U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE Solar Energy Technologies Program

FY09 Annual Report

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Photovoltaic Subprogram Overview

The mission of the Solar Energy Technologies Program (SETP) is to accelerate the development and large-scale deployment of solar technologies in the United States and to ensure that solar power is a viable and economic source for the nation's power needs. The near-term goal of the photovoltaic (PV) subprogram is to help the domestic PV industry achieve grid parity by 2015 through a program of research and development in PV materials, devices, and manufacturing technologies.

The PV industry has seen dramatic changes over the past several years. In 2009, First Solar became the first PV manufacturer to ship more than 1 GW of modules a year. SunPower achieved notable performance advances with their back contacted cells. These advances however, provide only a backdrop to the more dramatic changes in the industry concerning pricing. PV module prices have continued to fall and appear likely to fall significantly below $2/W in 2010. The program's 2015 grid parity goal, though challenging, is within reach with continued focus on the key cost drivers. However, to sustain a healthy domestic industry, the subprogram's effort to advance technology ahead of the cost curve requires that it maintains and continuously sharpens focus to reach these goals. While module prices continue to fall, the PV subprogram must ensure that domestic manufacturers can improve performance and reduce costs quicker than the rate of price erosion.

Subprogram funds were allocated among projects in critical PV research and development areas (R&D). Applied Research supports scientific research and development of materials, devices, and process technologies. Systems Development supports the development and transition of laboratory proven technologies into manufacturing. Within these two major areas fall projects that span from early-stage, applied R&D through market-oriented product and process development:

- Next-Generation Research projects investigate high-risk/high-payoff PV device and process concepts.
- Seed Fund projects at the national labs develop new ideas that upon maturity can develop into a cooperative research and development agreement (CRADA) or become a core lab research project.
- Conversion Technologies Research projects focuses on deepening our understanding of materials and device physics of commercial and near commercial semiconductors including: wafer silicon, film silicon, cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), organic photovoltaics (OPV), and SSC, as well as cross cutting research into Transparent Conducting Oxides (TCOs).
- University PV Process and Product Development projects leverage the knowledge of universities to bring technology from laboratory to marketplace.
- PV Pre-Incubator and PV Technology Incubators develop promising module technologies that have been successfully demonstrated on a small scale.
- Supply Chain projects funded through the American Recovery and Reinvestment Act of 2009 (ARRA) supports innovative companies developing cross-cutting technologies that provide leverage across supply chain.
- Technology Pathway Partnerships (TPPs) are industry-led, public-private partnerships. The partnerships bring together key players across the supply chain to focus on innovations that reduce total installed systems costs.

The PV subprogram continuously monitors and tracks performance of all of these funded activities to ensure that they are in alignment with program goals and the mission of the U.S. Department of Energy (DOE).

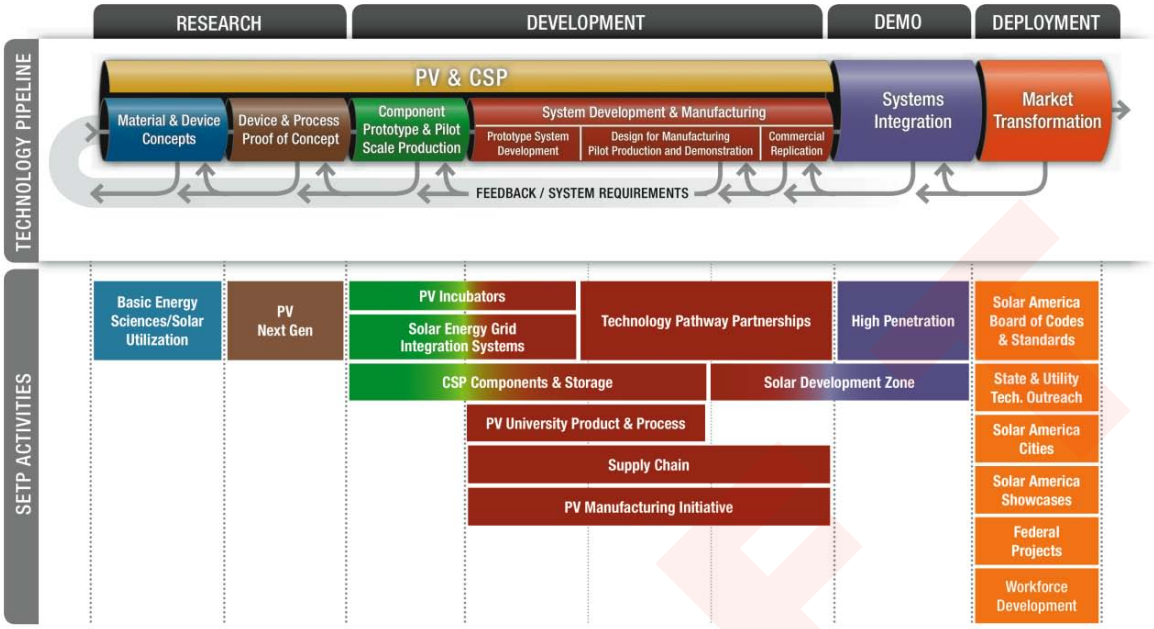

Fig. 1 This graphic captures the projects that are funded to help the domestic solar industry achieve grid parity by 2015.

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Applied Research Highlights

Applied Research and Development advances the performance of photovoltaic (PV) cells and modules through a process that deepens our understanding of the theory, materials science, device physics, and manufacturing technology of solar cells. It is a major part of the PV subprogram's goals. Applied Research is broken down into four major research categories, each with their own specific focus along the research, development, demonstration, and deployment pipeline.

Applied Research comprises the following areas:

- Exploratory Research: early stage research at national labs and academia that bridges Basic Energy Sciences research and Applied Research
- Conversion Devices: core research into PV materials and devices at the national labs
- Measurement and Characterization: M&C infrastructure support at the national labs to support government and industry as well as research and development (R&D) into new techniques to advance our understanding of PV materials and devices
- Process Development and Integration Laboratory Development and Utilization: new research facility with multiple cluster tools to enable rapid prototyping and development of new PV devices
- Operations and Planning

	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Applied Research	**31855**	**997**	**10303**	**43190**
Exploratory Research	**4604**	**510**	**7249**	**12363**
Conversion Devices	**14234**	**250**	**0**	**14484**
Measurement and Characterization	**10025**	**0**	**0**	**10025**
Process Development and Integration Laboratory Development and Utilization	**2692**	**0**	**0**	**2692**
Operations & Planning	**300**	**237**	**3054**	**3626**

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Exploratory Research Summary

The fiscal year 2009 Budget for Exploratory Research encompasses Next Generation Photovoltaic (PV) devices and processes, Minority University Research Associates (MURA) solicitation, industry cooperative research and development agreements (CRADAs), and seed funds. The Solar Program supports exploratory research in solar energy by the nation's best researchers from national laboratories, industry and universities for the purpose of discovering the next generation of PV technologies.

The Next Generation PV Devices and Processes projects represent innovative, revolutionary, and highly disruptive next-generation PV technologies. The NREL-MURA Project provides scientific and technical research opportunities for minority undergraduate students working on various solar energy technology projects through partnerships with minority universities. The Commercialization CRADAs project accelerates growth of partnerships with industry to move more SETP technology into production faster. Seed Funds provide temporary funding for exploration of new ideas, including new materials, devices, or processes that have not reached the proof-of-concept stage.

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
Exploratory Research	**4604**	**510**	**7249**	**12363**
Next Generation PV Devices and Processes	**0**	**0**	**7233**	**7233**
MURA Solicitation	**397**	**0**	**16**	**413**
Industrial CRADAs	**1967**	**0**	**0**	**1967**
Seed Funds	**2240**	**510**	**0**	**2750**

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Next Generation PV Devices & Processes

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); 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.

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FY 2009 Budget: $7,200K

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.

Accomplishment

- Reviewed Phase 1 critical milestones and grants approved to proceed to Phase 2 research evaluating advanced semiconductor materials.

Future Direction

- Evaluate progress of critical milestones and decide at the end of the each project's remaining Phases 2 or Phase 3 from FY 2009 and extending into FY 2011.

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1. Introduction

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

2. Technical Approach

The selected projects each received additional funding in FY 2009. The recipients are listed in the following table, and the specific accomplishments and future plans are summarized for each recipient in Section 3.

Institution, PI, and FY 2009 Funding	$K
ASU; Mark van Schilfgaarde; II-IV-V Based Thin Film Tandem PV Cell)	261
ASU; John Kouvetakis; Advanced Semiconductor Materials for PV	359
CIT; Harry Atwater; Abundant Cells from Earth-Abundant Semiconductors)	360
MIT; Vladimir Bulovic; Colloidal Nanocrystal Quantum Dot PV Devices	241
MIT; Emanuel Sachs; Recrystallization of Silicon Wafers in Thin Film Capsules	360
Mayaterials, Inc.; Richard Laine; Solar Grade Silicon from Ag By-Products	310
Penn State; Joan Redwing; High Aspect Ratio Semiconductor Heterojunction Cell	210
Penn State; Harry Allcock; Improved Electrodes and Electrolytes for Dye-Based Solar Cells	285
RIT; Seth M. Hubbard; High Efficiency Nanostructured III-V Cells for PV Concentrators	219
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Institution, PI, and FY 2009 Funding	$K
Solexant Corporation; Alison Breeze; High Efficiency Quantum Dot Cells Based on Multiple Exciton Generation	359
Soltaix LLC; Mehrdad Moslehi; Ultra-High-Efficiency, Thin-Film, Crystalline Silicon Solar Cells	360
Stanford; Yi Cui; Culn(Ga)Se_2 (CIGS) Nanowire Solar Cells	364
Stanford; Peter Peumans; Nanostructured Materials for Solution-Processed PV	356
UC–Davis; Adam Moule; Functional Multi-Layer Solution Processable Polymer Solar Cells	122
UC–San Diego; Edward T. Yu; High-efficiency PV Based on Semiconductor Nanostructures	364
CU; Josef Michl; Exciton Fission for an Ultra-High Efficiency, Low Cost Solar Cell	357
UD; William Shafarman; Novel Approaches to Wide Bandgap $CuInSe_2$ Based Absorbers	285
UF; Jiangeng Xue; High Efficiency Hybrid Organic-Inorganic PV Cells	360
University of Illinois; John Rogers; Transfer Printed Microcells with Micro-Optic Concentrators)	285
U-M; Stephen Forrest; Crystalline Organic PV Cells	276
USF; Christos Ferekides; Next Generation CdTe Technology: Substrate Foil-Based Cells	343
UW; Alex Jen; Interfacial Engineering for p-Conjugated Polymer-Based Heterojunction Devices	358
Voxtel, Inc.; David Schut; Optimization of Impact Ionization in Composite Nanocrystal Devices	222
Wakonda; Leslie Fritzemeier; Novel Manufacturing of Flexible III-V Thin Films	207

3. Accomplishments and Future Directions

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

Accomplishments

- Grew thin films of $ZnGeAs_2$ and $ZnSnP_2$ using pulsed-laser deposition and ZnGeAs films by sputtering
- Made *p-n* junctions from these films on different substrates, including Si, GaAs, CdS, and SnO and measured many optical and electrical device properties
- Detailed experimental study of the thermodynamics and kinetics of $ZnGeAs_2$ growth by vapor phase epitaxy
- Combined density functional calculations with thermodynamic theory to interpret the experimental findings.

Future Directions

- Using strategies developed to mitigate Zn volatility, a key challenge in the synthesis of the II-IV-V CPV (ZnK cells have been installed to facilitate Zn incorporation), determine optimum growth conditions and family of II-IV-V CPV by combining new systematic growth and annealing studies with theory
- Perform further theoretical calculations to clarify the mechanics of growth conditions in $ZnGeAs_2$ and the entire family of II-IV-V to narrow the possible materials systems to explore.

3.2 Advanced Semiconductor Materials for PVs (ASU—Kouvetakis)

Accomplishments

- Fully developed SiGeSn ternaries (grown lattice matched on Ge buffered Si) exhibiting direct band gaps in the desired 1-1.2 eV range required for the fabrication of hybrid IV/III-V cells
- Fabricated GeSn p-i-n diodes sensitive in the IR spectral range not accessible to conventional Ge-based solar cells
- Fabricated low-dark current Ge on Si PIN diodes deposited via a low temperature approach providing high quality material directly on Si
- Produced device-quality InGaAs layers on ASU's Ge-buffered Si for large-scale solar cell integration (partner Epiworks).

Future Directions

- Fabricate and characterize GeSn/Si solar cell structures on Si; Ge solar cell structures based on ASU's Ge-buffered Si and p-n junction devices; and InGaAs solar cells on ASU's Ge-buffered Si in collaboration with industrial partner Epiworks
- Determine band offsets between GeSiSn and Ge to provide critical parameters to design tunnel junctions in multiple-junction solar cells.
- Transition the deposition chemistry used for the ASU Ge-on-Si and GeSiSn technologies to ASM America, Inc.

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

Accomplishments:

- Achieved first room-temperature photoluminescence in Zn_3P_2; used photoluminescence and ellipsometry to definitively measure the bandgap in Zn_3P_2
- Fabricated Mg-doped Zn_3P_2 junction solar cells with V_{oc} = 560 mV (new record)

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- Fabricated thin film a-Si solar cells with plasmon-enhanced light absorption, enabling 30% enhancement in J_{sc} over flat reflector.

Future Directions:

- Fabricate Mg-doped Zn3P2 junction solar cells with high fill factor and low contact resistance
- Optimize junction profile in Zn_3P_2 cells for high open circuit voltage
- Optimize enhanced light absorption in plasmonic a-Si thin film solar cells.

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

Accomplishments

- Demonstrated Schottky-junction quantum dot (QD) PVs using PbS (lead sulfide) QD thin films
- Demonstrated heterojunction QD PVs using PbS QDs
- Demonstrated the highest Voc and FF for any published colloidal QD PV structure using the heterojunction QDs
- Demonstrated the first lateral heterojunction photodetector consisting of a metal-oxide charge transport layer and a colloidal QD charge-generation layer, to examine function of the heterojunction
- Demonstrated a spray-coating method for deposition of colloidal QDs in a PV structure, which dramatically reduces use (and waste) of the QD materials during deposition
- Demonstrated the influence of oxidative and plasma treatments on QD PV performance, using the results to develop a model for device operation.

Future Directions

- Continue to investigate the mechanism of operation of QD PV, focusing on the observed Voc/Isc tradeoffs
- Continue to improve the QD film quality and assess the influence of chemical treatments on QD film performance, e.g., layered structures
- Fabricate additional all-metal-oxide PVs.

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

Accomplishments

- Achieved very large grain recrystallizations (grain size > 2 cm^2) on larger 25x100 mm format
- Achieved proof of concept of a single crystal recrystallization on 25x100 mm format
- Measured minority carrier lifetimes of 10 microseconds
- Fabricated 4 cm^2 solar cell with active area efficiency of 15.0%
- Invented method of in situ temperature measurement based on diffusion of implanted n- and p-type dopants
- Gained understanding of super cooling allowed by different capsule materials using differential scanning calorimetry
- Improved fabrication of capsules to ensure release from substrates as well as provide low nucleation surface to silicon.

Future Directions

- Modify recrystallization parameters, especially cooling profiles, to further reduce dislocation density and support growth with an inclined interface
- Support above effort with in situ temperature measurement and with modeling
- Continue to improve cell efficiency.

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

Accomplishments

- Converted high purity silica and carbon obtained from agricultural by-products into silicon metal with impurities at or below 10 ppm total, 99.999% purity
- Converted high purity silica and carbon obtained from agricultural by-products into submicron-sized silicon carbide
- Scaled up of the production of SiC to 20 g batches; scale-up of silicon production is still under way.

Future Directions

- Increase scale of Si production
- Remove as much of remaining impurities as possible from silica before conversion.

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

Accomplishments

- Developed processing technology to fabricate Si pillar/wire array samples on Si substrates with controlled diameters and spacing using both deep reactive ion etching (DRIE) and vapor-liquid-solid (VLS) growth
- Performed reflectivity measurements on Si wire/pillar array samples and demonstrated a ~40% reduction in reflectivity as the wire diameter was reduced from 32 to 1 μm
- Photoelectrochemical characterization of VLS-grown Si wire arrays grown with gold and copper catalysts and DRIE-etched Si pillars. The photovoltage of the VLS-grown Si wire arrays varied over the range from 0.32 to

0.45V and was lower than that obtained for the DRIE-etched Si pillars and planar Si substrates (0.6V), most likely due to surface defects resulting from the metal-catalyzed growth technique

- Developed processing technology to fabricate radial p-n junction Si wire array structures using dopant diffusion and low pressure chemical vapor deposition (LPCVD); initial studies of amorphous Si coating deposited by plasma-enhanced chemical vapor deposition (PECVD) indicated that a uniformly thick, conformal coating was obtained on the high aspect ratio wire structures
- Demonstrated higher efficiency (~9%) for radial n^+-p^+ Si pillar solar cells fabricated by deep reactive ion etching and dopant diffusion compared to comparable planar samples (~4%), confirming that the radial junction geometry is effective at improving solar cell efficiency for material with short minority carrier diffusion length
- Developed a cleaning procedure to remove excess metal from the surface of VLS-grown Si wire arrays; demonstrated 2.3% efficiency in radial n+-p^- solar cells fabricated using gold-catalyzed Si wire arrays grown by vapor-liquid-solid growth on Si substrates and dopant diffusion to form the junction.

Future Directions

- Experimentally investigate effect of Si pillar diameter, spacing, and length on the optical properties and efficiency of radial n+-p+ junction solar cells and determine optimum device design
- Develop in situ p-type doping process for VLS-grown Si wire arrays and demonstrate radial n+-p+ junction devices on Si substrates
- Develop processing technology for VLS growth of Si wire arrays on glass substrates
- Demonstrate radial junction devices formed using lower temperature LPCVD and PECVD deposition processes.

