promoted quality training based on industry competency standards, and coordinated closely with multiple federal, state, and local stakeholders.

With the growth of the solar market over the past few years and the new attention to solar energy solutions, workforce development and quality training become a critical component for this expanding sector. For example:

- IREC works with community colleges, the North American Board of Certified Energy Practitioners, and subject matter experts.
- Training is provided by an accredited body such as a college, university, community college, vocational-technical institution, or certified installers with instructional experience.

3. Results and Accomplishments

IREC has accomplished the following to meet the objective to remove institutional and market barriers:

- Organized seven informative, interactive phone seminars.
- Convened six workshops for code officials.
- Convened two introductory workshops on training and one faculty development workshop in California.

4. Planned FY 2009 Activities

For solar training and certification, IREC will use an integrated approach that combines Web-based resources, on-site and electronic forums, print material, and technical assistance. IREC will:

- Promote quality standards for training.
- Conduct six phone seminars on current and "hot" topics.
- Hold six PV workshops for code officials.
- Hold four solar thermal workshops for code officials.
- Conduct two introductory training workshops.
- Hold at least one faculty development workshop.
- Publish 12 interconnection/net metering models.

5. Major FY 2008 Publications

- *Best Practices and Recommended Guidelines for Training*, September 2008.
- *Annual Trends and Update Report*, September 2008. Distributed at IREC's Annual Meeting in October 2008.
- Published 26 issues of the *IREC/SAI E-Newsletter*.
- *Occupational Profiles of Solar Industry*, August 2008.
- 5th edition of the *Connecting to the Grid* Guide.

6. University and Industry Partners

IREC works closely with many groups, industry, and community colleges, which include the following:

- North Carolina Solar Center at North Carolina State University
- The Southwest Technology Development Institute at New Mexico State University
- New York State Energy Research and Development Authority
- North American Board of Certified Energy Practitioners
- Hudson Valley Community College
- Lane Community College
- Industry and Stakeholder Groups.

State and Utility Outreach

Performing Organizations:	National Conference of State Legislatures (NCSL) Clean Energy Group, Inc. (CEG) National Association of Regulatory Utility Commissioners (NARUC) Solar Electric Power Association (SEPA)
Key Technical Contact:	Steven Palmeri, 303-275-4832, steve.palmeri@go.doe.gov
DOE HQ Technology Manager:	Charlie Hemmeline, 202-586-6646, charlie.hemmeline@hq.doe.gov
FY 2008 Budgets:	$83K NCSL*, $83K CEG*, $71K NARUC* $175K SEPA * (FY 2007 Funds)

Objectives

- Build relationships with state decision makers (such as state legislatures, energy office personnel, public utility commissions, and air quality office personnel) responsible for enacting policies, programs, and plans that are key drivers for solar technology market transformation.
- Provide key state actors with solar best practices and up-to-date, accurate information about solar technology characteristics.
- Enlist the assistance of a utility membership organization to deliver key technical and educational assistance to utilities to promote their acceptance and use of solar.

Accomplishments

- Created Solar State Legislation (www.ncsl.org/programs/energy/energypolicy.cfm) to provide a readily accessible database of current and previous years' bills on energy issues. The database is searchable by energy topic and by state. (NCSL)
- Launched the program Web site (www.statesadvancingsolar.org) that serves as a resource for state policy makers and decision makers interested in developing a solar program. (CEG)
- Released the "Solar Energy Technology and Policy Reference Guide" (www.naruc.org/programs.cfm?c=Domestic), which includes information on solar regulatory policies, technologies, and state and industry perspectives. (NARUC)
- Released "The Peer Matching Online Tool" (www.solarelectricpower.org/peer/), a service to share information and best practices to help utilities improve their solar programs. The database is searchable by location, utility type, experience, or by solar program type. (SEPA)

Future Directions

- Continue working on LegisBriefs and Solar Energy Institute sessions, as well as the solar energy database for solar legislators. (NCSL)
- Develop a state solar program survey. (CEG)
- Hold a regional dialogue for the Northeast and Mid-Atlantic to examine the regional solar initiative. (NARUC)
- Develop a solar program options tool (SPOT) and an online resource library. (SEPA)

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1. Technical Approach

To reach the targeted stakeholders in state government and utility companies, the DOE Solar Energy Technologies Program awarded cooperative agreements to four organizations that have expertise in working with these entities.

- SEPA has extensive experience working with utility partners and was chosen to lead the outreach efforts in this area.
- CEG, NARUC, and NCSL were chosen to perform outreach to the states.

These organizations have a broad membership network that has effectively done outreach to the targeted stakeholders in the United States.

Support Activities

Performing Organization: CH2M Hill, Inc.

Key Technical Contact: Joe Lucas (DOE Golden Field Office), 303-275-4849, joe.lucas@go.doe.gov

DOE HQ Technology Manager: Tom Kimbis (DOE), 202-586-7055, tom.kimbis@hq.doe.gov

FY 2008 Budget: $277K

Objectives

- Provide supplemental technical assistance to the market transformation projects.
- Serve in a coordination and communication role to ensure collaboration of Tiger Team members, across geographic areas, to maximize limited resources, avoid duplication of efforts, and achieve the highest quality product and delivery of services to the recipients.

Future Direction

- Continue providing support to market transformation projects, as needed.

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1. Introduction and Approach

CH2M Hill was competitively awarded a 5-year contract to be a technical assistance provider and Tiger Team integrator. In this role, CH2M Hill provides technical assistance to the DOE Solar Energy Technologies Program Market Transformation projects, including, but not limited to, Solar America Cities, Solar America Showcases, and Government Solar Installation Program projects.

Technical assistance is provided to the recipients by Tiger Teams, teams purposefully assembled to provide subject matter and technical expertise in specific areas, in order to address the needs and further the goals of each project. The Tiger Teams are primarily comprised of technical experts from the National Renewable Energy Laboratory, Sandia National Laboratories, Oak Ridge National Laboratory, and the Southwest and Southeast Regional Experiment Stations, which are housed at New Mexico State University and Florida Solar Energy Center, respectively. CH2M Hill participates as a member of the Tiger Teams to provide technical expertise to the recipients in addition to and complementary to that of the national laboratories and regional experiment stations.

The scope of the CH2M Hill products and services includes on-site technical assistance to recipients across the United States and its territories for activities that include: solar technology assistance, city/municipal planning, market/financial analysis support, architectural/structural analysis support, technical project implementation, communication, outreach and education, and project management.

Solar Thermal Overview

Frank (Tex) Wilkins, CSP Team Leader

In November 2007, the U.S. Department of Energy (DOE) announced that the department would support a dozen concentrating solar power projects (CSP) projects with more than $27 million in funding over 3 years. Work also began with the Bureau of Land Management (BLM) to identify the best sites on federal land in the West for building utility-scale solar power plants.

In September 2008, DOE announced that it would support 15 CSP projects with more than $35 million over 4 years. A week later, the 30% investment tax credit (ITC) for developers of solar power was extended for 8 years. Thus, FY 2008 began and ended with the arrival of exciting new concepts that could impact CSP for years to come. Many of these will move CSP technology toward its goal of becoming competitive in the intermediate power market by 2015.

The projects resulting from the two solicitations mentioned above provide a good indicator of DOE's priorities for CSP. The first solicitation funded trough, Fresnel, dish, and power tower technologies. It also funded work on mirrors and thermal storage. This was the first CSP solicitation in several years, and its objective was to look at a wide variety of new ideas. The second solicitation funded 14 thermal storage concepts and one for advanced heat transfer fluids. This focus on thermal storage is indicative of the increased importance DOE is placing on energy storage. All of the work done through these 27 contracts will be given an in-depth review at the end of their first-phase work (concept feasibility, which takes typically 9-12 months) to determine which will be allowed to move on to phase 2 (design and prototype development, which typically takes 15-24 months).

In addition to strengthening the program with the addition of industrial and university contracts, steps were taken to rebuild CSP capabilities at SNL and NREL. Funding was made available to increase the staffs at both labs, whose efforts resulted in some significant achievements during FY 2008. These included improvement in the design and reliability of the Stirling dish-engine system, improvement in the heat transfer properties of molten salt, the completion of a report to Congress identifying methods of minimizing the use of water by CSP power plants, development of a high-temperature/low emissivity receiver, development of optical tools that assist industry in evaluating their products, and the expansion of capabilities of the Solar Advisor Model, which has become important to the CSP industry. Funding was also made available to upgrade the National Solar Thermal Testing Facility at SNL after a long period of relative neglect.

During FY 2008, our attention turned to a potential roadblock to CSP deployment: land availability. Utility-scale solar power plants require a lot of land. A 300-MW plant, for example, requires 3 to 4 square miles of relatively flat land. To address this issue, we began working with BLM, which manages 219 million acres of federal land in the southwestern United States. Although most of this land has excellent solar resources, much of it is too hilly or has environmental restrictions that keep it from being available for solar development. DOE and BLM became co-leads in a solar programmatic environmental impact statement (PEIS); its objective is to find suitable land for solar technology. Argonne National Laboratory was selected to assist in identifying land with a slope of 5 degrees or less, a solar resource greater than 6.5 $kWh/m^2/day$, no environmental or cultural restrictions, and access to transmission. This effort will conclude with the issuance of the final PEIS in March 2010. We are also working with the Western Governors' Association and the California Renewable Energy Transmission Initiative, both of which are in the process of identifying land suitable for renewable energy projects.

Although the CSP program activity was suffused with optimism, no new CSP projects began to be constructed during the year. For much of the year, construction was held back by the end-of-year termination of the 30% ITC. When the ITC was finally extended, industry found that the national recession had dried up sources of investment. As one industry leader lamented: "We got the ITC only to find there was no 'I' available." Hopefully, economic policies will unleash the investment needed for industry to begin building CSP plants in FY 2009. This is important because the cost reductions necessary for achieving the CSP intermediate power goal are brought about through a combination of R&D and the building of projects.

A summary of the solar heating and cooling activities are also included in this section, but the management of these activities was moved into the DOE Building Technologies Program.

Parabolic Trough Research and Development

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Chuck Kutscher (NREL, Primary Contact), 303-384-7521, chuck_kutscher@nrel.gov
Greg Kolb (SNL), 505-844-1887, gjkolb@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2008 Budgets: $2,149K (NREL), $600K (SNL)

Objectives

- Support near-term parabolic trough technology for central station power generation.
- Support development of advanced technologies for next-generation parabolic trough solar fields, thermal energy storage, and power plant technologies to meet DOE long-term goals.
- Support expansion of U.S. industry to supply parabolic trough technology.
- Support continued SunLab, joint effort between SNL and NREL in support of DOE's research and development (R&D) activities on concentrating solar power (CSP) technologies, collaboration on parabolic trough technology development and testing.

Accomplishments

Trough Solar Field

Reflector Optical Measurement

- Used Video Scanning Hartmann Optical Test (VSHOT) instrument to evaluate mirrors from Guardian Glass and Naugatuck Glass and parabolic trough collectors from Abengoa and SkyFuel with capability transferred to Solar Systems.
- Developed two new VSHOT systems: one portable system for full aperture trough characterization in the field and at industry partner facilities and a system for laboratory testing of flat and single-axis curvature mirrors. (NREL)

TOP Alignment

- Used TOP alignment tool, aligned six trough modules at the Saguaro Solar Plant. Acquired TOP alignment data for one loop at every LS2 solar plant in California. Using this data, aligned two loops at the SEGS plants with an estimated 5%–10% performance improvement. (SNL)

Receiver Heat Loss

- Tested latest Schott and Solel receiver tubes and performed preliminary experiments on impact of xenon/hydrogen and argon/hydrogen mixtures in receiver vacuum space. (NREL)

Hydrogen Mitigation

- Developed model of hydrogen generation and transport in parabolic solar collector field. (NREL)

Optical Efficiency Test Loop

- Completed construction of the outdoor optical efficiency test loop and tested Acciona/Gossamer 8-meter parabolic trough. (NREL)

Advanced Trough Materials

- Selected U.S. industry partner to rapidly commercialize improved solar selective coating. (NREL)

Salt Freeze/Thaw Experiments

- Configured test loop and began series of freeze/thaw tests. (SNL)

Distant Observer Technique

- Completed feasibility study on use of Distant Observer technique and found it could provide a rapid and inexpensive means to detect optical alignment problems in the solar field. (NREL)

Power Cycle and Balance of Plant

Plant Optimization and Costing

- Validated steam cycle component correlations used in the Solar Advisor Model (SAM) and determine costs of Rankine cycle components to be incorporated into SAM.

Heat Rejection

- Produced joint report for Congress on reducing water consumption in CSP. (NREL)

Trough Systems Integration

Trough R&D Management

- Organized and hosted nine parabolic trough sessions at SolarPACES conference. (NREL)

Industry Support

- Provided technical support to a wide range of CSP companies, including SkyFuel, Abengoa, Schott, Solel, and Solar Systems and prepared report summarizing this assistance. (NREL)

Future Directions

Trough Solar Field

Reflector Optical Measurement

- Continue to improve VSHOT capability, specifically by extending it to measure larger reflector apertures and longer sections of reflector. (NREL)
- Extend capability of VSHOT to examine impacts of structural loads on reflector shape.

Top Alignment

- Improve algorithm calculating amount of mirror adjustments.
- Align one or more loops at an LS2 parabolic trough plant and document the improvement. (SNL)
- Design truck-mounted version of TOP Alignment system and will work on licensing TOP Alignment technology to an outside company. (SNL)
- Develop TOP Alignment system for LS3 type trough designs

Receiver Heat Loss

- Expand capability of receiver heat loss measurement rig for faster tests and testing of longer receiver tubes. This apparatus will see continued use for the testing of newest industry receiver tubes and for tubes incorporating NREL's latest high-performance absorber coating. (NREL)

Hydrogen Mitigation

- Establish working agreement with SEGS plant to perform on-site testing of procedures and/or methods that will remove hydrogen from the heat transfer fluid within the HCEs, and expansion tank of the power plant. (NREL)

Optical Efficiency Test Loop

- Conduct optical efficiency measurements of new SkyTrough parabolic collector, including both normal incidence and incident angle modifier tests. Also test additional state-of-the-art collector. (NREL)
- Upgrade software and rotating platform control box. (SNL)

Advanced Trough Materials

- Work with our licensing partner to develop advanced selective surface. (NREL)

Salt Freeze/Thaw Experiments

- Conduct about 20 freeze/thaw cycles, or until failure, to determine effect of salt in trough receivers when it freezes and when it is thawed out and document test in a report.

Distant Observer Technique

- Develop and test airborne experimental technique to measure optical performance of parabolic trough collector field and test it at an operating plant.

Power Cycle and Balance-of-Plant

Plant Optimization and Costing

- Develop parabolic trough collector field model with storage, using molten salt heat transfer fluid.

Heat Rejection

- Conduct analysis to optimize parallel hybrid cooling systems for trough plants in several climates.

Industry Support

- Continue to support industry contracts and other industry support on an as-needed basis.

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1. Technical Approach

The parabolic trough R&D effort is broken into three areas: (1) trough solar field, (2) power cycle and balance-of-plant, and (3) industry support.

1.1 Trough Solar Field

The solar field technology agreement focuses on SunLab development of new parabolic trough solar technology and tools for evaluation of trough technology. The focus is on these areas: reflector optical measurement, TOP Alignment system, receiver heat loss, hydrogen mitigation, optical efficiency test loop, advanced trough materials, salt freeze/thaw experiments, and distant observer technique.

1.2 Power Cycle and Balance of Plant

The Power Cycle and Balance of Plant agreement focuses on improving overall parabolic plant performance. The work is focused on plant optimization and costing and heat rejection.

1.3 Systems Integration

This activity focuses on general support for trough technologies and technical support to industry.

2. Results and Accomplishments

2.1 Solar Field Technology

Reflector Optical Measurement

The VSHOT instrument evaluated the accuracy of parabolic trough collectors from Abengoa and SkyFuel. This capability was specifically used to greatly improve the optical accuracy of SkyFuel's new SkyTrough collector that utilizes a polymer film reflector. We also performed VSHOT characterization of new mirror technology for Guardian Glass and Naugatuck Glass and developed two new VSHOT systems, one portable system for full aperture trough characterization in the field and at industry partner facilities and a system for laboratory testing of flat and single-axis curvature mirrors.

TOP Alignment

The time to acquire data was reduced from 70 seconds/module to 35 seconds/module. There are several ideas to reduce this time even further. Considering there are close to 5,000 modules for each 30 megawatt (mW) trough plant, reducing this time is very important. The quality of pictures taken by the cameras has been improved by using higher resolution cameras, but mostly by controlling the contrast of the pictures. This has greatly improved and reduced the time in analyzing the pictures. Tests were completed at the Saguaro parabolic trough power plant and at SEGS. Using this process has led to an estimated 10% improvement in the aligned loop at SEGSVI.

Receiver Heat Loss

NREL tested the latest Schott and Solel receiver tubes and performed preliminary experiments on the impact of xenon/hydrogen mixtures in the vacuum space.

Hydrogen Mitigation

NREL developed a computer model of hydrogen generation and transport within a parabolic trough plant and identified several means for removing hydrogen.

Optical Efficiency Test Loop

NREL completed the construction, data acquisition, and shakedown testing of the new outdoor optical efficiency test loop. We mounted an Acciona/Gossamer 8-meter parabolic trough and Schott receiver tubes and measured optical efficiency values obtaining approximately 75%.

Advanced Trough Materials

Patent filed in FY 2008 on ROI 05-02 "High Temperature Solar Selective Coatings". Worked with the NREL Technology Transfer Office to identify a U.S. industry partner to rapidly commercialize and license the improved solar selective coating. NREL reached an agreement with Schott to license our low-emissivity absorber coating.

Figure 1. Pictured is NREL#6A solar selective coating deposited by directly and reactively evaporating the layers by elemental co-deposition.

Salt Freeze/Thaw Experiments

SNL set up a new system with data acquisition, controller, impedance heating system and set up three trough modules for the freeze/thaw test. Initial testing showed the impedance heat system did have the power to properly heat two receivers but not three. One was removed, and the remaining two were filled with salt. Due to equipment problems, testing is still ongoing.

Distant Observer Technique
A feasibility study was performed on the use of a Distant Observer technique to determine the accuracy of a parabolic trough collector field and concluded that this method could provide a rapid and inexpensive means to detect performance problems in the field, from both mirror and receiver misalignment.

FY 2008 Milestones:

- Demo TOP systems in Arizona. (2/29/08)
- Complete laboratory testing and technical report on the heat loss performance of one or more next-generation heat collection elements. (12/31/07)
- Complete laboratory testing and technical report on heat loss performance of one or more next-generation heat collection elements. (12/31/07)
- Complete instrumentation and qualification tests optical efficiency test loop. (3/31/08)
- Complete optical testing of one or more industry-supplied collector designs integrated with next-generation heat collection element. (9/30/08)
- Assess efficacy of a distant observer tool capable of rapid analysis of large sections of collector fields in feasibility study. (9/30/08)

2.2 Power Cycle and Balance of Plant
Plant Optimization and Costing
Nexant performed an analysis comparing the Rankine steam cycle performance predicted by EES (the tool used for SAM) to GateCycle analyses. This showed the energy production predicted by the EES model was within 3% of the energy predicted by GateCycle, thus validating SAM. A spreadsheet model was developed to determine the costs of Rankine cycle components to be incorporated into SAM.

Heat Rejection
In response to a Congressional request, a joint report, "Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation," was produced. This report reviewed a number of studies of power plant cooling system options and concluded that water used for heat rejection can be reduced 80% via a hybrid parallel water/air cooling system with only couple percent drop in power output. Whereas air cooling would increase levelized electricity cost by about 8% compared to a water-cooled plant, it is estimated that a parallel system would have a penalty of only about half that much, although further work is needed to fully optimize the parallel system.

FY 2008 Milestones:

- Complete report on CSP power plant water needs and how to address them. (3/1/08)

2.3 Systems Integration
FY 2008 Milestones:

- Organize parabolic trough and thermal storage R&D sessions for SolarPACES Symposium in the U.S. (3/31/08)
- End-of-year report summarizing activities in support of FOA contractors. (10/31/08)
- Report summarizing industry support activities. (10/31/08)

3. Major FY 2008 Publications

E. Lupfert; K.J. Riffelmann; H. Price; F. Burkholder; Tim Moss. "*Experimental Analysis of Overall Thermal Properties of Parabolic Trough Receivers*", ASME Journal, 2007.

M. Lausten; C. Kutscher. *"Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation."*

F. Burkholder; M. Brandemuehl; C. Kutscher; E. Wolfrum. "Heat Conduction of Inert Gas-Hydrogen Mixtures in Parabolic Trough Receivers," presented at the ASME International Conference on Energy Sustainability in Jacksonville, Florida, August 2008.

G. Jorgensen; F. Burkholder; A. Gray; T. Wendelin. *"FY 2008 CSP Milestone Report: Assess the Efficacy of an Aerial Distant Observer Tool Capable of Rapid Analysis of Large Sections of Collector Fields."*

C. Kennedy. *"Progress to Develop an Advanced Solar-Selective Coating*" presented at 2008 SolarPaces Symposium in Las Vegas, Nevada, on March 2008. Selected for publication in ASME-*Journal of Solar Energy Engineering* (JSEE).

Industry Projects

Performing Organizations: Alcoa, Inc.
Abengoa Solar, Inc.

Key Technical Contacts: Carolyn Elam, DOE Golden Field Office (DOE/GO), 303-275-4953, carolyn.elam@go.doe.gov
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FY 2008 Budgets: $2,022K Recipients

Objectives

- Develop energy supply technologies that are reliable, affordable, and environmentally sound. Expand national electricity generation portfolio to increase energy security by diversifying domestic energy supply options. Concentrating solar power (CSP) is one of the most attractive renewable energy options in the Southwest U.S., with a nominal levelized cost of energy (LCOE) target of 7-10¢/kWh by 2015 and 5-7¢/kWh by 2020.
- Advance U.S.-based trough technology by encouraging development and eventual U.S. manufacturing of key parabolic trough components or subsystems.
- Emphasize design for manufacturability and/or near-term (commercial applications within the next 5 years) U.S. supply of key parabolic trough components or subsystems.

Accomplishments

- Held merit review of applications in September and announced selections in October 2007.
- Negotiated and awarded all three CSP parabolic trough development awards by mid-2008.
- Defined roles and responsibilities of program management team, including technical advisors at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories.

Future Directions

- Evaluate progress toward critical milestones and decisions will be made at the end of the each project's first phase, starting in FY 2009 and extending into FY 2010.

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1. Introduction

These CSP trough development activities within are expected to produce commercial parabolic trough components or subsystems within the next 5 years enabling CSP to meet a nominal levelized cost of energy (LCOE) target of 7-10¢/kWh by 2015 and 5-7¢/kWh by 2020.

One objective of this area of interest is to advance U.S. based trough technology by encouraging the development and eventual U.S. manufacturing of key parabolic trough components or subsystems that can only be obtained from a limited number of foreign companies.

The selected projects are:

Organization, PI, and Agreement Title	FY 2008 Budget ($K)
Alcoa, Inc. - Adam Schaut "Reflector Technology Development and System Design for CSP Technologies"	1,098
Abengoa Solar, Inc. - Keith Boyle "Development of Advanced Polymeric Reflector for Concentrating Solar Power"	439
Abengoa Solar, Inc. - Hank Price "Development of Next-Generation Parabolic Trough Collectors and Components for CSP Applications"	485

Reflector Technology Development and System Design for CSP Technologies (Alcoa)
Total Award: $3,658K, DOE/Recipient Share: $2,128K/$1,530K

Objectives
- Develop aluminum-intensive collector that provides superior total life cycle cost.
- Achieve 25%-50% cost savings for the solar field, lowering LCOE at least 20%.
- Achieve high performance optical performance and superior outdoor durability (10 Years).
- Positively impact U.S. manufacturing base.

Accomplishments
- Pursued two independent approaches to reflective surface.
- Evaluated various structural design architectural approaches before selecting “wingbox” design.
- Maximized material utilization efficiency while maintaining structural rigidity and strength.
- Developed cost models using concurrent FEA analysis with Solar Advisor Model LCOE calculations.

Future Directions
- Complete Phase 1 reflective surface and structural design activities.
- Perform a detailed design of the down-selected concept from Phase 1, develop a prototype, and validate performance.
- Developed detailed design (3D CAD), structural analysis (finite element analysis or FEA), and detailed cost modeling of the prototype.
- Complete internal critical design review of the prototype.
- Fabricate, evaluate and verify the full scale prototype.
- Revise framework for Phase 2, based on Phase 1 results.

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1. Introduction

Current baseline solar trough collectors differ in supporting structure (aluminum space frame vs. steel torque-box), but both predominantly use parabolic, silver-metallized glass mirrors, which have disadvantages such as fragility, weight, and cost. Alcoa is using an optimized system design approach to develop an aluminum-intensive collector.

2. Results and Accomplishments

Two aluminum-based reflective surface development approaches were finalized; thin film and silver film. For thin film, deposition testing on coated and leveled aluminum sheets was performed and tested via accelerated procedures. More than 25 different actual coil-coated aluminum samples were tested, and two good candidates were identified. A laminate of a batch silver-metalized clear film adhesively bonded onto an aluminum sheet is under testing.

Alcoa evaluated options for incorporating the reflective surface as a structurally significant component of the solar trough assembly and identified three basic architectures: space frame, torque box, and monocoque, or “wingbox.” Preliminary structural evaluations indicated the wingbox approach has the most potential for efficient material utilization based on the goal of incorporating a stressed-skin approach. Analysis of this design continues with encouraging results.

3. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 (k)
CSP Services (DLR)/ Eckhard Luepfert	Cologne, Germany	Subcontractor to Alcoa, Inc., CSP technology and performance expertise	$27*

*Included in the total Phase I

Development of Advanced Polymeric Reflector for Concentrating Solar Power
(Abengoa Solar, Inc.)
Total Award: $2,076K, DOE/Recipient Share: $1,512K/$565K

Objectives

- Reduce cost of parabolic trough collector systems by reducing cost of reflector.
- Develop reflector technology that will be used in Abengoa Solar's U.S. projects that are planned for initial operation in 2010-2013 timeframe.
- Source as much collector technology (e.g., reflector components) from U.S. sources as possible.

Future Directions

- Transfer and validate initial process, since phase 1 started at end of FY 20008.
- Complete Phase 1 objectives.
- Use phase 1 results to show a reasonable path to reduced LCOE.

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1. Introduction

The Abengoa team is evaluating the possibility of commercial production of a lab-scale advanced solar reflector material (ASRM) for CSP. The technology has the potential for lower cost reflectors, and possible design flexibility which may lead to entirely new approaches to low-cost concentrator design.

2. Technical Approach

The ASRM (produced in 2003 under sponsorship by NREL) will be scaled up from laboratory-scale to limited production runs on a commercial-scale 48-inch wide roll coater. During Phase 1, the scale-up to commercial roll-to-roll coating will be tested and validated, and production costs will be modeled. During Phase 2, the process will be scaled up to a ½-width pilot production system. The operating information will be used to create a full-scale reflector to demonstrate the technical and cost specifications of the system and to refine the cost model. This phase will demonstrate limited scale-up and cost effects of that scaling effort. During Phase 3, the team will scale the ASRM up to full width to demonstrate pilot production runs. The products from this test run will be used in a full scale reflector to test the product in the field. Outdoor reflector performance of the production-scale product will also be demonstrated.

3. University and Industry Partners

Task work will start in FY 2009, so the following chart refers to the FY 2009 first-phase costs.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
SAIC Dr. Russell Smilgys	McLean, VA	Transition and adoption of previous ASRM work into commercial environment	102	2.5
CSI/Marian Mike Martin	San Diego, CA	Integration of new ASRM into commercial equipment and scale-up of production	246	16.25
Swisher & Assoc. Dr. Richard Swisher	Northfield, MN	Transition, adaption, and model revision for new ASRM	63	0

Development of Next-Generation Parabolic Trough Collectors and Components for CSP Applications (Abengoa Solar, Inc.)

Total Award: $606K, DOE/Recipient Share: $485K/$121K

Objectives

- Reduce cost of collector technologies that could be deployed in first U.S. CSP plants in 2010–2013 time frames.
- Develop alternative collector structures, components, and field deployment techniques.
- Employ innovative approaches to developing next generation of lower-cost parabolic trough technologies that can compete on equal footing with conventional power generation.
- Build on results of initial phases, complete initial deployment of new generation of trough technology aimed at achieving major cost reductions for medium-term deployments.

Accomplishments

- Generated generally applicable collector cost metrics.
- Detailed finite element analysis models of three collector design possibilities.
- Characterized conflict in existing collector wind tunnel studies' design implications.

Future Directions

- Finalize assessment of existing designs and foundations, specify and advanced collector, and perform construction labor review.
- Complete small-scale prototype testing (Phase 2).
- Expand to full-loop scale testing and validation (Phase 2).
- Complete advanced collector design and fabrication (Phase 2).

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1. Introduction

The goal is to develop the technology that is needed to build a competitive parabolic trough industry for the U.S. utility market. To achieve this objective, the project plans to reduce the cost of collector technologies and use innovative approaches to develop the next generation of lower cost parabolic trough technology.

2. Technical Approach

Phase 1 focuses on analysis and assessment of collector designs, foundations, and fabrication techniques. The team will conduct a detailed evaluation of existing collector designs, first specifying the metrics by which they will be evaluated, then evaluate them using comparable testing environments and methods. Next, the team will analyze foundation designs for material and fabrication cost reductions. The team will determine possible new collector design criteria and will specify an advanced collector based on cost impacts using metrics developed earlier. Subsequently, the team will conduct a construction labor review. Outside experts (i.e. academia) will be consulted to analyze and review project construction and fabrication techniques for possible cost savings.

3. Results and Accomplishments

A uniform set of metrics for collector comparison (operations, survival, cost) has been developed and the documentation is in progress. These metrics are being used in the evaluation tasks. Work continues on the side-by-side comparison of module designs. These comparisons encompass optical, structural, and cost analysis. The cost comparisons are fully developed and can be quickly adapted for 'what-if' scenarios. The optical analysis provides a reasonable basis for comparison, with additional detail from ray tracing about 75% complete. The benefits and drawbacks of each design are nearly complete, with work remaining in structural comparisons.

The fabrication of prototype modules is 20% complete. The ASTR0 jigs are in progress, and module materials have been delivered. Structural testing data has been located that may save time and cost in the evaluation of the module's performance.

Experience at Abengoa's Solana plant is being used in the assessment of foundation structures. Basic analysis of trade offs and cost is underway for a detailed analysis and design.

Dish Engine Research and Development

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contact: Charles Andraka (SNL), 505-844-8573, ceandra@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2008 Budget: $1,471K

Objectives

- Improve reliability and reduce cost of dish/engine components and systems.
- Support industry in commercialization of the technology.
- Perform research and development on dish/engine system components and systems.
- Test, evaluate, and improve performance of dish/engine components and systems.
- Develop tools for industry to characterize their systems and components

Accomplishments

- Continued to operate, maintain, and improve the Stirling Energy Systems (SES) six-dish model power plant, cataloging more than 100 development areas.
- Participated as a key member of the commercial product design team.
- Developed real-time mirror characterization prototype system for 100% inspection of mirrors on assembly line.
- Developed engine simulator for development of modern engine control hardware and software.
- Mentored new solar engineers through SNL programs and at industry partners.
- Developed tradeoff study of facet performance and cost to guide commercialization efforts.
- Assisted Infinia in optical design and systems design of 3-kilowatt (kW) free piston Stirling engine (FPSE) dish system.
- Enhanced CIRCE2 model to support finite element analysis-modeled deflections.
- Participated in funding opportunity announcement (FOA) team for dish Brayton system.

Future Directions

Primary activities in fiscal year (FY) 2009 will support industry's efforts toward commercialization:

- Continue to evaluate the reliability of the six-dish mini-power plant.
- Identify and resolve operational and reliability issues.
- Install and commission four pre-production dish systems at SNL.
- Retrofit and commission six model power plant (MPP) dishes with production units.
- Develop highly automated rapid alignment system for production dishes.
- Continue to participate on commercial product design team.
- Install two next-generation Infinia dish systems at SNL.
- Continue to support Infinia's commercialization effort.
- Evaluate possible additional dish/engine products, as needed.

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1. Introduction

Staff members work closely with the industry to improve dish-Stirling system performance and reliability and to support industry deployment in the near term. While SNL continued to gain operational experience with the SES 6-dish MPP, the primary focus was on next-generation system design, with an emphasis on manufacturability.

SES is pursuing the aggressive deployment of 25-kW dish-Stirling systems for bulk power generation. The success of the MPP has led to SES agreements with Southern California Edison for up to 850 megawatts (MW) of power and with San Diego Gas and Electric for up to 900 MW.

Infinia, previously Stirling Technology Corporation (STC), has developed a system around a 3-kW free-piston Stirling engine. This system is hermetically sealed and requires no maintenance. Infinia plans both large and small deployments and has targeted photovoltaics as a competitor. SNL was involved in the conceptual design, detailed design, and deployment of the first prototype systems. SNL has entered into a memorandum of understanding with Infinia to support several Infinia staff on SNL premises. A prototype dish was set up at SNL, and optically characterized, providing feedback to the facet manufacturer.

2. Results and Accomplishments

By the end of FY 2008, the MPP dish systems had accumulated over a total of 24,000 hours on sun. The performance of the system continues to exceed the performance of the MDC systems, primarily as a result of improved system optics, alignment, and cooling.

On January 31, 2008, SES and SNL set a world record for sunlight to grid electricity with one of the MPP units. This new record was 31.25% net conversion efficiency, averaged over a full hour of operation. This significant accomplishment was awards a “Breakthrough Award” by Popular Mechanics, recognition of life-changing and society-changing technical accomplishments.

SES has used the reliability data captured in the Failure Reporting, Analysis, and Corrective Action System (FRACAS) to guide the design work during the commercialization effort. Many of the issues are software related, and the solutions have been folded into the software specification. Likewise, their engine manufacturer has addressed outstanding issues in the design of the commercial engine. This formalized path from testing to final design is key to producing a highly reliable system. SES and Linamar will install a number of production engines in test cells to provide accelerated testing of the commercial package.

Continued refinement of the dish system leading to the commercial system has led to a weight reduction of nearly 6,000 pounds and resulted in a stiffer optical system. This was facilitated over the last 3 years by SNL’s optical code (CIRCE2) combined with SES’s structural model. SES’s steel fabrication partner has designed a highly automated fabrication plant in conjunction with the redesign effort. The refinement of this design is continuing, taking into account the key environmental implications of the California sites.

The combination of CIRCE2 with the structural modeling has been a key insight by SNL and implementation by the SES team. We have continued to refine this connection. While most of the work performed to date imposed structural deflections as rigid-body rotations of the facets, new improvements to CIRCE2 will allow the actual facets to be shape-distorted in the optical model, based on finite element model results.

SNL continued the development of an alignment system suitable for high rate production. Such a system requires computer interpretation of the alignment status, and digital feedback to technicians or to actuators. We have developed an approach based on fringe reflection measurements, and we have tested key components of the software. The approach appears to be very robust within a significant range of mirror quality.

A spinoff of the alignment tool has been a facet characterization system, also based on fringe reflection techniques. This tool accurately measures slope errors and shape errors of facets in less than 10 seconds, allowing application to the production line for quality control.

SES announced the delivery of their application for certification for the Solar 2 plant in California, and the acceptance of this documentation as “data adequate”. This is a key document leading to the deployment of systems in California.

SNL also continued to support Infinia in the development of its 3-kW dish engine system with two prototype systems to be installed at SNL. Infinia completed a prototype system at its headquarters in Kennewick, Washington, to refine system controls and performance.

SNL published an ASME paper that explores the relationship between facet optical performance and system economic performance. The thesis of the paper, confirmed through the analysis presented, discusses the affordability of quality optics, or conversely, in high temperature systems, the cost savings of “cheap” optics is typically more than offset by revenue losses and loss of system value. This has been a key and consistent finding in the SNL dish development activities, starting in the Cummins and Advanced Dish Development System efforts.

Industry Projects

Performing Organizations: Brayton Energy
Infinia Corporation

Key Technical Contacts: Carolyn Elam, DOE Golden Field Office (DOE/GO), 303-275-4953, carolyn.elam@go.doe.gov
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DOE HQ Technology Managers: Frank (Tex) Wilkins, (202) 586-1684, frank.wilkins@ee.doe.gov
Tommy Rueckert, (202) 586-0942, thomas.rueckert@ee.doe.gov

FY 2008 Budgets: $595K (Recipients)

Objectives

- Develop energy supply technologies that are reliable, affordable, and environmentally sound. Expand national electricity generation portfolio to increase energy security by diversifying domestic energy supply options. Concentrating solar power (CSP) is one of the most attractive renewable energy options in southwest U.S., with a nominal levelized cost of energy (LCOE) target of 7-10¢/kWh by 2015 and 5-7¢/kWh by 2020.
- Provide preliminary exploration/feasibility of new CSP approaches for electrical power production. In-depth systems analysis is desired that specifies characteristics of system (e.g., size, components, operating temperature, component and system efficiencies, storage and heat transfer fluids), major technical barriers and proposed approaches to overcoming them, estimated system and component costs, and operation and maintenance costs.

Accomplishments

- Held merit review of applications in September and announced selections in October 2007.
- Negotiated CSP Dish/Stirling research and development awards, awarded by mid-2008.
- Defined roles and responsibilities of program management team, including technical advisors at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL).

Future Directions

- Evaluate progress toward critical milestones and decisions will be made at the end of the each project's first phase, starting in FY 2009 and extending into FY 2010.

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1. Technical Approach

The funding opportunity announcement (FOA) investigated three areas to address market barriers for utility-scale generation of CSP technologies: thermal storage; trough component manufacturing; and advanced CSP systems and/or components (Dish/Stirling R&D).

The selected projects are listed in the table below.

Organization, PI, and Agreement Title	FY 2008 Budget ($K)
Brayton Energy - James Kesseli "Brayton Solar Power Conversion System"	274
Infinia Corporation - Qiu Songgang "30-kW Maintenance Free Stirling Engine for High Performance Dish Concentrating Solar Power"	321

Brayton Solar Power Conversion System (Brayton Energy)
Total Award: $4,269K, DOE/Recipient Share: $2,300K/$1,969K

Objectives

- Design and demonstrate novel Dish-Brayton hybrid concentration solar power module.
- Achieve LCOE of $0.075 to 0.10/kWH with an engine lifetime of 40,000 hours.
- Achieve low emissions in alternate modes using natural gas, ethanols, or bio-oils.

Accomplishments

- Completed Phase 1, delivering 232-page technical report.
- Applied proven components and design principals to Dish-Brayton design.
- Prepared novel solar receiver design, subjected to review by U.S. government labs.
- Operated air-bearing turboalternator at full speed on bench-test rig, without heat.

Future Directions

- Fabricate and test purpose-built gas turbine engine with hydrocarbon fuels.
- Integrate receiver and engine with purpose-built solar concentrator.
- Test and characterize two subassemblies:
    - Turboalternatort: complete power conversion system in a laboratory setting with hybrid fuel systems but no solar receiver, measuring efficiencies and emission levels.
    - Solar receiver: in lab environment and 320-square meter dish, characterizing cavity and overall heat losses.

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1. Introduction

Brayton Energy has performed extensive design and analysis of a novel CSP conversion system. The system employs a specialized recuperated gas turbine generator with a solar receiver. Prototype units will be fabricated, and an assembly plant for volume manufacturing begun near Phoenix. The focus is on the engine/receiver module design and component tests.

2. Results and Accomplishments

The design of the turbo-alternator and recuperator are complete and analysis is ongoing for durability of critical elements in the design. The LCOE analysis is complete and has met objectives, based upon performance analyses, capital cost, and life/maintenance expectations. Findings support the achievability of near-term DOE cost targets of $0.075 to $0.10/kWh. The final design employs intercooling, high levels of recuperation and re-heat, enabling engine thermal-electric efficiency to exceed 37% at moderate turbine inlet temperatures. A detailed a bill or materials has been prepared for the engine and receiver, to assist fabrication in Phase 2.

3. FY 2008 Special Recognitions and Patents

Brayton Energy has received two patents on this system on power conversion systems and variable position turbine nozzle. Six other filings related to recuperators, turbomachinery, and solar receivers have been submitted to the U.S. patent office.

4. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Oak Ridge National Labs/Dr. Bruce Pint	Oak Ridge, TN	High-temperature materials evaluation	26	0
SolarCAT Inc., Herb Hayden	Glendale, AZ	Dish design, fabrication, testing. Assembly factory deployment. 100-MWe site development	0	73

30-kW Maintenance-Free Stirling Engine for High-Performance Dish Concentrating Solar Power (Infinia Corporation)

Total Award: $3,196K, DOE/Recipient Share: $2,062K/$1,134K

Objectives

- Develop 30-kW CSP system that utilizes a multi-cylinder free-piston Stirling engine (MCFPSE).
- Provide prototype engine design for Phase 1, demonstration 30-kW engine prototype for phase 2, and field test a production-like prototype for phase 3.

Accomplishments

- Preliminary design of six-cylinder fully balanced, dual-engine configuration almost complete, with projected engine performance of 58%, Carnot and engine/alternator efficiency approaching 33%.

Future Directions

- Finalize prototype engine design, fabricate and assemble engine, and test and evaluate engine.
- Complete preliminary LCOE cost analysis.
- Complete Integration design of engine with Science Applications International Corporation Gen 1 dish for demonstration.
- Finalized preliminary design of the 30-kW multi-cylinder engine.
- Complete manufacturing cost analysis for the engine and dish.
- Verify impact of reduced engine operating and maintenance (O&M) costs on LCOE of CSP system.
- Determine any residual technical or cost barriers.

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1. Introduction

For dish Stirling CSP, two issues of concern are engine life/reliability and O&M costs. The objective is to address these concerns with a maintenance-free 30-kW MCFPSE for Dish Stirling CSP applications, improving reliability and lowering costs.

2. Technical Approach

Infinia focused on the preliminary design and analysis of a 30-kW multi-cylinder configuration. The approach is to adapt prior MCFPSE conceptual design approaches to develop a 30-kW design, heavily leveraging the existing 3-kW commercial engine. To facilitate this process, SAGE analysis is used to evaluate 3- and 6-cylinder designs and other factors.

3. Results and Accomplishments

Infinia completed the SAGE analysis and selected a fully balanced 6-cylinder configuration composed of two 3-cylinder engine modules. The engine performance is excellent at 58% of Carnot with engine/alternator efficiency exceeding 33%. The conceptual design of a hybrid heater head was selected. Linear alternator optimization was conducted to estimate the efficiency, weight, and size of the linear alternator. The engine controller conceptual design is largely finished. Cost analysis for the engine and dish is ongoing.

4. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)
Butler Sun Solutions Barry Butler	Solana Beach, CA	Sourcing of dish and dish costing analysis	3
Consultant Barry Penswick	Stevenson, WA	Stirling engine design	27

Storage Components

Performing Organization:	Sandia National Laboratories (SNL)
Key Technical Contacts:	Nathan Siegel (SNL), 505-284-2033, npsiege@sandia.gov Bob Bradshaw (SNL), 925-294-3229, rwbrads@sandia.gov Greg Kolb (SNL), 505-844-1887, gjkolb@sandia.gov Tom Mancini (SNL), 505-844-8643, trmanci@sandia.gov
DOE HQ Technology Manager:	Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov
FY 2008 Budget:	$93K (SNL)

Objectives

- Develop components and systems necessary for incorporating thermal storage into concentrating solar power (CSP) facilities.
- Support industrial partners who are developing thermal storage technologies.

Accomplishments

- Completed preliminary design of a test facility upgrade to evaluate components (e.g., heat exchangers, pumps, valves, instrumentation) required by power plants, using molten salt heat transfer and storage fluids.

Future Directions

- Support funding opportunity announcement (FOA) awardees.

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1. Results and Accomplishments

Freeze Recovery

- Constructed impedance heating test platform.
- Performed preliminary freeze/thaw studies.

Several industry partners have proposed using molten salt in the field for parabolic trough plants. A strategy must be developed that will enable the facility to recover from a freeze. One option is to treat the HCEs as electrical resistors that can be used to thaw the frozen salt within them when an electrical current is applied. Questions remain as to whether the HCEs can be adequately heated in this manner without damage. We are exposing the HCEs, which have been filled with salt, to successive freeze thaw cycles. Preliminary results show some tube motion during cycling due to induced stresses. In addition, Solar Millennium, a FOA awardee, has requested test support using this platform.

Molten Salt Test Facility Design

- Completed preliminary facility design.
- Began industry workshop planning to further define the required upgrades and test and evaluation needs.

There is an industry-wide need for qualification and de-risking of the components used to handle heat transfer and thermal storage media, particularly molten salts. A suitable test and evaluation platform does not exist. To meet industry needs, our design of the upgraded facility would be built off of existing infrastructure and be able to accommodate an expanded suite of component testing and development. We are soliciting input from industry partners in fully defining the capabilities of the facility.

2. Planned FY 2009 Activities

Freeze Recovery

- Continue evaluating the impedance heating strategy and identifying technical hurdles.
- Develop inroads with international partners working on similar technologies.

Molten Salt Test Facility Design

- Host industry workshop for design input.
- Complete conceptual design.
- Place a contract with an A&E firm to begin the detailed design.
- Place construction contracts and begin construction.

Storage Systems

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Mark Mehos (NREL), 303-384-7458, mark_mehos@nrel.gov
Tom Mancini (SNL), 505-844-8643, trmanci@sandia.gov
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DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov

FY 2008 Budgets: $319K (NREL), $130K (SNL)

Objectives

- Develop conceptual designs for thermal storage of a molten salt system that uses stratified storage of hot and cold fluids.
- Assess the potential for reducing the cost and complexity of the storage systems for power generation from CSP.

Accomplishments

- Developed sizes and nominal conceptual designs for single and multiple storage tanks for CSP power system of nominal 280-MWe capacity. (NREL)
- Developed CFD analyses results for transient heat transfer between filler media and molten salt.
- Developed two-dimensional analyses results for flow and heat transfer in tanks with and without filler material. (NREL)
- Established long-term behavior of stratified tanks charged and discharged with salts of constant temperature. (NREL)
- Evaluated the use of multiple tanks (such that they may be binned as the collection temperature varies with solar radiation intensity). (NREL)

Future Directions

- Analyze material requirements and performance of thermocline systems as a function of the number of storage vessels (1 – 6). (NREL)
- Analyze operational strategies for multiple storage vessel systems (1 – 6). (NREL)
- Analyze operation under nonideal conditions including input fluid with varying temperature. (NREL)
- Further characterize the dynamic response of the filler material to a change in fluid temperature and estimate the effect on thermocline degradation. (NREL)
- Integrate performance results and material estimates into new cost models. (NREL)
- Estimate the cost benefits of using thermocline storage as opposed to constant temperature, two-tank storage. (NREL)

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1. Introduction

The objective of the thermal storage modeling activity is to develop advanced technologies and effective integrated thermal storage systems directed at meeting the DOE Concentrated Solar Power (CSP) subprogram goals.

2. Technical Approach

<u>*NREL*</u>

For this study, we assumed a power plant nominal name plate capacity of 280 MWe, to be located in the arid deserts of Arizona. Detailed flow and thermal modeling was developed and analyzed using modern computational fluid dynamics (CFD) software from Fluent. We limited our study to a storage capacity of 6 hours. The storage tanks were assumed to be filled with sand and rocks to make up 75% of the volume. We defined the geometric and thermal loss characteristics of the chosen tank(s). Throughout the simulations, cold and hot salts were assumed to be available at constant temperatures of 300°C and 385°C, respectively.

For the power plant of 280 MWe capacity, a six-hour thermal storage requirement amounts to about 20 GJ and a stored mass of 153,000 metric tons of salt. The molten salt volume is about 85,000 cubic meters (23 million gallons). With the effective withdrawal volume being less than the tank overall volume, we used a nominal 100,000-m3 tank for the simulations for this preliminary study. A mixture of quartzite rocks along with silica sand was chosen as the filler material. The quartzite rocks were nominal ¾ inch (sieve 0.75, with nominal 20-mm particle size) in size. Sand sieved was in the 8 to 12 sieve range, with a nominal particle size of 2 mm. The mixture occupied seventy-five percent of the storage tank volume.

SNL
We developed a model of an advanced parabolic trough system that incorporates several improvements relative to current technology including increased concentration ratio and higher operating temperature.

3. Results and Accomplishments

NREL
To assess whether these solid particles would respond fast enough to the surrounding flow of molten, we conducted a transient conduction/ convention study of the heat transfer between the solid and the liquid. The time response for heating and cooling of the solids is important in maintaining sharp thermocline as the fluid is withdrawn.

Using CFD analysis, we modeled the heat transfer from a single solid sphere to the molten salt. At the end of roughly 10 minutes, we note that the solid has cooled off considerably, attaining a maximum temperature of only 306°C in the core. At this time, the heat content of the sphere is less than 5% of its initial content. Simulation of a single particle was followed by analysis of a complete tank geometry with baffles to diffuse the vertical momentum of the incoming salt streams. A nominal 100-m diameter tank with a height of 15 m was chosen. Cold molten salt was introduced at an inlet velocity of 1 m/s; this would correspond to a discharge rate of about 8 hours for the entire tank volume. Side wall heat losses were set at 100 W/m^2 for all the external walls including top and bottom. Modeling results indicate that the thermocline is well maintained throughout the withdrawal process. This analysis shows that thermoclines in stratified tanks can be well maintained.