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

Accomplishments

- Formulated liquid/gel electrolytes based on mixture of phosphazene electrolyte materials and organic liquid additives; performed electrochemical experiments and assembled test cells for efficiency evaluation; analyzed thermal stability of above electrolyte-additive mixtures
- Identified ease or difficulty of penetration of polymeric compounds into various nanoporous /nanotubular/nanocolumn electrodes under different infiltration conditions; examined difference in interfacial interactions for electrodes fabricated through different procedures
- Continued to test assembly of various phosphazene-based electrolytes with nanoporous and nanowire electrodes with additional results related to difference in assembly methods and component combinations.

Future Directions

- Continue work of the last 2 years to optimize cell fabrication of existing electrolyte/electrode pairs
- Synthesize and test ionic-liquid based phosphazene electrolyte materials with optimal molecular structures
- Explore additives to formulate cost-effective, thermally stable gel/liquid electrolytes, focusing on mass transport and dielectric effects
- Fabricate electrodes with surface-modified nanopatterns and assembly and test corresponding dye cells
- Study fabrication procedures to improve cell performance and viability of mass production.

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

Accomplishments

- Grew QD enhanced solar cells using 5-20-stacks of InAs QD inserted within the i-region of a GaAs p-i-n solar cell and observed significant enhancement in one sun AM1.5; Jsc under concentration, with QD cell efficiency exceeding the baseline by 1% absolute at 400 sun concentration
- Developed modified continuum elasticity theorem to model strain balancing in QD superlattice (SL), which correlated well with XRD values for QD-SL samples; used model to predict best GaP strain compensation thickness
- Developed gold electroplating process to increase gold grid finger thickness at reduced cost; incorporated approach into a typical concentrator solar cell fabrication process; achieved peak efficiencies >400 suns and a corresponding drop in series resistance of the device
- Produced electroluminescence results that are experimental evidence of wavefunction

overlap in strain-balanced QD solar cell devices
- Developed and verified a new module for modeling software NanoTCAD incorporating solar illumination on a standard GaAs solar cell
- Modeled temperature and dot-size dependence of thermal conductivity of QD structures to use to thermally optimize nanostructured solar cells (UC– Riverside).

Future Directions
- Investigate effect of QD "tuning" on triple junction solar cells under concentration; characterize QD-enhanced InGaP/GaAs tandem solar cells
- Continue optimizing QD growth and uniformity by MOCVD
- Develop model to predict QD incorporation effects in multijunction solar cells
- Incorporate best concentrator design principles into the QD solar cells using developed models
- Continue investigation into graphene as transparent conductive coatings (UC–Riverside)..

3.10 High Efficiency Power via Separated Photo and Voltaic Pathways (Solasta—Naughton)
- Work was discontinued on this grant when Solasta was awarded a subcontract under the NREL PV Incubator Program.

3.11 High Efficiency QD Cells Based on Multiple Exciton Generation (Solexant—Breeze)
Accomplishments
- Synthesized PbS/CdS core/shell materials for improved surface state passivation
- Demonstrated atomic layer deposition process for SnS_x films via liquid metal-organic precursor
- Tested conformal atomic layer deposition of Cu_2S using new precursor materials
- Continued optimizing mesoporous template for high surface area QD solar cells
- Incorporated buffer layers in QD solar cells.

Future Directions
- Characterize temperature dependence of QD solar cells and apply insights to improve the device design
- Optimize QD film deposition and ligand exchange treatment
- Incorporate new ALD hole transport layers into QD devices
- Develop inorganic ligands as alternate hole transport layer deposition techniques and incorporate into devices
- Optimize back-contact electrode
- Perform numerical simulations of QD solar cells.

3.12 Ultra-High-Efficiency, Thin-Film, Crystalline Silicon Solar Cells (Soltaix—Moslehi)
Accomplishments
- Demonstrated multiple reuses of the silicon template by improving the various process
- Developed a porous Si process enabling successful release of substrates with low defect densities
- Developed an epitaxial substrate release techniques and a laser scribe technique to replace manual scribe to help minimize chipping and cracking of the released substrates, thus increasing release yield
- Improved bulk minority carrier lifetime with world-class defect densities on both flat cell and 3-D cell structures
- Demonstrated multiple reuses on 3-D and on flat templates
- Demonstrated low defect density on 3-D cell structure and on flat cell
- Demonstrated front-to-back contact cell on 156 X 156 mm released thin film substrate with 15.8% efficiency
- Optimized cell architecture, metal coverage, doping profiles, and ARC layer thickness using modeling.

Future Directions
- Continue focus to increase the number of reuses on flat substrates and improve cell efficiency on flat substrates and the quality of epitaxial thin film substrates
- Further improve bulk minority carrier lifetime and defect density and improve efficiency by incorporating texture process on flat cells, optimizing substrate thickness.

3.13 Culn (Ga) Se2 (CIGS) Nanowire Solar Cells (Stanford —Yi Cui)
Accomplishments
- Successfully synthesized a family of Cu-In-Ga-Se nanowire materials, including GaSe, In_2Se_3, $In_{2-x}Ga_xSe_3$, and $CuInSe_2$
- Understood the structure evolution during $CuInSe_2$-CdS junction formation
- Developed a facile new method in forming $CuInSe_2$.nanowires by using In_2Se_3 nanowires as template

- Collected data on single $CuInSe_2$ nanowire transport
- Fabricated single nanowire solar cells and study their property
- Designed the antireflection and light trapping within nanocone and nanodome to be applied in CIGS cells
- Developed the rolling process for producing nanocone substrates to be applied to CIGS solar cells.

Future Directions

- Perform CIGS nanostructure solar cell fabrication and measurement
- Develop roll-to-roll nanostructure fabrication process.

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

Accomplishments

- Demonstrated tandem organic solar cells with Ag nanowire as transparent electrodes
- Produced $CuInS_2$ nanoparticles as solar absorbers and demonstrated bandgap tuning by doping
- Incorporated ZnO nanowires in bulk heterojunction cell, leading to increased short-circuit current
- Achieved control over ZnO nanostructure shapes during synthesis (nanowires, nanoparticles, nanoparticle assemblies of various size and roughness)
- Demonstrated outstanding light trapping ability (haze > 0.3 at 1200 nm) of ZnO nanoparticle films
- Built and qualified spray-coater to coat uniformly large area (30x30 cm) with Ag nanowires or ZnO nanostructures
- Demonstrated Ag nanowire/conducting polymer composite transparent conductors with reduced roughness adequate for high-performance thin-film photovoltaics. Cell performance shown to be equivalent to conventional metal oxide (indium tin oxide, ITO) transparent conductors
- Demonstrated a bending radius < 2 mm on 3-mil-thick Mylar foil
- Demonstrated sheet resistances approaching 1 Ohm/sq for Ag nanowire mesh films under pressure
- Demonstrated large-area deposition of Ag nanowire mesh films using spray coating.

Future Directions

- Improve performance of silver nanowire electrodes to sheet resistances < 5 ohm/sq and transparencies > 90% by a combination of pressure and annealing
- Continue to improve sheet resistance of ZnO nanowire electrodes
- Fabricate nanocrystal solar cells with Ag and ZnO nanowires as transparent electrodes
- Develop large-area deposition of uniform films of ZnO and Ag nanowires with controlled density
- Measure scattering properties of ZnO nanostructures as a function of shape, size, density, and processing conditions
- Analyze industrial-scale manufacturing.

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

Accomplishments

- Developed a multiple layer deposition method and test to make sure layers don't mix
- Determined that material layers mix upon heat tempering and the electrical consequences
- Developed a method for using mixed electrode-active layer interlayer to fix work function
- Perform optical and electrical measurements of organic electrode materials from Plextronics
- Determine kinetic difference between various fullerene acceptors
- Determine that PCBM crystallization is controlled by trace solvents and that the nonsolvent additives can be used to increase the stability of polymer/fullerene morphology
- Investigated published methods for making bi-layer devices from solution
- Determined that the ligand size on the fullerene, not the reduction potential, determines the lifetime of the charge-separated state using UC–Davis ultra-fast spectroscopy measurements of recombination with four different functionalized fullerenes.

Future Directions

- Use multiple layer technique to fabricate devices to make the process more generally applicable
- Develop predictive optical and electrical modeling tools.

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

Accomplishments

- Demonstrate 5–7% increased power conversion efficiency in GaInAsP/InP quantum-well solar cells compared to InP homojunction solar cells

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- Demonstrated ~17% increased power conversion efficiency in quantum-well solar cells incorporating nanostructure scattering effects relative to quantum-well solar cells without nanostructured scatterers
- Demonstrated PV power conversion in nanowire-based solar cells consisting of n-InAs nanowires on p-Si substrates
- Demonstrated extended wavelength response in quantum well/QD solar cells.

Future Directions

- Integrate scattering-based engineering of photon propagation in waveguide modes of thin-film heterostructure devices with antireflection coatings for high power conversion efficiency
- Fabricate and characterize semiconductor nanowire heterostructures for high-efficiency PV devices.

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

Accomplishments

- Prepared thin layers of a model chromophore, 1,3-diphenylisobenzofuran, and demonstrated triplet quantum yields up to 160% by direct triplet-triplet absorption measurement
- Produced nanocrystals of 1,3-diphenylisobenzofuran
- Discovered that in polar solvents, singlet fission proceeds by a new two-step mechanism via a charge-transfer state.

Future Directions

- Improve understanding of the competition between one-step and two-step singlet fission as a function of chromophore coupling and the relation to the difference in fission rates in crystals and covalent dimmers
- Optimize covalent dimer structure for high triplet yields from singlet fission.

3.18 Novel Approaches to Wide Bandgap $CuInSe_2$ Based Absorbers (UD—Shafarman)

Accomplishments

- Demonstrated a $(AgCu)(InGa)Se_2$ cell with V_{OC} = 0.89 V and efficiency = 13% by implementing a three-stage evaporation process, superior to the performance of other wide bandgap $CuInSe_2$-based solar cells
- Determined optical bandgaps for the complete $(AgCu)(InGa)Se_2$ composition space and optical bowing parameters for fixed relative Group I or Group III composition
- Showed that $(AgCu)(InGa)Se_2$ lattice parameters determined from XRD measurements had a general fit to a plane described by Vegard's law, showing linear behavior with respect to both Group I and Group III alloying and with no evidence of phase miscibility that has been reported in ingot samples
- Showed laser/film annealing treatments that modify the $Cu(InGa)Se_2$ surface and provide partial melting or recrystallization of the films to be insufficient for improved V_{OC} in wide bandgap solar cells
- Measured transient photocapacitance in $(AgCu)(InGa)Se_2$ devices, showing that a defect band centered at 0.8 eV above the valence band is unchanged by Ag alloying; This may play a critical role in the recombination that limits V_{OC}
- Determined differences in the metastabilities of $(AgCu)(InGa)Se_2$ devices after light soaking compared to $Cu(InGa)Se_2$ devices; these may be a change in the recombination states limiting V_{OC}.

Future Directions

- Quantify effects of evaporation process modifications and relative Ag content in wide bandgap $(AgCu)(InGa)Se_2$ films with respect to materials properties and device behavior
- Use current-voltage-temperature and capacitance-based characterization of $(AgCu)(InGa)Se_2$ devices to develop basis and guide for improving these devices.

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

Accomplishments

- Developed ternary Zn_1-xCdxSe nanospheres and nanorods with variable composition and a minimum bandgap of 1.8 eV
- Synthesized PbSe nanospheres with bandgap of 1.5–1.1 eV
- Synthesized phenylene, ethynylene, and thiophene-based oligomers with phosphonic acid end groups and bandgaps between 2.9 and 1.9 eV
- Demonstrated photoluminescence quenching between reactive oligomer and CdSe nanocrystals
- Demonstrated alignment of CdSe nanorods in a matrix of P3HT with external electric field
- Enhanced the efficiency and lifetime of hybrid PV devices by incorporating a ZnO nanoparticle layer
- Demonstrated hybrid PV devices based on low gap polymer with efficiency of 3.3%.

Future Directions

- Synthesize ternary nanorods with bandgap of 1.5–1.8 eV
- Optimize morphology of hybrid thin films and align nanorods assisted by an external field
- Fabricate hybrid PV cells based on functionalized oligomer/polymers and ternary nanocrystals and study effect of ternary composition on Voc in these devices.

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

Accomplishments

- Perfected design, transfer printing, and module-level integration of dual junction GaAs microcells
- Designed and fabricated two-stage high concentration optics (> 1000X)
- Fabricated more than 20 full modules using dual stage 1000X concentrator optics and dual junction GaAs/GaInP solar cells
- Completed validating benchmarking measurements at NREL and Sandia National Laboratory on second generation modules
- Completed optimized cell epi design for high concentration performance
- Installed, certified, and initiated operations of tracking module platform test facility
- Developed semi-automated testing and sorting tools.

Future Directions

- Develop prototype quad-junction inks
- Model designs to boost cell performance at concentration ratios exceeding 1000X
- Improve materials and integration schemes for devices integrated on lightweight, flexible substrates.

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

Accomplishments

- Established the relationship between crystalline order and the exciton diffusion length in organic semiconductors, indicating the advantage of crystalline tandem architectures
- Extended range of high-efficiency donor materials for tandem subcell incorporation with variable absorption into near infrared (NIR) through squaraine and phthalocyanine derivatives
- Demonstrated high-efficiency (>2.5%) inverted OPV architectures for incorporation on low cost flexible substrates where avoiding glass substrates could significantly reduce overall cost FOM
- Demonstrated 4.3% efficient cells based on polycrystalline squaraine donors
- Demonstrated scaling capability of organic vapor phase deposition for large area (Gen 6) solar cell production
- Modeled tandem performance for a range of subcell configurations to optimize power efficiencies > 6.5%.

Future Directions

- Design high-efficiency organic tandem cell using diffusion lengths and absorption characteristics of a range of crystalline and polycrystalline organic materials
- Fabricate and characterize nanocrystalline tandem cells using optimized materials and growth conditions
- Complete reliability testing of packaged single junction and tandem cells
- Characterize key degradation mechanisms in various high-performance planar, bulk, nanocrystalline, and crystalline junctions and determine optimal routes to long-lifetime cells.

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

Accomplishments

- Established baseline process for substrate foil-based CdTe cells with efficiencies in the 6+% range
- Demonstrated highest V_{OC} for substrate foil cells: above 700 mV; baseline V_{OC}: 650 mV
- Demonstrated high spectral response, equivalent to substrate cells, indicating that collection in substrate foil cells is not key factor in limiting performance
- Highest efficiency measured to-date in-house approx 6.5–7.0%; this is not corrected for reflection losses, which are higher than the typical glass superstrate CdTe cell
- Continued to investigate various back-contact materials.

Future Directions

- Focus on factors limiting V_{OC} and FF
- Continue to develop and investigate back contact materials and model solar cell behavior to better understand performance-limiting mechanisms
- Investigate heterojunction formation process and window layer properties to advance V_{OC} to 800+ mV
- Investigate impact of front transparent electrode configuration, and optimize for maximum performance.

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

Accomplishments

- Developed new low bandgap polymers based on alternating donor-acceptor backbone for high performance OPVs (power conversion efficiency= 6.4% with potential to go beyond 7% after optimization)
- 6.4% with potential to go beyond 7% after optimization)
- Developed chromophore-containing side-chain conjugated polymers with easily tunable absorption and energy levels for systematic optimization of OPV devices
- New polymer in the inverted cells tested, with a record PCE as high as 5.4%
- Developed new thermally crosslinkable fullerene derivatives with tunable crosslinking conditions and electron-transporting properties
- Achieved complete control over the externally initiated synthesis of region-specific conjugated polymer P3HT, which shows 100% initiation with an extremely narrow polydispersity
- Developed metal grids/conducting polymer transparent electrode with sheet resistance and transparency similar to those of commercial ITO conducting glass. Inverted OPV cell fabricated on the new hybrid transparent electrode shows similar PCE compared to that fabricated from ITO
- Developed PCBM derivatives as new acceptors to improve morphological stability and lifetime of BHJ devices.

Future Directions

- Develop n-type materials with good isotropic charge transporting properties to replace C_{60}
- Optimize the ITO replacement electrode to ensure low-cost fabrication of OPVs
- Combine material development and SAM-mediated interface engineering to improve charge transport, selection, and collection
- Use theory-guided synthesis to systematically optimize both electrical and optical properties of conjugated polymers.

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

Accomplishments

- Performed in situ synthesis of Janus Type II nanocrystalline QDs (J2NQD) on ITO/TiO_2 substrates
- Observed fluorescent quenching on ligand substitution of PbS(oleic acid) with bifunctional ligands. Ligand dimmers and oligomers reduced the quantum confinement effect
- Studied the performance of PbS NQDs with various ligands with different types of hole transfer layer materials or electrolytes for best performance
- Investigated the performance of several different types of TiO_2 to determine best substrate upon which to place the PbS(ligand) NQDs; hybrid of hydrothermally generated TiO_2 covered with nanoparticle-sintered TiO_2 gave the best results
- Observed that smaller PbS NQDs were more effective at injecting charge than smaller PbS NQDs.

Future Directions

- Continue to analyze performance and characterize J2NQDs
- Increase fill factor with J2NQDs and PbS NQDs in general.

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

Accomplishments

- Reengineered virtual single crystal (VSC) substrate for mechanical and physical properties matched to compound
- Improved projected manufacturing costs to < $0.50/Wp at module level
- Extended VSC substrate applicability to II-VI materials, demonstrating epitaxial CdTe cells.

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 2009 Special Recognitions, Awards, and Patents

CIT

Best Poster Award, 34th IEEE Photovoltaics Specialists Conference, June 7-9, 2009 Philadelphia PA, "Modeling, Synthesis, and Characterization of Thin Film Copper Oxide for Solar Cells," D.E. Darvish and H.A. Atwater.

MIT

Patent application filed; US, PCT, and others: "Recrystallization of Semiconductor Wafers in a Thin Film Capsule and Related Processes," E. Sachs, J. Serdy, and E. Hantsoo.

Mayaterials, Inc.

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Patent filed for "Low Cost Routes to High Purity Silicon and Derivatives Thereof."

Penn State

Joan Redwing co-organizer of the symposium "Semiconductor Nanowires: Growth, Size-Dependent Properties and Applications," at the 2009 Spring Meeting of the Materials Research Society (MRS).

Solexant

Provisional patent filed by Glenn Alers and Qiaoer Zhou: "Atomic Layer Deposition of Tin Sulfide Films Using Dibutyl-Tin-Diacetate and Hydrogen Sulfide as Precursors" (61/212727).

University of Colorado

J. Michl elected vice-president of the International Academy of Quantum Molecular Sciences.

University of California-San Diego

E. Yu invited to give talks at a LANL functional materials workshop, and two international conferences on semiconductor devices. E. Yu appointed to Swearingen Regents Chair in Engineering at U of Texas at Austin.

Wakonda

Wakonda received request from U.S. Army to develop packaging solutions for high-efficiency flexible PV.

5. Major FY 2009 Publications

ASU

T.J. Peshek, Z. Tang, L. Zhang, R.K. Singh, B. To, N. Newman, T.A. Gessert, T.J. Coutts, and M. van Schilfgaarde, "Suitability of $ZnGeAs_2$ Thin Films for Photovoltaics," *Proc., 34th IEEE Photovoltaic Specialists Conference, 2009*.

CIT

G.M. Kimball, A.M. Muller, N.S. Lewis, and H.A. Atwater, "Photoluminescence-based Measurements of the Energy Gap and Diffusion Length of Zn_3P_2," *Appl. Phys. Lett*, **95**, 11 (2009).

MIT

A. Appapillai and E. Sachs, "The Effect of Substrate Material on Nucleation Behavior of Molten Silicon for Photovoltaics," *Conference of the American Association on Crystal Growth and Epitaxy, August 2009*.

Penn State University

Y. Ke, X.J. Weng, J.M. Redwing, C.M. Eichfeld, T.R. Swisher, S.E. Mohney, and Y.M. Habib, "Fabrication and Electrical Properties of Si Nanowires Synthesized by Al Catalyzed Vapor-liquid-solid growth," *Nano Lett.* **9**, 4494 (2009).

Rochester Institute of Technology

C. Bailey, S.M. Hubbard, D. Forbes, and R. Raffaelle, "Evaluation of Strain Balancing Layer Thickness for InAs / GaAs QD Arrays Using HRXRD and Photoluminescence," *Appl. Phys. Lett.* **95**, 203110 (2009).

Stanford (Cui)

H. Peng, X.F. Zhang, R.D. Twesten, and Y. Cui, "Vacancy Ordering and Lithium Ion Insertion in In_2Se_3 Nanowires," *Nano Res.* **2**, 327 (2009).

D.T. Schoen, H. Peng, and Y. Cui, "Anisotropy of Chemical Transformation of In_2Se_3 to $CuInSe_2$ Nanowires through Solid State Reaction," *J. Am. Chem. Soc.* **131**, 7973 (2009).

Stanford (Peumans)

H. Peng, C. Xie, D.T. Schoen, and Y. Cui, "Large Anisotropy of Electrical Properties in Layer-Structured In2Se3 Nanowires," *Nano Lett*. **8**, 1511 (2008).

C.-M. Hsu, S.T. Connor, M. Tang, and Y. Cui, "Wafer-Scale Silicon Nanopillars and Nanocones by Langmuir-Blodgett Assembly and Etching," *Appl. Phys. Lett*. 93, 133109 (2008).

L. Goris, R. Noriega, M. Donovan, G. J. Kusinski, J. R. Jokisaari, and A. Salleo, "Al and Ga Doped ZnO Nanowires for Transparent Electrodes," *J. Electron. Mater*. **38**, 586 (2009).

R. Devan, M. Marinkovic, R. Noriega, S. Phadke, A. Salleo, and D. Knipp, "Light Trapping in Thin Film Silicon Solar Cells with Periodic Pyramid Texture," *Optics Express* **17**, 23058 (2009).

W. Gaynor, J.-Y. Lee, and P. Peumans, "Fully Solution-Processed Inverted Polymer Solar Cells with Laminated Nanowire Electrodes," *ACS Nano*, Article ASAP (2009).

University of California, Davis

B.V. Andersson, D.M. Huang, A.J. Moulé, and O. Inganäs, "An Optical Spacer Is No Panacea for Light Collection in Organic Solar Cells," *Appl. Phys. Lett.* **94**, 043302 (2009).

University of California, San Diego

C.O. McPheeters, C.J. Hill, S.H. Lim, D. Dekacs, D.Z. Ting, and E.T. Yu, "Improved Performance of In(Ga)As/GaAs Quantum Dot Solar Cells via Light Scattering by Nanoparticles," *J. Appl. Phys.* **106**, 056101 (2009).

University of Colorado

E.C. Greyson, J. Vura-Weis, J. Michl, and M. A. Ratner, "Singlet Fission in Organic Dimers: Maximizing the Triplet Yield within the Regime of Localized Excitation and Fast Coherent Electron Transfer", *J. Phys. Chem. B* (2010, in press).

University of Florida

Y. Zheng, R. Bekele, J. Ouyang, and J. Xue, "Organic Photovoltaic Cells with Vertically Aligned Crystalline Molecular Nanorods," *Organic Electron.* **10**, 1621 (2009).

University of Illinois

B.Y. Ahn, E.B. Duoss, M.J. Motala, X. Guo, S.I. Park, J. Yoon, and R.G. Nuzzo, **"**Direct-write

Assembly of Flexible, Spanning, and Stretchable Silver Microelectrodes for Printed Electronics,"
J. A. Rogers, J.A. Lewis *Science* **323**, 1590-1593. 2009

University of Michigan

N. Li and S.R. Forrest, "Tilted Bulk Heterojunction Organic Photovoltaic Cells Grown by Oblique Angle Deposition," *Appl. Phys. Lett.*, **95**, 123309 (2009).

R.R. Lunt, N.C. Giebink, A.A. Belak, J.B. Benziger, and S.R. Forrest, "Exciton Diffusion Lengths of Organic Semiconductor Thin Films Measured by Spectrally Resolved Photoluminescence Quenching," *J. Appl. Phys.* **105**, 053711 (2009).

Voxtel

T. Novet, T. Allen, G. Williams, D.R. Tyler, J. Sambur, B. Parkinson, and D.M. Schut, "Dipole Induced Carrier Extraction Mechanisms in Nanocrystal Sensitized Solar Cells," *Presentation at the Center for Green Materials and Chemistry Symposium, Bend, OR*.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	**Location/E-mail**	**Description/Title of Research Activity**
Northwestern University Mark Ratner	Evanston, IL ratner@chem.northwestern.edu	quantum chemical calculations for singlet fission sensitizers
NREL Art Nozik and Justin Johnson	Golden, CO Arthur.Nozik@nrel.gov	time-resolved spectroscopy
Rochester Institute of Technology Dr. Ryne Raffaelle	Rochester, NY rprsps@rit.edu	GaAs cell analysis and optimization
Research Triangle Institute Dr. Rama Venkatasubramanian	Research Triangle, NC rama@rti.org	GaAs junction growth and optimization
Ahura Scientific Dr. Chris Pinzone	Wilmington, MA cjpinzone@ahurascientific.com	GaAs junction growth
University of South Florida Prof. Chris Ferekides	Tampa, FL ferekide@eng.usf.edu	CdTe cell processing and analysis
University of Delaware Brian McAndless	Newark, DE bem@udel.edu	CdTe doping and analysis

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Minority University Research Associates Solicitation

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: Scott Stephens, 202-586-0565, scott.stephens@hq.doe.gov

FY 2009 Budgets: $397K (NREL), $16K (DOE/GO)

Objectives

- Provide scientific and technical research opportunities for minority undergraduate and graduate students in solar technologies via the Minority University Research Associates (MURA) project.
- Facilitate the creation of a diverse and competent workforce for existing and developing solar technologies.

Accomplishments

- Presented MURA student research findings at the Renewable Academic Partnership (REAP) Conference in conjunction with the 19th Workshop on Crystalline Silicon Solar Cells: Materials and Processes, August 9-12, 2009, in Vail, Colorado.
- Supported Merit Review Committee (MRC) meeting for the SETP Funding Opportunity Announcement (FOA): MURA Program (MURA)

Future Directions

- MURA Program activities have been transferred and will be coordinated through the DOE Golden Field Office.
- Continue to assist DOE Golden Field Office (DOE/GO) in monitoring the MURA project.
- Facilitation of the REAP2010 Summer Program.

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1. Introduction

The NREL-MURA Project (1995-2009) provided scientific and technical research opportunities for minority undergraduate students working on various solar energy technology projects through partnerships with minority universities. The universities performed subcontracted research under NREL's University and Exploratory Research Project. During the school year, undergraduate and graduate students are involved in solar technology-related research at the universities. The students are awarded internships in industry or at national laboratories such as NREL during the summer. The program helps retain minority students in the science and technology areas and enables many students to reach their educational and career goals. Through these sub contracts, the MURA program continues to contribute to the development of a diverse and competent workforce ready to supply the nation's growing energy industries.

2. Technical Approach

The MURA project consists of eight individual university faculty/student research programs which focus on solar energy technologies. All of the current sub contracts have been completed and are closed.

Agreement Tasks	FY 2009 Budget ($K)
Minority University Research Associates Program	397
DOE-GO	16
TOTAL	$413

3. Results and Accomplishments

3.1 **North Carolina A&T State University**: Several students continued their research project on "Synthesis and Characterization of Photovoltaic (PV) Active Polymer Nanocomposites." Students designed a 1 KW PV system to be installed on the roof of Biological Engineering Building at NCA&T SU.

3.2 **Fisk University**: Eight undergraduate and graduate students compose the team. Two MURA students received graduate degrees in physics last semester. The Fisk-MURA Team was published in three refereed journals and gave 11 presentations at professional workshops and conferences.

3.3 **Central State University**: A 3-week introductory energy laboratory course was

provided for 12 undergraduate students majoring in engineering and natural sciences; Central State was an active affiliate of the University Clean Energy Alliance of Ohio (UCEAO).

3.4 **University of Texas Brownsville**: The Tonatiuh software was extended to model reflective systems, such as CPC collectors, hyperbolic mirrors, parabolic trough, solar tower, dish/Stirling systems and refractive systems, such as none-imagine Fresnel lenses. The following web sites have been enhanced and include video: www.tonatiuh.googlecode.com www.youtube.com/user/TonatiuhRaytracer.

3.5 **Southern University**: Successfully organized eight renewable energy education and curriculum development workshops for science teachers in East and West Baton Rouge parishes for implementing and integrating renewable energy content in the high school physical science and environmental science courses. Two MURA graduates secured positions in the California solar energy industry while attending graduate education. The SUBR-MURA Team published 12 papers in peer reviewed journals.

3.6 **North Carolina Central University**: The computationally efficient effective potential model developed earlier at NCCU was extended to model InxGa1-xAs QDs with significant Ga fractions. This work was featured in the September, 2009 issue, *NASA Tech Briefs*.

3.7 **University of Texas El Paso**: MURA students presented papers at IEEE, ACS and the International Materials Congress conferences in 2009.

3.8 **Howard University:** A module for the Energy Conversion course was designed. It focuses on a rigorous introduction to various Renewable Energy technologies and associated technologies as well as their applications.

4. Planned FY 2010 Activities

A new solicitation was issued in the summer of 2009 by the DOE Golden Field Office. NREL will continue to assist GO in the management of the new sub contracts to be awarded in 2010.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title/Research Activity	FY 2009 ($K)
Southern University/R. Bobba	Baton Rouge, LA rambabu@cox.net	"Energy Conversion and Storage Devices: Solar Energy Research and Education."	26 15*
University of Texas at El Paso/Gregory Lush	El Paso, TX lush@ece.utep.edu	"Fabrication, Characterization and Modeling of Solar Cells."	15 15*
Fisk University/Richard Mu	Nashville, TN rmu@fisk.edu	"Development of Quantum-Dot-Sensitized ZnO and TiO2 Nanorod-Array Solar Cells."	70 15*
Howard University/J. Momoh	Washington, DC jmomoh@howard.edu	"PV and Renewable Energy Research/Training for Optimal Power Management and Distribution."	53
North Carolina Central University/J.Dudda & Mn Wu	Durham, NC mwu@nccu.edu	"Investigation of Photovoltaic and Thermoplastic Semiconductors."	49 15*
University of Texas Brownsville/Manuel Blanco & William Berg	Brownsville, TX wberg@utb.edu	"Design, Development, and Implementation of Simulation Tools for Analysis of Solar Concentrating Systems."	48 15*
North Carolina A&T State University/G. Shahbazi	Greensboro, NC ash@ncat.edu	"Performance Testing and Utilization of Photovoltaic Energy in Residential Environments."	10 15*
Central State University/Clark Fuller	Wilberforce, OH cfuller@prodigy.net	"Renewable Energy Technology and Technology Transfer in Developing Countries."	34 10*

* Funded with prior year (FY 2008) funds

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Commercialization Cooperative Research & Development Agreements

Performing Organization: National Renewable Energy Laboratory (NREL)

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

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

FY 2009 Budget: $1,967K (NREL)

Objectives

- Apply program funding to advance technologies to a state ready for industrial collaborations
- Reduce financial and administrative barriers impeding the development of substantial industry partnerships.

Accomplishments

- Solicited internal proposals, selecting three for award starting in February 2009:
  - Coincident epitaxy for high performance multijunctions (Phase 0)
  - Crystalline CdTe multijunctions of silicon (EPIR Phase 2)
  - Ink precursors for copper indium gallium selenide (CIGS) (HelioVolt Phase 3)
- Conceived the Innovation by Design project and developed concept with DOE (01/09)
- Selected Nucleated Innovation by Design teams (04/09)
- Reviewed five proposals (selected members of NREL's Venture Capital Advisory Board, 06/09)
- With DOE review and concurrence (07/09), started the leading team with a project to develop 20% efficient thin-film solar cells with low-cost fabrication.

Future Directions

- Explore potential for privately funded cost share for 2010 Innovation by Design project
- Open pathways to launch new photovoltaics (PV) business derived from licensing a suite of NREL-generated intellectual property protecting a complete, new product.

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1. Introduction

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

2. Technical Approach

Transferring our technologies to industry is the culmination of years of research. This is also perhaps the most difficult stage of development. Although NREL can point to numerous examples of successful tech transfer, including many patents that have been licensed, the majority of our contributions have occurred "under the radar." Vast amounts of know-how, 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. Equally damaging, we have experienced apparently effective collaborations instantly evaporating as corporate senior management redirects all technical resources to the new, most pressing problem. These result in a large waste of resources. The remedy is to raise the visibility of the interaction through formalizing the agreement in a Technical Services Agreement (TSA) or CRADA. The attention of management of the partnering companies is particularly enhanced when they have their own resources on the line.

The nature of the PV business has fundamentally changed the way that NREL must interact with

industry. As private funding has rocketed past federal support and the total investments move toward $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 our resources. This change again drives us toward using a coordinated process to select partners and manage the success of each partnership.

Finally, the opportunity to leverage program support to bring in increasing amounts of private investment at NREL helps maintain and expand our capabilities to meet the growing demands from the very rapidly growing U.S. industry.

3. Results and Accomplishments

This project was conceived in 2008 and has realized its primary objective of increasing the number and size of technology partnership agreements. Because of the business-sensitive nature of these partnerships, a comprehensive listing of these agreements is inappropriate for a public report. Some partners, however, are pleased to have their associating with NREL highlighted. For example, our research with HelioVolt Corporation to develop processes using deposition from liquid sources to form precursors for their proprietary FASST process resulted in receipt of an R&D 100 award.

Perhaps the most significant accomplishment of 2009 is the creation of a new mode for developing core intellectual property to stimulate partnerships of a far larger scale. NREL's largest CRADAs were generated by the potential to develop an entirely new product by cooperative development around a suite of inventions. The project called Innovation by Design has the primary objective of creating a product concept. Modeled after commercial methods for structuring the process of innovation, the project requires participation from interdisciplinary teams—teams of investigators who do not work together routinely. Seeded with common background reading in fruitful topics, the team meets in facilitated sessions to explore potential technology significance. Where a new PV product is conceived, the team then carries out a search on relevant intellectual property (IP) and develops an IP strategy. This strategy is then used to establish experiments planned to deliver data needed to support the patent applications. At this stage, the team develops a proposal that is evaluated on both a technical and a business basis, with a team selected to receive funding to complete investigations on an initial schedule of 12 months. Five teams entered the competition in 2009, and NREL's Venture Capital Advisory Board reviewed their proposals. The winning project will seek to prove that highly crystalline GaAs can be grown epitaxially faster than 200 nm/minute to deliver a low-cost pathway to a 20% efficient thin-film module.

4. Planned FY 2010 Activities

As in 2009, in 2010 the project funding will be split, with roughly equal portions used to support the original concept of reducing barriers to creation of industry partnerships and to the newer idea of launching a new product. The major new challenge will be to determine it is possible to engage cost-sharing with venture capital investment at this early stage of product development in a national laboratory. If so, we would initiate two new Innovation by Design teams in 2010.

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Seed Funds

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
Vipin Gupta (SNL, Primary Contact), 505-844-5876, vpgupta@sandia.gov

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

FY 2009 Budgets: $2,240K (NREL), $510K (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 to provide a stream of next-generation photovoltaic (PV) technology options.

Accomplishments

- Demonstrated lift-off of 14-µm-thick c-Si cell with a measured 14.9% efficiency
- Synthesized p-type amorphous Zn-Co-O thin films by sputtering deposition
- Demonstrated lift-off of 2.7-µm-thick backside-contact III-V cell with a measured 10% efficiency
- Evaluated feasibility of silicon quantum dots (QDs) as novel solar cell absorber material
- Reduced water vapor transport rates (WVTR) even with evaporated metal thin films by five orders of magnitude (i.e., ~10^{-4} g/m^2-day) compared to standard TCO materials, giving clear indication that the metal layer improves WVTRs by more than 10-fold
- Developed a solution deposition method for NiO hole transport layers and demonstrated greatly enhanced performance in high Voc polymer solar cell systems relative to PEDOT:PSS
- Demonstrated 3.1% efficiency for hybrid organic photovoltaics (OPV) cell.