SNL
- Performed an initial system analysis of an advanced parabolic trough system (2X Trough) having double the concentration ratio of current systems

Lowering the LCOE for parabolic trough power plants requires several technical advances including increased concentration ratio, better selective surfaces, higher temperature operation, and thermal storage. We modeled a facility having these attributes to determine the level of the specific performance and cost gains. The results indicate that high temperature operation (500°C) can only be efficiently achieved if the concentration ratio is doubled and better selective coatings are used on the HCE.

4. Planned FY 2009 Activities

NREL
- Develop operational strategies to increase the overall effectiveness of the storage system
- Analyze material requirements and performance of thermocline systems as a function of the number of storage vessels (1 – 6),
- Analyze operational strategies for multiple storage vessel systems (1 – 6),
- Analyze operation under nonideal conditions including expected temperature swings in the hot and cold salts,
- Further characterize the dynamic response of the filler material to a change in fluid temperature and estimate the effect on thermocline degradation,
- Estimate the cost benefits of using thermocline storage as opposed to constant temperature, two-tank storage.

SNL
- Construct a finite-element structural/optics model of the advanced 2X trough initially analyzed in FY 2008.

Advanced Heat Transfer Fluid Development

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Mark Mehos (NREL), 303-384-7458, mark_mehos@nrel.gov
Tom Mancini (SNL), 505-844-8643, trmanci@sandia.gov
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Greg Glatzmaier (NREL), 303-384-7470, greg_glatzmaier@nrel.gov
Nathan Siegel (SNL), 505-284-2033, npsiege@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov

FY 2008 Budgets: $169K (NREL), $56K (SNL)

Objectives

- Develop advanced heat transfer fluids (HTF) for power towers and parabolic troughs in an effort to improve dispatchability and achieve levelized cost of energy (LCOE) goals. (SNL)
- Formulate HTF for advanced parabolic troughs enabling higher operating temperatures (500°C) than current fluids and thus higher efficiency (LCOE objective ~7¢/kWh). (SNL)
- Increase thermal storage densities by a factor of five over current storage materials for solar thermal systems. (NREL)
- Explore a new class of nanotechnology-based heat transfer and thermal storage materials with enhanced thermophysical properties. (NREL)

Accomplishments

- Developed multi-component molten nitrate salt mixtures that solidify below 100°C. (SNL)
- Demonstrated thermal stability of these salts to 500 ^{o}C and completed long-term corrosion testing of carbon and stainless steels. (SNL)
- Performed molecular dynamics (MD) simulations to elucidate the microscopic mechanism of solid/liquid phase transitions for bare aluminum nanoparticles without surrounding fluid. (NREL)
- Predicted theoretical heat capacities for several nanoparticles in different categories that agreed with the corresponding experimental results for these particles. (NREL)

Future Directions

- Perform extensive MD for more diverse sizes of particles, ranging from 70 to 100 atoms, and for encapsulated aluminum nanoparticles in core-shell structures. (NREL)
- Investigate the nanoscale melting of these encapsulated structures and clarify the role of the ligands and the partial oxidation on the performance of the thermal storage materials. (NREL)
- Compare experimental results with theoretical results and develop more accurate models for these new experimental systems. (NREL)
- Extend physical property determinations of molten nitrate salt HTF to include density, heat capacity and thermal conductivity. (SNL)
- Complete evaluation of 3,000-hour corrosion test specimens to confirm suitable materials of construction corresponding to the new molten salt HTF. (SNL)
- Complete exploratory study of nitrate-nitrite molten salt system for low-melting compositions and preliminary evaluation of viscosity and chemical stability. (SNL)
- Determine effects of impurities in bulk commodity grades of constituent nitrate salts. (SNL)
- Explore MD computational methods to discover better low-melting salt compositions. (SNL)

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1. Technical Approach

SNL's strategy for developing improved molten nitrate salt heat transfer fluid (HTF) was to survey published phase diagrams for freezing point data, then expand the basis of formulations to include constituents that promised lower liquidus temperatures. A limited combinatorial experimental matrix was used to observe low-melting mixtures and to estimate the direction of optimal composition for the next sequence of experiments. The candidate low-melting salt mixtures were then subject to determinations of chemical stability, viscosity, and corrosion activity.

NREL's goal is to increase, by the use of new nanoscale materials, thermal storage densities by a factor of five over the current state of the art for solar thermal systems. To achieve this goal, we are exploring a new class of nanotechnology-based heat transfer and thermal storage materials: (1) nanoscale "capsule" structures containing solid/solid, solid/liquid, or solid/gas phase change materials (nanoPCMs) as thermal storage materials and (2) nanoparticles suspended in fluids (nanoFLUIDs) as heat transfer fluids that may also act as thermal storage fluids..

2. Results and Accomplishments

SNL

- Developed multi-component molten nitrate salt mixtures that solidify below 100°C by limited combinatorial experiments and demonstrated their chemical stability to 500°C.
- Determined viscosity of molten salt HTF as suitable for applications in trough systems.
- Completed long-term exposure phase of corrosion testing of container alloys ranging from stainless steels to carbon steel.

This project achieved an innovation in an HTF capable of both low and high temperature operation and well suited for parabolic trough facilities as a direct replacement for the relatively costly organic HTF currently in use. Mixtures of the four salts (sodium, potassium, lithium and calcium nitrates) were identified that display liquidus temperatures less than 100°C.

Exploratory lab work investigated the properties of mixtures of nitrate (NO3-) and nitrite (NO2-1) salts. The cations added to the mixtures were sodium, potassium, and lithium. Preliminary results indicate that low-melting salts are achievable with mixed anion compositions and melting points near 80 °C were observed for a 1:1 mol ratio of nitrate-nitrite.

NREL

The melting point of aluminum can be controlled by selecting a size of aluminum particles, ranging from a bulk value of 660 ^{o}C to 150 ^{o}C for nanoparticles with 50-60 atoms. These phase change temperatures match with the operating temperature range (220-600 ^{o}C) of molten salt HTF. This tunability of size-dependent melting points enables the thermal storage systems to operate efficiently with multiple phase change temperatures. A fundamental understanding of phase-change behavior of the nanoparticles is crucial for the design of efficient thermal storage materials.

We performed molecular dynamics (MD) simulations to elucidate the microscopic mechanism of the solid/liquid phase transition for bare aluminum nanoparticles without HTF. The melting points and the latent heat of nanoparticles depend sensitively on the inter-atomic potentials and the geometry of nanoparticles. We found that the theoretical heat capacities agree well with the experimental results, proving the predictive power of our theoretical methods.

The melting transition from solid-like to liquid-like particles is not abrupt, as in the bulk, but occurs over a finite temperature range, within which the liquid-like and solid-like phases coexist. Thus, the heat capacity curve for this nanoparticle shows a broad peak, rather than the sharp peak seen in the bulk case. The peak of the heat capacity appears at a significantly lowered temperature of 340 ^{o}C as compared to the bulk melting point (660 ^{o}C). The overestimated heat capacities at low temperature are attributed to the quantum effect of vibrations, which is ignored in our simulations.

3. FY 2008 Special Recognitions and Patents

R.W. Bradshaw; D.A. Brosseau. Patent application S-112,575, Low-Melting Point Inorganic Nitrate Salt Heat Transfer Fluid, filed May 12, 2008, in USPO review. (SNL)

4. Major FY 2008 Publications

SNL

- R.W. Bradshaw; D.A. Brosseau. "Improved Molten Salt Formulations for HTF in Parabolic Trough Solar Power Systems." *SolarPACES 2008*; March 4-7, Las Vegas, Nevada.
- R.W. Bradshaw; N.P. Siegel. "Molten Nitrate Salt Development for Thermal Energy Storage in Parabolic Trough Solar Power Systems." Paper ES2008-54174, ASME 2nd International Conference on Energy Sustainability; Aug. 10-14, 2008, Jacksonville, Florida.
- G.J. Kolb; R.B. Diver. "Conceptual Design of an Advanced Trough Utilizing a Molten Salt Working Fluid." *SolarPACES 2008*.

Industry Projects

Performing Organizations:	Abengoa Solar, Inc. Hamilton Sundstrand Corporation
Key Technical Contacts:	Carolyn Elam, DOE Golden Field Office (DOE/GO), 303-275-4953, carolyn.elam@go.doe.gov Jim Payne, DOE/GO, 303-275-4756, jim.payne@go.doe.gov Brad Ring, DOE/GO, 303-275-4930, brad.ring@go.doe.gov
DOE HQ Technology Managers:	Frank (Tex) Wilkins, (202) 586-1684, frank.wilkins@ee.doe.gov Tommy Rueckert, (202) 586-0942, thomas.rueckert@ee.doe.gov
FY 2008 Budgets:	$862K Recipients

Objectives

- Develop energy supply technologies that are reliable, affordable, and environmentally sound. Expand national electricity generation portfolio to increase energy security by diversifying domestic energy supply options. Concentrating solar power (CSP) is one of the most attractive renewable energy options in southwest U.S., with a nominal levelized cost of energy (LCOE) target of 7-10¢/kWh by 2015 and 5-7¢/kWh by 2020.
- Develop low cost, high temperature storage that enables CSP trough systems to reach nominal levelized cost of energy (LCOE) target of 5-7¢/kWh with storage (12 – 17 hours) by 2020. To achieve these targets, storage cost of less than $15/kWh thermal is desired with round trip efficiencies at or greater than 93%.

Accomplishments

- Held merit review of applications in September and announced selections in October 2007.
- Negotiated and awarded CSP thermal storage awards.
- Defined roles and responsibilities of program management team, including technical advisors at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL).

Future Directions

- Evaluate progress toward critical milestones and decisions will be made at the end of the each project's first phase, starting in FY 2009 and extending into FY 2010.

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1. Introduction

The CSP thermal storage R&D activities are expected to develop low cost, high temperature storage that enables trough technologies to reach a nominal levelized cost of energy (LCOE) target of 5-7¢/kWh with storage (12 – 17 hours) by 2020. To achieve this goal, storage cost of less than $15/kWh thermal is desired with round trip efficiencies at or greater than 93%. .

The selected projects are:

Organization, PI and Agreement Title	FY 2008 Budget ($K)
Abengoa Solar Inc., Bruce Kelly "Development of Molten Salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants"	500
Hamilton Sundstrand Corporation, Michael McDowell "Concentrating Solar Power-Molten Salt Pump"	362

Development of Molten-Salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants (Abengoa Solar, Inc.)

Total Award: $625K, DOE/Recipient Share: $500K/$125K

Objectives

- Determine economic potential of low freeze point molten salts.
- Develop technologies required for use of molten salts.
- Conduct field tests necessary for introduction of molten salts in commercial project.

Accomplishments

- Completed draft design basis for a molten salt parabolic trough plant.
- Used GateCycle program calibration calculations, using previous heat balances.
- Developed heat balances, collector field piping layouts, and steam generator designs for reference Therminol and baseline molten salt plants.
- Assembled initial capital cost data for reference to Therminol plant with baseline molten salt plant.

Future Directions

- Test prototype components for molten salt use (ball joints, high temperature receivers).
- Develop detailed models of thermocline thermal energy storage system.
- Use Phase 1 results to illustrate reduced LCOE and risk mitigation.

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1. Introduction

Commercial parabolic trough projects use an organic fluid as the heat transport fluid (HTF) in the collector field and the steam generator. The high vapor pressure of this fluid requires an indirect thermal storage system. The project will determine whether inorganic fluids offer a sufficient reduction in LCOE to pursue further development and to develop the components required for molten salt use.

2. Results and Accomplishments

Abengoa developed solar field piping layouts for both the baseline Therminol (organic HTF) and the reference molten salt plant, with an option to use molten salts with very low (~100 °C) melting points. Preliminary analysis of the low melting point salts are focused on economic concerns, performing a design tradeoff between the higher cost of these salts and the lower equipment cost entailed by their use. Heat balances were also developed for the reference Therminol, and the baseline molten salt plants. An engineering assessment, using capital cost data, is being developed for the reference Therminol and the baseline molten salt plants, based on the 250-MWe Solana project for Arizona Public Service.

Hamilton Sundstrand Corporation Concentrating Solar Power - Molten Salt Pump

Total Award: $4,374K, DOE/Recipient Share: $3,219K/$1,155K

1. Introduction

This is a new project that started work on Oct. 1, 2008.

2. Technical Approach

The intent of this project is to design, build and test a long-shafted, molten salt pump necessary for a thermal storage system in a commercial-scale solar trough plant. The level of technical innovation necessary for this project reflects the need to expand the performance envelope range of long-shafted molten salt pumps. The high operating temperature of the design will demonstrate a bearing design able to work in most solar thermal plants that utilize molten salt as a thermal storage medium. The pump design shall be extensible to a solar power tower application by adding pumping stages to reach head levels necessary for solar power tower types of solar thermal power plants.

Advanced Concepts R&D

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL) DOE Golden Field Office (DOE/GO)
Key Technical Contacts:	Cheryl Kennedy (NREL, Primary Contact), 303-384-6272, cheryl_kennedy@nrel.gov Greg Kolb (SNL), 505-844-1887, gjkolb@sandia.gov
DOE HQ Technology Manager:	Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov
FY 2008 Budgets:	$283K (NREL)*, $233K (SNL)** *$210K and **$163K will carryover to FY 2009

Objectives

- Develop technology that dramatically reduces cost of concentrating solar power (CSP) to less than 10¢/kWh by 2015.
- Advance mirror technologies, reducing cost of mirrors by half by moving from heavy glass mirrors to lightweight front-surface reflectors that include surface coatings to reduce soiling. (NREL)
- Develop advanced reflector materials that are low in cost (less than $2.50/ft^2 or $26.90/m^2) and maintain high specular reflectance (90%–95% into a 4-mrad cone angle) for long lifetimes (20 to 30 years) under severe outdoor environments. (NREL)
- Test durability of optical materials to determine lifetime of solar reflector materials. (NREL)
- Support development of advanced power tower systems. (SNL)

Accomplishments

- Performed durability testing and published results of optical materials that potentially reduce cost of levelized cost of energy (LCOE) of CSP to less than 10¢/kWh by 2015. (NREL)
- Provided significant industry support to CSP and concentrating photovoltaic (CPV) industries on solar reflectors. (NREL)
- Trained power tower developer to use SNL's design and analysis software. (SNL)
- Performed first test of heliostat at distance of 1 mile. (SNL)

Future Directions

- Continue durability testing of optical materials to determine lifetime of solar reflector materials. (NREL)
- Continue optical characterization of advanced reflector materials, accelerated and outdoor testing of commercial, experimental, CSP FOA, CSP industry, and CRADA supplied reflector materials to determine lifetime of solar reflector materials, and support of industry/program needs. (NREL)
- Analyze and publish testing results of reflector materials applied to CSP technologies. (NREL)
- Develop with industry advanced power tower and trough components. (SNL)

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1. Results and Accomplishments

1.1 Advanced Concepts R&D Agreement

- Completed installation of new accelerated exposure chambers (i.e., 1st Ci5000, Ci4000, and BlueM) to test durability of commercial and experimental solar mirrors. (7/08)
- Determined optical performance, lifetimes, and cost goals for advanced reflectors consistent with CSP program objectives. (4/08)
- Compared durability of silvered thin-glass, copper-free, and lead-free mirrors after accelerated exposure testing (AET) and outdoor exposure testing (OET) at Golden, Colorado (NREL); Miami, Florida (FLA); Phoenix, Arizona (APS); and Northern Territory, Australia. (6/08)
- Provided status of test results of candidate solar mirror samples and identified promising candidates and how advanced solar mirrors will help meet cost goal for electricity. (11/08)

DOE and the CSP industry agreed that modification of the historical specular reflectance requirements, cost goals, qualification tests, and standards for solar mirrors need to be determined by the international industry, based on utility costs and technology needs. These changes will require significant industry acceptance and will continue into FY 2009. Until then, the outdated 1992 reflector cost goal of a $1/ft^2 was dropped and replaced with “reduce mirror cost by half”.

The Advanced Concepts task participated as a committee member and plenary presenter for DOE Specialty Glass Needs for the U.S. Solar Industry Workshop; participated in CSP road mapping; and task member of International Energy Agency Task III: Solar Technology and Advanced Applications.

Advanced solar reflector research and durability testing of reflectors, supplied by industry, is ongoing. Flabeg converted their mirror line to 4- or 5-mm glass and a new low-lead paint system in 2003. Side-by-side exposure testing began in 2005. The original mirrors with the high-lead paint system appear to exhibit better optical durability than the new reduced-lead mirrors. The high-lead mirrors have degraded 1.7% and the reduced-lead mirrors have degraded 2.8% after 45 months.

Significant corrosion has been observed in deployed thin-glass mirrors in CSP and CPV plants in Arizona and Australia. Some thin-glass silvered copper-free lead-free mirrors sold for outdoor applications have not passed the minimum requirements for mirrors to qualify for indoor applications. More than 40 experiments of thin glass mirrors are in AET and OET from nearly all of the world thin-glass mirror suppliers. Completion of a technical paper is pending the results of new samples and humidity experiments.

Alanod (Germany) developed an aluminum solar reflector with a nanocomposite oxide protective layer that has improved durability in urban and industrialized (polluted) locations. Preliminary exposure testing results of Alanod’s Miro-Sun samples (received in 2005) are encouraging, and the durability testing is ongoing.

A polymeric solar reflector has been developed through collaborative research between ReflecTech and NREL. The initial pilot-run material shows minimal loss in solar-weighted reflectance after 5 years of real-time outdoor exposure. However, accelerated WeatherOmeter (WOM) results showed significant reflectance loss earlier than anticipated from the proof-of-concept materials. Modifications to the baseline construction were identified and incorporated into the third pilot-plant run that should improve the WOM durability. Testing is ongoing, and the material is being field-tested. Based on AET, Glass, ReflecTech, and Alanod mirrors should meet 10-year lifetime goals. Since the chemistry and construction of all solar reflectors has significantly changed, all commercially available reflectors have been in OET for less than 4 years.

1.2 Advanced Concepts FOA Support

NREL supported four CSP solar reflector FOA awardees: 3M, Abengoa, Alcoa, and PPG.

1.3 CEC/CSP Collaboration

The market study for CSP/CPV collaboration was not placed. The milestone was reassigned to Selya Price, NREL senior energy analyst, and added to FY 2009 System Analysis milestones.

1.4 Advanced Power Tower Components

Solar Reserve and Rocketdyne are commercializing power tower technology. The computational resources of the in-house codes are extensive, becoming an impediment to the quick turn-around requirements of their commercial venture. So, SNL trained them on the use of SNL’s DELSOL and SOLERGY computer codes, less computationally extensive but accurately predicts power tower optical design and performance.

The Solar Reserve tower plant is capable of producing 100 MWe or more. The heliostat field within their commercial plant is more than 10 times larger than was demonstrated at Solar Two, where the distance from the tower to the furthest heliostat was 0.25 mile versus 1 mile in a commercial plant. SNL performed a 1-mile test by aiming a 95-m^2 heliostat at towers located 1 mile away. Test data indicated the spot size was 20 meters in diameter, similar to DELSOL prediction.

2. Planned FY 2009 Activities

- Upgrade database of candidate solar mirrors to Web based. (3/09)
- Survey CSP and reflector supplier industry and use SAM to determine specular requirements and cost goal. (3/09)
- Report durability of silvered thin-glass copper-free and lead-free mirrors after exposure to Ci5000 WOM and damp-heat at different humidity conditions and OET. (6/09)

- Document assessment of existing relevant accelerated reliability test procedures, applicable to materials, components, and systems. (6/09)
- Develop instrument to measure specular reflectance at 2-mrad cone at different wavelengths on curved substrate. (9/09)
- Provide status of test results of candidate solar mirror samples and identify promising candidates and how advanced solar mirrors will help meet cost goal for electricity. (9/09)
- Help eSolar assess performance and reliability of their steam-type power towers (7/09).
- Modernize SNL's power tower design and analysis software (9/09).
- Begin to explore development of 2X trough, i.e. double concentration of today's trough (9/09).

3. Major FY 2008 Publications

C. Kennedy. "Advances in CSP Collectors: Mirrors and Solar-Selective Coatings." *Proceedings of Association of Industrial Metallizers, Coaters and Laminators (AIMCAL) Fall Technical Conference 2007 and 21st International Vacuum Web Coating Conference; October 2007, Scottsdale, Arizona.*

C. Kennedy. "Advances in CSP Collectors: Mirrors and Solar-Selective Coatings." *Vac. Tech. Coat*, June (2008).

C. Kennedy, "Advancements in CSP (CSP) Reflectors and Solar-Selective Coatings." *Proceedings of E3 2007 - The Midwest's Premiere Energy, Economic, and Environmental Conference Proceedings;* November 2007, University of Minnesota, Minneapolis, Minnesota.

C. Kennedy. "Optics Reliability for Concentrators." *SPIE 2008 Conference Proceedings;* August 2008, San Diego, California.

G.J. Kolb; R. Diver. "Conceptual Design of an Advanced Trough Utilizing a Molten Salt Working Fluid (2X Trough)." *SolarPACES Conference Proceedings;* March 2008, Las Vegas, Nevada.

4. University and Industry Partners

Significant industry interaction occurred with CSP reflector manufacturers and CPV manufacturers on the durability of solar mirrors. A partial list includes: 3M, A Better Focus, Abengoa, ACA, Acciona, Aerospace Group, AGC (Glaverbel), Alanod, Alcan, Alcoa, Alvek, Ammonix, Applied Image, Arch Aluminum & Glass, Arontis, Atlas, Ausra,BEI Space, Blach & Vetch, Boeing, Cardinal Glass, CENIM/CSIC, Chevron, Chisso, CNRC, Concentrator Optics, Convergent Solar, Cooper Lighting, Corning, Cosmo Films, Cyanto, Dow Chemical, Dow Corning, Emcore, Energy Innovations, Enfocu, ESG, eSolar, Evonik, FEP, Flabeg, Gardner Glass, Google, GreenVolts, Guardian, HelioFocus, Honeywell, Hydro Aluminum, Infinia, International Solar technologies, ITRI, JDSU, JX Crystals, Kearney & Assoc., K&B Assoc, KERI, Light Prescription Innovators, Luz II, MegaWatt Solar, Nanotron, Naugatuck, Nitinol, Northside, ORNL, PARC, Pilkington, PPG, Pratt & Whitney, Praxair, QPanel, RAflector, Raytheon, ReflecTech, Replex, Rio Glass, Rocky Development, Rohm & Haas, Rooney Eng., SAIC, Saint Gobain, Sandia, Sandvik, Schott, SEIA, SkyFuel, Skyline Solar, Spraylat, SolarGenix, SolarTech USA, Solaria, Solel, SolFocus, Soliant, Solucar, Solyndra, Southwall, SPAWAR, Spinnaker Energy, Spraylat, SRI International, Stanford, Stirling Energy Systems, SunPower, Sunray, SunTechnics, Surface Optics, Symmorphix, United Solar, University of Baleric Islands, University of California Merced, University of Colorado, University of Hartford, University of Minnesota, Valspar, Veridian, Von Ardenne, Wooly Parsons, Xcel Energy, Xerocoat.

The following organizations partnered in the research activities.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Solar Systems Ken Cheah	Melbourne, Australia Kcheah@solarsystems.com.au	CRADA/Optical durability of thin-glass mirror panels	35.2*	39.3**
SolFocus Mark Spencer	Mountain View, CA mark_spencer@solfocus.com	CRADA/Durability of small mirror dishes and front surface reflectors and bond joints	100.4†	234.0‡

*NREL Funded Amount: $29.3.2k 10/1/07 - 1/25/08 + $5.8k directly paid travel expenses 6/30/08
**Sponsor Contract Value $39.3k 6/6/07 - 1/25/08
†NREL Funded Amount: $100.4k 10/1/07 - 9/30/08
‡Sponsor Contract Value $234.0k 6/15/07 through 8/14/11

Thermochemical Project

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contact: Cheryl Ghanbari, 505-845-3426, cghanba@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, Thomas.Rueckert@doe.ee.gov

FY 2008 Budget: $1,000K

Objective

- Upgrade heliostat control system for Central Receiver Test Facility (CRTF) at the National Solar Thermal Test Facility (NSTTF).

Accomplishments

- Completed the design of the new control system.
- Built and tested a prototype of the control system upgrade hardware and communications.
- Purchased new motors and encoders for the drives.

Future Directions

- Complete installation of controls hardware and test the system.
- Complete α-level design of the master control system and test it.

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1. Introduction

Over the last 32 years, SNL has successfully tested 13 central receivers and performed numerous other large-scale tests using the 5-megawatt thermal (MW_{th}) CRTF, located at the NSTTF in Albuquerque, New Mexico. In addition to testing the central receiver (a.k.a. power tower receivers), the facility has been used to perform work-for-others test in support of several National Aeronautics and Space Administration (NASA) centers, U.S. Air Force, and other DOE customers as part of its designated-user facility role.