Future Directions

- Explore new self-assembly approaches to make PV modules from micro-PV cells
- Explore III-V PV on a low-cost substrate and TCOs deposited by hot-wire CVD

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1. Introduction

SETP funds research to develop commercially attractive PV technologies. In general, these efforts support national lab in-house R&D (e.g., NREL), universities, and existing industry or new companies. These efforts may last for multiple years and can be most successful with stable funding of a sustained effort. It is also useful for SETP to fund temporary R&D that explores new ideas. If the new concepts reach the proof-of-concept stage, the efforts may be expanded; if they are unsuccessful in reaching their goals or reach a successful negative conclusion, then they are terminated to free those funds for new projects. Success of an individual project is not necessarily defined by continued funding or transition into the core program. Rather, success of an individual project could be an unequivocal answer to a question about the practicality of a new concept. The goal of the aggregate of projects in the Seed Fund is to seed the core PV conversion technology effort with innovation. Collaboration with other elements of the program is encouraged to facilitate transfer of projects that demonstrate the feasibility of a concept.

2. Project Details

Thirteen projects were funded in 2009, executed within the calendar year to facilitate the start of new projects. The approach, accomplishments,

and plans are described in a single section to facilitate presentation of the 13 projects.

Agreement Title	FY 2009 Budget ($K)
1. Doped polymeric molecular semiconductor p-n junction OPV	300
2. Carbon nanotube architectures for low cost and high efficiency	300
3. Incorporation of third generation mechanisms into OPV devices	200
4. Thin III-V cells	168 SNL/ 55 NREL
5. Novel nanocrystal-based solar cell to exploit MEG	300
6. Ultra-thin c-Si cells	315 SNL/ 44 NREL
7. Multifunctional TC and self-healing impermeable barriers	150
8. Si quantum dot solar cells	300
9. Amorphous oxide semiconductors for ambient temperature deposited PV	221
10. New absorber materials for thin-film PV beyond 1 TW	140
11. Hole transport layers for excitonic solar cells	40
12. Flexible OPV made by lamination	40
13. Massive parallel assembly for low-cost modules	27

Task #1: Doped polymeric molecular semiconductor p-n junction OPV; PI: Brian Gregg

Purpose: Investigate new approach to creating a stable OPV cell by using a class of materials that has been extensively engineered for 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.

Potential impact: OPV has the potential to achieve very low costs because of its low materials usage combined with the potential to use very low cost deposition techniques. To date, the OPV cells have achieved efficiencies of only ~7% and this efficiency often decreases to <3% when the sample is exposed to air. Very little is understood about the wealth of materials that could be used and the hope of this new approach is that it will reveal a pathway to higher efficiency as well as be insensitive to air.

Milestone:

- Preparation and characterization of new type of OPV cell, >4% efficiency.

Accomplishments:

- A new n-type perylene diimide material was developed that has twice the absorption coefficient of the original polymer and absorbs much more sunlight (being black versus red).
- Improved photostability was demonstrated.

Task #2: Carbon nanotube architectures for low-cost and high-efficiency photovoltaics; PI: Jeff Blackburn

Purpose: Leverage the expertise already developed at NREL in synthesizing carbon nanotubes (CNTs) to determine their utility for use in photovoltaic 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.

Potential impact: Carbon nanotubes may be an enabling technology for any of the thin-film approaches. Implementing CIGS in a flexible form factor is currently limited by the sensitivity of zinc oxide (the most commonly used transparent conductor) to moisture. Similarly, the PEDOT used for hole transport in OPV cells is commonly considered to be a contributor to the instability of OPV. In addition, if CNTs are successfully implemented, they may reduce the cost of the thin-film cells or enable configurations that could not be achieved with transparent conductors deposited at higher temperatures.

Milestone:

- Use sprayed SWNT films as electrodes in PV devices and evaluate system performance, e.g., stability and efficiency, relative to conventional TCOs. Journal publication of results.

Accomplishments:

- Demonstrated spray process of SWNT TCOs with carboxymethyl cellulose inks and acid post-processing step applied to OPV devices with efficiencies > 3.0%
- Certified 2.6%-efficient OPV device on SWNT TC with no PEDOT:PSS (ITO control <1%)
- Developed method to remove CMC matrix without acid post-processing step and applied to CdTe devices with efficiencies ~8%
- Developed preliminary inks with no surfactants that require no post-processing treatment.

Task #3: Incorporation of third-generation mechanisms into OPV devices; PI: David Ginley

Purpose: Explore using third-generation concepts such as multijunction, QDs, and other quantum-confined structures with conjugated polymers to create solar cells with high efficiencies. This work focuses specifically on implementing a multijunction polymer solar cell, incorporating colloidal semiconductors into conjugated oligomers, polymers, and dendrimers.

Potential impact: Although OPV solar cells have the potential to deliver very-low-cost solar cells, to date OPV has not surpassed 7% efficiency. This approach has the potential to improve the efficiency while retaining the low cost.

Milestones:

- Demonstrate enhanced Voc to at least 600 mV with a ZnO/QD/P3HT structure
- Demonstrate additive photoresponse to 700 nm for a P3HT/QD hybrid cell.

Accomplishments:

- Demonstrated 3.1% efficiency for hybrid OPV cell.

Task #4: Thin III-V solar cells; PI: Greg Nielson

Purpose: Epitaxial lift-off (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 interlayer cracks. We are exploring ELO and other lift-off techniques to create small-area cells (<1 cm^2).

Potential impact: We anticipate multiple cost benefits for flat panel or coarse tracking CPV systems resulting from this work. The ability to remove the grown cell structure from the underlying substrate and reuse that substrate for subsequent epitaxial growth represents a significant cost savings over the current III-V cell technique, which requires a new substrate for each growth. Further, we expect that going to smaller cell sizes should reduce interlayer cracking, leading to improved performance and better yields. Within a concentrator module based on small cell sizes, additional benefits include simplified tracking, fluid-based assembly techniques, and easier thermal management.

Milestone:

- Demonstrate lift-off of single-junction III-V cells.

Accomplishments:

- Demonstrated lift-off of 2.7-µm-thick backside-contact III-V cells with confinement layers and a measured efficiency of 10%
- Modified the material stack to improve handling for testing purposes and enhance device performance.

Task #5: Novel nanocrystal-based solar cell to exploit MEG; PI: Matt Beard

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/photon be collected in an external circuit? Cells with efficiencies > 2% have already been demonstrated.

Potential impact: If the multiple-exciton process can be used efficiently, a single-junction solar cell may be able to achieve efficiencies exceeding the Shockley-Queisser limit.

Milestone:

- 4% cell with area ≥ 1 cm^2; demonstrate collection of more than one electron per photon at short wavelengths; spectroscopic demonstration of MEG in device-quality film under bias.

Accomplishments:

- Successfully inverted the device design so that the high-energy photons are absorbed within the active region of the solar cell. The resulting new solar cell design achieves a higher Voc and a higher efficiency. Achieved an efficiency of ~ 3.8%.

Task #6: Ultra-thin c-Si solar cells; PI: Greg Nielson

Purpose: This project seeks to develop a method that creates c-Si cells on a standard c-Si substrate, then lifts off the 10–20-µm-thick c-Si cells from the 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.

Potential impact: This project manufactures cells in a material-conserving manner with the c-Si cell thickness optimized for minimal cost/watt. The small cell size further allows other system-level cost savings, including fluidic parallel assembly methods that can create large modules at high rates and low cost. Other benefits include the ability to use low temperature and flexible substrates for the c-Si cells, increasing the utility and lowering costs, perhaps allowing new types of building integrated solar devices. The method also

produces a flat concentrator module with simple tracking and heat management.

Milestone:

- Demonstrate lift-off of thin c-Si cells with 12% efficiency.

Accomplishments:

- Demonstrated lift-off of 14-µm-thick c-Si cell with a measured 14.9% efficiency
- Created high-quality (ohmic) contacts with metallization process.

Task #7: Multifunctional transparent conducting and self-healing impermeable barriers; PI: Lin Simpson

Purpose: Develop a multilayer coating grown with low-temperature (<80°C) deposition techniques, resulting in a coating that is highly transparent with high electrical conductance, low water-vapor transmission, and lower cost than ITO.

Potential impact: This new barrier could reduce the cost of thin-film cells by using lower cost processes/materials than typically used for transparent conductors. A barrier that achieves very low water-vapor permeability may enable flexible CIGS modules and be especially useful for OPV.

Milestone:

- Demonstrate scalable low temperature processing to form TCO/metal/TCO structures and improve impermeability ($<10^{-4}$ g/m^2/day).

Accomplishments:

- Reduced the WVTR, even with evaporated metal thin-films, by five orders of magnitude (i.e. ~10^{-4} g/m^2-day) compared to standard TCO materials. More conformal film processing should improve WVTR performance further. These results indicate that the metal layer improves WVTRs by > 10 fold.
- Demonstrated transparent conducting materials with ~5 Ω/sq resistivities and >90% transmission. This exceeds the conductivity (<10 Ω/sq.) and light transmission (>80%) performance goals.
- Improved structural integrity/enhanced cyclic loading durability and strain tolerance.
- Demonstrated the potential to reduce TCO and barrier layer costs by more than 100X. This type of cost reduction enables substantial market penetration increases for new technologies, not only reducing PV manufacturing costs by 10% to 25% but also enabling other technologies that ultimately could reduce energy usage by ~40%.

Task #8: Si quantum dots; PI: Pauls Stradins

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

Potential impact: Create disruptive technology by exceeding 30% efficiency with a third-generation, nanostructured Si solar cell.

Milestone:

- Use quantitative analysis of Si QDs as PV material to identify structure that can achieve adequate absorption.

Accomplishments:

- Si nanoparticles synthesized and characterized structurally and optically
- Theory simulations showed that good PV Si QD material requires densely packed, closely spaced, uniform size Si nanoparticles; quantum confinement is preserved
- Optical studies show that adequate optical absorption in Si QD absorber layers is achieved with a thickness in the micrometer range
- Nanoparticle synthesis reported in MRS 2009 Fall Meeting.

Task #9: Amorphous oxide semiconductors for ambient temperature deposited PV; PI: John Perkins

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

Potential impact: A thin-film cell that could be lower cost than today's thin-film devices. If successful, this could form a whole new class of thin-film photovoltaic devices. Appropriate n-type amorphous oxides (e.g., a-InZnO) are known. The clear initial challenge is to develop an appropriate p-type amorphous oxide absorber. Candidates include a-ZnCuO, a-CuNiO, and a-ZnCoO.

Milestone:

- Publish paper on Zn-Cu-O system in peer-reviewed journal.

Accomplishments:

- Amorphous ZnCuO and ZnCoO thin films synthesized by sputtering
- a-ZnCoO demonstrated to be p-type as desired

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- Optical absorption in a-ZnCuO and a-ZnCoO determined to be too weak for application as PV absorber material. Decision made to bring current work to publication and wrap up this project in FY 2010.

Task #10: New absorber materials for thin-film photovoltaics beyond 1 TW; PI: Jennifer Leisch, Glenn Teeter

Purpose: Develop new thin-film PV absorber materials that are abundant.

Potential impact: Extend the vision of CdTe and CIGS to the TW scale.

Milestone:
- Synthesize thin-film Cu_2ZnSnS_4 or $Cu_2ZnSnSe_4$ or both.

Accomplishments:
- Developed capability to deposit uniform or combinatorially graded thin-film samples
- Performed in situ thermal-desorption mass spectrometry to quantify the thermal stability of Cu-Zn-Sn thin films.

Task #11: Inorganic hole-transport layers for excitonic solar cells; PI: Dana Olson, Joe Berry

Purpose: Develop inorganic hole transport layers to replace PEDOT in OPV cells.

Potential impact: Would be an enabling technology for OPV cells. Currently, PEDOT is the most commonly used material, and it shows problems with respect to morphology, chemistry, stability, and scalability. Thus, successful implementation of this project would increase the chances of developing a low-cost, high-reliability, high-performance OPV cell.

Milestone:
- Validate NiO results and optimize deposition conditions for enhanced current extraction; use the optimized NiO material to enable OPV devices using ZnO-based TCOs.

Accomplishments:
- Established equivalent performance of PLD and sputtered NiO HTL materials on OPV devices made on ITO and Ga-doped ZnO transparent conducting oxides
- Developed a solution deposition method for NiO HTL and demonstrated similar performance after processing to vacuum deposited NiO materials
- Demonstrated enhanced performance of high Voc polymer electron donor compared to PEDOT:PSS—5.6% PCE for solution NiO compared to 3.5% PCE for PEDOT:PSS.

Task #12: Flexible OPV made by lamination; PI: Nikos Kopidakis

Purpose: Explore the possibility of assembling an OPV cell by laminating a coating on a flexible substrate with a second coating.

Potential impact: This assembly technique could open new possibilities for OPV cell fabrication by allowing control of the structure of the active layer, allowing fabrication of structures when the processes for the different layers are incompatible, providing access to interfaces, providing the encapsulation in the same step as the cell assembly, avoiding the problems with the metal contact evaporation directly onto the active layer, and providing for a means of using nontransparent substrates by avoiding the need to use a high-temperature process to apply a transparent, conducting contact.

Milestone:
- Demonstrate an inverted OPV device with laminated PEDOT/ITO top contact; demonstrate rectifying behavior in J-V curves of that device and evaluate its photoresponse.

Accomplishments:
- Fabricated a 3% efficient OPV device with laminated top contact. This efficiency equals the efficiency of similar devices in the literature with an evaporated-metal top contact.
- Routinely demonstrated better fill factor, indicating that avoiding hot metal deposition is beneficial to certain OPV architectures.
- As an example of alternative electrodes for flexible OPV, laminated a CNT flexible electrode (in collaboration with task #2) to complete an OPV device with 1.7% efficiency. This was achieved with an unoptimized nanotube electrode.
- Presented “Hot Press Lamination of Inverted Organic Photovoltaic Devices” at the MRS Fall 09 meeting in Boston.

Task #13: Massive parallel assembly for low-cost modules; PI: Greg Nielson

Purpose: Develop a method to handle small and thin c-Si and III-V PV cells that will allow assembly of many of these cells at once to create large-area modules.

Potential impact: If successful, this project will leverage the successes of the ultra-thin c-Si and III-V cell projects to develop a method to create large

modules of the thin and small chips rapidly using parallel manufacturing concepts. The arrays of thin and small PV cells can be formed in either dense arrays for one-sun modules or in sparse arrays for concentrator modules. This manufacturing technique may be implemented in a commercial process as a roll-to-roll process. In addition to lowering the costs of assembling modules, this method allows the use of low-temperature and flexible substrates. This may further create benefits by enabling building-integrated PV concepts.

Milestone:

- Explore a variety of methods for parallel assembly of small, thin PV cells onto inexpensive substrates.

Accomplishments:

- Developed three distinct concepts for fluidic self-assembly of small, ultrathin PV cells onto substrates.

3. FY 2009 Special Recognitions, Awards, and Patents

Patent application #11/933,438 filed with claims on microsystem-enabled PV design, manufacturing, and operation.

Submitted PCT patent entitled "Multi-functional Transparent Conducting & Self-Healing Impermeable Barriers."

4. Major FY 2009 Publications

M. Beard, A. Midgett, M. Law, O. Semonin, R. Ellingson, and A. Nozik, "Variations in the Quantum Efficiency of Multiple Exciton Generation for a Series of Chemically Treated PbSe Nanocrystal Films," *Nano Lett.* **3**, 836 (2009).

J. Berry, N. Widjonarko, B. Bailey, A. Sigdel, D. Ginley, and D. Olson, "Surface Modification of NiO Hole Transport Layers for Organic Solar Cells," *J. Selected Topics Quantum Electron*. (in press).

J. Chesin, K. Steirer, N. Widjonarko, J. Berry, A. Miedaner, D. Ginley, and D. Olson, "Solution Deposited NiO Thin-films as Hole Transport Layers in Organic Photovoltaics," *Adv. Mater.*

S. Dayal, N. Kopidakis, D. Olson, D. Ginley, and G. Rumbles, "Direct Synthesis of CdSe Nanoparticles in Poly(3-hyxylthiophene)," *J. Am. Chem. Soc*. **131**, 17726 (2009).

S. Dayal, N. Kopidakis, D. Olson, D. Ginley, and G. Rumbles, "Photovoltaic Devices with a Low Band Gap Polymer and CdSe Nanostructures Exceeding 3% Efficiency," *Nano Lett*. **10**, 239 (2010).

Duenow et al., *Proc. IEEE 2009*.

H. Hillhouse and M. Beard, "Solar Cells from Colloidal Nanocrystals: Fundamentals, Materials, Devices, and Economics," *Current Opinion Colloidal & Interface Sci.* **14**, 245 (2009).

B. Jariwala, P. Stradins, J. Beach, R. Collins, P. Taylor, J. Radziszewski, S. Williams, J. Cheng, J. Fields, K. Kiriluk, C. Ciobanu, and S. Agarwal, "Next-Generation Photovoltaics Devices Based on Silicon Nanocrystals," *Mater. Res. Soc. Fall Meeting, Boston, Nov. 2009*.

Z. Liang, R. Cormier, A. Nardes, and B. Gregg, "Air Stable and Solution Processable n-type Perylene Diimide Polymers," *Macromolecules* (submitted).

G. Nielson, M. Okandan, P. Resnick, J. Cruz-Campa, P. Clews, M. Wanlass, W. Sweatt, E. Steenbergen, and V. Gupta, "Microscale PV Cells for Concentrated PV Applications," *24th European PVSEC, 2009*.

G. Nielson, M. Okandan, P. Resnick, J. Cruz-Campa, T. Pluym, P. Clews, E. Steenbergen, and V. Gupta, "Microscale c-Si (C)PV Cells for Low-Cost Power," *34th IEEE PVSC, Philadelphia, PA, 2009*.