Due to its age, the CRTF has operated with obsolete hardware in the heliostat field and software in the control room. Much of this equipment is no longer supported by the original vendors, and spare parts are either non-existent or very expensive to procure. Additionally, the performance requirements for the control system have changed significantly during the past 32 years, and the existing system can no longer meet test requirements.

Therefore, we are developing a new control system for the 5-MW_{th} CRTF at the NSTTF. The new control system will include upgrades in hardware, motors encoders and field control, and software for the master control system for the field.

Fig. 1 Central Receiver Test Facility at SNL's National Solar Thermal Test Facility

2. Technical Approach

Already been approved by the CRTF staff, the design lists the lessons learned throughout the 32 years of operation at the CRTF and describes a new control system built to address the limitations of the current design and to upgrade hardware to modern control technology.

3. Results and Accomplishments

- Developed lessons-learned document for field operation and control, identifying needs and issues.
- Reviewed hardware and software alternatives and down selected a design to meet cost and performance objectives.
- Purchased motors and encoder hardware.
- Tested a prototype design.

4. Planned FY 2009 Activities

We will complete validation of the design and upgrade the hardware and software at the CRTF facility, based on the validated design. This process will be completed in phases.

The first phase consists of completing the development of a new heliostat controller (HCE). The HCE is the unit that directly controls the movement of a single heliostat.

The second phase of the upgrade consists of assembling, installing and testing HCE units to control a small but significant part of the heliostat field. This will allow us to develop and test the communications system for managing multiple heliostats.

The third phase consists of developing and testing the master control system (MCS). The MCS is the field control system that the facility's operators use to design and operate a test.

Finally, the fourth phase of the upgrade will consist of duplicating several of our customers' tests, with dummy samples, to validate the operation of the field.

Industry Projects

Performing Organizations:	PPG Industries; SkyFuel, Inc.; 3M Company; Hamilton Sundstrand Corporation; Solar Millennium, LLC
Key Technical Contacts:	Carolyn Elam, DOE Golden Field Office (DOE/GO), 303-275-4953, carolyn.elam@go.doe.gov Jim Payne, DOE/GO, 303-275-4756, jim.payne@go.doe.gov Brad Ring, DOE/GO, 303-275-4930, brad.ring@go.doe.gov
DOE HQ Technology Managers:	Frank (Tex) Wilkins, 202-586-1684, frank.wilkins@ee.doe.gov Tommy Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov
FY 2008 Budgets:	$3,086K Recipients

Objectives

- Develop energy supply technologies that are reliable, affordable, and environmentally sound. Expand national electricity generation portfolio which will increase energy security by diversifying domestic energy supply options for use both in normal and emergency situations. CSP is of the most attractive renewable energy options in southwest U.S., with a nominal levelized cost of energy (LCOE) target of 7-10¢/kWh by 2015 and 5-7¢/kWh by 2020.
- Identify concepts that can generate low-cost power (under 7¢/kWh) with storage (12-17 hours) by 2020.

Accomplishments

- Held merit review of the applications in September and announced selections in October 2007.
- Negotiated and awarded advanced CSP concepts awards.
- Defined roles and responsibilities of program management team, including technical advisors at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL).

Future Directions

- Evaluate progress toward critical milestones and decisions will be made at the end of the each project's first phase, starting in FY 2009 and extending into FY 2010.

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1. Introduction

Advanced CSP concepts activities are expected to identify concepts that can generate low cost power with a nominal levelized cost of energy (LCOE) target of under 7¢/kWh with storage (12-17 hours) by 2020. The funding opportunity announcement (FOA) investigated three areas to address market barriers for utility-scale generation of CSP technologies: thermal storage; trough component manufacturing; and advanced CSP systems and/or components.

The selected projects are:

Organization, PI and Agreement Title	**FY 2008 Budget ($K)**
PPG Industries, Inc.-James McCamy, "High Performance Reflector Panels for Concentrating Solar Power Assemblies"	774
SkyFuel Inc. – Randy Gee, "Commercial Development off an Advanced, High-Temperature, Linear-Fresnel Based Concentrating Solar Power Concept"	385
3M Company – Susannah Clear, "Cleanable and Hardcoat Coatings for Increased Durability of Silvered Polymeric Mirrors"	350
Hamilton Sundstrand Corporation – Michael McDowell, "Solar Power Tower Receiver Development"	313
Solar Millennium, LLC – Michael McDowell, "Advanced High Temperature Trough Development"	1,264

High Performance Reflector Panels for Concentrating Solar Power Assemblies (PPG)

Total Award: \$3,639K, DOE/Recipient Share: \$2,185K (DOE), \$1,453K (Recipient)

Objectives

- Develop and commercialize large-area high value mirrors (HVM) with lower cost and higher performance, resulting in reduced LCOE.
- Develop one or more protective coatings and associated application process.
- Develop mirrors with different (flat/bent) geometries and mechanical strengths.

Accomplishments

- Identified two primary candidates for organic protective coating.
- Demonstrated feasibility of producing mirrors with different geometries and strengths.
- Indicated expected 7.5% improvement in LCOE with evaluation of produced mirrors.

Future Directions

- Focus on process development for low-cost manufacturing of large-area mirrors having differing geometries and mechanical strengths.

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1. Introduction

PPG plans to develop and commercialize large-area mirrors that are superior in value, in terms of cost and performance, to existing mirrors available on the market today. The expected outcomes are a design and fabrication process for a mirror having a high solar weighted specular reflectance, minimal optical performance degradation over the service lifetime, and a cost to the CSP systems builder that reduces the overall capital expenditure of the CSP system.

2. Technical Approach

PPG is conducting R&D into alternate materials, structures, and fabrication processes for reflector components. The base material for this work is their high-transmission SOLARPHIRE® low-iron glass. PPG will evaluate various reflecting layers with protective back coatings applied to the second surface for optical performance, durability, and environmental resistance. PPG will also evaluate whether it may be possible to bend the resulting mirror into a parabolic or other advantageous shape using standard equipment.

3. Results and Accomplishments

PPG used damp heat ($85^{o}C$ / 85%RH) testing as the initial screening test to determine potential materials candidates for the organic protective coating. Five different encapsulant compositions were identified. Further testing on these five coatings has indentified primary and secondary coating materials. Mirrors with different shapes and treatments were tested for compatibility with the encapsulants. Acceptable results were obtained in all cases. The Solar Advisory Model (SAM) was used to evaluate the impact on LCOE and total capital expenditure due to changes in performance and anticipated cost for the mirror under development in this project. For all the systems modeled, the candidate's HVM showed 5% or better improvement in both LCOE and total capital expenditure (for the entire CSP system) when compared with the baseline mirror.

4. Planned FY 2009 Activities

- Develop/demonstrate mirror processes necessary for low-cost fabrication of these mirrors by end of Phase 2.
- Develop protective coating with optical layers; identify process parameters required for manufacturing.
- Develop a high rate fabrication process.
- Identify manufacturing process parameters, equipment, and technical challenges associated with larger scale, high-rate, mirror fabrication.
- Field test large-area prototype mirrors.

Commercial Development off an Advanced, High-Temperature, Linear-Fresnel Based Concentrating Solar Power Concept (SkyFuel)

Total Award: $4,139K, DOE/Recipient Share: $2,423K (DOE), $1,716K (Recipient)

Objectives

- Develop advanced CSP system using linear Fresnel reflective technology.
- Enable use of molten salt as a heat transfer fluid (HTF) in linear concentrator systems and as direct thermal energy storage.

Accomplishments

- Initiated detailed conceptual design work and completed baseline wind-tunnel testing.
- Compared SkyFuel's trough technology to linear power tower technology.
- Developed advanced in-house optical and thermal analytical capability.

Future Directions

- Complete collector design, analysis and optimization.
- Design, prototype and demonstrate advanced, high-precision, low-cost reflector panel designs and advanced receiver designs for linear Fresnel systems.
- Refine wind tunnel testing and structural characterization activities for collector design.
- Assess overall performance and economic efficacy of the Linear Power Tower design relative to SkyFuel's SkyTrough™ parabolic trough concentrator.

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1. Introduction

The objective of SkyFuel's proposed multi-phased project is to develop an advanced CSP system, using linear Fresnel reflective technology, to achieve significantly lower delivered electricity costs from utility-scale solar thermal power plants. The design uses molten-salt HTF to enable higher operating temperatures and direct thermal storage, eliminating the need for heat exchangers.

2. Results and Accomplishments

The advantages of linear Fresnel can be combined with cutting edge reflective film and receiver technology to allow the design of a system with a high degree of economic merit. SkyFuel completed wind tunnel testing and is using the results to help guide and optimize its reflector panel design. An analysis defined the significant level differences in optical character that influences cost targets for Linear Fresnel, and overall system design for the energy market, and are illustrated in Figure 1.

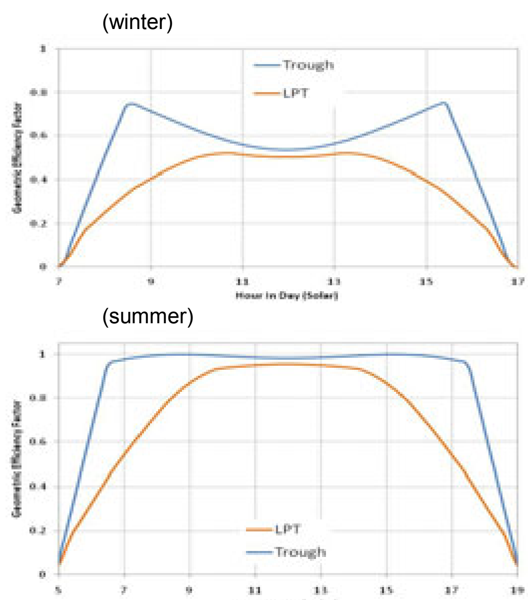

Fig. 1. A comparison between the daily performance of a trough and Fresnel system in the winter and summer.

3. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
CPP Wind Engineering	Fort Collins, CO	Collector wind tunnel testing, structural load characterization	100	28

Cleanable and Hardcoat Coatings for Increased Durability of Silvered Polymeric Mirrors (3M)
Total Award: $3,614K, DOE/Recipient Share: $2,312K (DOE), $1,302K (Recipient)

Objectives

- Develop durable and/or cleanable coatings specifically for silvered polymeric mirrors having polymethylmethacrylate (PMMA) front surfaces.
- Demonstrate manufacturing processes for these durable and/or cleanable coatings.
- Evaluate and validate the performance of these mirrors and their LCOE costs.

Accomplishments

- Screened chemistries and approaches for durable hardcoats and cleanable coatings.
- Identified three top hardcoat formulations that approach the performance of glass.
- Developed coating processes for these formulations and began environmental testing.
- Began development of additives and modifications to formulations to improve cleanability.

Future Directions

- Perform accelerated weathering and performance testing on samples.
- Select process conditions that are suitable for scale-up to manufacturing.
- Recommend top five candidates for hardcoat coatings and for cleanable coatings.
- Optimize coating conditions on a roll-to-roll coater for the top candidates.
- Collect soiling and cleanability data.
- Develop LCOE model to evaluate performance of coated versus uncoated PMMA mirrors.

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1. Introduction

Silvered polymeric mirrors with protective acrylic front surfaces show promise as alternative low-cost replacements for thick glass mirrors in parabolic trough CSP installations, and have the potential to reduce the installed system cost and LCOE for a trough installation substantially. 3M plans to address two aspects of silvered polymeric mirror films related to long-term durability–abrasion resistance and anti-soiling surfaces of the acrylic protective layer.

2. Technical Approach

3M's approach is to screen candidate hardcoat and cleanable coatings, use accelerated aging to test for durability and performance, and develop process optimization on samples with greatest promise. Top candidates will be evaluated to determine their feasibility for manufacturing and roll-to-roll coating processes. During phase 2, PPG will develop laboratory and pilot-scale equipment for selected coatings. Results from bench and pilot work will be incorporated into the economic model, and final candidates will be selected for scale-up to large width, manufacturing scale, mirror coating in the final phase of the project. Coated mirror film from this phase will undergo field trial weathering and results analyzed and incorporated into LCOE calculations.

3. Results and Accomplishments

PPG screened and selected approximately 20 candidate hardcoat materials with representative chemistries and coating methods. Screening criteria included UV, thermal and hydrolytic stability, expected abrasion resistance, compatibility with mirror surfaces, and cleanability. A preliminary economic study based on the SAM model was begun. From this analysis, three candidates approached glass in abrasion resistance and two others are promising. After 2,000 hours of accelerated weathering, the first three candidates have shown little degradation. Optimizing the top formulations and their respective coating, curing, and/or drying conditions is underway and manufacturing approaches appropriate for these selected compositions have been identified.

4. Major FY 2008 Publications

R. Messner. "Cleanable and Hardcoat Coatings for Increased Durability of Silvered Polymeric Mirrors," DOE Annual Solar Peer Review, April 22-24, Austin, TX, 2008.

Hamilton Sundstrand Corporation Solar Power Tower Receiver Development
Total Award: $2,881K, DOE/Recipient Share: $1,856K (DOE), $1,025K (Recipient)

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1. Introduction

The objective of this project is to validate the manufacturability of a large-scale molten salt receiver panel and then confirm its operation in prototypic solar flux. This work is an important step in reducing the levelized cost of energy (LCOE) from a central receiver solar power plant.

2. Technical Approach

The key technical risk to building larger power towers is building the larger receiver systems, specifically the issues involved with key receiver panel features such as the large headers and longer tubes. Therefore, this proposed technology project includes the design, fabrication and testing of an advanced molten salt prototypic sub-scale receiver panel that can be utilized in a large receiver system. The overall project is divided into three phases; concept feasibility, technology design and prototype development, and field validation.

3. Results & Accomplishments

The project started work on 10/01/2008.

Advanced High Temperature Trough Development (Solar Millennium)
Total Award: $5,919K, DOE/Recipient Share: $3,311K (DOE), $2,608K (Recipient)

Objectives

- Lower LCOE of Trough Power through advanced molten salt heat transfer fluids and improved collector.
- Evaluate benefits and costs of molten salt as an HTF in a full sized solar field.
- Complete design and installation of next generation collector at Kramer Junction as test platform.
- Modify test loop to be a molten salt parabolic trough test system.

Accomplishments

- Completed molten salt evaluation study, showing 12% decrease in LCOE.
- Improved understanding of freeze protection systems as design basis for test loop.
- Developed commissioning/decommissioning operations strategy using water dilution.
- Improved understanding of detailed design requirements for molten salt-based plant.

Future Directions

- Construct test loop and evaluate construction methods, verify optical shape, and validate assembly procedures.
- Validate baseline loop performance.
- Complete detailed systems designs for molten salt test loop.

1. Introduction

Solar Millennium had several key technical achievements that resulted in proposing this project, using molten salts as a heat transfer fluid (HTF). New, low melting point salts open up a variety of strategies, and a wider collector aperture can be designed for different HTFs.

2. Results and Accomplishments

Phase 1 was completed. The company completed a study demonstrating that a molten salt plant has the potential to reduce LCOE by 12%. The study was based upon a 100MW plant with 8 hours of thermal storage. Efficiencies are gained because molten salt operates at a higher temperature, and in a pressurized system this results in higher temperature steam which increases the power turbine's efficiency. Storage efficiency also improves, as the higher delta T in molten salt storage fluid is more efficient when compared to oil as a HTF, and is therefore lower cost. The study found an 8 hour Thermal Energy Storage system for a 100 MW plant costs 45% less with salt compared to an oil HTF. The studies also identified several methods to commission and decommission a salt-solar field, alleviating salt freezing issues. The company also continued working to improve the collector assembly, and redesigned the jig for the Kramer Junction Phase 2 test loop.

3. Major FY 2008 Publications

Dracker and Riffelmann. "Advanced High Temperature Trough Collector Development," 2008 Solar Annual Review Meeting April 22-24, Austin, Texas.

4. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)
Nexant, Inc. Babul Patel	San Francisco CA	Nexant performed several subsystem analysis and process designs for the molten salt plant.	80
SEGS V Plant Harvey Stephens	Kramer Junction, CA	Provided use of Kramer Junction site for Test Loop activities	0
Flagsol GmbH Dr. Frieder Borgmeier	Cologne, Germany	Salt Property testing and long term stability test	0

Southwest Stakeholder Outreach

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL)
Key Technical Contacts:	Mark Mehos (NREL), 303-384-7458, mark_mehos@nrel.gov Tom Mancini (SNL), 505-844-8643, trmanci@sandia.gov
DOE HQ Technology Manager:	Tommy Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov
FY 2008 Budgets:	$160K (NREL), $56K (SNL)

Objective

- Act as an information resource to concentrating solar power (CSP) stakeholders in accordance with the DOE southwest stakeholder outreach activity. Stakeholders include federal/state/local governments, utilities, regulatory commissions, the Western Governors' Association (WGA), the Bureau of Land Management (BLM), and various transmission groups.

Accomplishments

- Presented "CSP Markets and Policy Impacts" to former Vice President and Nobel Laureate Al Gore, January 9, 2008, New York, New York.
- Presented "Utility Scale Solar: Opportunities and Obstacles" to U.S. House Subcommittee on Energy and Environment, Committee on Science and Technology, Field Hearing, March 17, 2008, Tucson, Arizona.
- Presented CSP overview to the Western Interstate Energy Board (WIEB) Committee on Regional Electric Power, April 8, 2008, San Diego, California.
- Presented CSP overview to National Association of Regulatory Utility Commissioners (NARUC) Summer Annual Meeting special session on Implications of Climate Change Policy for State Regulators, July 23-24, 2008, Portland, Oregon.

Future Direction

- This agreement has been discontinued in fiscal year (FY) 2009; however, stakeholder outreach activities will be continued within the FY 2009 market transformation agreements.

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1. Introduction

The long-term goal of the CSP subprogram is to develop CSP systems that produce electricity that is competitive with electricity from conventional fossil-fuel power technologies in identified markets, e.g., intermediate and baseload power. Detailed systems analyses have shown that major factors contributing to cost reduction include 1) technology research and development to improve performance and reduce component costs, 2) solar plant scale-up to minimize project development and operations and maintenance costs, and 3) deployment to take advantage of volume production and learning. The work performed within the southwest stakeholder outreach agreement supports outreach efforts intended to encourage these last two avenues for cost reduction. The outreach efforts rely heavily on work funded under the market analysis/grid integration, resource assessment, and solar advisor support agreements within the CSP market transformation activities.

2. Major FY 2008 Publications

M. Mehos. "Another Pathway to Large-Scale Power Generation: Concentrating Solar Power." MRS Bulletin, Vol. 33 (April 2008).

CSP Resource Assessment

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Craig Turchi (NREL), 303-384-7565, craig_turchi@nrel.gov
Dave Renné (NREL), 303-384-7408, david_renne@nrel.gov
Tom Stoffel (NREL), 303-384-6395, thomas_stoffel@nrel.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2008 Budget: $650K (NREL)

Objectives

- Provide high-quality, reliable solar resource information, including information on the long-term variability and trend characteristics, that allows policymakers and developers to evaluate the potential of concentrating solar power (CSP).
- Identify and qualify solar resource measurement equipment suitable for CSP applications.
- Maintain and expand the ease-of-use of solar resource databases and models.

Accomplishments

- Released an updated National Solar Radiation Database (NSRDB) that contains a substantial increase in the number of stations with hourly direct normal irradiance (DNI) data estimates in comparison to those in the previous version.
- Developed Typical Meteorological Year (TMY) data sets relevant for CSP plant operations from the updated NSRDB
- Created a Solar Prospector Web tool to allow easy access to satellite-derived solar resource data in the United States.
- Performed a preliminary assimilation of several solar resource forecasting methods pertinent to CSP operations.
- Developed specifications for solar monitoring stations with a range of performance and costs. Compiled requests for measurements sites and selected a subset of 12 sites for FY 2009 deployment of instrumentation. Cooperative Research and Development Agreements (CRADAs) are in process.

Future Directions

- Deploy ground measurement stations with data collection and processing available from the NREL Measurement & Instrumentation Data Center (http://ww.nrel.gov/midc), consistent with the applicable CRADA.
- Utilize incoming ground data to validate and refine satellite-based resource models.
- Investigate hourly and day-ahead forecasting methods for DNI.
- Document and disseminate resource information using tools such as Geographic Information Systems (GIS) to provide the data to CSP stakeholders in an understandable and easy-to-use fashion.

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1. Major FY 2008 Publications

S. Wilcox; W. Marion. *"Users Manual for TMY3 Data Sets."* NREL/TP-581-43156. Golden, CO: National Renewable Energy Laboratory, 2008. www.nrel.gov/docs/fy08osti/43156.pdf.

D. Renné; R. George; S. Wilcox; T. Stoffel; D. Myers; D. Heimiller. *"Solar Resource Assessment."* NREL/TP-581-42301.Golden, CO: National Renewable Energy Laboratory, 2008.

J. Michalsky; C. Gueymard; P. Kiedron; B. McArthur; R. Philipona; T. Stoffel. "Proposed Working Standard for the Measurement of Diffuse Horizontal Shortwave Irradiance," *J. of Geophysical Research*; 2007; p. 112.

Market Analysis and Grid Integration

Performing Organization:	National Renewable Energy Laboratory (NREL)
Key Technical Contacts:	Craig Turchi (NREL), 303-384-7565, craig_turchi@nrel.gov Mark Mehos (NREL), 303-384-7458, mark_mehos@nrel.gov Nate Blair (NREL), 303-384-7426, nate_blair@nrel.gov
DOE HQ Technology Manager:	Tommy Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov
FY 2008 Budget:	$535K (NREL)

Objectives

- Provide support for concentrating solar power (CSP) subprogram analysis efforts relating to large-scale implementation of CSP in the southwestern United States.
- Support CSP-specific analysis related to implementation of the systems-driven approach within the DOE Solar Energy Technologies Program (SETP).
- Support DOE and Energy Information Administration analysis requests on an as-needed basis.

Accomplishments

- Adapted the Wind Deployment System Model (WinDS) to include CSP parabolic trough with storage. Subsequent addition of other renewable energy models resulted in establishment of a more general Regional Energy Deployment System model (ReEDS).
- Used ReEDS for policy impact analysis, such as the 30% Investment Tax Credit, and research and development (R&D) impact analysis. Shared results with Al Gore's Climate Change Solutions Summit.
- Participated in and supported regional transmission analysis efforts, including analysis supporting the ongoing western wind and solar integration study and the involvement within Western Renewable Energy Zone (WREZ) study group.
- Established CSP Market Transformation Project to encompass the growing and diverse factors (land access, environmental impact, transmission, grid integration, etc.) affecting CSP market penetration.

Future Directions

Specific market transformation activities will include:

- Modify ReEDS to include CSP systems without storage to assess advantages of CSP configurations with storage (e.g., troughs or towers) versus solar configurations without storage (e.g., Dish/Stirling or photovoltaic)
- Continue CSP stakeholder outreach (e.g., staff in state energy, economic, and environment offices and utilities)
- Continue to improve and promote tools for Geographic Information Systems (GIS), market analysis, and economic impact analysis for use in supporting the activities described above
- Continue providing support of CSP model development in the Solar Advisor Model framework
- Continue and expand work related to market penetration, with a new emphasis on grid integration and expansion studies
- Initiate efforts on a Programmatic Environmental Impact Statement (PEIS) for solar energy development on southwestern lands administered by the Bureau of Land Management (BLM).

Solar Advisor Support

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Craig Turchi (NREL, Primary Contact), 303-384-7565, craig_turchi@nrel.gov
Nate Blair (NREL), 303-384-7426, nate_blair@nrel.gov
Mark Mehos (NREL), 303-384-7458, mark_mehos@nrel.gov

DOE HQ Technology Manager: Tommy Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov

FY 2008 Budget: $250K (NREL)

Objectives

- Maintain and expand the Solar Advisor Model (SAM), which allows calculated energy output, energy costs, and cash flows using up-to-date component and system data while enabling parametric analysis.
- Utilize SAM for analysis of concentrating solar power (CSP) configurations for a variety of applications and locations to identify configurations that predict the lowest levelized cost of energy (LCOE).
- Promote SAM use by industry and government to guide research and development (R&D) priorities and to provide credible energy production and cost data using a common platform for project development, evaluation, and due diligence.

Accomplishments

- Released SAM 2.0 and Users Guide. Improvements included a generic technology option for consistent comparison with conventional fuel-based technologies, a third-party ownership option to commercial projects, new workbook and graphing features, and a compressed file format (SCIF) that stores only inputs in small files for easier file sharing.
- Implemented dry-cooling capability for CSP systems.
- Added new Solel UVAC3 heat-collection element (HCE) to CSP model library.
- Developed Dish/Stirling performance model (supported by University of Wisconsin subcontract), which is currently in beta-testing.
- SAM experienced a significant increase in use by CSP stakeholders (laboratories, industry, developers, and investors) in fiscal year (FY) 2008.