R. Tenent, T. Barnes, J. Bergeson, A. Ferguson, B. To, L. Gedvilas, M. Heben, and J. Blackburn, "Ultrasmooth, Large-Area, High-Uniformity, Conductive Transparent Single-Walled-Carbon-Nanotube Films for PV Produced by Ultrasonic Spraying," *Adv. Mater.* **21**, 3210 (2009).

M. Woodhouse, C. Perkins, M. Rawls, R. Cormier, and B. Gregg, "Photophysical and Electronic Properties of a New Class of Polymers for Organic Photovoltaics," *J. Phys. Chem C* (submitted).

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
University of Florida/ P. Holloway	Gainesville, FL pholl@mse.ufl.edu	Fundamental research on growth of p-type mixed metal oxide thin films for PV absorber application	30	0
University of Minnesota	Minneapolis, MN kakalios@umn.edu	Si nanoparticle synthesis and embedding into various matrices for material characterization at NREL for PV potential	30	0
University of Toledo/ R. Ellingson	Toledo, OH randy.ellingson@utoledo.edu	Novel nanocrystal-based solar cell to exploit multiple exciton generation	110	20

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Conversion Devices Summary

Conversion Devices research at the national laboratories is the primary effort for materials and device research to advance the performance of photovoltaic (PV) devices. Research at the national labs explores new and novel device processing techniques with the potential for much wider industrial impact. The primary topic areas include:

- Wafer Silicon: advancement of wafer silicon (c-Si and mc-Si) cell processing techniques for higher efficiency silicon cells
- Film Silicon: develop silicon film growth and cell fabrication techniques on inexpensive substrates
- Copper Indium Gallium Diselenide (CIGS): work closely with industry to close the efficiency gap between best National Renewable Energy Laboratory (NREL) cell result and industrial production efficiency
- Cadmium Telluride (CdTe): increase understanding of efficiency limiters in CdTe fabrication processes
- Concentrating Photovoltaics (CPV): advance Inverted Metamorphic Multi-junction (IMM) CPV cell architecture and processing
- Organic Photovoltaics (OPV): develop state of the art active layers, contacts, and understanding of degradation mechanisms
- Sensitized Cells: screen cell materials and configurations for environmental stability
- Transparent Conducting Oxide (TCOs): cross-cutting research aimed at reducing transparent conductor sheet and contact resistance for the semiconductor absorbers listed above
- Theory and Computational Science: scientific modeling and prediction for novel materials to accelerate development as a PV absorber material.

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
Conversion Devices	**14234**	**250**	**0**	**14484**
Wafer Silicon	**1775**	**0**	**0**	**1775**
Film Silicon	**3225**	**0**	**0**	**3225**
Copper Indium Gallium Diselenide	**1835**	**0**	**0**	**1835**
Cadmium Telluride	**1226**	**0**	**0**	**1226**
Concentrating Photovoltaics	**1860**	**0**	**0**	**1860**
Organic Photovoltaics	**1751**	**250**	**0**	**2001**
Sensitized Cells	**694**	**0**	**0**	**694**
Transparent Conducting Oxide	**618**	**0**	**0**	**618**
Theory & Computational Science	**915**	**0**	**0**	**915**

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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: Scott Stephens, 202-586-0565, scott.stephens@hq.doe.gov

FY 2009 Budget: $1,775 K (NREL)

Objectives

- Develop a low-cost and high-efficiency cell process to meet U.S. Department of Energy (DOE) goal of levelized cost of energy (LCOE).The 2015 targets for residential, commercial, and utility markets are 8–10, 6–8, and 5–7¢/kWh, respectively.
- Help U.S. solar industry.

Accomplishments

- Achieved 16.8% conversion efficiency in nanopore black silicon (Si) approach.
- Demonstrated Si heterojunction solar cells for low concentrator and developed 5-in.Si wafer cells.
- Completed the installation of the CZ crystal grower.
- Achieved more than 10% heterojunction BIC c-Si solar cell and solve the S-shape of JV curve.
- Achieved conductive narrower line of 30–40 µm at 10 µm thick using ink-jet printing.
- Produced and delivered strong conference presentation and publications.

Future Directions

- Establish quick evaluation of solar Si feedstock.
- Develop high-efficiency Si heterojunction solar cells on thin wafers.
- Develop novel materials for better surface passivation.

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1. Introduction

Wafer Si solar cells and modules are well-developed and the leading technology in photovoltaic (PV) production—about 90% of all PV production in 2008 was wafer Si. To keep the leading position of wafer Si and meet DOE goal of LCOE in 2015, many laboratories and PV industries focus their R&D on low-cost Si feedstock, selective emitters, thinner wafers, epi-Si wafers, laser assisted doping and contacts, simplified processes for high efficiency solar cells, advanced diagnostic techniques, and improved reliability.

2. Technical Approach

This project will focus on accelerating solar Si feedstock evaluation, high-efficiency c-Si solar cells, next-generation surface and bulk passivation, novel front contacts, and advanced light management. A summary of the project is itemized as the following:

- Crystal growth
  - Growth and evaluation of Si feedstock
- High-efficiency solar cells
  - Heterojunction solar cells
  - Heterojunction BIC solar cells
  - Novel light trapping
  - Surface and bulk passivation materials
- Si solar cell process development
  - Novel metal contact processing
  - New metallization schemes.

Table I. Task list of wafer-Si agreement in FY 2009

Wafer Si	**FY 2009 Budget ($K)**
CZ grower	194
Silicon heterojunction solar cells	654
Passivation of mc-Si	216
Heterojunction BIC solar cells	260
Black Si	151
Direct writing contact	200
Fire-through metallization	100
Total	1775

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3. Results and Accomplishments

We completed assembly of the CZ crystal Si grower in Figure 1 in early 2009. After it passed the acceptance test at the factory, the system was delivered and installed at NREL at the end of 2009. This system can grow 3–4 in. diameter Si ingot up to 10 in. long or 4.9 kg per load. It also has a capability of vacuum bake-out at 10^{-6} Torr. We are bringing this system on-line. In FY 2010, we expect the CZ puller to start growing solar Si feedstock, and we will evaluate the feedstock. We expect to complete the TSA with a few PV companies that have shown interest.

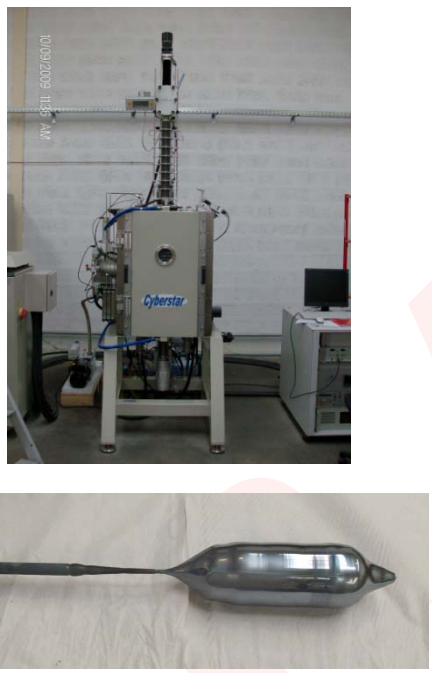

Fig. 1. Czochralski crystal growth chamber and grown Si crystal.

We made continual progress in the silicon heterojunction solar cell task in FY 2009. The summary report was published in *APL* (Wang et al., 2010). In that publication, we described our research on p-type wafers with the highest reported efficiency of 19.3% and the understanding of how the Si heterojunction cell works. We also studied the Si heterojunction cells under concentrated light to understand the heterojunction and the possibility of their use in concentrator applications. Figure 2 shows the cell performance under light intensity up to 50 suns. We found the p-type based heterojunction solar cell performance to be better than the n-type based under intensive illumination. This work was submitted to *APL* as well.

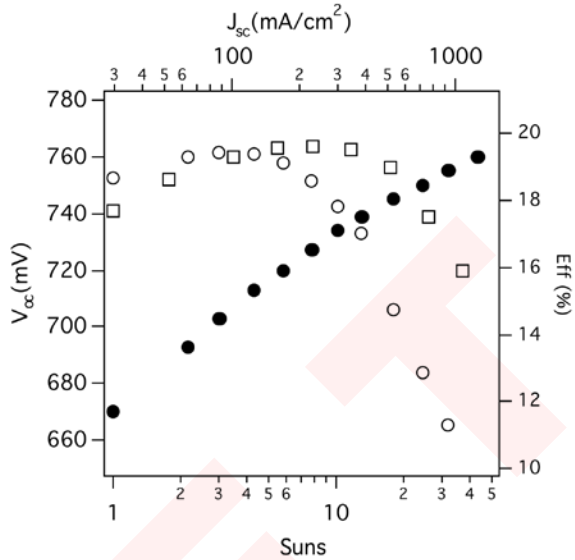

Fig. 2. Solar cell performance of V_{oc} and efficiency of silicon heterojunction cells on *p*-type wafers under low concentrated light. Solid symbol = V_{oc}, open symbol = efficiency, circle = cell at 1 cm^2, and square = cell with dense front grid at 0.1 cm^2.

A wafer-sized Si heterojunction solar cell was developed in the newly installed Si cluster tool in the Process Development and Integration Laboratory. We successfully tested a-Si:H films and indium tin oxide (ITO) in the Si cluster tool. We also developed a wafer final cleaning process before a-Si:H deposition and JV measurement up to 10 A for high current, large solar cells. About 10 wafer-size Si heterojunction cells were made to optimize the i/p/ITO junction. More reports about HJ solar cell are expected in FY 2010.

Work under the black Si task aims to archive high-efficiency silicon solar cells with a better anti-reflection with a

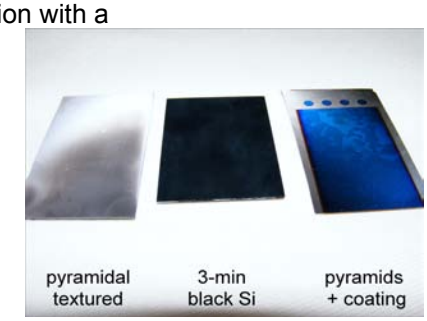

Fig. 3. Photograph at tilted angle of silicon wafers with industrial micron-scale texture (left), micron-scale texture combined with an interference coating (right), and after our black silicon anti-reflection (center).

simpler process. It has been known for decades that lower reflection can be achieved with a density-graded surface. Such density-graded anti-

reflection also suppresses reflection across a wider range of wavelengths and for light incident at any angle. Techniques of fabricating such "black silicon" have been expensive, however, and the best solar cells based on density-graded anti-reflection, without interference layer coatings, previously reached only 13.9% efficiency.

In FY 2009, the NREL team has developed an inexpensive, nanocatalyzed liquid etch to make nanotextured black silicon that reflects less than 2% of light across the entire usable solar spectrum (see Fig. 3). We also fabricated a confirmed 16.8% efficient black silicon solar cell (see Fig. 4). This advance goes far beyond our FY 2009 milestone of a 15% efficient demonstration cell. Except for the advanced anti-reflection strategy, our cell is made with standard silicon processes used to make more than 80% of today's solar cells. We also demonstrated 14.9% efficient black silicon cells on a less-expensive multicrystalline silicon wafer. Because our nanocatalyzed etch is likely to be less expensive than present anti-reflection coatings, a start-up company is now licensing the technology from NREL to spearhead commercialization efforts. Equally important, our work demonstrates the practicality of density-graded anti-reflection in solar cells and may inspire applications of this anti-reflection principle to other photovoltaic materials and solar energy devices.

Direct writing contact uses inkjet printers to make fine conductive lines on c-Si cells. In FY 2009, we reduced the printed line width to 30–40 µm at 10 µm thick; reduced contact resistance to values below those of screen printed contacts (<2

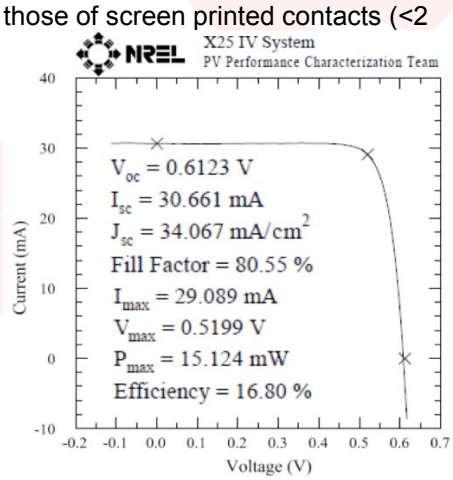

Fig. 4. Independently confirmed IV curve of our 16.8% efficient black silicon solar cell.

mOhm cm^2) by continued development of proprietary inkjet printable burn-through material; reduced resistivity of printed nickel and copper (both at 5x bulk); developed dopant inks for deposition of doped contacts and tested contacts on both n-type and p-type wafers with promising results; and installed an Atmospheric Processing Platform (APP) for scaling of printed contacts to full 156 x 156 mm wafers. The APP also includes full wafer thermal processing capabilities; we added aerosol spray to deposition techniques as an alternative to inkjet printing. Deposited material properties are similar to those of inkjet.

The fire-through process task is using an optical furnace to develop a process for mc-Si solar cells that will yield cell performance equal to or exceeding that of the commercial vendor. We are working with two solar cell manufacturers, who supply us with unfired screen-printed cells. The firing of the cells is done at NREL and cell performance is compared with the performance of cells from the respective vendor.

In FY 2009, we successfully changed the firing profile. First, we designed a unique procedure to create a uniform aluminum (Al) melt on Si by altering the wetting properties of the Si surface using diffusion of Si into Al during a firing process. Next, we determined that in most practical cases, the thickness of the back surface field (BSF) is limited by the growth rate of the epitaxial layer from the Si-Al melt (rather than the melt thickness itself). Hence, the BSF is typically controlled by the cooling rate between the peak temperature and about 600°C.

With these changes we were able to make cells that exceeded the V_{oc} and J_{sc} values obtained by the conventional firing cycles. This work was presented at the IEEE meeting and more recently at the MRS 2009 Fall meeting. We will continue to apply the new firing profile and make improvements such that can be used for the commercial cells.

In August 2009, the 19th c-Si workshop was held in Vail, CO. It was a successful meeting, where we discussed solar-grade Si and the future of mono- and multicrystalline Si. Many university, national lab, and solar industry representatives attended the conference.

4. Planned FY 2010 Activities

In FY 2010, we will work on many projects, but we will focus on the following areas:

- Operationalize the CZ-crystal grower
- Develop efficient 5-in. heterojunction solar cells

- Study the surface and bulk passivation with a-Si layers and hydrogenation
- Develop interdigitated solar cells using heterojunction a-Si:H layer
- Work on black Si solar cells and technology transfer.
- Study direct writing contact
- Examine efficient furnace and fire-through metal contact.

5. FY 2009 Special Recognitions, Awards, and Patents

ROI 09-10V: V.E. Yost, H.-C. Yuan, M.R. Page, "Anti-Reflection Black-Etching Technique for Deep n-type Dopant (phosphorus) Diffused Silicon Wafers Using Anionic/Organic and Inorganic Wet Chemistry."

6. Major FY 2009 Publications

Kh.A. Abdullin, B.A. Beketov, G.N. Chumikov, B.N. Mukashev, M.F. Tamendarov, T.S. Turmagambetov, M.R. Page, and D.M. Kline, "Compensated Silicon Crystals and Monosilane by Metallurgy Route," to appear in *Proc. 24th European Photovoltaics Solar Energy Conf. and Exhibition, Hamburg, Germany*.

H.M. Branz, V.E. Yost, S. Ward, K.M. Jones, B. To, and P. Stradins, "Nanostructured Black Silicon and the Optical Reflectance of Graded-Density Surfaces," *APL* **94**, 231121 (2009).

B.N. Mukashev, Kh.A. Abdullin, M.F. Tamendarov, T.S. Turmagambetov, B.A. Beketov, M.R. Page, and D.M. Kline, "A Metallurgical Route to Produce Upgraded Silicon and Monosilane," *Sol. Energy Mater. Sol. Cells* (2009).

B. Sopori, V. Mehta, D. Guhabiswas, R. Reedy, H. Moutinho, B. To, A. Shaikh, and A. Rangappan, "Formation of a Back Contact by Fire-through Process of a Screen Printed Silicon Solar Cell," *Proc. 34th IEEE PVSC, Philadelphia, June 7–12, 2009,* 1963–1968.

B. Sopori, V. Budhraja, P. Rupnowski, S. Johnston, N. Call, H. Moutinho, M. Al-Jassim, "Defect Clusters in Multicrystalline Silicon: Their Nature and Influence on the Solar Cell Performance," *Proc. 34th IEEE PVSC Philadelphia, June 7–12, 2009,* 1969.

B. Sopori, P. Rupnowski, V. Mehta, V. Budhraja, S. Johnston, N. Call, H. Mountinho, M. Al-Jassim, Aziz Shaikh, M. Seacrist, and D. Carlson, "Performance Limitations of mc-Si Solar Cells Caused by Defect Clusters," *ECS Trans*. **18**(1), 1049–1058 (2009).

M.F.A.M. van Hest, C.J. Curtis, A. Miedaner, R.M. Pasquarelli, J. Kreuder, P. Hersh, and D.S. Ginley, "Inkjet Printed Contacts for Use in Photovoltaics," *IEEE PVSC Philadelphia, June 2009*.

Q. Wang, "High-Efficiency Hydrogenated Amorphous/Crystalline Si Heterojunction Solar Cells," *Philosophical Magazine*, Prof. Walter E. Spear Commemoration Issue, **89,** 2587 (2009).

Q. Wang, M. Page, E. Iwaniczko, Y. Xu, and F. Hasoon, "Light Management for Efficient Crystalline Si Heterojunction Solar Cells," in *Proc. 216th ECS , Vienna, Austria, October 2009*.

Q. Wang, M.R. Page, E. Iwaniczko, Y.-Q. Xu, L. Roybal, A. Duda, F. Hasoon, S. Ward, P.R. Yu, and Dong Wang, "Amorphous/Crystalline Silicon Heterojunctions under Intensive Illumination," submitted to *APL*.