Future Directions

- Continue to expand SAM with added features and improve the speed and ease of use of the code. FY 2009 activities will include:
  - A major update (Version 3.0) of the code and user manual
  - Debugged Dish/Stirling model
  - Inclusion of Power Tower model
  - Improved Rankine cycle model (applicable to trough and tower system simulations)
  - Improved financial optimization algorithm
- Host a SAM users' workshop to promote use of the software and solicit additional feedback from stakeholders.

Programmatic Environmental Impact Study

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL) DOE Golden Field Office (DOE/GO)
Key Technical Contacts:	Doug Dahle (NREL, Primary Contact), 303-384-7513 Lisa Jorgenson (DOE/GO), 303-275-4906
DOE HQ Technology Manager:	Tommy Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov
FY 2008 Budget:	$125K (NREL)

Objectives

- Provide NREL solar technology expertise to support development of Bureau of Land Management (BLM)/DOE Solar Programmatic Environmental Impact Statement (PEIS).
- Support and present at public scoping meetings in six states.
- Provide solar, concentrating solar power and photovoltaic, geographic information system (GIS) mapping data for six southwest states (Arizona, California, Colorado, New Mexico, Nevada, and Utah).

Accomplishments

- Launched Solar PEIS Information Center Web site http://solareis.anl.gov – May 2, 2008.
- Developed NREL presentation component for solar PEIS scoping meetings.
- Participated in 11 public scoping meetings on July 10, 2008:
  - Riverside, California
  - Barstow, California
  - Las Vegas, Nevada
  - Sacramento, California
  - Denver, Colorado
  - Phoenix, Arizona
  - Salt Lake City, Utah
  - Albuquerque, New Mexico
  - Tucson, Arizona
  - San Luis Obispo, California
  - El Centro, California.
- Provided GIS solar data and recommended exclusions for Argonne National Laboratory (ANL) development of maps for PEIS alternatives.
- Performed technical review of PEIS Solar Technology Overview appendix.
- Provided consultation and advice for two ANL/BLM/DOE solar project planning meetings.
- Completed preliminary solar CSP and PV resource maps with exclusions for BLM lands in six southwestern states – May 23, 2008.

Future Directions

In fiscal year (FY) 2009, these are the goals:

- Lead solar power plant site tours for ANL team.
- Provide technical input and review of draft PEIS.
- Conduct GIS analysis and run Regional Energy Deployment System (ReEDS) model for PEIS alternatives.
- Offer technical response to public comments from scoping meetings and draft PEIS (2nd quarter).

In FY 2010, these are the goals:

- Provide technical input, review, and comments for final PEIS (3rd quarter).

SHC Systems Development and Market Development

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)
Solar Rating and Certification Corporation (SRCC)

Key Technical Contacts: Tim Merrigan (NREL, Primary Contact), 303-384-7349, tim_merrigan@nrel.gov
Greg Kolb (SNL), 505-844-1887, gjkolb@sandia.gov

DOE HQ Technology Manager: Bob Hassett, 202-586-8163, robert.hassett@hq.doe.gov

FY 2008 Budgets: $1,110K (NREL), $100K (SNL), $500K (SRCC)

Objectives

- Identify the solar thermal systems that can significantly contribute to attaining cost-neutral zero-energy homes.
- Support field trials and refinement of low-cost solar water heaters in mild climates that reduce the levelized cost of energy by at least 50%. (NREL)
- Provide technical support for the emerging U.S. solar water heater market. (SRCC)
- Improve reliability of fielded systems. (SNL)

Accomplishments

- Supported development of a low-cost, solar water heating system, the second to enter the marketplace in FY 2008. The SunCache is a glazed, passive-type, polymer solar water heating system that can be purchased at less than half the cost of copper, aluminum, and glass solar water heating systems. (NREL)
- Established durability of proposed polymer components, including glazings and connectors. (NREL)
- Helped to produce combined photovoltaic (PV)/thermal component models for system simulation. (NREL)
- Identified liquid desiccant-based cooling systems as preferred for solar-activated cooling, and explored synergies with strong liquid-desiccant as a latent heat storage mechanism. (NREL)
- Created reliability data base of fielded systems. (SNL)

Future Directions

- Continue development of exemplary low-cost solar water heating systems for zero-energy homes in cold climates. (NREL)
- Continue development of combined PV/thermal systems for zero-energy homes that will be cost-competitive with conventional technologies and that can be used for water heating and space conditioning as well as electricity production. (NREL)
- Develop tools for assessing and optimizing solar thermal systems addressing major end uses of water heating, space heating, and/or space cooling in zero-energy homes. (NREL)
- Develop system design guidelines to improve reliability and availability. (SNL)

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1. Introduction

Solar Heating and Cooling (SHC) is now an integral part of the R&D effort to reach the zero-energy buildings goal. In 2008, SHC was transferred from the Solar Energy Technologies Program to the Building Technologies (BT) Program to more effectively integrate SHC energy supply technologies with energy efficiency technologies.

SHC consists of research and technology development activities for solar water heating (SWH) and solar space conditioning systems for heating, cooling and dehumidification. The program works with industry, the national laboratories, and others to develop and demonstrate systems and components that will improve the reliability and reduce the cost of these solar systems. To ensure that safe and reliable systems are installed, the program also supports the testing and certification activities of the Solar Rating and Certification Corporation (SRCC).

One of the primary goals of BT is to have cost-neutral zero-energy homes (ZEH) in all U.S. climate zones by 2020. Although ZEH are readily attainable with today's technologies, the cost is prohibitively high and not cost-neutral. The transfer of SHC into BT recognizes that solar thermal is a critical element of a cost-neutral ZEH.

To support the ZEH effort, SHC research includes the development of active solar systems that cost-effectively meet the sensible and latent thermal energy loads of ZEH, including water heating and space conditioning loads associated with heating, cooling and dehumidification.

Development of low-cost SWH remains as part of the SHC R&D effort, because the water-heating load is a relatively large percentage of total load (especially in ZEH) and is hard to reduce by other means. Gas tankless water heaters are becoming popular, but they can achieve only ~30% savings. Further reductions require SWH, and are necessary in going to the 50% savings level and beyond. SHC will also continue to support the existing SWH industry, which is essential to providing the products for ZEH.

In FY 2008, the expanded SHC effort focused on the following activities:

- Low-cost solar water heaters for ZEH
- Combined solar heating, cooling, and water heating systems for ZEH
- Solar electric/solar thermal pathways to ZEH
- IEA Solar Heating & Cooling (SH&C) Program
- System certification and reliability.

2. Technical Approach

Low-cost solar water heaters for ZEH: Simple, durable and low-cost solar hot water systems are one of the technologies needed to reach the BT Program goal of net zero-energy homes by 2020. The overall objective of this activity is to develop low-cost solar water heaters for ZEH in cold climates that will be cost-competitive with conventional technologies. Significant advances in materials, design, and manufacturability are required to lower the cost of solar water heaters, improve their performance, and make installation easier. For example, for active systems in which storage is separate from the collector, storage is a major cost component.

Combined solar heating, cooling and water heating systems for ZEH: A combined system allows for better overall utilization, multi-use, and potentially larger jobs. The objective is to develop low-cost combined three-function ("triple play") systems that have high solar fractions. Innovative approaches are clearly needed.

Solar electric/solar thermal pathways to ZEH: An average single-family home requires a 4-6 kW PV system to provide sufficient on-site renewable energy generation. A PV array of this size does not typically allow sufficient south-facing roof space for any solar thermal collectors that could be used to meet a meaningful portion of the home's thermal loads, i.e., space conditioning and water heating. Therefore, a ZEH requires a combined solar electric/solar thermal system that will be cost-competitive with conventional technologies and that can be used for water heating and space cooling as well as for electricity production.

IEA Solar Heating & Cooling (SH&C) Program: Collaboration with the International Energy Agency (IEA) SH&C Implementing Agreement provides added value, benefit and merit to DOE SHC by leveraging its limited resources through task-shared RD&D activities in countries participating in IEA. Current and planned activities include solar rating and certification, polymeric materials for solar thermal applications, solar air-conditioning and refrigeration, PV/thermal systems, testing and validation of building energy simulation tools, and advanced storage concepts for solar thermal systems in low energy buildings.

System certification and reliability: In support of the Solar Investment Tax Credit provisions of the Energy Policy Act of 2005 requiring SRCC certification, in FY 2008 SRCC certified 83 solar collectors and 81 solar water heating systems. By the end of the fiscal year, there were a total of 252 SRCC-certified solar collectors from 61 companies and 707 SRCC-certified solar water heating systems from 29 companies. Annual performance summaries for all SRCC-certified systems are now available for 100 cities. SRCC also worked with the Florida Solar Energy Center to improve solar collector performance testing operations as well as to develop revised accreditation policies for new testing laboratories.

Although SHW systems have been in use for many years, very little is documented about their long-term reliability. Certifying agencies, like SRCC, use laboratory tests from new systems in controlled settings, but few tests are conducted for long-term performance and reliability. The best reliability data come from fielded systems. However, installations tend to be geographically dispersed and information about performance and reliability are collected sporadically. Current and planned activities include data collection and analysis that ultimately lead to design improvements that increase system reliability and availability.

3. Results and Accomplishments

DOE supported the development of a low-cost, solar water heating system, the second one to enter the marketplace. The SunCache is a glazed, passive-type, polymer solar water heating system that costs less than half as much as current copper, aluminum, and glass solar water heating systems. The SunCache was certified by the SRCC in June 2008.

Researchers also established the durability of proposed polymer components, including glazings and connectors.

Program members also helped to produce combined PV/thermal component models for system simulation.

SNL launched a study of SHW reliability with more than 10 organizations providing input. The study will be completed in FY 2009 and recommendations to improve long-term system reliability and availability will be made to SRCC.

Finally, program participants identified liquid desiccant-based cooling systems as preferred for solar-activated cooling. They also explored synergies with strong liquid-desiccant as a latent heat storage mechanism.

Program Management

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)
Sentech Incorporated
McNeil Technologies

Key Technical Contacts: Roland Hulstrom (NREL), 303-384-6420, roland_hulstrom@nrel.gov
Charles Hanley (SNL), 505-844-4435, cjhanle@sandia.gov
Mike Reed (Sentech), 240-223-5509, mreed@sentech.org
Lumas Kendrick (McNeil), 703-921-1632, lumas@kendrick.com

DOE HQ Technology Manager: Thomas Rueckert, DOE, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2008 Budgets: $1,813K (NREL), $1,326K (SNL), $1,326K (Sentech), $225K (McNeil)

Objectives

- Effectively plan, administer, manage, and review the NREL/SNL Solar Program, which includes photovoltaics (PV), concentrating solar power (CSP), and solar hot water (SHW) research and development. (NREL/SNL)
- Provide technical analysis and support services to the DOE Solar Energy Technologies Program (SETP). (Sentech)
- Provide technical support for grid integration activities. (McNeil)

Accomplishments

- Successfully implemented PV, CSP and SHW science, R&D, and market transformation activities, as directed by DOE through the FY 2008 Annual Operating Plan. (NREL/SNL)
- Organized 2 ½-day CSP roadmap meeting in Albuquerque, New Mexico. (SNL)
- Completed PV installation on the roof of the DOE's Forrestal Building. (Sentech)
- Completed 2008 Solar Program Technical Risk Analysis Pilot Project. (Sentech)
- Completed Solar America Cities Web site and tracking database. (Sentech)
- Helped develop advanced inverter solicitation development, documentation, and analysis. (McNeil)

Future Directions

- Support SETP management of the overall in both its PV and CSP efforts. (NREL/SNL)
- Plan, administer, manage, and review the Solar Program at the national labs. (NREL/SNL)
- Continue market transformation activities, risk analysis, and CSP/Bureau of Land Management support, expanded support for PV and Grid Integration. (Sentech)

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1. Technical Approach

<u>NREL</u>
In supporting the management of the overall Solar Energy Technologies Program, the activities include, but are not limited to,: developing and implementing the FY 2008 Annual Operating Plan (AOP) for NREL R&D and market transformation activities; tracking AOP and Joule milestones and performance; analyzing technical activities and adjusting course based on results; developing multi-year and strategic plans with DOE guidance; preparing for and implementing program reviews; manage and administer the PV, CSP, and SHW programs at NREL; track and manage budgets; and prepare information/reports as requested. NREL solar activities are managed by Roland Hulstrom.

<u>SNL</u>
SNL will continue to manage its contributions to all of the above-mentioned activities, reports, plans, and strategy development. This is all coordinated closely with NREL and SETP. The CSP activities are managed by Jeffrey Nelson with day-to-day management being the responsibility of Thomas

Mancini. The PV activities are managed by Charles Hanley.

Sentech

Sentech provides technical and analytical support to SETP, including systems analysis, GPRA, PART, Joule metrics, risk analysis, carbon and other environmental benefits, and technical and economic review of proposals submitted to the Program. Sentech also provides support in planning, coordinating, facilitating, documenting and reporting on SETP meetings, including peer reviews, technical workshops, and annual meetings.

McNeil

McNeil provides technical support for the advanced inverter activities and related balance of systems activities; assists in development of program planning documents and supporting analyses; assists with technical meetings; and prepares reports.

Agreement Title	FY 2008 Budget ($K)
NREL Program Management	1,813
SNL Program Management	1,326
Sentech Technical Support	1,326
McNeil Grid Integration Support	225

2. Results and Accomplishments

NREL

- Supported the DOE-EERE CPS transition to the Basic and Applied Research & Development Integration (BARDI) business management system, utilizing CPS as the NREL FY 2008 AOP.

SNL

- Completed development of FY 2008 Annual Operating Plan and assured completion of all FY 2008 CPS milestones.
- Provided SETP support to evaluation, validation, and analysis activities, as well as other general program support, through on-site assignment of Joe Tillerson.
- Contributed to development and execution of all appropriate program meetings, such as the annual review, the FY 2009 AOP development meetings, and other related events.

Sentech

- Completed and published the SETP Multi-Year Program Plan 2008-2012 (April, 2008).
- Supported the planning and installation of a PV installation on the roof of DOE's Forrestal Building in September.
- Completed in July the 2008 Solar Program Technical Risk Analysis Pilot Project, soliciting input from industry, national lab, and academia experts for projected improvements of PV and CSP technologies resulting from DOE program activities.
- Supported the development and design of the Solar America Cities Web site and tracking database.

McNeil

- Assisted in the documentation and analysis to support implementation of solicitations for advanced inverter activities.

3. Planned FY 2009 Activities

NREL

- Support SETP management with PV and CSP efforts. The activities include: developing and implementing the FY 2009 AOP for NREL R&D and market transformation activities; track AOP and Joule milestones and performance; analyzing technical activities and adjusting course based on results; developing multi-year and strategic plans per DOE guidance; preparing for and implementing program reviews as required; manage and administer the PV and CSP activates; track and manage budgets; and prepare information/reports as requested.

SNL

- Participate in all of the above-mentioned program management activities, in close coordination with NREL and SETP.
- Work with DOE CSP leadership to develop strategic and near-term plans consistent to support accelerated commercial development and deployment of CSP systems.
- Hire new staff in support of expanded R&D funding and testing at the NSTTF, as well as to meet current and future PV program commitments.

Sentech

- Lead the revision and update of the risk analysis process for SETP by addressing issues identified in the pilot risk project and identifying a new and expanded pool of experts to provide input.
- Continue to support CSP activities, including CSP funding award evaluations and reviews, the coordinated Program Environmental Impact Statement (PEIS) development and planning for a possible new DOE/BLM renewable energy project land lease management program.
- Continue to support the Market Transformation activities, including Solar

America Cities, Solar America Showcase review and award selection, workforce development, codes and standards, and state and utility technical outreach activities.

- Expand its support services to the PV and Grid Integration subprograms by supporting and participating in technical workshops, program planning and analyses, and stage-gate reviews.
- Assist SETP in planning and conducting the peer review in March 2009.

4. FY 2008 Special Recognitions and Patents

Sentech

- K. Lynn, recognized by DOE in appreciation for his contribution to rebuilding New Orleans with clean energy and efficient technologies for its schools, homes, and citizens.
- K. Lynn, received 2008 Transformational Energy Action Management Special Achievement Award for Technology Demonstration, presented by Department of Energy Federal Energy Management Program.

5. Major FY 2008 Publications

NREL/SNL

- FY 2008 Annual Operating Plan

Sentech

- Solar Energy Technologies Program Multi-Year Program Plan 2008-2012.
- SETP Report to Congress on CSP Water Consumption.

Equipment and Facilities

Performing Organizations:	Sandia National Laboratories (SNL) National Renewable Energy Laboratory (NREL)
Key Technical Contacts:	Thomas R. Mancini (SNL), 505-844-8643, trmanci@sandia.gov Charles Hanley (SNL), 505-844-4435, cjhanle@sandia.gov Cheryl Kennedy (NREL), 303-384-6272, cheryl_kennedy@nrel.gov
DOE HQ Technology Manager:	Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov
FY 2008 Budgets:	$1,424K (SNL), $420.8K* (NREL) *Includes $137.8K in carryover from FY 2007

Objectives
- Maintain core capabilities within photovoltaic R&D and prepare for characterization challenges with new components and systems configurations. (SNL)
- Maintain up-to-date training requirements for staff at the National Solar Thermal Test Facility (NSTTF) and implement new training requirements when needed. (SNL)
- Maintain safe operational conditions for the test facilities at the NSTTF. (SNL)
- Bring all electrical equipment operated at the NSTTF into nationally recognized testing laboratory (NRTL) compliance per SNL, DOE, and Occupational Safety and Health Administration (OSHA). (SNL)
- Rebuild and upgrade optical measurement and accelerated exposure testing (AET) capabilities and maintain preeminence as the world leader in mirror durability testing. (NREL)

Accomplishments
- Achieved NRTL compliance for about 75% of the NSTTF site. (SNL)
- Procured, as planned, new PV equipment. (SNL)
- Developed draft 5-year PV equipment recapitalization plan, which was submitted to DOE. (SNL)
- Procured and installed new concentrating solar power (CSP) optical and AET equipment. (NREL)

Future Directions
- Begin major upgrades in facilities at the NSTTF in FY 2009. (SNL)
- Complete NRTL compliance for Central Receiver Test Facility (CRTF) heliostat field and a few other outstanding pieces of equipment. (SNL)
- Expand recapitalization plan from equipment to cover facilities, assuring preparedness for upcoming R&D opportunities and challenges. (SNL)
- Continue to replace aging and largely unserviceable equipment. (SNL and NREL)

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1. Results and Accomplishments

Equipment and Facilities	FY 2008 Budget ($K)
PV Capital Equipment (SNL)	360
CSP Facilities Operation (SNL)	1,064
CSP Capital Equipment (NREL)	420.8
Total	1,844.8

1.1 PV Capital Equipment (SNL)

Capital equipment funds were well utilized in the procurement and installation of equipment necessary, as we prepare for upcoming R&D challenges. The Solar Energy Grid Integration Systems (SEGIS) activities will need a set of hardware deliverables that will require new infrastructure to conduct developmental and evaluative testing. In the laboratory, we have dramatically increased our capability to conduct parallel module, array, and systems characterizations through the acquisition of new outdoor monitoring systems.

In one area, rather than purchase a new tracker to conduct high-accuracy characterizations of concentrating PV systems (another growing need/challenge), we acquired an unused tracker from a local PV manufacturer and spent considerably less on its install and refurbishment than a new tracker would have cost. This tracker is installed and being fitted for full operation. Additional purchases are described below:

UV-Visible-IR Optical Spectrophotometer
The Cary 5000 spectrophotometer and diffuse reflectance accessory was purchased as a replacement unit for an outdated Cary 5 that no longer operated up to the specifications of the instrument and was no longer supported by the manufacturer. The new instrument was upgraded to produce more accuracy in measurements as a result of electrically cooled photodetectors.

Outdoor Performance Characterization System
These systems are needed to collect performance data from modules tested on the trackers. This addition will upgrade and expand outdoor performance characterization capabilities. The data acquisition equipment supports modeling, reliability, and test and evaluation activities.

Inverter R&D Validation DC Power Source
The addition of a 20-kW PV power supply has enabled SNL's Distributed Energy Technologies Laboratory (DETL) to analyze the effectiveness of the MPPT algorithms of commercial and developmental PV inverters and report the findings to researchers and engineers working on improving the reliability and performance of their SAI and other products.

AC/DC Calibration Standards
The voltage and current standards enable the DETL to conduct end-to-end AC and DC calibrations on all of data acquisition systems. The calibration procedure is needed when conducting assessment on the performance of developmental hardware associated with industry support.

1.2 CSP Capital Equipment & Facilities (SNL)
NSTTF – TRAINING
The NSTTF is devoted to the development and test of next-generation CSP systems. The NSTTF was built in the late 1970s on 117 acres and comprises an 8-acre heliostat field and power tower, molten-salt test loop, rotating platform for solar thermal testing of trough concentrators, 16-kW solar furnace, facilities for dish engine testing, engine test facility, and numerous buildings and specialized test equipment.

This activity involves all of the training requirements at the NSTTF. Recurring training includes: hazardous waste and environmental management, lockout/tagout, first aid, respiratory protection, R&D electrical safety training, safe operations of hand trucks and pallet jacks, forklift training, fall prevention, rigging, hoisting evacuation team, metal working liquids and lubricants, chemical carcinogens, compressed gases, adhesives, corrosives, asbestos, laser safety, and laboratory standards.

NSTTF – Basic Operations
Ongoing activities at the NSTTF include safety and readiness testing and inspection associated with the following: chemical safety, confined spaces, cranes and rigging, electrical safety, environmental regulations, environmental management, evacuation, fire protection, hazardous waste, hoisting and rigging, lasers, local exhaust ventilation, lockout/tagout, machine shops, respiratory and hearing protection, compliance reviews, corporate stand-downs, and property inventory. General activities include: maintain OUO, site security, safety, monitor site access, coordinate maintenance and deliveries SNL security, computer security, Foreign Corrupt Practices Act, counterintelligence, EEO/AA, ethics, drug free workplace, OUO, export control, property, diversity, annual review of site security plan, SNL satellite badge office, process foreign national requests, coordinate tours, and process out-of-hours access.

NSTTF – NRTL Certification
All facilities must be certified NRTL compliant. Much of the equipment installed at the NSTTF is one-of-a-kind or built specifically to meet a particular test requirement. Consequently, a large part of test and operations equipment has never been tested or certified by a Nationally Recognized Testing Laboratory. In order to bring equipment into compliance, SNL has staff who are trained to inspect equipment and determine the appropriate actions to be taken to bring it into compliance. For equipment that is modified for operation, we have it reinspected and certified as NRTL compliant.

Throughout the initial evaluation phase, which started in FY 2007, over 500 items were inspected and identified as non-NRTL compliant. The only remaining items that need to be inspected and certified are associated with on-going controls upgrades in the CRTF heliostat field.

1.3 CSP Capital Equipment & Facilities (NREL)
Historically, the accelerated exposure chambers used to test the long-term durability of solar mirrors and glazing materials have been primarily an Atlas Ci65 (Ci65) WeatherOmeter (WOM) and an Atlas Ci5000 WOM (Ci5000). The Ci65 and Ci5000 WOMs were purchased in 1995 and 1998; the Ci65 is no longer manufactured nor supported by Atlas. If new capital equipment was not purchased, NREL could lose its preeminence and the U.S. mirror and solar industry could lose a valuable resource costing them market share.

In the FY 2008 budget, $283k was allocated, specifically $61K for a reflectometer, $87K for a spectrophotometer, and $135k for a WOM (#2). A major expected accomplishment of this project included upgrading the optical measurement and AET capabilities.

A new Perkin-Elmer Lambda 1050 UV-VIS-NIR dual beam spectrophotometer with 150-mm integrating-sphere and universal reflectance accessory (URA) attachments was purchased to measure the hemispherical reflectance, transmittance, and absorptance of samples. The 150-mm integrating sphere attachment is able to measure relative reflectivity with higher resolution, better accuracy, and faster speed than the Lambda 9 and 900.

Surface Optics Corporation (SOC) hand-held directional hemispherical reflectance (DHR) reflectometer was purchased to replace/upgrade the +20-yr-old D&S 15R to measure specular reflectance of solar mirrors and with the purchase of a second head, the emittance of solar selective coatings. A second head was purchased to measure absorption and emittance of solar selective coatings. In addition, two remote control accessories were purchased to measure the samples on a lab bench. The SOC instruments were delivered and installed Aug 08.

The conversion of FY 2007 Other Direct Cost (ODC) funds to capital equipment funds was requested for the purchase of a new CSP Ci5000 WOM, which was purchased in FY 2007 and delivered and installed in FY 2008 to replace the SH Ci5000 exposure space. When installed, this Ci5000 WOM#1 was at its 350-sample capacity.

A large factory refurbished BlueM FRS humidity test chambers was purchased in FY 2007 (factory refurbished $8.5k; new >$45k) and installed in FY 2008 to operate at 85ºC /85% RH/dark. The BlueM FRS test chamber is much larger than the bench ovens and runs in the dark with no solar irradiation.

Glass mirrors sold for outdoor applications have not passed the minimum ASTM standard tests required for glass mirrors to qualify for indoor applications. NREL did not have the capability to perform these ASTM tests. NREL purchased a corrosion test chamber to allow glass mirrors to be qualified in short periods of time (i.e., 120 or 480 h) before performing the long-term durability testing of the materials in the WOM. The list price of the upgraded BCX2000 would normally cost $27,674, after the Atlas promotion, the cost was $12,582. The BCX was ordered in FY 2007, delivered in FY 2008, and installed in FY 2009.

A second CSP Ci5000 was ordered in June and delivered in October. It replaces the unserviceable Ci65 WOM, This installation is awaiting subcontract quotes. In July, an additional, $152.2k of FY08 ODC money was requested to be converted from operating to capital to purchase a third Ci5000 WOM with extended temperature capability. With the extended temperature option, a refrigeration unit extends the temperature range for the standard Ci5000 WOM from 40°C —120°C to -10°C —120°C (with light). It is scheduled for delivery on Feb. 3, 2009.

A Tenney T10RS1 ($28k) was ordered in August and delivered in November 2008 to operate at 85ºC cycling to -40ºC /85%RH/dark. The chamber will systematically cycle the temperature and/or relative humidity exposure conditions for thin glass and front surface reflector samples. The installation is awaiting subcontract quotes.

2. Planned FY 2009 Activities

2.1 PV Capital Equipment (SNL)
SNL has received no FY 2009 budget for capital equipment; thus, we have no planned activities. We will be updating our 5-year strategic capital and facility recapitalization plan and will be submitting this to DOE.

2.2 CSP Facilities Operation (SNL)
<u>NSTTF Basic Operations</u>

- Molten-salt facilities for testing valves, instrumentation, flex hoses, freeze/thaw, etc. It is yet to be determined what types of pumps are to be tested. An industry meeting is planned to pursue this.

- Upgrade instrumentation and controls at engine test facility.
- Laboratory test equipment – oscilloscopes, power meters, etc.
- Complete refurbishment of the heliostat control system.
- Bring in temporary office space (portable building) for expanding visitors needs.
- Pull fiber optic communications to 9981.
- Install digital phone capability at NSTTF.
- Clean up/remodel office space.

<u>NRTL Certification</u>

- Complete the heliostat field upgrades and inspect and certify modifications.
- Address non-NRTL issues associated with the solar furnace heliostat and the large area ATS heliostat.

2.3 CSP Capital Equipment (NREL)

The installation of the equipment ordered in FY 2008 should be complete, specifically the CSP Ci5000#2, Ci5000#3, and Tenney. We plan to purchase a 4th CSP Ci5000 WOM to test the CSP subcontract materials samples and with different weathering protocols. We also expect to purchase a new solar simulator to replace the solar simulator that reached the end of its serviceable lifetime in FY 2006. The solar simulator will be used to test the FOA subcontract materials using the service lifetime methodology and with different weathering protocols. A new Mocon oxygen permeation instrument will be purchased to rapidly screen oxygen permeation barrier properties of hardcoats, front surface mirrors, and back coatings. In addition, two subcontracts are planned to upgrade the current database of optical materials containing more than 1,000 experiments, 20,000 samples, and 300,000 measurements and to develop a laboratory instrument capable of measuring specular reflectance at a 2-mrad cone angle or less accurately and repeatedly at different wavelengths on a curved substrate.

Communications

Performing Organization: National Renewable Energy Laboratory

Key Technical Contacts: Ruby Nahan (NREL, Primary Contact), 303-384-7401, ruby_nahan@nrel.gov
Linh Truong (NREL), 303-384-6624, linh_truong@nrel.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert.ee.doe.gov

FY 2008 Budget: $790.8K (NREL)

Objectives

- Provide communications strategy, execution, production, and evaluation to meet the core communications needs of the Solar Energy Technologies Program (SETP) and its Market Transformation activities.

Accomplishments

- Maintained and updated SETP Web site (approximately 300 pages and 650 files), making changes to better reflect the current activities of the program.
- Produced 12 new documents, including the FY 2007 SETP Annual Report, and contributed to programmatic documents, such as the quarterly newsletter.
- Represented the program at the National League of Cities, International Builders' Show (IBS), American Solar Energy Society's Solar 2008 conference, National Association of Homebuilder's Greenbuilding conference, Pacific Coast Builders conference, and completed all preparations for Solar Electric Power Association's Solar Power International conference.
- Conducted strategic communications planning with Market Transformation team.
- Consulted with program partners and subcontractors on strategy and specific communications products.

Future Directions

- Conduct further strategic planning to ensure the communications tactics meet the most current and essential needs of the program.
- Make significant changes to the Web site to better meet the needs of program partners and industry.
- Evaluate efficacy of and make changes to exhibiting activities to ensure they are meeting current needs of the program.
- Support Market Transformation to ensure that critical information about these activities is captured and available for its stakeholders, so that they can better emulate these activities within their own sphere of influence.
- Enhance support to Concentrating Solar Power subprogram: target CSP-specific conferences, develop new exhibit, and outreach materials.

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1. Introduction

We provide comprehensive communications services to SETP. These services include:

- Strategic planning to ensure specific activities are necessary and are conducted in the most cost-effective and efficient way possible
- Writing, designing, and producing print products for programmatic, technical, and outreach audiences
- Exhibit planning, design, and staffing
- Web site development and maintenance
- Communications consulting for partners who do not have expertise available.

Agreement Title	FY 2008 Budget ($K)
Core Program Communications	578.8
Market Transformation Communications	212

2. Results and Accomplishments

- Conducted a 2-day strategic communications planning meeting for Market Transformation projects to identify communications goals, target audiences, key messages, and specific tactics. We provided a list of tactics to DOE to prioritize and assign for completion.
- Produced FY 2007 SETP Annual Report, coordinating individual reports on all SETP activities. We edited, produced, printed, and distributed the report.
- Promoted the benefits of incorporating solar in new home construction at IBS. SETP exhibited along with other federal agencies in a larger pavilion, entitled "Ask the Experts." With nearly 100,000 IBS attendees, the pavilion garnered 600 leads from attendees interested in energy efficiency and solar. Three new publications were produced for the builder audience. For the Greenbuilding conference, we incorporated lessons learned from IBS and developed a new, single publication for builders, which is one of the most popular PDFs on the Web.
- Developed a completely new presence for the program at Solar Power International, including tagline, exhibit, and four fact sheets.
- Responded to ~150 Webmaster inquiries from a wide range of users and developed a comprehensive maintenance plan to ensure every page of the EERE solar Web site is updated regularly. Ongoing posting requests such as funding announcements and activity prospectus were met throughout the year.
- Expanded CSP content to better represent the program activities.
- Developed an on-line repository for solar images for use by the program, labs, subcontractors, and partners. Using a free software tool (Google Picasa), we created a folder structure and populated them with PV, BIPV, and CSP photos with captions.
- Supported Solar America Cities and Solar America Showcases in a variety of ways. We updated and produced multiple publications for the funding announcement for 12 new cities. We also updated Web content, timed to go live with the Secretary's announcement of the cities. We developed publications to assist cities in understanding the technical assistance process.
- Provided communications consulting to the Solar America Board for Codes and Standards. We work to identify key audiences and outreach tactics for each report, and we helped to develop one-page overviews for outreach activities.

3. Major FY 2008 Products

Web site: www.solar.energy.gov

DOE Solar Photo Gallery:
www.picasaweb.google.com/solargallery

Publications:

- "A Homebuilders Guide to Going Solar" www.solar.energy.gov/pdfs/43076.pdf
- "Furthering Energy Security," NREL Report No. FS-840-42780; DOE/GO-102008-2560, (2008). www.nrel.gov/docs/fy08osti/42780.pdf
- "Making Cents Out of Solar: Put More Power into Your Building Plans," NREL Report No. BR-840-42731; DOE/GO-102008-2553, (2008). www.solar.energy.gov/pdfs/making_cents.pdf
- "Planning for PV: The Value and Cost of Solar Electricity," NREL Report No. FS-840-42733; DOE/GO-102008-2555,(2008) . www.solar.energy.gov/pdfs/planning_for_pv.pdf
- "Solar America Showcases," NREL Report No. FS-520-42654; DOE/GO-102008-2547, (2008). www.nrel.gov/docs/gen/fy08/42654.pdf
- "Solar America City - San Diego, California," NREL Report No. FS-840-43097; DOE/GO-102008-2603, (2008). www.nrel.gov/docs/fy08osti/43097.pdf
- "Solar Energy Technologies Program Concentrating Solar Power," NREL Report No. FS-840-43685; DOE/GO-102008-2649, (2008). www.solar.energy.gov/pdfs/43685.pdf
- "Solar Energy Technologies Program Grid Integration," NREL Report No. FS-840-43682; DOE/GO-102008-2646, (2008). www.solar.energy.gov/pdfs/43682.pdf
- "Solar Energy Technologies Program Market Transformation," NREL Report No. FS-840-43683; DOE/GO-102008-2647, (2008). www.solar.energy.gov/pdfs/43683.pdf
- "Solar Energy Technologies Program Photovoltaics," NREL Report No. FS-840-43684; DOE/GO-102008-2648, (2008). www.solar.energy.gov/pdfs/43684.pdf
- "Solar Successes: The Best of Today's Energy Efficient Homes," NREL Report No. FS-840-42732; DOE/GO-102008-2554, (2008). www.solar.energy.gov/pdfs/solar_success.pdf

International Activities

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Ruby Nahan (NREL), 303-384-7401, ruby_nahan@nrel.gov
Tom Mancini (SNL), 505-844-8643, trmanci@sandia.gov

DOE HQ Technology Manager: Kathleen Bolcar, 202-586-2820, kathleen.bolcar@hq.doe.gov

FY 2008 Budgets: $125K (NREL), $25K (SNL)

Objectives

International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) Programme

- Act as operating agent for Task 10, Urban Scale PV Applications.
- Represent U.S. in Task 1, Exchange and Dissemination of Information on PVPS.
- Organize or participate in meetings and workshops and submit deliverables as required by the membership agreement.

IEA Concentrating Solar Power (CSP) Solar Power and Chemical Energy Systems (SolarPACES)

- Provide operating agent for implementing agreement (IA).
- Coordinate activities of Task 1 CSP Electric Power Systems.
- Organize and chair two meetings.

Accomplishments

PVPS Programme

- Produced the U.S. content for the 2007 IEA PVPS Annual Report and the 2007 National Survey Report of PV Power Applications in the United States. (Task 1)
- Represented the United States at the Task 1 Annual Meeting in Nice, France. (Task 1)
- Represented the United States at the technical experts meeting in Kedah, Malaysia and the Executive Committee meeting (ExCo) and operating agents meeting in Oslo, Norway. (Task 10)

CSP SolarPACES

- Completed and submitted annual report.
- Organized and held the 2008 SolarPACES CSP Symposium in Las Vegas, Nevada, with 450 attendees and more than 130 technical papers presented.

Future Directions

- Complete 2008 IEA PVPS Annual Report and 2008 National Survey Report (Task 1).
- Improve IEA PVPS Web site (Task 1).
- Disseminate information, such as Annual Report, National Survey Report, and PV Power Newsletter to U.S. audiences. (Task 1)
- Coordinate U.S. participation by organizing, leading, and attending technical experts meetings; developing status reports and presentations for ExCo meetings; and attending the ExCo meetings and IEA PVPS Operating Agents meetings. (Task 10)
- Review Implementing Agreement Charter and determine how to incorporate industry formally into task activities. (SolarPACES)

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1. Major FY 2008 Publications

Annual Report 2007, International Energy Agency PV Power Systems, April 2008.

IEA Solar Power and Chemical Energy Systems, Annual Report, 2007.

L. Poole; P. Maycock; W. Bower. *National Survey Report of PV Power Applications in the United States 2007,* International Energy Agency Cooperative Programme on Photovoltaic Power Systems, June 2008.

EERE Crosscutting Activities

Performing Organizations:	U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Programs
Key Technical Contact:	Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov
DOE HQ Technology Manager:	Daniel Birns, DOE, 202-586-8767, daniel.birns@ee.doe.gov
FY 2008 Budgets:	$5,967K (EERE), $1,548K (Congressional Rescission)

Objectives
- Provide funds for Office of Energy Efficiency and Renewable Energy (EERE)-wide projects that cut across multiple technologies and are best funded and managed at the EERE level.
- Adhere to Congressional rescission, which are appropriated funds that are returned to Congress.

Accomplishments
- Completed photovoltaic (PV) panel installation on the DOE Forrestal building.
- Supported Greensburg (www.greensburggreentown.org/) and New Orleans Rebuild Projects.
- Supported Hawaii Clean Energy Project (www.eere-pmc.energy.gov/Hawaii.aspx).

Future Directions
- Continue to support Hawaii Clean Energy Initiative.
- Develop bi-lateral agreement with Israel.
- Provide EERE with analytic support to selected projects, as needed

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1. Project Summary

These funds are managed by EERE, primarily by the technology managers in the Office of Planning, Budget, and Analysis. These projects range from technology specific (e.g. Forrestal PV System) to crosscutting efforts (e.g. Hawaii Clean Energy Project). Funding allocations are based on the relevance of a project to a given technology area. These funding allocations do not require a special request to Congress, as they relate to the goals of each program area within EERE.

The following organizations performed the tasks listed below: National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), TMS, Sentech, Sandia National Laboratories (SNL), Energetics, and others that will be determined at a later time.

Agreement Title	Performer	Budget ($K)
Forrestal PV System	DOE HQ	2,059
Tech Communications	NREL/ORNL	744
Climate Change Analysis	NREL	302
China EE Buildings	Various	270
ORBS – Science on Sphere	NREL	243
Hawaii Clean Energy	Various	222
Deloitte EE-20 Support	TMS	198
Innovation Study	NREL	175
Sentech Technical Services	Sentech	167
Greensburg Rebuild	NREL	159
New Orleans Rebuild	NREL	150
Sentech Support Services	Sentech	149
Entrepreneur in Residence	Various	105
Advanced Buildings in India	Various	100
DCA Audit	DCAA	96
TAO & Commercialization	TMS	95
Department of Defense (DOD)/DOE Partnership	NREL	87
Tech Communications	Sandia	82
American Assoc. for the Adv. of Science Fellows	ORISE	78
Greening the Parks	NPS	77
Info and Know - DSIRE	NC	57
Support Services	Various	46
Remain Corp Priority	TBD	40
EERE-Asia Solar Decathlon	NREL	40
SBIR Review	Energetics	40
DOD National Defense Infra	TBD	40

NREL Tech Trans	NREL	35
CA Clean Tech	CA	28
NREM Conference	CFRS	25
Greenpower	TBD	25
Morocco Collaboration	TBD	24
New Energy Finance	DOE HQ	11

Small Business Innovation Research

Performing Organization: DOE HQ Solar Energy Technologies Program

DOE HQ Technology Manager: Alec Bulawka, 202-586-5633, alec.bulawka@ee.doe.gov

FY 2008 Budget: $3,450K

Objectives

- Support small business energy research and development (R&D).
- Implement Executive Order 13329, which involves assisting the private sector in manufacturing innovation.
- Continue to pursue wise cost/benefit investments.
- Augment the core research of the U.S. Department of Energy (DOE) Solar Program.
- Effectively support the Solar America Initiative (SAI).

Accomplishments

- Produced films of aluminum ink on a silicon substrate.
- Successfully developed holographic optical elements solar application.
- Developed a new photovoltaic (PV) concentrator configuration based on novel reflective lens concept and ring-array concentrator design for flat plate.
- Developed a PV manufacturing diagnostics system capable of analyzing structured surfaces.
- Developed a new method for the synthesis of fullerene derivatives.
- Optimized the reflective performance of gold materials applied to glass in solar mirrors.
- Successfully developed and optimized the flexible sol-gel hybrid matrix (nanocomposite adhesive system with excellent optical properties, durability and flexibility).
- Achieved targeted level of printed CIGS AM1.5g power conversion efficiency constructed on a flexible foil substrate (vs. glass-based), supporting the enablement of grid-parity solar energy.

Future Directions

- Improve ink formulations and processing methods to lower the resistivity and improve adhesion.
- Evaluate crucibles and coatings for production of the highest quality feedstocks.
- Build and evaluate a true-scale prototype of the Ring-Array Concentrator PV module for the subsequent product development and commercialization.
- Develop a thin-film analysis algorithm and validate and test the developed PV manufacturing diagnostics system.
- Develop software to support production grade Resonance Ultrasonic Vibration (RUV) system prototype and test at industrial environment.
- Correlate experimental and quantum chemical results to establish predictive pathways for fullerene derivatives optimization and novel device fabrication.
- Continue optimizing surface functionalization methods for glass to create homogeneous coating layers for dielectric mirror fabrication (to improve solar thermal conversion efficiency in collectors).

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1. Introduction

Each year, ten federal departments and agencies, including DOE, are required by the Small Business Innovation Research (SBIR) Program to reserve a portion of their R&D funds for award to small, U.S.-owned businesses. Over the life of the SBIR Program, the DOE Solar Energy Technologies Program has contributed $18 million and received $41 million in research funding.

As in the past, the Solar Program has also benefited to a large extent this past year from the Office of Basic Energy Sciences contribution, again mostly in nanotechnology topics for PV in 2007. The 2008 Solar Program is nested mainly in the Solar Energy (Topic 23) SBIR category.

Once again the SBIR activities complements the DOE Solar Program Multi-Year Technical Plan because they continue to augment and support the core program, in all respects, with integrated solutions from the vast U.S. small business community. The community continues to participate actively in the Solar America Initiative (SAI) through carefully selected and tailored supportive solicitations.

2. Technical Approach

Renewable energy technologies have achieved significant advances in recent years, but further improvements are needed if they are to reach their full potential. The solar technologies included in the scope of this SBIR work address both solar electric, PV, and concentrating solar power (CSP) systems. Grant applications for FY 2008 were required to clearly demonstrate the applicants' ability to proceed to hardware development fabrication, testing, and manufacture of technologies.

3. Results and Accomplishments

Several SBIR awards advanced their goals and produced very encouraging results of their R&D to date. (See table below)

4. Planned FY 2009 Activities

Further development of PV and CSP systems, as well as systems integration, will be addressed through creative and innovative approaches in engineering and design, new materials, and new processes. A concerted effort has been made to have the SBIR activity, once again, dovetail in support of the SAI.

4.1 PV Devices with Reduced Silicon Intensity – The growth of the semiconductor and solar industries has put increasing pressure on limited supplies of high-quality silicon, thus driving up the price of the material by up to 200% to 800%. Development is underway for a number of processes aimed at reducing the use of silicon (Si) material. Kerfless wafering, epitaxial growth, direct solidification, and recrystallization are all thin crystalline silicon processes that promise Si intensity well below 3g/W with cells above 15% efficiency.

4.2 High Efficiency Organic (OPV) or Sensitized Photovoltaic Cells – Lightweight and flexible conjugated polymer-based solar cells currently suffer from low efficiency. Nonetheless such cells represent a highly promising area of low cost PV technology, offering greatly increased functionality and potential to meet future challenges of scalability, flexibility, integration and cost. A more effective utilization of the incident solar spectrum (beyond the current wavelength limitation) and into the near infra-red could provide significant improvement in OPV performance.

4.3 Advanced Concentrating Systems – Recent progress in high efficiency multijunction cells has fostered considerable interest in concentrating PV. The majority of efforts in this area involve traditional, non-imaging high-concentration (100-1000X) optics and square cells approximately 1cm2 in area. Although many companies are beginning to mass produce such concentrating systems, their designs suffer from inherent limitations: (1) the requirement for conventional 2-axis tracking, which increases cost and reduces field packing density; and (2) the significant material requirements (i.e., for framing, support, etc.), which adds cost, complicates manufacture, and creates reliability concerns. Innovative concentrating solutions that overcome either of these limitations are of pertinent interest.

For utility-scale solar thermal power generation, system capital cost reductions and improved dispatchability are necessary to increase the market penetration of CSP. In particular, advancements are needed for solar-collection-field cost reduction, low cost, high-performance thermal energy storage (TES) and high-temperature, high-heat-capacity heat transfer fluids (HTF).

4.4 Device Manufacturing, Packaging and Assembly – There is room for improvement in the area of module packaging and assembly. Areas of interest include (1) module technologies – such as low-cost, flexible encapsulants, light trapping layers, advanced contacts, and advanced transparent conductors, which offer increased performance/reliability or reduced costs broadly across the PV industry; (2) building-integrated module designs, optimized system configurations, and innovative deployment options, which offer dramatically lower installation and maintenance costs than conventional approaches; and (3) approaches to improve the lifetime of photovoltaic systems (such as thermal management, material compatibility, and other systems impacted by the physical environment) and components (such as inverters, sensors, connectors, capacitors, surge protection, integrated circuits, and input/output ports) subject to electrical noise, mechanical abuse, and the like. Also, sensor and control technologies are needed to ensure that newly emerging PV systems (with improved performance/reliability) can be manufactured to quality standards.

5. Major FY 2008 Publications

The SBIR Program holds the awardee responsible for a final report at the end of both Phase 1 and Phase 2. The SBIR Office in Germantown, Maryland, has on file the final reports of all the projects awarded in the past.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2008.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2008 ($K)
Applied Nanotech. Inc. Dr. Max Roundhill	Austin, TX mroundhill@appliednanotech.net	Solar energy materials solutions for cells and modules	100*
Luminit, LLC Dr. Kevin Yu	Torrance, CA kyu@luminitco.com	Multifunctional UV curable Sol-Ge	100*
Spire Corporation Dr. William R. Neal	Bedford, MA wrneal@spirecorp.com	Microcrack Detection in Crystalline Silicon Solar Cells	99.7*
Crystal Systems, Inc. Dr. David Bruce Joyce	Salem, MA djoyce@crystalsystems.com	Material Utilization and Waste Reduction through Kerf Recycling	98.3*
Sky Train Corporation Mr. Karl William	Palm Harbor, FL kguenther@skytraincorp.com	Energy Exchanger For a Solar-Powered Monorail/Light Rail	100*
Luminit, LLC Mr. Kevin Yu	Torrance, CA kyu@luminitco.com	Flexible Spectrum Splitting Holographic Concentrator	750**
SVV Technology Innovations, Inc. Dr. Sergiy Vasylyev	McClellan, CA vasilyev@svvti.com	High Performance PV Concentrator	750**
Luna Innovations Incorporated Dr. Vladimir Kochergin	Roanoke, VA submissions@lunainnovations.com	High-Throughput In-Line PV Manufacturing Diagnostic System	750**
Ultrasonic Technologies, Inc. Dr. Sergei Ostapenko	Wesley Chapel, FL sergei.ostapenko@ultrasonictech.com	In-line Crack Detection in Silicon Solar Cell Production Using Resonance Ultrasonic Vibrations	737**
Nanosolar, Inc. Dr. Chris Eberspacher	Palo Alto, CA chris@nanosolar.com	Printed Solar Cell Using Nanostructured Ink	750**
TDA Research, Inc. Dr. Michael D. Diener	Wheat Ridge, CO mikee@tda.com	Improved Fullerenes for OPV	750**
NanoSonic, Inc. Mrs. Michelle Berg	Blacksburg, VA mberg@nanosonic.com	High Performance, Low-Cost Nanostructured Mirror Surfaces	750**
Midwest Optoelectronics, LLC Dr. Aarohi S. Vijh	Toledo, OH vijh@mwoe.com	Novel Interconnection Process for Lightweight Flexible Photovoltaic Modules	746**

* Phase I funding.
** Phase II funding paid over 2 years.

Congressional Earmarks

Performing Organizations:	CEC Stuyvesant Cove, Inc. (CEC); CENTRIA, Inc.; Crowder College; Eikos, Inc.; Greenfield Community College; Hackensack University Medical Center; Nevada Institute for Renewable Energy Commercialization (NIREC); North Dakota State University (NDSU); Nye County, NV; Regents of New Mexico State University (NMSU); Rensselaer Polytechnic Institute (RPI); Rural Development, Inc.; San Francisco Public Utilities Commission; Solar Energy Consortium: University of Arizona; University of Arkansas at Little Rock (UALR); University of Hartford; University of Louisville Research Foundation, Inc.; University of Nebraska at Kearney; University of Nevada, Las Vegas Research Foundation
Key Technical Contacts:	Carolyn Elam (DOE/GO, Primary Contact), 303-275-4953, carolyn.elam@go.doe.gov Margie Bates (DOE/GO), 303-275-4845, margie.bates@go.doe.gov Joe Lucas (DOE/GO), 303-275-4849, joe.lucas@go.doe.gov Steve Palmeri (DOE/GO), 303-275-4832, steve.palmeri@go.doe.gov Jim Payne (DOE/GO), 303-275-4756, jim.payne@go.doe.gov Brad Ring (DOE/GO), 303-275-4930, brad.ring@go.doe.gov Holly Thomas (DOE/GO), 303-275-4818, holly.thomas@go.doe.gov
DOE HQ Technology Manager:	Thomas Rueckert, 202-586-0942, thomas.rueckert.ee.doe.gov
FY 2008 Budget:	$18,665K (DOE/GO)

Objectives

- Fund 18 congressional earmarks, 15 new awards and three continuation awards, through the Consolidated Appropriations Act, 2008.
- Conduct research related to DOE Solar Energy Technologies Program and Solar America Initiative (SAI) program objectives.