Q. Wang, M.R. Page, E. Iwaniczko, Y. Xu, L. Roybal, R. Bauer, B. To, H.-C. Yuan, A. Duda, F. Hasoon, Y.F. Yan, D. Levi, D. Meier, H.M. Branz, and T.H. Wang, "Efficient Heterojunction Solar Cells on p-type Crystal Silicon" *APL* **96,** 013507 (2010).

H.-C. Yuan, V.E. Yost, M.R. Page, P. Stradins, D.L. Meier, and H.M. Branz, "Efficient Black Silicon Solar Cell with a Density-Graded Nanoporous Surface: Optical Properties, Performance Limitations, and Design Rules," *APL* **95**, 123501 (2009).

DRAFT

Film Silicon

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Howard Branz (NREL), 303-384-6694, howard.branz@nrel.gov

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

FY 2009 Budget: $3,225K (NREL)

Objectives

- Develop cost-effective wafer-replacement film crystal silicon materials and devices as prototypes for a PV module technology that can be manufactured for $0.50/W
- Improve growth rates and quality of lowgap thin-film silicon alloys for amorphous silicon mulitjunction solar cells
- Transfer technology and support industrial partners manufacturing thin-film and film crystal silicon

Accomplishments

- Fabricated 6.3% hot-wire chemical vapor deposition (HWCVD) epitaxial test solar cell on wafer, with open-circuit voltage of 570 mV achieved in October 2009
- Grew HWCVD epitaxial silicon (Si) at low temperature with dislocation density less than 2 x 10^5 cm^{-2} and minority-carrier diffusion length of 14 µm
- Demonstrated submicron control of doping in device structures
- Led Si material research and photovoltaic (PV) device design efforts through a cooperative research and development agreement that contributed to Ampulse Corporation's successful raising of $8 million in Series A venture capital
- Published first-principles modeling of structure and electronic properties of promising γ-Al2O3/Si heteroepitaxial interface for film c-Si applications
- Fabricated 10.1%-efficient a-Si:H solar cell in the new 6-in. Process Development and Integration Laboratory (PDIL) cluster tool, exceeding 9% milestone.
-

Future Directions

- Deposit efficient epitaxial Si solar cells on oriented seed layers on display glass
- Fabricate efficient high deposition rate VHF-CVD nanocrystalline Si solar cells that minimize capital costs.

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1. Introduction

Silicon is abundant, nontoxic, well-understood, and accepted in the marketplace. There is a highly developed industrial base in all forms of Si, and an enormous, rapidly growing scientific literature. Si PV costs must be reduced, however, to reach the U.S. Department of Energy (DOE) 2020 goal of $0.06/kWh PV electricity. This requires module costs well below $1/W. Today, the Si feedstock contract cost alone is greater than $50/kg and is unlikely to fall further. Even with utilization improving to 8 g/W, wafer materials costs alone will top $0.40/W, making it 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 using silane to grow Si films, rather than feedstock, and by leveraging the existing crystal Si and amorphous Si industrial infrastructure from PV, displays, and computer chips. Although the basic physics of Si semiconductors are quite well understood, considerable materials, defect, and device research is needed to enable a low-cost PV technology using low-cost forms of Si.

This film Si project addresses key research problems toward near-term expansion of the thin-film Si industry based on amorphous silicon (a-Si:H) and allied materials and midterm creation of a wafer-replacement crystalline film Si technology.

2. Technical Approach

The NREL PDIL is a unique platform for vacuum transfer of PV materials and devices among deposition and advanced characterization tools without breaking vacuum. Our new robotic-transfer silicon cluster tool is now operating in the PDIL, giving us the ability to deposit 157-mm thin-film a-Si:H, a-SiGe:H, nanocrystalline solar cells and to collaborate with industrial partners on these larger devices. The tool is a unique system for studying and developing thin-film Si technologies for PV applications. For thin-film Si process development, the Si cluster tool has six plasma-enhanced CVD chambers and an HWCVD chamber; a sputter tool deposits transparent conduction oxides for contacts. In FY 2009, we tested all chambers in the system and worked to optimize the layers and test devices.

To assess HWCVD for wafer-replacement c-Si film PV, we grew high-quality epitaxial layers on heavily doped "dead" c-Si wafers and designed, modeled in PC1D, and fabricated test solar cells to see how well the epitaxial Si performs on an ideal seed layer. In addition, we improved the epitaxial quality at low T and performed gas-to-solid phase modeling that suggests viable paths to epitaxial growth rates higher than the 300 nm/min we have so far achieved (corresponding to 6 minutes for a 2-μm cell). Finally, we collaborated closely with industry partners who develop low-cost seed layers and worked to develop new types of seed layers ourselves by laser-assisted thermal crystallization, by microwave seeding, and by ion-beam assisted deposition of oxide layers matched to c-Si on glass.

3. Results and Accomplishments

Our PC1D simulations clearly show that film c-Si cells have the potential to approach wafer-based PV device efficiencies with L_{eff} orders of magnitude below the millimeter range required of 200–300 μm wafer cells. A 5 μm thick c-Si absorber needs L_{eff} ~ 5–10 μm to reach 10% efficiency, and adding 5X to 10X light trapping (i.e., the optical path length is 5 to10 times the absorber thickness) would increase J_{SC} and improve the efficiency to greater than 15%. The simulations also suggest that defective absorbers with short L_{eff} can be thinned to capitalize on a gain in V_{OC}, as long as the surface recombination remains low.

Figure 2 displays the JV characteristics of three representative epitaxial devices grown at different T, along with their corresponding plan-view electron beam induced current (EBIC) images revealing threading dislocations. The V_{OC} and efficiency improvement in the devices grown at higher T correspond to a marked decrease in N_d in the absorber; clearly dislocation density determines cell performance. The highest V_{OC} is 570 mV. As we reduce dislocation densities at lower T on display-glass substrates and hydrogenate the defects, our design goal of 610 mV should be achievable.

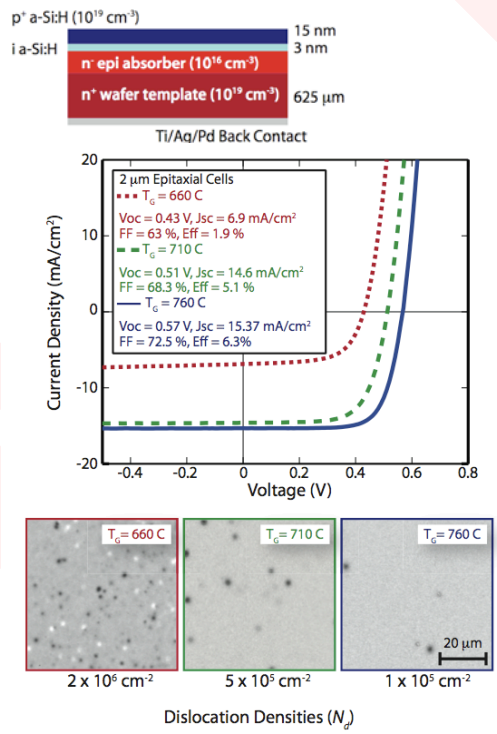

Fig. 1. (top) Schematic of the test device structure on "dead" c-Si wafers. (middle) J-V curves and parameters of epitaxial Si test solar cells, correlated with (bottom) EBIC dislocation densities, for a range of substrate temperatures.

We developed an analytic model that explains the insensitivity of our very thin PV cells to impurities (and other point defects). Minority carrier bulk lifetime, τ_{bulk}, scales inversely with the concentration, N, of the most recombination-active impurity or defect, and therefore the carrier diffusion length, $L_{eff} = (D\tau_{bulk})^{1/2}$, scales as $N^{-1/2}$ because of the random walk that minority carriers undergo before recombining. Here D, the minority carrier diffusion coefficient, is assumed weakly dependent on N. For efficient carrier collection at

the surface of an absorber of thickness d, L_{eff} must be about 3 times d, as described below. Consequently, the maximum impurity density a cell can tolerate depends on thickness as $N_{max} \propto d^{-2}$. Compared to the bulk impurity concentration that can be accommodated in a 200-μm thick wafer cell [20], the impurity or defect concentration in a 2-μm cell can be 10^4 times higher without performance degradation; i.e., metal impurity levels of at least 10^{17} cm^{-3} can be tolerated. Secondary ion mass spectrometry (SIMS) reveals ~10^{17} cm^{-3} of both O and C throughout our absorber layers. In our growth chamber, W (from the hot filament) and Ni are present; the concentration of each in the epitaxial layers is comparable to the 10^{14}–10^{15} cm^{-3} noise of the SIMS measurement, but T-dependent EBIC shows that the impurities do not limit performance. In wafer cells, randomly distributed metal contaminant concentrations of only 10^{13}–10^{14} cm^{-3} would be sufficient to degrade wafer cell performance.

When limited by highly recombination-active dislocations, three length scales control the relationship between material quality and film c-Si device performance: L_{eff}, d, and the characteristic distance between dislocations, $l_d \sim N_d^{-1/2}$. Our IQE measurements (not shown) show that the red response of a 2-μm cell reaches ideal behavior at 4 μm < L_{eff} < 8 μm, experimental confirmation of our simulated results that $L_{eff} \sim 3d$ is required for efficient carrier extraction. This relationship applies because minority carriers do not drift directly to the junction but, instead, reverse direction frequently during their random walk to the emitter. Second, correlation of EBIC and IQE measurements indicates that $L_{eff} \sim l_d/2$. With equal probability of traveling in any direction, recombination at a dislocation naturally limits L_{eff} to about half of l_d. Thus, our experiments suggest that $l_d \geq 6d$ for efficient film Si cells. For example, our 2-μm cell requires a dislocation density ≤ 5 x 10^5 cm^{-2} for efficient carrier collection, but a 5-μm cell would require an unpassivated dislocation density of 1 x 10^5 cm^{-2} and a higher-current 10-μm cell would require 3 x 10^4 cm^{-2}. More dislocations could be tolerated if they are well-passivated by hydrogenation.

In the Si cluster tool, we optimized a-Si:H film uniformity, deposition rate, dark and light conductivity, bandgap, and activation energy of both intrinsic and doped films. We varied substrate temperature, process gas flow rate, gases mixtures, and radio frequency power. We also optimized the indium tin oxide and ZnO:Al transparent conducting oxide (TCO) layers to achieve film transmittance > 85% and sheet resistance < 10 Ω/square.

Figure 2 shows the J-V curve and performance parameters of a 10.15% cell on Asahi U-type glass coated with surface-textured SnO:F TCO. The cell structure is glass/TCO/p-i-n/Ag, the cell area is at 0.5 cm^2, and the i-layer thickness is about 350 nm. The cell stabilizes at 8% after 1000 hours of light soaking. The 10.15% initial efficiency exceeds the FY 2009 milestone of 9% and allows us to assist industrial partners with cell development in the PDIL.

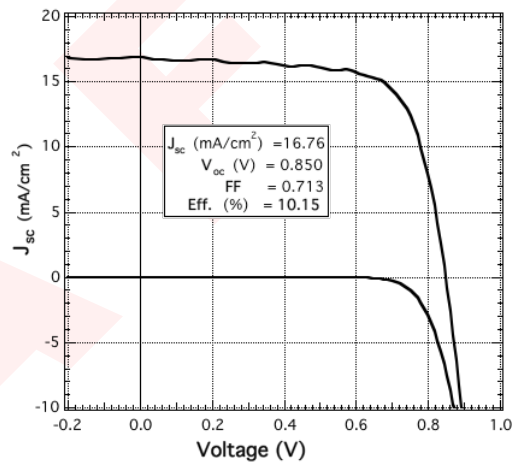

Fig. 2. Light and dark J-V of a 10.15% efficient a-Si:H solar cell fabricated in the Si cluster tool.

We also identified key parameters for a p-layer that supports high cell efficiency by eliminating "S-shaped" J-V curves that we linked to poor electrical contact between the TCO and p-layer that reduces fill factor (FF). By controlling p-layer bandgap, dopant concentration, and thickness, we were able to eliminate the S-shape. The best FF of our cells reached 73%.

4. Planned FY 2010 Activities

In FY 2010, we will apply our experience with devices on wafers to solar cells on inexpensive templated-coated substrates such as display glass and metal foil. Goals include improved low-T epitaxial layer quality, hydrogenation-passivated dislocations, and increased deposition rate. As we improve our own novel seed layers on glass, we will measure grain sizes and orientation and will deposit and characterize Si epitaxial layers and

devices to assess PV potential. We will also demonstrate nc-Si solar cells for use as a lowgap partner to a-Si:H in tandem cells and increase growth rates in the Si cluster tool. Milestones include:

- Publish paper on quality of epitaxial Si on seed layers on inexpensive substrates. (9/30)
- Fabricate solar cell device on wafer with open-circuit voltage above 560 mV. (8/31)
- Demonstrate 2% absolute improvement in epi-PV efficiency by hydrogenation. (03/10)
- Publish effect of film thickness on grain size in thermal annealing of a-Si after subthreshold laser crystallization. (8/31)
- Fabricate 7% baseline nc-Si solar cell in PDIL Si Cluster Tool (09/10).

5. FY 2009 Awards and Patents

Charles Teplin received an NREL Outstanding Performance Staff Award for his PV work with Ampulse. In addition, we filed for 4 U.S. patents:
A Photovoltaic Cell with Back-Surface Reflectivity and Scattering, filed 08/06/09, US12/537,185
Back Contact to Film Silicon on Metal for Photovoltaic Cells filed 08/07/09,US 12/537,152
Crystal Silicon Processes and Products, filed 02/12/09, US PCT/US09/33937
Epitaxial Growth of Silicon for Layer Transfer, filed 08/21/08 US and World: PCT/US08/73834.
We submitted 4 new Records of Invention.

6. Major FY 2009 Publications

I.T. Martin, C.W. Teplin, H.M. Branz, and P. Stradins, "Silicon Epitaxy Rate Optimization and Modeling for Hot-Wire Chemical Vapor Deposition from 600 to 800°C," *J. Applied Physics*, in press (2010).

H.J. Xiang, J.L.F. Da Silva, H. M. Branz, and S.-H. Wei, "Heteroepitaxial Interface without Defects or Gap States: Single Crystal Si on Al_2O_3," *Phys. Rev. Lett.* **103**, 116101 (2009).

P. Stradins, C.W. Teplin, and H.M. Branz, "Phase Evolution in Nanocrystalline Silicon Films: Hydrogen Dilution and the Cone Kinetics Model," *Phil. Mag.* **89**, 28, 2461-2465 (2009).

D.L. Young, H.M. Branz, F. Liu, R. Reedy, and Q. Wang, "Electron Transport and Structure in Highly-Conducting P-doped Polycrystalline Si Thin Films," *J. Appl. Phys.* **105**, 33715 (2009).

I.T. Martin, H.M. Branz, P. Stradins, D.L. Young, K.M. Jones, R.C. Reedy, and C.W. Teplin, "Doping of High-Quality Epitaxial Silicon Grown by Hot-Wire Chemical Vapor Deposition near 700°C," *Thin Solid Films* **517**, 3496-3498 (2009).

C.W. Teplin, K. Alberi, M. Shub, C. Beall, I.T. Martin, M.J. Romero, D.L. Young, K.M. Jones, R. Reedy, P. Stradins, and H.M. Branz, "Mechanisms Controlling the Phase and Dislocation Density in Epitaxial Silicon Films Grown from Silane below 800°C," submitted to *Appl. Phys. Lett.*

K. Alberi, I.T. Martin, M. Shub, C.W. Teplin, M.J. Romero, E. Iwaniczko, A. Duda, P. Stradins, H.M. Branz, and D.L. Young, "Material Quality Requirements for Efficient Epitaxial Film Silicon Solar Cells," *Appl. Phys. Lett.*, in press (2010).

M.S. Dabney, P.A. Parilla, L.M. Gedvilas, A.H. Mahan, and D.S. Ginley, *Appl. Phys. Lett.* **95**, 251902 (2009).

A.H. Mahan, M.S. Dabney, P.A. Parilla, and D.S. Ginley, "The Effect of the Film H Content on the Crystallization of Laser Processed and Thermally Annealed HWCVD a-Si:H," *Phys. Stat. Solidi*, in press (2010).

A.H. Mahan, T. Su, D.L. Williamson, L.M. Gedvilas, S.P. Ahrenkiel, P.A. Parilla, Y. Xu, and D.A. Ginley, "Identification of Nucleation Center Sites in Thermally Annealed Hydrogenated Amorphous Silicon," *Adv. Funct. Mater.* **19**, 2338 (2009).

Liu, F., K.M. Jones, Y. Xu, W. Nemeth, J. Lohr, J. Neilson, M.J. Romero, M.M. Al-Jassim, and D.L. Young, "Ultra-High Crystalline-Quality Silicon Pillars Formed by Millimeter-Wave Annealing of Amorphous Silicon on Glass," *Adv. Mater.* **21**, 3002 (2009). Cover story.

Project scientists delivered more than 25 conference and workshop presentations in FY2009, including 9 invited talks.

7. University and Industry Subcontracted Partners

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Jeff Neilson, Lexam Research	10 Black Fox Way, Redwood City, CA 94062 jeff@lexamresearch.com	Microwave wave optical design assistance	6	0

Copper Indium Gallium Diselenide

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Ingrid Repins (NREL), 303-384-7678, ingrid.repins@nrel.gov

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

FY 2009 Budget: $1,835K (NREL)

Objectives

- Assist with development of goals and metrics associated with copper indium gallium diselenide (CIGS) Technology Roadmaps, including those related to stability, in situ sensors, device physics, decreased cost, and enhanced module efficiency
- Support the needs of the expanding CIGS photovoltaics (PV) industry
- Install vacuum components of CIGS Process Development and Integration Laboratory (PDIL) platform to enhance capabilities for both industrial support and research
- Expand intellectual property related to CIGS PV.