Accomplishments

- Awarded 15 new congressional earmarks and three continuation awards.

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1. Introduction

Eighteen congressionally directed projects were negotiated and funded in fiscal year (FY) 2008. These funds were directed by the Consolidated Appropriations Act, 2008. The projects were fully-funded this year, although several are multi-year.

2. Technical Approach

Two of the 18 awards were continuations of existing, previously funded projects. In addition to the 18 projects funded in 2008, four projects from prior years were active during FY 2008, although they received no additional funding. The awards are summarized in the following table:

Agreement Title	FY 2008 Budget ($K)
CEC Stuyvesant Cove, Inc.; Christopher Collins (Solar 2 Green Energy, Arts & Education Center)	492
CENTRIA, Inc.; Richard A. Mowrey (Building-Integrated Photovoltaic Solar Energy System)	295
Crowder College; Dan Eberle (Crowder College Missouri Alternative & Renewable Energy Technology (MARET) Center)	0*
Eikos, Inc.; Paul J. Glatkowski (Transparent Coatings for Solar Cell Research Project)	1,818
Greenfield Community College; Glen Haywood	394

Agreement Title	FY 2008 Budget ($K)
(Sustainable Energy Model Greenhouse)	
Hackensack University Medical Center; Helen Cunning (Hackensack University Medical Center Green Building Project)	0*
Nevada Institute for Renewable Energy Commercialization; Christine Gulbranson (Renewable Energy Research and Development)	1,476
North Dakota State University; Dr. Philip Boudjouk (Center for Nanoscale Energy)	5,904
Nye County; Pam Webster (Nye County Renewable Energy Feasibility Study)	492
Regents of New Mexico State University; Shuguang Deng (High Efficiency Cascade Solar Cells)	984
Rensselaer Polytechnic Institute; Anna Dyson (Rensselaer Polytechnic Institute Green Build)	0*
Rural Development, Inc.; Anne Perkins (Wisdom Way Solar Village)	394
San Francisco Public Utilities Commission; John F. Doyle (MUNI Ways and Structures Building Integrated Solar Membrane Project)	610
The Solar Energy Consortium; Vincent Cozzolino (Solar Consortium of New York Photovoltaic Research and Development Center)	1,476
University of Arizona; Roger Angel (Development of Concentrator PV Systems for Solar Electricity)	984
University of Arkansas at Little Rock; Dr. Alexandru Biris (Novel Photovoltaic Devices Based on Polymeric and Carbon Nanostructured Materials)	1,181**
University of Hartford; Dr. Barry T. Lubin (Evaluation of Economic Benefits of Distributed Photovoltaic Systems)	492
University of Louisville Research Foundation, Inc.; M. Keith Sharp (Sustainable Buildings: Using Active Solar Power)	394**
University of Nebraska at Kearney; Christopher L. Exstrom (CIBS Solar Cell Development)	935
University of Nevada - Las Vegas Research Foundation; Wilber Pittinger (Photonics Research and Development)	0*
University of Nevada, Las Vegas ; Dr. Biswajit Das (Solar Cell Nanotechnology)	738

Agreement Title	FY 2008 Budget ($K)
University of Nevada, Las Vegas Research Foundation ; Wilbur Pittinger (Solar Technology Center)	0*

* Funded with prior year funds

** Continuation of existing (prior year) Congressional Earmark

3. Accomplishments and Future Directions

3.1 Solar 2 Green Energy, Arts & Education Center (CEC - Collins)

Objective

- Complete preliminary design work on a net-zero energy consumption, Leadership in Energy and Environmental Design (LEED) platinum-rated center, located in New York.

3.2 Building-Integrated Photovoltaic (PV) Solar Energy System (CENTRIA – Mowrey)

Objectives

- Increase adoption of solar energy by developing standard designs for building-integrated PV (BIPV).
- Develop standard PV-system designs, specifications, and support for standing-seam roof manufacturers, including electrical component design, roof wire management, testing, commercialization, and complete standards development.

3.3 Crowder College Missouri Alternative & Renewable Energy Technology (MARET) Center (Crowder College – Eberle)

Objective

- Develop 27,500-ft^2 facility as a living laboratory to support solar and other renewable energy development through professional degrees, new product commercialization, renewables business incubation, and consumer education.

Accomplishments

- Completed work on prototype roof section, modular bays, and site and structural plans for first phase of construction.

Future Directions

- Finish environmental assessment to comply with National Environmental Policy Act (NEPA) standards.
- Complete design work on the integrated mechanical and electrical energy collection, recovery and exchange systems.

3.4 Transparent Coatings for Solar Cell Research Project (Eikos – Glatkowski)

Objectives

- Synthesize and characterize novel nanomaterials for transparent conductive coatings (TCCs) for use in thin-film PV and other energy applications.
- Formulate inks for printing high conductivity nanomaterial-based coatings.
- Demonstrate coating environmental stability.
- Evaluate cost-performance-processing tradeoffs.

Accomplishments

- Surveying TCC performance, processing, and cost metrics for comparison with nanomaterials TCCs.
- Synthesized nanomaterials for TCCs.

Future Directions

- Create novel high-performance, environmentally-stable nanomaterial TCCs.
- Integrate these coatings into thin film organic and polycrystalline PV.

3.5 Sustainable Energy Model Greenhouse (Greenfield Community College – Haywood)

Objectives

- Build a zero-net energy impact solar greenhouse that incorporates passive solar design, thermal storage, energy conservation features, PV, and an active geothermal heating system.

3.6 Hackensack University Medical Center Green Building Project (Cunning)

Objectives

- Develop a LEED-certified medical facility with PV system and associated complementary energy efficiency equipment and materials.

3.7 Renewable Energy Research and Development (NIREC - Gulbranson)

Objectives

- Move research from Nevada academic institutions into viable businesses.

Accomplishments

- Sponsored week-long Green Technology Entrepreneurship Academy for graduate students, post-docs, and faculty (7/08).
- Assembled coalition of institutional research partners.
- Set up Entrepreneurs-in-Residence (EIR) Program and appointed 2 EIRs.
- Issued competitive request for proposal (RFP) and awarded approximately $320,000 to four projects.

Future Directions

- NIREC will continue to search for, assess, and award funds to deserving projects.
- Annual RFP planned, integrating researchers, experienced entrepreneurs, business executives.
- Partnering with Nevada Small Business Development Center to sponsoring a 2009 Small Business Innovation Research (SBIR) conference on energy.

3.8 Center for Nanoscale Energy (NDSU – Boudjouk)

Objectives

- Investigate applicability of liquid silanes as precursors to flexible PV that utilize semiconducting silicon as basis of the sunlight-absorbing layer.
- Investigate low-temperature routes to silicon-based solar cells on glass substrates and evaluate hybrid organic/inorganic strategies that might allow flexible PV on plastic substrates.
- Investigate integration of printed active and passive components into local control electronics for solar panels.

Accomplishments

- Plasma enhanced chemical vapor deposition (PECVD) of both a-Si and alloys (i.e., SiN and SiO_x) using Si_6H_{12}.
- Established system coupling a printing methodology with laser annealing under inert atmosphere.
- Developed schematics and electrical models for max power-point tracking system.

Future Directions

- Refine PECVD of a-Si from Si_6H_{12} and compare to other precursors (e.g., silane, disilane, trisilane).
- Establish route to printed silicon from Si_6H_{12}-based inks where low-temperature treatments yield materials that maintain carrier properties appropriate device for the application.
- Demonstrate panel-based maximum powerpoint tracking system.

3.9 Nye County Renewable Energy Feasibility Study (Nye County – Webster)

Objectives

- Develop comprehensive land use and infrastructure plans for the Amargosa Valley and Beatty areas.
- Develop land use and community preparedness plans.

- Develop a feasible design for Barrick Mine Energy Park for energy production projects and university-directed educational and energy research programs at the site.
- Measure and characterize wind behavior in support of a feasibility study of Beatty-area wind energy generation projects.
- Evaluate potential effectiveness of PV-powered county buildings.
- Evaluate potential performance, benefits, costs, and long-term sustainability of a new landfill with one or more concepts: biomass energy production, feedstock availability, recyclables diversion, and similar practices.

3.10 High Efficiency Cascade Solar Cells (NMSU–Deng)

Objectives

- Develop new organic semiconducting PV.
- Develop band-enhancing layers.
- Study mechanisms of percolation for charge transfer in new organic semiconductors.
- Use cascade solar cell architecture to develop semiconductors.

Accomplishments

- Initiated composite fabrication using nanotubes and polymers.
- Built two chemical vapor deposition reactors for synthesizing carbon nanotubes (CNTs).
- Performed preliminary studies on synthesis conditions affecting CNT quality.
- Launched computer cluster for modeling and simulations.
- Initiated theoretical studies of the structures and physical characteristics of electro-active nanoscale systems.

Future Directions

- Synthesize single-walled, double-walled, multi-walled, and nitrogen and boron-doped CNTs.
- Develop suitable nanocomposites for all aspects of new architecture.
- Obtain spectroscopic and morphological control of nanocomposites through materials characterization.
- Optimize nanocomposites for use in a flat panel cell, develop new cells.
- Continue theoretical studies of functionalized and doped CNTs and self-assembled complexes between organic molecules and nanotubes and initiate theoretical studies of optically active nanoparticles embedded in emissive polymers.

3.11 Rensselaer Polytechnic Institute Green Build (Rensselaer Polytechnic Institute – Dyson)

Objectives

- Complete testing of a building-scale curtain wall prototype for a daylighting system that incorporates concentrating modules for heat and power production with dramatically reduced cost payback periods.
- Achieve system goal levelized cost of energy (LCOE) of $0.19/kWh; efficiency (72.2-80.9% combined); $2.68 per peak watt.

Accomplishments

- Completed testing of prototype version 4.1 (See Figure 1).
- Value engineering and reduction by 50% of all components for version 5.

Figure 1. IC Solar Façade – Version 4.1

Future Directions

- Independent testing of IC Solar Module at NREL (3/09).
- Independent testing of curtain-wall panel(s) with 100 modules at BEESL Labs and the Syracuse Center for Excellence in Energy and Environmental Systems.

3.12 Wisdom Way Solar Village (Rural Development, Inc. – Perkins)

Objectives

- Enhance Wisdom Way Solar Village, 20 proto-typical “near zero*net energy” affordable homes by adding solar hot water systems and high efficiency windows. Researchers with the DOE “Building America Program” will monitor the homes for performance.
- Enable residents to reduce their energy budgets for electricity, heat, and hot water to as low as $300 per year (in 2007 dollars).

3.13 MUNI Ways and Structures Building Integrated Solar Membrane Project (San Francisco Public Utilities Commission – Doyle)

Objectives

- Install BIPV system using best available highest efficiency technology to provide about 25% of the total facility load of an average of 52,560 kWh per month.

Accomplishments

- Completed preliminary roof structural and electrical evaluation as well as California Environmental Quality Act (CEQA) requirements.
- Completed preliminary designs for installation of BIPV on the facility roof, specified monitoring of BIPV system.

Future Directions

- Advertise RFP 1/09.
- Start construction in late summer 2009 with completion estimated for December 2009.

3.14 Solar Consortium of NY PV R&D Center (TSEC – Cozzolino)

Objectives

- TSEC is an industry-led not-for-profit realizing the promise of solar energy by mobilizing resources of New York State.

Accomplishments

- Collaborated with NYS economic development agencies and NY Power Authority for Globe Specialty Metal's solar grade silicon manufacturing facility in Niagara Falls, New York, resulting in 500 new jobs.
- Coordinated Clarkson University project to develop unique manufacturing process to enhance feasibility of Globe's solar-grade manufacturing.
- Created a projected additional 600 jobs to New York State by applying region's technology skills to enhancing products and processing.
- Coordinated SUNY New Paltz Solar usage projects (apple farm, solar for 3 Ulster County, NY hospitals, off-grid PV Air National Guard installation Newburgh NY, new LED approach from Brite Components).

Future Directions

- Expand use of off-grid applications of solar energy products and to drive increases in the region's work force through business attraction and expansion.

3.15 Development of Concentrator PV Systems for Solar Electricity (U of Arizona – Angel)

Objectives

- Develop and test a focal plane generator capable of delivering > 1 kW at the dish focus.
- Develop and test a 3m-test reflector dish.
- Develop outreach program by integrating solar activity into educational program Biosphere II.

3.16 Novel PV Devices Based on Polymeric and Carbon Nanostructured Materials (U of Arkansas at Little Rock – Biris)

Objectives

- Incorporate unique optical and electronic properties of carbon nanotubes for improved performance of PV devices. Single-wall carbon nanotubes (SWNTs) will be directly configured as energy conversion materials to fabricate thin-film solar cells, with nanotubes serving as both photogeneration sites and charge carriers collecting/transport layers.

Accomplishments

- Synthesized carbon nanotubes using a variety of catalysts and methods.
- Synthesized P3HT product at larger scale.
- Fabricated very first hybrid-PV devices based on single wall carbon nanotube/n-silicon heterojunctions.
- Synthesized polyaniline (PANI) by the self-stabilized dispersion polymerization (SSDP) technique and processed into thin films for hole transport materials (HTMs).
- Synthesized Graphite-Polyaniline (G-PANI) and processed 60/40 composite into pristine films for contact layer (electrode) as possible replacement for Al and Ca.
- Characterized bulk properties of G-PANI composites.
- Developed methods for producing magnetic and soluble MWNTs using lignins and tannins.
- p-GaN / $In_xGa_{1-x}N$ / n-GaN (PiN) nanorods were grown by plasma assisted molecular-beam-epitaxy (MBE) method.
- Control of nanorod diameter for n-GaN from 70 nm to 150 nm achieved by varying growth temperature.
- Demonstrated 30% In incorporation into $In_xGa_{1-x}N$ layer, producing a 2.3 eV bandgap.

Future Directions

- Characterize SSDP-PANI thin films for HTMs.
- Characterize pristine G-PANI films for electrodes to replace Ca and Al.
- Demonstrate carbon nanotube length control.
- Fabricate and characterize carbon nanotube composite cell structures.
- Develop and characterize transparent carbon nanotube based electrodynamic screens for dust mitigation for solar panels
- Study quantum confinement effect of light and charge carriers in the nanostructures.

3.17 Evaluation of Economic Benefits of Distributed PV Systems (U of Hartford – Lubin)

Objectives

- Use existing research to develop economic and engineering models.
- Use existing PV installations to obtain data on both generation and load.
- Use engineering models to calculate effective load carrying capacity and as input to the economic model to predict multiple value streams that accrue from distributed generation using PV.

Accomplishments

- Organized advisory board, includes utilities and utility-related companies.
- Established basis of models to relate Equivalent Load Carrying Capacity to value streams.

Future Directions

- Continue to collect local insolation data.
- Investigate potential storage strategies.
- Use PV installation at the University of Hartford to develop and validate models.
- Work with owner operated and third party owners for access to their generation and host companies load data.

3.18 Sustainable Buildings: Using Active Solar Power (U of Louisville – Sharp)

Objectives

- Install solar technologies; demonstrate to public officials, developers, commercial establishments, industries, and citizens the benefits of using solar technologies.
- 2005 project established an Energy Center. FY 2008 funding to continue FY 2005 and 2006 activities for two research projects (Solar Hydrogen Electric Power System and Solar Heat Pipe), PV demonstration, and 2 educational subprojects (training for installers of solar electric systems, and education).

Future Directions

- Collaborate with Kentucky Solar Partnership to conduct educational outreach through a renewable energy roadshow.

3.19 CIBS Solar Cell Development (University of Nebraska at Kearney – Exstrom)

Objectives

- Fabricate and study new VP material, copper indium boron diselenide, $CuIn_xB_{1-x}Se_2$ (CIBS).
- Through chemical composition changes, exceed $CuIn_{1-x}Ga_xSe_2$ (CIGS) PV efficiencies with CIBS goals of 25% (single-film) and 15% (module).

Accomplishments

- Optimized solvothermal reaction conditions to produce a first-generation nanocrystalline CIBS material.
- Initial investigations into *ex-situ* sequential and simultaneous selenization/sulfurization of $Cu(In_{0.5}B_{0.5})$ precursors were performed. Initial X-ray diffraction data indicate that sulfur has been incorporated into the $CuInSe_2$ lattice to some degree.

Future Directions

- Investigate and optimize annealing effects on model nanocrystalline chalcopyrites and CIBS.
- Determine primary reaction and annealing factors that determine boron composition control in CIBS.
- Develop CIBS nanocrystalline-to-thin-film processing via rapid thermal annealing, inkjet spray techniques, or related technology.
- Deposit CIS and CIBS films using the in-situ deposition chamber.
- Deposit CuIn and CuInB precursor films and subject them to various ex-situ selenization/sulfurization procedures.

3.20 Photonics Research and Development (UNLV – Pittinger)

Objectives

- Develop advanced lighting technologies.
- Establish photonics academics along with research and development at UNLV to improve lighting technologies.
- Provide credentialed lighting professionals for the national industry.

Accomplishments

- Improved understanding of the characteristics of quantum dot LEDs.
- Improved efficiency of green LEDs.
- Established and enhanced UNLV Display Lighting Laboratory.

Future Directions

- Continue to develop process parameters for synthesizing high quality CdSe QD's with an increased percentage of monocrystalline particles.
- Continue to collaborate with Boston University; additional RTA-treated samples will be investigated by WDS x-ray mapping to provide more information on the contact formation mechanism.
- Commercialize hybrid solar lighting technology.

3.21 Solar Cell Nanotechnology (UNLV – Das)
Objectives

- Develop low cost non-lithographic nano-fabrication technology to fabricatie thin-film porous templates as well as uniform arrays of semiconductor nanostructures to make high efficiency solar cells. These are expected to have very high energy conversion efficiencies due to the increased absorption coefficients of semiconductor nanostructures. Thin film porous templates can be used to optimize surface texturing of solar cells for additional enhanced energy conversion efficiency.

3.22 Solar Technology Center (UNLV – Pittinger)
Objectives

- Develop solar and renewable energy information center within Eldorado Valley Energy Zone.
- Provide public information services on both current and emerging solar and other renewable energy technologies.
- Provide schools and interested public a practical means of observing solar and other renewable energy systems.
- Provide a facility for demonstration and research on existing and emerging renewable energy technologies.

Accomplishments

- Performed civil engineering activities for site development, began NEPA process, including preparation of environmental assessment.
- Began procurement process for securing modular building for a center.

Future Directions

- Pending DOE approval on Environmental Assessment (NEPA), proceed with Phase II – installation of building and related infrastructure.
- Identify and enter into research partnerships.

4. FY 2008 Special Recognitions and Patents

Eikos, Inc

- Innovator of the Year, Small Times 2007Finalist, Paul Glatkowski.
- NASA Certificate of Recognition, Electrically Conductive Coatings with High thermal Oxidative Stability and Low Thermal Conduction, 2008, Paul Glatkowski.

RPI

- IN 219411, titled "Concentrating Type Solar Collection and Daylighting System Within Glazed Building Envelopes" issued on 05/06/2008

UALR

- “Multi-Junction Solar Cell”, *U.S. patent pending* (07) File #: 60/897,542.

5. Major FY 2008 Publications

Eikos, Inc.

- D.A. Britz, et al. “Highly Transparent Carbon Nanotube Films for ESD Protection,” *Proceedings of SPRAT XX, Sept. 25-27, Cleveland, OH, 2007*.
- M.A. Contreras, et al. “Replacement of transparent conductive oxides by single-wall carbon nanotubes in Cu(In,Ga)Se-2-based solar cells,” *J. of Physical Chemistry C*, **111**, 14045-14048 (2007).

TSEC

- State University of New York at New Paltz Case Study

University of Nebraska at Kearney

- J. Olejníček,et al. “A Non-vacuum Process for Preparing Nanocrystalline $CuIn_{1-x}Ga_xSe$ Materials Involving an Open-air Solvothermal Reaction,” *International Materials Research Congress, Aug. 17-21, Cancun, Mexico, 2008.*
- J. Olejníček, et al. “A Non-vacuum Process for Preparing Nanocrystalline $CuIn_{1-x}Ga_xSe$ Materials Involving an Open-air Solvothermal Reaction,” *Solar Mater. Solar Cells*, submitted for publication.

UALR (29 published or submitted, including the following):

- Z. Li, et al. “$SOCl_2$ enhanced photovoltaic conversion of single wall carbon nanotube/n-silicon heterojunctions”, *Applied Physics Letters* – accepted-in press, 2008.
- Y. Xu, et. al.“Surface Area and Thermal Stability Effect of the MgO Supported Catalysts for the Synthesis of Carbon Nanotubes”, *J. of Materials Chemistry* – accepted-in press, 2008.
- Z. Li, et al. “Influence of CO_2 on Carbon Nanotube Growth by Using Hydrocarbon as Carbon Source”, *Chemical Communications*, 28, 3260-3262, 2008.
- A.R. Biris, et al. “High Quality Double Wall Carbon Nanotubes Grown by a Cold-Walled Radio Frequency Chemical Vapor Deposition Process”, *Chemistry of Materials*, 20(10), 3466-3472, 2008.
- R.B. Little, et al. “On the dynamical ferromagnetic, quantum Hall, and relativistic

effects on the carbon nanotubes nucleation and growth mechanism", *J. of Magnetism and Magnetic Materials*, 320(3,4), 540-547, 2008.

- A.R. Biris, et al. "Hydrogen influence on the growth process and properties of single wall carbon nanotubes", *Physics Letters A*, 372(17), 3051-3057, 2008.
- Z. Li, et al. "Effects of the Fe-Co Interaction on the Growth of Carbon Nanotubes", *J. of Chemical Physics*, 129(7), 074712/1-074712/6, 2008.
- S. Bourdo, et al. "Structural, electrical, and thermal behavior of novel graphite-polyaniline composites with increased crystallinity", *Advanced Functional Materials*, 18(3), 432-440, February, 2008.
- A.R. Biris, et al. "Multiwall carbon nanotubes synthesized from acetylene by RF-CCVD on novel CaO supported catalysts", *Physics Letters* A, 372(42), 6416-6419, 2008.
- A.R. Biris, et al. "Hydrogen Storage in Carbon-Based Nanostructured Materials", *Particulate Science and Technology J.*, 26(4), 297-305, 2008.
- Four papers, Annual Meeting of the American Chemical Society, New Orleans, 2008.
- Two papers presented at the annual meeting IEEE-IAS, 2008.

UNLV

- E. Dimakis, et al. "Growth and properties of near-UV light emitting diodes based on InN/GaN quantum wells", *Phys. Stat. Sol.* (a) 205, No. 5, 1070 (2008).
- C. Thomidis, et al. "InGaN-based LEDs grown by plasma-assisted MBE on (0001) sapphire with GaN QDs in the nucleation layer", *Phys. Stat. Sol.* (c) 5, No. 6, 2309 (2008).