Accomplishments

- Completed ES&H and facilities requirements for full functionality of equipment in Science and Technology Facility (STF) at NREL
- Finished installation of vacuum components for CIGS PDIL platform, brought them into compliance with NREL ES&H regulations, and commenced operation
- Gathered data on industrial and laboratory samples showing minority carrier lifetime to be a useful metric of CIGS quality
- Quantified the damp heat reliability of various transparent conductors used in the CIGS device; identified possible strategies to mitigate sensitivities.

Future Directions

- Develop processes in each component of the PDIL CIGS platform and proceed with industrial collaborations, state-of-the-art CIGS devices, and characterization.
- Adapt minority carrier lifetime as an in situ metric of CIGS quality, suitable for installation on manufacturing deposition equipment.
- Test success of identified strategies to improve resistance of CIGS device to damp heat.

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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 photovoltaic 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 understanding that builds a solid technical foundation for continuing improvement of thin-film PV products. Within this framework, the FY 2009 project supported thin-film technologies related to the substrate, Mo, CIGS, and transparent conducting oxide (TCO) components of the thin-film technology. Activities and time frames are consistent with those identified in the *DOE Solar Program Multi-Year Technical Plan* and related *Technology Roadmaps.*

NREL's CIGS technologies continue to lead the world in demonstrated cell performance, and 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 involves research on CIGS device development. FY 2009 activities were funded via four agreements, as listed next.

Task Title	FY 2008 Budget ($K)
PDIL	900
Sensors	500
TCO	250
Reliability	185

These research tasks are detailed as follows:

- PDIL—This task enables numerous near-term to long-term research activities at NREL using the PDIL (http://www.nrel.gov/pv/pdil/about_pdil.html). The task involves the installation, acceptance, verification, integration, and commissioning of the CIGS platform, followed by demonstration of the deposition and fabrication of state-of-the-art CIGS solar cells.
- Sensors—Achieving rapid transfer of the essential characteristics of 20.0% small-area devices to manufacturing environments requires real-time measurements (sensors) of the important qualities of each device layer. Such measurements enable higher yields and real-time process optimization, as well as enhance the understanding of the device. This task seeks to develop these measurements.
- TCOs—Advances in TCOs can help improve device performance, decrease materials costs, increase reliability, and enable a wider variety of encapsulants (through increased damp heat stability).
- Reliability —Improving the quality of CIGS PV products requires reliability and stability studies. Of particular interest to this task is identifying the failure mechanisms caused by environmental activity on the cell. Such reliability studies could have a direct impact on improving the environmental tolerance of CIGS solar cells and therefore produce reliable and useful long life products.

3. Results and Accomplishments

3.1 PDIL

In FY 2009, we installed, operated, and integrated all vacuum components of the CIGS platform in the PDIL. These components are the CIGS evaporation tool, the DC sputtering chamber (for Mo back contact and related materials), the RF1 sputtering chamber (for the ZnO bi-layer top contact and related materials), the RF2 sputtering chamber (for sputtered buffer layers and related materials), the central robot chamber, which moves samples between the different processes, and the system load lock. Figure 1 is a photo of the CIGS platform.

Fig. 1. CIGS platform installed and functioning in PDIL.

Additionally, a large-area prototype for bath-deposited CdS, the baseline process for high efficiency devices, was designed, tested, and proven successful. Equipment specifications were written for such a tool, in a form compatible with the PDIL's mechanical interfaces and high degree of automation.

3.2 Sensors

During FY 2009, a correlation between lifetime measured on CIGS films and subsequent device voltage was demonstrated. This correlation was shown to be valid for samples made in the laboratory and those originating from a manufacturing line, and agrees approximately with results expected from basic physics. The sample set included a wide range of efficiencies, carrier densities, Ga gradings, and CIGS deposition temperatures. The correlation is shown in Figure 2. The measurement technique, time-resolved photoluminescence, is therefore likely to be successful as a diagnostic tool for process monitoring, control, and optimization.

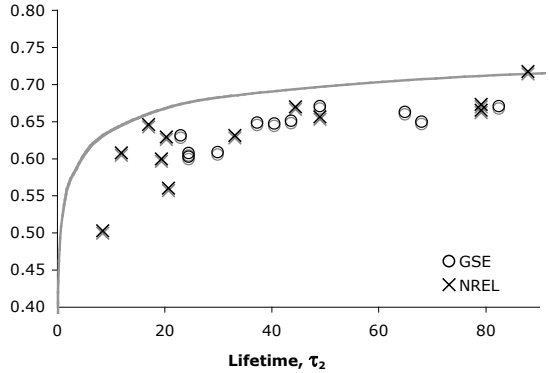

Fig. 2. Measured V_{oc} as a function of lifetime for samples from NREL (x) and Global Solar Energy (o), and comparison with prediction from basic device physics (solid line).

3.3 TCO

Progress in the area of TCOs proceeded in two areas: ZnMgO replacement of the resistive i-ZnO layer, and application of protective metal oxides.

Using a ZnMgO layer to replace the i-ZnO layer can create CIGS devices with equal or better device performance. The importance of limiting sputtering power in this layer that is very close to the junction was demonstrated. The results are important for understanding the constraints on processing layers near the junction during manufacture, enabling wide bandgap CIGS devices with correct band alignment at the junction, and decreasing absorption losses in the TCO.

Second, preliminary data indicate success in improving the moisture-resistance of the CIGS device via application of a protective transparent metal oxide (PTMO) film. Initial experiments show that, with the sputtering-deposited PTMO layer, the degradation rate of the AZO window layer is reduced by four to five orders of magnitude and the degradation rate of CIGS device is four to five times. The PTMO may therefore enable a wider family of lower-cost and flexible encapsulants.

3.4 Reliability

FY 2009 accomplishments under the reliability agreement include the following:

- Expanded the lab/test capability with acquisition, installation, and operation of a new ESPEC environment chamber.
- Evaluated/ranked the damp-heat (DH) stability of a number of TCOs for CIGS, verified that InZnO and ITO are the most DH-stable.
- Verified the usefulness of a simple wet-chemical process to protect the bi-layer ZnO.

3.5 Summary of Milestones Achieved

The accomplishments described satisfy the following milestones from the FY 2009 annual operating plan:

- Complete installation and operation readiness of PDIL CIGS evaporation module (02/09).
- Integrate PDIL central robot chamber with other modules (08/09).
- Demonstrate correlation between device performance and ex situ noncontact characterization for sensor use (06/09).
- Fabricate ZnMgO films with electro-optical properties similar or exceeding those of ZnO (03/09).
- Assess the performance and reliability of ZnMgO in the CIGS device (09/09).

4. Planned FY 2010 Activities

The group's mission and the accomplishments described suggest the following activities for FY 2010:

- Tune processes in each component of the PDIL CIGS platform such that film properties are consistent with high-efficiency CIGS devices.
- Assess whether CdS deposition in the PDIL should be performed via sputtering (existing tool, significant process development required) or chemical bath (existing process, wet tool required).
- Adapt lifetime measurement to small, inexpensive instrumentation that can be used as an in situ sensor for CIGS.
- Quantify benefits of identified strategies for moisture-hardening of CIGS device.

5. FY 2009 Special Recognitions, Awards, and Patents

One of the group's papers, "19.9%-efficient ZnO/CdS/$CuInGaSe_2$ Solar Cell with 81.2% Fill Factor," was identified by *Research Trends* in October 2009 as the most highly cited 2008–2009 paper in the field of energy research.

F.J. Pern was an invited speaker and served in the organizing committee at the SPIE Solar Energy and Tech. Conf. (08/09).

F.J Pern was a co-chair and invited speaker at the APP International PV Reliability workshops (December 2008, 07/09).

I.L. Repins was an invited speaker at the IEEE PVSC (06/09).

I.L. Repins was an invited speaker at the SPIE Solar Energy and Tech. Conf. (08/09).

M. Contreras was chair of "Symposium M: Thin-Film Compound Semiconductors," at the MRS Spring Meeting (04/09).

M. Contreras was an organizer of the 18th International Material Research Congress (08/09, Mexico).

X. Li was a committee member for OPTOmism conference (05/09).

Record of invention filed with DOE. "Fiber fed time resolved photoluminescence for CIGS quality control," IR10-04. I.L. Repins.

Record of invention filed with DOE. "Protective metal oxides for CIGS thin-film solar cells," ROI 09-70. X. Li, J Pern, S. Glick.

6. Major FY 2009 Publications

FY 2009 publications for which the first author worked in the CIGS group are listed.

M.A. Contreras, I.L. Repins, W. Metzger, M. Romero, and D. Abou-Ras, "Se Activity and its Effect on CIGS PV Thin-Film Materials," *Phys. Stat. Solidi A – App. Mater. Sci.* **206**(5), 1042–1048 (2009).

X. Li, A. Kanevce, J.V. Li, and I. Repins, "Impact of Front Contact ZnO:Al/$Zn_{1-x}Mg_xO$ Layer on CIGS Thin-Film Solar Cells," *Phys. Stat. Solidi C* (2009).

X. Li, I. Repins, B. Egaas, J.V. Li, and A. Kanevce, "The Impact of $Zn_{1-x}Mg_xO$ on CIGS Thin Film Solar Cells," *Proc. IEEE PVSC* **34** (2009).

J.R. Mann, N. Vora, and I. Repins, "*In Situ* Thickness Materials of CBD CdS," accepted *Sol. En. Mater. Solar Cells* (2009).

F.J. Pern, B. Egaas, B. To, C.-S. Jiang, Jian V. Li, S. Glynn, and C. DeHart, "A Study on the Humidity Susceptibility of Thin-Film CIGS Absorber," *34th IEEE PVSC, 2009*.

F.J. Pern, S.H. Glick, X. Li, C. DeHart, T. Gennet, M. Contreras, and T. Gessert, "Stability of TCO Window Layers for Thin-Film CIGS Solar Cells upon DH Exposures—Part III," *Rel. of PV Cells, Mod., Comp., and Sys.—2009 Solar Conf*.

F.J. Pern, R. Jones, L. Gedvilas, and T. Gessert, "Preliminary Evaluation of Conductive Adhesive Tapes as Potential Interleafing Connects for Flexible Thin-Film PV Applications," *MRS Spring Meeting*, *2009*.

Repins, S. Glynn, J. Duenow, T.J. Coutts, W. Metzger, and M.A. Contreras, "Required Materials Props. for High-Efficiency CIGS Modules," *SPIE Solar Energy Technol.* **7409**, 74090M (2009).

I.L. Repins, W.K. Metzger, C.L. Perkins, J.V. Li, and M.A. Contreras, "Measured Minority-Carrier Lifetime and CIGS Device Performance," *Proc. IEEE PVSC* **34**, 2009.

R. Sundaramoorthy, F.J. Pern, C. DeHart, T. Gennett, F.Y. Meng, M. Contreras, and T. Gessert, "Stability of TCO Window Layers for Thin-Film CIGS Solar Cells upon DH Exposures—Part III," *Rel. PV Cells, Mod., Comp., Sys.—2009 Solar Conf*.

R. Sundaramoorthy, I.L. Repins, T. Gennett, Jian V. Li, D. Albin, F.J. Pern, C. DeHart, S. Glynn, J. Perkins, D. Ginley, and T. Gessert, "Comparison of a-InZnO and PX ZnO:Al as a Conductive Layer for CIGS PV Solar Cells, *Proc. IEEE PVSC* **34** (2009).

N. Vora, I. Repins, S. Robbins, J. Mann, H. Castenada, B. Armstrong, and D. Weber, **"**Large-Area Chemical Bath Deposition of CdS on CIGS," *MRS Proc.* **1165** (2009), doi 1165-M05-05.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009. Cost share for Optony was provided through the NREL Technology Transfer Office. Cost share for DuPont was provided through a National Center for Photovoltaics entrepreneurial CRADA.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Optony	825 E. Evelyn Ave., Suite 339; Sunnyvale, CA 94086	Development of thin film CIGS solar cells for concentrator applications	15	15
Dupont	Harland.l.tate@usa.dupont.com	Evaluation of novel substrates for CIGS solar cells.	180	0

Cadmium Telluride

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Tim Gessert (NREL), 303-384-6451, tim.gessert@nrel.gov

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

FY 2009 Budget: $1,226K (NREL)

Objectives

- Complete contract, legal, and vendor review necessary to release cadmium telluride (CdTe) Process Development and Integration Laboratory (PDIL) tool request for quotes (RFQ)
- Test process sequence for all-dry CdTe and establish baseline design 6”x6” close spaced sublimation (CSS) source
- Expand research staff and lab facilities needed for expanded cooperative research and development agreement (CRADA) requests
- Expand NREL intellectual property (IP) for novel transparent conducting oxides (TCOs) for use in thin-film CdTe photovoltaics (PV)
- Develop new techniques for rapid assessment of CdTe cell-level reliability
- Assist with developing goals and metrics associated with CdTe Technology Roadmaps, including coordinating PDIL platform designs.

Accomplishments

- Benchmarked 14% efficient CdTe devices using all-dry processing
- Confirmed 3”x3” CSS design with improved uniformity, established 6”x6” design for PDIL
- Established TCO/soda-lime glass processes and 3”x3” CTO/ZTO/CdS:O hardware for CRADAs
- Expanded NREL IP related permittivity control of TCO for PV applications
- Published reports on using transient CV for analyzing mechanisms of CdTe junction stability
- Published report on increase in minority carrier lifetime during Cu diffusion into CdTe.

Future Directions

- Finalize procurement of CdTe PDIL tool. Expect delivery of some components in fiscal year (FY) 2010
- Expand IP base in TCO permittivity control, CTO, ZTO, CdS, and moisture-tolerant TCOs
- Develop techniques to assess rapidly intrinsic CdTe cell-level reliability
- Expand Cu/lifetime studies to differentiate various layers (space-charge vs. quasi-neutral)
- Initiate partnerships with commercial companies to accelerate CdTe PV-product development.

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1. Introduction

The research undertaken by the CdTe Technology Area studies semiconductor materials, device properties, and fabrication processes to improve the efficiency, stability, and cost of PV solar energy conversion using CdTe thin-film devices. This research can be broadly placed into three categories: applying capabilities to assist industry in resolving current problems; exploring 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 FY 2009 activity supported glass, TCO, CdS, CdTe, and back-contact 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.*

NREL’s CdTe technology leads the world in demonstrated cell performance, and 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 dollars/watt), thin-film PV is the fastest growing segment of the PV market. Further, CdTe PV is rapidly achieving (or possibly has achieved) grid parity in some markets. Creating innovations and a technical foundation for this rapidly expanding industry is at the heart of the efforts of the CdTe Technology Area.

2. Technical Approach

The CdTe Research Activity focuses on research associated with CdTe device-level development and understanding. In FY 2009, efforts in CdTe cell-level reliability were moved back into the CdTe Research Activity from the Module Reliability Activity. Additional FY 2009 support that directly benefited the CdTe Research Activity was from the Industrial Program Funds managed within the National Center for Photovoltaics. These funds were targeted to accelerate research in certain NREL IP to enable licensing potential and establish background IP to enhance success for CRADAs (i.e., Redlen Inc., Solexant, and EPIR Technologies).

- Perform studies needed for CdTe PDIL tool.
  - All-dry CdTe device processing
  - Uniform CdTe on 3”x3” substrates
  - Thermal modeling for 6”x6” substrates.
- Establish infrastructure for industry collaborations.
  - High-quality SnO_2:F on soda-lime glass
  - 3”x3” sputter deposition of Cd_2SnO_4, $ZnSn_xO_y$, and CdS:O.
- Develop new TCO materials using NREL IP related to permittivity engineering.
- Re-establish CdTe cell-level reliability within CdTe Research Activity.
- Advance understanding of defect evolution during Cu contacting.

3. Results and Accomplishments

This NREL CdTe Research Activity leads the world in developing CdTe thin-films and related materials for use in high-performance and stable single-junction solar cells. The project objectives support near-term manufacturing, build the knowledge and technology base for future manufacturing improvements, allow for training of the next generation of CdTe PV device technologists, and sustain innovation that supports progress toward the future and the long-term Solar Program goal of 15%-efficient commercial modules. Over the past decade, we have steadily improved the quality of the layers in the CdTe device and achieved a world-record efficiency of 16.5%. The following represent highlights from FY 2009 CdTe research activities.

The capital procurement of the CdTe PDIL tool proceeded on schedule, with all the required documentation cleared by the NREL Contracts and NREL Legal Offices by September 2009. The RFQ was submitted in October 2009. Because this particular type of tool has not been commercially constructed, the final design specification required a patent filing ([Record of Invention]ROI-09-08, Provisional Patent filed 3/09). To test that the components identified in the design are likely to perform as expected, we demonstrated 14% devices using the all-dry process steps specified in the RFQ. These results were reported in Duenow et al. (2009b). We also conducted foundational studies of the thermal and mass transport characteristics through computer simulation (ComSol Program). Simulation results were confirmed by producing an actual 3”x3” CdTe CSS source for an existing test system. Results of this testing are a foundation for the final 6”x6” PDIL source design. Simulation studies will be presented at the 35th IEEE PVSC meeting.

The number of requests for assistance from the PV industry increased rapidly in FY 2009. To respond to these requests, we designed/constructed/established infrastructure consistent with the industry requirements. Specifically, we began a project to produce TCO-coated glass consistent with the 3.2-mm soda-lime commercial product. This allows production of CdTe devices onto any new TCO or glass options to be compared directly to NREL baseline devices. Similarly, we modified a system to sputter Cd_2SnO_4, $ZnSn_xO_y$, and CdS:O (i.e., CTO, ZTO, CdS) films on 3”x3” substrates. This required building much larger equipment designed for toxic material use (i.e., Cd-containing).

We expanded studies to engineer permittivity control into our next generation of TCO materials (ROI]-#09-30). Specifically, we added Zr into SnO_2:F to produce a $SnZrO_2$ alloy that shifts the plasma edge 200–600 nm farther into the infrared. If adopted by the glass industry, this should allow CdTe modules to produce more current and thus higher performance. We also filed an ROI that allows for production of a Cd_2SnO_4-like material at temperatures consistent with soda-lime glass (ROI-08-28). We also continued studies to improve the electrical performance of TCOs using multiple improved dopant design.