6. University and Industry Partners

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)	Cost Share ($K)
Eikos, Inc. NREL	Golden, CO	Expertise, device fabrication, characterization, and materials.	492	37
NIREC: Desert Research Institute Dr. H. Kuhns	Reno, NV	Developing Utility Accountant – tool to help manage utility costs.	90	50
University of Nevada, Reno Dr. Andrzej M Trzynadlowski	Reno, NV	Power electronic converter-controller for off-grip wind-turbine systems.	97	
UC Davis, Dr. Mark Mascal	Davis, CA	Direct conversion of sugars, cellulose, and cellulosic biomass into fuels.	60	
University of Nevada, Reno D. K. Kim	Reno, NV	Condenser for geothermal applications.	70	
NDSU: UC-Riverside Dr. R. Haddon	Riverside CA	Evaluate novel electro catalyst materials for fuel cells	533	33
University of Toledo Dr. Marsillac	Toledo OH	Liquid silane-derived films.	200	50
RPI/Harvard CVM Don Schneider Sr.	Cambridge, NY	Value engineering/optimization of system components.	50	50
Syracuse University Jianshun Zhang	Syracuse, NY	System testing.	0	0
Island Bay Window and Curtain Wall	Long Island, NY	Curtain wall panel fabrication	0	100

* Funded with prior year funds
** Continuation of existing Congressional Earmark

Solar Energy Technologies Program
Total FY 2008 Budget ($K)

	NREL Total	Sandia Total	Other Total	Solar Total
Solar Energy Technologies	**69,754**	**15,983**	**84,264**	**170,000**
Photovoltaics	**64,064**	**11,309**	**62,628**	**138,000**
Applied Research	**29,024**	**818**	**7,358**	**37,200**
Exploratory Research	**7,218**	**470**	**7,019**	**14,707**
Silicon Center of Excellence	0	0	712	712
Thin Film Center of Excellence	600	0	0	600
Future Generation Projects	156	0	6,000	6,156
MURA Projects	292	0	7	299
Industrial CRADAs	2,100	0	0	2,100
Fundamental R&D	1,706	0	300	2,006
Seed Fund Projects	1,870	470	0	2,340
Exploratory Project Management	494	0	0	494
Electronic Materials & Devices	**10,149**	**250**	**0**	**10,399**
Silicon Materials & Devices	3,541	0	0	3,541
Processes & Advanced Concepts	2,605	250	0	2,855
Thin-Film Polycrystalline Compounds	2,225	0	0	2,225
Concentrator Crystalline Cells	1,578	0	0	1,578
EMD Project Management	200	0	0	200
Measurements & Characterization	**9,492**	**0**	**0**	**9,492**
Analytical Microscopy	2,462	0	0	2,462
Electro-Optical Characterization	2,455	0	0	2,455
Surface Analysis	1,670	0	0	1,670
Cell and Module Performance	2,125	0	0	2,125
M&C Project Management	780	0	0	780
M&C Project Management	780	0	0	780
Process Develop Integrate Lab	**1,830**	**0**	**0**	**1,830**
PDIL Hardware Development	1,125	0	0	1,125
PDIL Project Management	336	0	0	336
PDIL Software Integration	369	0	0	369
Operations & Planning	**335**	**98**	**339**	**772**
Program Management - AR	335	98	0	433
Rescission - AR	0	0	339	339
Earmarks – AR*	0	0	12,900	12,900
Systems Development	**21,216**	**871**	**42,713**	**64,800**
PV Systems Development	**160**	**0**	**39,300**	**39,460**
Technology Pathway Partnerships	0	0	35,500	35,500
University Process & Product Dev	0	0	3,500	3,500
SAI Project Monitoring	160	0	300	460
PV Component Development	**20,089**	**0**	**0**	**20,089**
PV Incubator Solicitation	11,598	0	0	11,598
Industry Thin Film Partnerships	2,435	0	0	2,435
University Thin Film Research	1,591	0	0	1,591
PV Manufacturing R&D	3,032	0	0	3,032

PV Comp Project Mgmt	**1,434**	**0**	**0**	**1,434**
PV Systems Project Mgmt - CR	600	0	0	600
PV Systems Project Mgmt - Plus	834	0	0	834
Operations & Planning	**967**	**871**	**3,413**	**5,251**
Program Management - SD	**967**	**511**	**695**	**2,172**
PV Capital Equipment	**0**	**360**	**0**	**360**
PBA Activities - SD	0	0	2,118	2,118
Rescission – SD	0	0	600	600
Test & Evaluation	**10,736**	**8,305**	**2,659**	**21,700**
Modeling & Analysis	**2,490**	**730**	**250**	**3,470**
System Modeling	**1,140**	**730**	**0**	**1,870**
Systems Analysis	**1,350**	**0**	**250**	**1,600**
Market - Solar Annual Report	300	0	0	300
Market - PV Roadmap Support	100	0	0	100
Market - Solar DS Model	100	0	0	100
Value - GPRA Analysis	100	0	0	100
Value - PNNL/NEMS Model	50	0	100	150
Value – PV Value Clearinghouse	50	0	0	50
Policy - General Analytic Support	300	0	0	300
Policy - Topical Reports	150	0	150	300
Financial Analysis	200	0	0	200
Grid Integration	**400**	**4,404**	**0**	**4,804**
PV Grid Integration	**400**	**400**	**0**	**800**
Inverter/BOS R&D	**0**	**775**	**0**	**775**
Inverter/EMS Solicitation	**0**	**3,229**	**0**	**3,229**
Inverter Awards	0	3,000	0	3,000
Lab Support	0	229	0	229
Reliability R&D	**4,625**	**2,040**	**0**	**6,665**
Module Screening & Field Eval	**1,945**	**320**	**0**	**2,265**
Industry Reliability & Codes	**475**	**445**	**0**	**920**
SLP Models & Failure Modes	**270**	**645**	**0**	**915**
Accelerated Lifetime Testing	**1,935**	**630**	**0**	**2,565**
Accelerated Lifetime Testing	1,935	630	0	2,565
Systems Engineering	**1,775**	**1,070**	**1,750**	**4,595**
Module, Array & Systems T&E	**1,575**	**840**	**0**	**2,415**
PV Module Database	**0**	**180**	**0**	**180**
Energy Ratings Method Validations	**200**	**0**	**0**	**200**
Regional Experiment Stations	**0**	**50**	**1,750**	**1,800**
Thin-Film Hot/Humid Exposure	0	25	875	900
Thin-Film Hot/Humid Exposure	0	25	875	900
Resource & Safety R&D	**1,380**	**0**	**470**	**1,850**
Solar Radiometry and Modeling	**800**	**0**	**0**	**800**
Resource Assess & Character	**580**	**0**	**0**	**580**
ES&H/Lifecycle Research	**0**	**0**	**470**	**470**
Operations & Planning	**66**	**61**	**189**	**316**
Program Management - TE	**66**	**61**	**0**	**127**
PBA Activities - TE	0	0	1	1
Rescission – TE	0	0	188	188

Market Transformation	**3,087**	**1,315**	**9,898**	**14,300**
Codes & Standards	**200**	**100**	**750**	**1,050**
Solar America Board of Codes & Standards	**200**	**100**	**750**	**1,050**
Training & Certification	**0**	**0**	**485**	**485**
PV Installer Training	**0**	**0**	**300**	**300**
PV Installer Certification	**0**	**0**	**185**	**185**
Building Integration & Finance	**2,155**	**0**	**65**	**2,220**
Solar Decathlon	**1,155**	**0**	**65**	**1,220**
Solar Decathlon Pro	**1,000**	**0**	**0**	**1,000**
Technical Partnerships	**0**	**1,140**	**5,766**	**6,906**
Solar America Showcases	**0**	**190**	**800**	**990**
Solar America Cities	**0**	**870**	**4,416**	**5,286**
Government Solar Installation Program	**0**	**80**	**550**	**630**
Integrator	0	0	400	400
RES Support	0	0	150	150
Lab Support	0	80	0	80
Technical Outreach	**497**	**0**	**1,889**	**2,386**
Utility Tech Outreach	**0**	**0**	**45**	**45**
Builder Tech Outreach	**0**	**0**	**63**	**63**
State Technical Outreach	**115**	**0**	**1,465**	**1,580**
MT Support Activities	**382**	**0**	**316**	**698**
Market Data & Surveys	270	0	0	270
SETP Annual Conf/CPS	0	0	165	165
MT Communications/NBM	112	0	26	138
ASES Solar Home Tour	0	0	125	125
Operations & Planning	**235**	**75**	**943**	**1,253**
Core Communications – PV	**110**	**50**	**25**	**185**
IEA PV Activities	**125**	**25**	**0**	**150**
PBA Activities – MT	0	0	569	569
Rescission - MT	0	0	130	130
Earmarks – MT*	0	0	5,320	5,320
Solar Thermal	**5,690**	**4,674**	**21,636**	**32,000**
Concentrating Solar Power	**4,400**	**4,574**	**21,026**	**30,000**
Parabolic Trough R&D	**648**	**75**	**2,351**	**3,074**
Trough Solar Field	**183**	**75**	**0**	**258**
Power Cycle & BOP	**84**	**0**	**0**	**84**
Trough Systems Integration	**216**	**0**	**0**	**216**
CSP FOA – Trough	**165**	**0**	**2,351**	**2,516**
Next Generation Trough	0	0	500	500
Advanced Polymeric Reflector	0	0	439	439
All Aluminum Trough	0	0	406	406
FOA - Analysis & Engineering Support	165	0	150	315
Phase II Awards	0	0	856	856
Dish/Stirling R&D	**70**	**0**	**920**	**990**
Dish Solar Field	**30**	**0**	**0**	**30**
CSP FOA – Dish	**40**	**0**	**920**	**960**
30kW Free Piston Dish/Stirling	0	0	321	321
200kW Dish/Brayton w/Storage	0	0	300	300
FOA Adv Dish Engine Support	40	0	0	40

Phase II Awards	0	0	299	299
Thermal Storage R&D	**489**	**379**	**7,593**	**8,461**
Storage Components	**0**	**93**	**0**	**93**
Storage Systems	**79**	**130**	**0**	**209**
Advanced HTF Development	**110**	**56**	**0**	**166**
CSP FOA – Storage: Phase 1	**0**	**100**	**2,593**	**2,693**
2nd Rnd (HTF, Tower, CLFR)	**300**	**0**	**5,000**	**5,300**
Advanced HTF Solicitation	0	0	5,000	5,000
Advanced HTF Support	300	0	0	300
Advanced CSP Concepts	**460**	**3,333**	**2,256**	**6,049**
Advanced Concepts R&D	**210**	**233**	**400**	**843**
CSP FOA - Advanced Concepts	**250**	**100**	**1,856**	**2,206**
Thermo-Chemical H2 Earmark	**0**	**3,000**	**0**	**3,000**
Heliostat Field Upgrades - Hardware	0	1,500	0	1,500
Heliostat Field Upgrades - Software	0	500	0	500
Advanced Heliostat Development	0	1,000	0	1,000
CSP Market Transformation	**1,720**	**56**	**1,425**	**3,201**
Southwest Stakeholder Outreach	**160**	**56**	**25**	**241**
CSP Resource Assessment	**650**	**0**	**0**	**650**
Market Analysis & Grid Integration	**535**	**0**	**0**	**535**
Solar Advisor Support	**250**	**0**	**0**	**250**
Programmatic Support for EIS	**125**	**0**	**1,400**	**1,525**
Programmatic EIS on BLM Lands	125	0	400	525
Additional Funding	0	0	1,000	1,000
Operations & Planning	**1,013**	**731**	**6,482**	**8,226**
Program Management - CSP	**295**	**656**	**838**	**1,789**
CSP Capital Equipment & Facilities	**283**	**0**	**0**	**283**
IEA SolarPACES	**45**	**25**	**0**	**70**
CSP Communications	**390**	**50**	**0**	**440**
PBA Activities – CSP	0	0	3,259	3,259
SBIR – CSP	0	0	2,110	2,110
Rescission – CSP	0	0	273	273
Earmarks – CSP*	0	3,000	0	3,000
Solar Heating & Lighting	**1,290**	**100**	**610**	**2,000**
SHC Systems Development	**1,100**	**100**	**0**	**1,200**
Solar Electric/Thermal Pathways to ZEH	**400**	**100**	**0**	**500**
Low-Cost SWH for ZEH	**500**	**0**	**0**	**500**
Solar Heating & Cooling for ZEH	**200**	**0**	**0**	**200**
PV Thermal Systems	20	0	0	20
Lab Support	180	0	0	180
SWH Market Transformation	**0**	**0**	**530**	**530**
Solar Water Heating Barriers	**0**	**0**	**500**	**500**
NABCEP - SHL	**0**	**0**	**30**	**30**
Operations & Planning	**190**	**0**	**80**	**270**
Program Management - SHL	**150**	**0**	**18**	**168**
SHL Communications	**40**	**0**	**0**	**40**
PBA Activities - SHL	0	0	21	21
SBIR - SHL	0	0	23	23
Rescission - SHL	0	0	18	18

* Earmarks were funded outside of the Solar Program.

Acronyms and Abbreviations

A2LA	American Association for Laboratory Accreditation
AC	alternating current
AES	Auger electron spectroscopy
AFM	atomic force microscopy
AIC	aluminum-induced crystallization
ALT	accelerated lifetime test
AOP	Annual Operating Plan
APD	antiphase domain
APS	Arizona Public Service
AR	antireflection
ASES	American Solar Energy Society
ASHRAE	American Society of Heating, Refrigeration, and Air-conditioning Engineers
a-Si	amorphous silicon
ASOS	Automated Surface Observing System
ASRC	Atmospheric Sciences Research Center (at State University of New York)
ASRM	advanced solar reflective mirror
ASSET	Analysis of State Energy Tradeoffs Databank
ASTM	American Society for Testing and Materials
ASU	Arizona State University
BES	Basic Energy Sciences (within U.S. DOE Office of Science)
BEW	Behnke, Erdman & Whitaker Engineering
BIPV	building-integrated photovoltaics
BLM	Bureau of Land Management
BNL	Brookhaven National Laboratory
BOS	balance of systems
BSC	Basic Sciences Center (within the National Renewable Energy Laboratory)
BSF	back-surface field
Btu	British thermal unit
BU	Boston University
CAD	computer-assisted design
C-AFM	conductive atomic force microscopy
Caltech	California Institute of Technology
CBD	chemical bath deposition
CdTe	cadmium telluride
CEC	California Energy Commission
CEG	Clean Energy Group, Inc.
CET	Center for Ecological Technology
CIGS	copper indium gallium diselenide
CIGSS	copper indium gallium sulfur selenide
CIS	copper indium diselenide
CL	cathodoluminescence
CNT	carbon nanotube
COP	coefficient of performance
COSE	cost of saved energy
COTS	commercial off the shelf
CPS	Corporate Planning System
CPUC	California Public Utilities Commission
CPV	concentrating photovoltaics
CRADA	Cooperative Research and Development Agreement
C_{save}	cost of saved energy
CSDS	Concentrating Solar Deployment System
c-Si	crystalline silicon

CSR	Climatological Solar Radiation
CSS	close-spaced sublimation
CSP	concentrating solar power
CU	University of Colorado
CVD	chemical vapor deposition
CY	calendar year
CZ	Czochralski
DC	direct current
DEG/SE	Davis Energy Group/SunEarth
DETL	Distributed Energy Technologies Laboratory (at Sandia National Laboratories)
DFMA	design for manufacturing and assembly
DFMECA	design failure mode effects and criticality analysis
DFR	design for reliability
DJ	dual junction
DLR	German Aerospace Center
DLTS	deep-level transient spectroscopy
DMA	dynamic mechanical analysis
DNI	direct normal incident
DoD	Department of Defense
DOE	Department of Energy
DSC	differential scanning calorimetry
DSP	digital signal processing
EAO	Energy Analysis Office
EBSD	electron backscatter diffraction
EERE	Energy Efficiency and Renewable Energy (U.S. Department of Energy office)
EFG	Edge-defined, Film-fed Growth
Eg	bandgap energy
EH&S	environmental health and safety
EIA	Energy Information Administration
EM&D	Electronic Materials and Devices
ENEA	Italian National Agency for New Technologies, Energy and the Environment
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
EPC	Engineer, Procure, Construct
EPS	environmental portfolio standard
EPV	Energy Photovoltaics
EUL	enhanced use leasing
EVA	ethylene vinyl acetate
EVMS	Earned Value Management System
FAQ	frequently asked questions
FF	fill factor
FFPT	fixed focal point trough
FIB	focused ion beam
FOA	Funding Opportunity Announcement
FOUP	Front-Opening Unified Pod
FR	flame retardant
FSEC	Florida Solar Energy Center (at University of Central Florida)
FTIR	Fourier transform infrared
FY	fiscal year
FZ	float zone
GB	grain boundary
GE	General Electric
GIS	geographical information system
GMS	gas management system
GO	Golden Field Office (U.S. Department of Energy)
GOES	Geostationary Operational Environmental Satellite

GPRA	Government Performance and Results Act
GPS	Global Positioning System
GSE	Global Solar Energy
GSIP	Government Solar Installation Program
GW	gigawatt
HALT	highly accelerated lifetime testing
HCE	heat collection element
HBCU	Historically Black Colleges and Universities
HEM	heat exchanger method
HFSF	High-Flux Solar Furnace
HFSS	high-flux solar simulator
HIPSS	high-intensity pulsed solar simulator
HiPerf PV	High-Performance Photovoltaics Project
HQ	headquarters
HRII	High-Reliability Inverter Initiative
HRTEM	high-resolution transmission electron microscopy
HSL	hybrid solar lighting
HTF	heat transfer fluid
HVAC	heating, ventilating, and air-conditioning
HWCVD	hot-wire chemical vapor deposition
IBAD	ion-beam-assisted deposition
IC	integrated circuit
ICP	inductively coupled plasma
ICS	integral collector storage
IDIP	In-Line Diagnostics and Intelligent Processing
IEA	International Energy Agency
IEC	Institute of Energy Conversion (at University of Delaware)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEP	Independent Energy Producer
IMA	impact-modified acrylic
IPO	initial public offering
IPP	independent power producer
IR	infrared
IREC	Interstate Renewable Energy Council
IRR	internal rate of return
ISES	International Solar Energy Society
ISET	International Solar Electric Technologies
ISIS	Integrated Surface Irradiance Study
ISO	International Standards Organization
ISP	Institute for Sustainable Power
IST	Industrial Solar Technology
ITN/ES	ITN Energy Systems
ITO	indium tin oxide
I-V	current voltage
JEDI	Jobs and Economic Development Impact
JGCRI	Joint Global Change Research Institute
J_{sc}	short-circuit current
J-V	current density voltage
KIESD	Kentucky Institute for the Environment and Sustainable Development
kW	kilowatt
kWhe	kilowatt hour electric
kWht	kilowatt hour thermal
LACSS	large-area, continuous-solar simulator
LBNL	Lawrence Berkeley National Laboratory
LCA	life-cycle analysis

LCOE	levelized cost of energy
LD	laser diode
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
LIPA	Long Island Power Authority
LOI	letter of interest
LP QCM	liquid-phase quartz crystal microbalance
MBE	molecular beam epitaxy or mean bias error
MBMDPE	metallocene-based multi-density polyethylene
mc	multicrystalline
MDC	McDonnell Douglas Corporation
MEG	Multiple-exciton generation
MLTE	module long-term exposure
MOCVD	metal organic chemical vapor deposition
MPP	model power plant
MPPT	maximum power point tracking
MSR	Million Solar Roofs
MT	market transformation
MTBF	mean time between failure
MURA	Minority University Research Associates
MW	megawatt
MYPP	Multi-Year Program Plan
MYRP	Multi-Year Research Plan
MYTP	Multi-Year Technical Plan
NABCEP	North American Board of Certified Energy Practitioners
NAHB	National Association of Home Builders
NARUC	National Association of Regulatory Utility Commissioners
NASA	National Aeronautics and Space Administration
NCPV	National Center for Photovoltaics
nc-Si	nanocrystalline silicon
NEC	National Electrical Code
NEMS	National Energy Modeling System (of the International Energy Agency)
NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
NGO	non-governmental organization
NIR	near infrared
NIST	National Institute of Standards and Technology
NMSU	New Mexico State University
NOCT	normal operating cell temperature
NRCC	Northeast Regional Climate Center
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Data Base
NSTTF	National Solar Thermal Test Facility (at Sandia National Laboratories)
NTUA	Navajo Tribal Utility Authority
NWS	National Weather Service
NYSERDA	New York State Energy Research and Development Authority
OATS	Outdoor Accelerated-weathering Testing System
O&M	operations and maintenance
OMB	Office of Management and Budget
OMCVD	organometalic chemical vapor deposition
OPV	organic photovoltaics
ORC	Organic Rankine Cycle
ORNL	Oak Ridge National Laboratory
OTF	Outdoor Test Facility (at National Renewable Energy Laboratory)
OWIP	Office of Weatherization and Intergovernmental Programs
PAE	planning, analysis, and evaluation

PBA	Office of Planning, Budget, and Analysis
PC	polycarbonate
PCD	photoconductive decay
PCU	power conversion unit
PDIL	Process Development and Integration Laboratory
PEC	photoelectrochemical
PECVD	plasma-enhanced chemical vapor deposition
PED	pulsed electron-beam deposition
PERT	Performance and Energy Ratings Testbed
PET	polyethylene terephthalate
PI	principal investigator
PIER	Public Interest Energy Research (program of the California Energy Commission)
PLD	pulsed laser deposition
PMMA	polymethyl methacrylate
PNNL	Pacific Northwest National Laboratory
PP	polypropylene
PPA	power purchase agreement
PPR	polypropylene random copolymer
PTL	Photovoltaic Testing Lab (at Arizona State University)
PV	photovoltaics
PVD	physical vapor deposition
PVME	polyvinylmethylether
PVMR&D	PV Manufacturing R&D
PVPS	Photovoltaic Power Systems Programme (of the International Energy Agency)
PVSAC	Photovoltaic Systems Assistance Center
PVSAM	PV Systems Analysis Model
PVSC	Photovoltaic Specialists Conference
PVSOL	PV System Optimization Laboratory (at Sandia National Laboratories)
QCM	quartz crystal microbalance
QD	quantum dot
QDLED	quantum dot light-emitting diode
QE	quantum efficiency
QSSPC	quasi-steady-state photoconductance
RCPCD	resonant-coupled, photoconductive decay
R&D	research and development
REAP	Renewable Energy Academic Partnership
REC	renewable energy certificate
RES	Regional Experiment Station
RFP	request for proposal
RFQ	request for qualifications
RITH	roof-integrated thermosiphon
RMOTC	Rocky Mountain Oilfields Testing Center
RMSE	root mean square error
RO	reverse osmosis
ROI	return on investment
ROWPU	reverse osmosis water purification unit
RPS	renewable portfolio standard
RSI	renewable systems integration
RSM	reciprocal space map
RT	room temperature
RTA	rapid thermal annealing
RTSE	real-time spectroscopic ellipsometry
RUS	Rural Utilities Service (of the U.S. Department of Agriculture)
SAC	Solar America Cities
SAI	Solar America Initiative
SAIC	Science Applications International Corporation

SAM	Solar Advisor Model
SAS	Solar America Showcases
SBC	systems benefit charge
SBIR	Small Business Innovation Research
SDA	Systems-Driven Approach
SDHW	solar domestic hot water
SDSU	South Dakota State University
SEGIS	Solar Energy Grid Integration Systems
SEIA	Solar Energy Industries Association
SEM	scanning electron microscope
SEPA	Solar Electric Power Association
SERES	Southeast Regional Experiment Station (at University of Central Florida)
SERF	Solar Energy Research Facility (at National Renewable Energy Laboratory)
SETP	Solar Energy Technologies Program
SES	Stirling Energy Systems
SHC	solar heating and cooling
SHGR	Solar Hydrogen Generation Research
SHJ	silicon heterojunction
SHW	solar hot water
SIF	stress intensity factor
SIMS	secondary ion mass spectrometry
SKPM	scanning Kelvin probe microscopy
SLP	service life prediction
SMIF	Standard Mechanical InterFace
SMUD	Sacramento Utility District
SNL	Sandia National Laboratories
Solar PACES	Solar Power and Chemical Energy Systems
SolarDS	Solar Deployment Systems (model)
SOW	statement of work
SPC	solid-phase crystallized
SPIE	International Society for Optical Engineering
SRCC	Solar Rating and Certification Corporation
SRP	Salt River Project
SSE	Surface Meteorology and Solar Energy (a NASA project)
SSI	Shell Solar Industries
STC	Standard Test Conditions
STCH	solar thermochemical hydrogen
S&TF	Science & Technology Facility (at National Renewable Energy Laboratory)
SUNY	State University of New York
SURFRAD	Surface Radiation Budget Network
SWH	solar water heating
SWRES	Southwest Regional Experiment Station (at New Mexico State University)
SWTDI	Southwest Technology Development Institute (at New Mexico State University)
TA	technical assistance
TBD	to be determined
TCA	thermal cycle annealing
TCC	transparent conductive coating
TCDF	Technology Commercialization Development Fund (at Sandia National Laboratories)
TCO	transparent conducting oxide
TDMS	thermal-desorption mass spectrometry
TEM	transmission electron microscopy; also technical exchange meeting
TEP	Tucson Electric Power
TES	thermal energy storage
TIO	Technology Improvement Opportunity
TMY	typical meteorological year

TOP	theoretical overlay photographic
TOU	time of use
TPD	temperature-programmed desorption
TPP	Technology Pathway Partnership
TRNSYS	TRaNsient SYstem Simulation Program
TRPL	time-resolved photoluminescence
TVA	Tennessee Valley Authority
TW	terrawatt
UHV	ultrahigh vacuum
UL	Underwriters Laboratories
ULRF	University of Louisville Research Foundation
UN	United Nations
UNLV	University of Nevada Las Vegas
UNM/ME	University of New Mexico Mechanical Engineering Department
U of L	University of Louisville
UPS	ultraviolet photoelectron spectroscopy
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
USGBC	U.S. Green Building Council
UV	ultraviolet
VASE	variable-angle spectroscopic ellipsometry
VB	valence band
VBM	valence band maximum
V_{oc}	open-circuit voltage
VSHOT	Video Scanning Hartmann Optical Test
VTD	vapor transport deposition
WCPEC	World Conference on Photovoltaic Energy Conversion
WGA	Western Governors' Association
WIP-I	Weatherization and Intergovernmental Program-International
WMO	World Meteorological Organization
WOM	weatherometer
WREC	World Renewable Energy Congress
WRR	World Radiometric Reference
WVTR	water vapor transport rate
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction
YDR	yield, durability, and reliability
ZEH	zero energy homes

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