Our understanding of new methods to study CdTe cell-level reliability was advanced by capacitance-voltage analysis to monitor transient effects of potentially mobile charges in CdTe PV devices. In FY 2009, reports were presented where the CV transients were observed and linked to CdTe device stability. These studies were reported in Albin and del Cueto (2009) and Albin et al. (2009a, 2009b).

Studies continued to improve our under-standing of the effect of minority-carrier lifetime in typical CdTe devices. FY 2009 studies included low-temperature photoluminescence to probe the defect functionality that ultimately limits Cu-induced lifetime improvements. These were reported in Gessert et al. (2009a).

4. Planned FY 2010 Activities

In FY 2010, efforts will continue to expand from producing small and medium-sized devices and related films toward larger devices required to establish operations in the CdTe PDIL laboratory. Efforts will also be expanded for CdTe-related CRADAs. This and other planned activities are outlined below.

- Finalize procurement of CdTe PDIL tool. Expect delivery of some components in FY 2010.
- Expand IP base in TCO permittivity control, CTO, ZTO, CdS, and moisture-tolerant TCOs.
- Expand techniques to assess rapidly intrinsic CdTe cell-level reliability. Determine if transients are caused by mobile charges or defect variations
- Expand Cu/lifetime studies for CdTe layers.
- Initiate partnerships with commercial companies to accelerate development of CdTe PV-specific products.

5. FY 2009 Special Recognitions, Awards, and Patents

ROI-08-28. "Transparent Conducting Oxide Films Produced by CVD," X. Li, T. Burst, T.A. Gessert. Discuss to file as non-provisional.

ROI-09-08. "Research-Scale CdTe Device Development Platform," T.A. Gessert, T. Barnes. ROI Submitted 11/08. Provisional Patent Filed 03/09.

ROI-09-30. "SnO_2 Films with High Permittivity," X. Li, J. Burst, T.A. Gessert, ROI Submitted 03/02/09.

ROI-09-63. "TCO Films with Improved Properties," T.A. Gessert, X. Li, T.M. Barnes, S.E. Asher, C.L Wyse. ROI Filed 07/09.

ROI-09-70. "Protective Metal Oxides for CIGS Thin-Film Solar Cells," X. Li, F.J. Pern, S. Glick, R. Noufi. ROI Filed 08/09.

ROI-09-71. "Fluorine Compounds for Doping Conductive Oxide Thin Films," T.A. Gessert, S. Li, T. M. Barnes, R. Torres, C.L. Wyse. ROI Filed 09/09.

ROI-09-72. "Growth of $CuInSe_2$- Based Solar Cells Using Close-Spaced Sublimation of Highly Volatile Cu Precursors," D. Albin. ROI Filed 09/09.

6. Major FY 2009 Publications

D.S. Albin, R.G. Dhere, S.C. Glynn, J.A. del Cueto, and W.K. Metzger, "Degradation and Capacitance-Voltage Hysteresis in CdTe Devices," *SPIE Solar Energy + Technology Conference, San Diego, CA* (2009a). NREL Conference Paper NREL/CP-520-46304. Invited paper.

D.S. Albin, R.G. Dhere, S.C. Glynn, and W.K. Metzger, "The Direct Correlation of CdTe Solar Cell Stability with Mobile Ion Charge Generation During Accelerated Lifetime Testing", *Proc. 34th IEEE Photovoltaics Specialists Conf.* (2009b).

D. Albin and J. del Cueto, "New Diagnostic Tool to Assess Thin-film Solar Cell Reliability," SPIE Newsroom Item. DOI 10.1117/2.1200908.1790. http://spie.org/x36691.xml?Articleid=X36691, (2009). Invited Paper.

J.M. Burst. S. Choi, M.G. Scott, X. Li, T.J. Coutts. T.A. Gessert, S.M. Weiss, and B.R. Rodgers, "Permittivity-Engineered TCOs: Optimizing Optical Properties of SnO_2:F," *Proc. 34th IEEE Photovoltaics Specialists Conf.* (2009).

R.G. Dhere, J.N. Duenow, A. Duda, S.E. Asher, W.K. Metzger, H.R. Moutinho, and T.A. Gessert, "Recent Results for All-Dry-Processed CdTe/CdS Solar Cells," *MRS Symp. Proc. 1165* (2009a).

R. Dhere, B. Fluegel, A. Mascarenhas, J. Duenow, and T.A. Gessert, "Investigation of Effects of Processing and Impurities on the Properties of CdTe Using Microscopic 2D PL Imaging Technique," *Proc. 34th IEEE Photovoltaics Specialists Conf.* (2009b).

J.N. Duenow, T.M. Barnes, R.G. Dhere, J.D. Bergeson, B.A. Larson, J.L. Blackburn, A. Duda, G. Teeter, and T.A. Gessert, "Comparison of Transparent Back Contacts for CdTe Top Cells in Tandem Thin-Film Photovoltaic Devices," *Proc. 34th IEEE Photovoltaics Specialists Conf.* (2009a).

DRAFT

J.N. Duenow, R.G. Dhere, J. Li, W.K. Metzger, A. Duda, and T.A. Gessert, "Development of ZnTe Contacts for Cd1-xMgxTe Thin-Film Solar Cells for Tandem Applications," *MRS Symp. Proc. 1165* (2009b).

T.A. Gessert, W.K. Metzger, P. Dippo, S.E. Asher, R.G. Dhere, and M.R. Young, "Dependence of Carrier Lifetime on Cu-Contacting Temperature and ZnTe:Cu Thickness in CdS/CdTe Thin Film Solar Cells," *Thin Solid Films* **517**, 2370–2373 (2009a).

T.A. Gessert, Y. Yoshida, C. Fesenmaier, and T.J. Coutts, "High Transparency Sputtered In_2O_3 and ITO Films Containing Zirconium," J. *Appl. Physics,* 105 pp. 083547.1-6 (2009b).

T.A. Gessert, Y. Yoshida, C.C. Fesenmaier, and T.J. Coutts, "TCO Films with Permittivity Control," *MRS Symp. Proc. 1165*, (2009c). Selected as one of the most influential papers presented at the symposium.

X. Li, J. Pankow, and Y. Yan, "Impurity Study of Optical Properties in Fluorine-Doped Tin Oxide for Thin-Film Solar Cells," *MRS Symp. Proc. 1165*, (2009).

T.J. Peshek, Z.Z. Tang, L. Zhang, R.K. Singh, B. To, N. Newman, T.A. Gessert, T.J. Coutts, and M. van Schilfgaarde, "Suitability of $ZnGeAs_2$ Thin Films for Photovoltaics," *Proc. 34th IEEE Photovoltaics Specialists Conf.* (2009).

C. Wyse, R. Torres, T. Barnes, M. Scott, M. Young, and X. Li, "Sulfur Hexafluoride (SF_6) as a Dopant Precursor for Production of Fluorine Doped Tin Oxide Films by MOCVD," *Proc. 34th IEEE Photovoltaics Specialists Conf.* (2009).

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Primestar Solar Fred Seymore	Wheatridge, CO fred.seymour@primestarsolar.com	Broad assistance with start-up company, CdTe devices to module reliability	100* 869** 969***	5* 20***
Eikos Paul Glatkowski	Lexington, MA pglatkowski@eikos.com	Development of materials and devices for carbon nanotubes	50* 410** 560***	0
Phase A Industry Development (Redlen) Glenn Bindy	Canada Glenn.bindy@redlen.com	Competitive solicitation for "Research on Low-Cost, High- Efficiency Organic Solar Cells"	0	50*
Phase A Industry Development (TCO)	TBD	Testing of new CdTe source materials in actual devices	0	150* 200**
Matheson Tri Gas Rob Torres	Longmont, CO RTorres@Matheson-Trigas.com	Development of CVD precursors for advanced TCO materials	75* 75** 90***	5
Solexant Craig Liedholm	San Jose, CA Craig.liedholm@solexant.com	Development of superstrate CdTe PV devices for alternative Substrates.	50* 100**	50* 100***
St. Gobain Frank Gromball	Herzogenrath, Germany Frank.Gromball@satin-Gobain.com	Development of CdTe devices on St. Gobain glass/TCO materials	110* 110** 229***	0
EPIR Chris Grien	Bolingbrook, IL grein@epir.com	Fundamental research on new semiconductor materials	150† 1,150†***	20* 150***
Corning Mark Taylor	Sullivan Park, NY TaylorMP@Corning.com	Development of high temperature CdTe devices and TCOs	250†	20†
Abound Solar Kurt Barth	Fort Collins, CO Kbarth@abound.com	Lectures at Abound and discussions of Abound process	100†	0†

* Approximate amount spent in 2009 ; ** approximate total amount spent to date; ***total amount of activity planned,
† award pending.

Concentrating Photovoltaics

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Dan Friedman (NREL), 303-384-6472, daniel.friedman@nrel.gov

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

FY 2009 Budgets: $1,860K (NREL)

Objectives

- Evaluate use of back surface reflector (BSR) in inverted metamorphic (IMM) triple-junction cells, targeting higher efficiency and decreased cell thickness, which translates to lower cost
- Identify environmental contributors to AlInP window-layer degradation
- Initiate a study of the stability of lattice-mismatched solar cells
- Strengthen scientific underpinnings of effects of growth conditions on mismatch epitaxy
- Test and validate advanced tool for the simulation of multijunction cells.

Accomplishments

- Demonstrated V_{OC} gain in 1 eV metamorphic junctions thinned for BSR implementation
- Quantified advantages of sub-gap infrared rejection to heat load caused by BSR
- Demonstrated that AlInP degradation is enhanced by the photoelectrochemical effect
- Developed high-power laser-based degradation capability to study cell stability
- Demonstrated a low defect density GaAsP virtual substrate for growth of high bandgap GaInP, used for both solar cells and ordering studies
- Compared graded layers in both compression and tension and both continuous and step-graded structures
- Expanded our full three-dimensional circuit model of a multijunction solar cell to enable batch processing and better visualization of the input and output
- Applied our 2D simulation model successfully to the operation of a GaInP/GaAs dual junction solar cell with nonuniform irradiance.

Future Directions

- Compare degradation in InGaAs cells with different amounts of strain and defect density
- Extend study of graded structures to different materials and structures
- Develop the capability to simulate nonisothermal effects in multijunction III-V solar cells
- Add functionality to the SPICE model: variable temperature, perimeter recombination, and possibly a nonlinear tunnel junction resistance; extend application to U.S. Department of Energy and cooperative research and development agreement (CRADA) tasks.

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1. Introduction

The Concentrating Photovoltaics (CPV) group will further the high-efficiency multijunction cell technology, with a continued emphasis on the inverted lattice-mismatched (LMM) approach introduced by NREL in 2005. This approach has proven very fruitful and provides a number of promising paths for future developments in efficiency, heat management, and cost, giving a clear path to significantly improved levelized cost of energy (LCOE) for CPV systems. These developments are in strong demand by CRADA partners and the CPV industry.

2. Technical Approach

The project approach included tasks oriented at cell development; reliability; studies of semiconductor materials for cell applications; and advanced cell modeling for application in real-world systems.

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3. Results and Accomplishments

3.1 Task 1: Three-Junction IMM Cell Development

In FY 2009, we explored practical issues and advantages of the triple-junction IMM solar cell design. Previously, we had demonstrated higher room temperature efficiencies of triple-junction designs with two metamorphic junctions (40.8%, a world record at the time) than the original design with one metamorphic junction, but device modeling indicates that the advantages of this more complicated device are much diminished at the higher temperature most likely typical in real life operation. We therefore focused on the original IMM structure with lattice matched GaInP and GaAs top junctions and a single metamorphic 1-eV InGaAs junction. We developed an improved understanding of doping in the tunnel junction and contact layers, allowing us to routinely achieve peak efficiencies around 300 suns with limiting series resistance from the top sheet resistance rather than the tunnel junction. We furthermore developed improved process control that allows us to reproducibly achieve 10^6 defects/cm^2 in metamorphic 1-eV InGaAs.

Because of the extremely thin nature of the IMM solar cell, it is well suited to selectively absorbing only the light that is needed for producing electric energy while rejecting much of the infrared (IR) light that contributes only to heating. The IR light in the direct solar spectrum below 1.0 eV makes up almost 16% of the total power flux, most of which can be rejected from the IMM by a BSR to reduce the heat load. A simple gold BSR reflects at least 80% of this power from the cell. We also demonstrated an Al_2O_3/Al BSR that has the potential to reduce the amount of the IR power absorbed within the device by a factor of two compared to the simple gold BSR, at a cost of some increased complexity of the processing and resistive losses at the back grid. By comparing IMM bottom junctions with a BSR to IR transparent devices, we showed that the BSR allows the bottom junction to be thinned somewhat without a large current loss. The V_{OC} does increase slightly as shown in Figure 1, but only at small thicknesses (about 0.5 µm) incur too much current loss for current matching. These results indicate good interface recombination velocities with $(S_bL_b/D_b) \sim 1$ or less, where S_b is the base surface recombination velocity and D_b/L_b is the bulk recombination velocity of minority carriers. Given the current quality of the metamorphic InGaAs junction and its interfaces, we therefore find that thinning cannot be used to increase the Voc. These findings fulfill a major FY 2009 milestone.

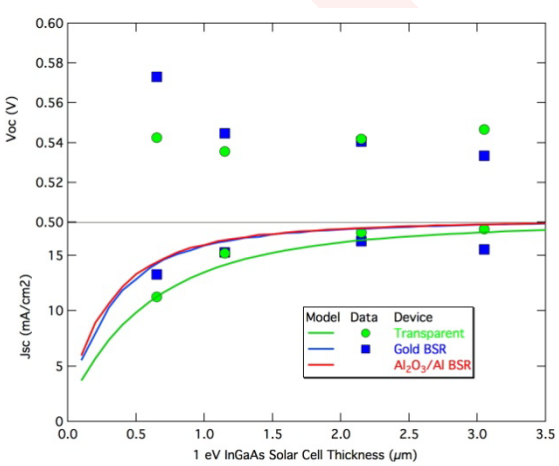

Fig. 1. Dependence of VOC and JSC on junction thickness, compared for different BSRs.

3.2 Task 3: Cell Reliability

In FY 2009 we completed our experiment on the oxidation of AlInP window layers and began experiments to probe the degradation of lattice-mismatched concentrator cells. Testing the hypothesis that the oxidation of AlInP is enhanced by the photoelectrochemical effect, we investigated the degradation of the AlInP layers with varying levels of n-type and p-type doping under different conditions of temperature, humidity, and light exposure. The data suggest that n-type window layers are more susceptible to oxidation than p-type layers. Without the inclusion of ultraviolet (UV) light, the oxidation proceeds at a slower rate equivalent to established damp heat oxidation rates for AlInP, which may indicate the need for UV filtering in field-deployed concentrator cells. We mentored an ACTS summer intern who was trained to use the weatherometer and assisted with data collection. A publication is under preparation.

In accordance with our FY 2009 milestone, we began investigating degradation in LMM InGaAs solar cells by evaluating changes in performance after operation under high forward-bias currents. Preliminary experiments showed very slight decreases in Voc, Jsc, and shunt resistance with accumulating bias time. To better probe the degradation of these cells operating at high currents, we developed a high power laser-based degradation system, which will be used to both degrade the cell and monitor the electrical characteristics of the cell during degradation.

3.3 Task 4: Science of Dislocations

The study of LMM epilayers and graded layers in both compression and tension was continued. In accordance with our milestones; our work this year has led to a publication and multiple submitted manuscripts. We completed installation of an in situ wafer curvature sensor on our molecular beam epitaxy growth system and developed its usage for 2D analysis. We used this technique to measure the anisotropy between the strain relaxation in different crystal directions of InGaAs epilayers. Varying the growth condition changes various relaxation properties, including the onset of relaxation, the initial direction of relaxation, the rate of relaxation, and the final strain state after 2 µm of epilayer growth. Thus, control over these aspects of relaxation is demonstrated; a manuscript on this work is under review. Relaxation of GaAsBi epilayers was also studied using the wafer curvature technique. In comparison with InGaAs, the relaxation of GaAsBi occurs at a slower rate and is less complete.

We studied graded layers of GaAsP in tension by varying the grading rate, stress profile, mismatch per step, and total number of steps. Optimization of these properties achieved growth of low-defect-density, high bandgap GaInP. We varied the alloy ordering in this material using Sb surfactant and published this work in the *Journal of Applied Physics*. Additionally, a high bandgap GaInP cell using these grades was grown and characterized. A manuscript on this work is under review. We studied continuously graded and step-graded layers in compression. Almost no difference in the in situ relaxation behavior and dislocation density was observed between step grades and continuously varied grades with the same total thickness and average grade rate.

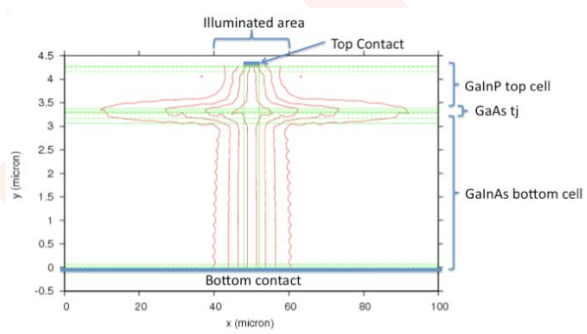

Fig. 2. Total current flowlines for a dual junction cell illuminated with a beam of light centered on the top contact. Local irradiance is 3000 suns; average irradiance is 600 suns. Peak tunneling current for this device is about 800 suns.

3.4 Task 6: Advanced Cell Modeling

SPICE circuit analysis: We expanded our full three-dimensional circuit model of a multijunction solar cell to enable batch processing and better visualization of the input and output. The limits of performance were also tested and expanded to 264 (x) by 24 (y) nodes for a three-junction cell (z direction). We performed a study of the effect of chromatic aberration and nonuniform irradiance on a GaInP/GaAs/Ge triple-junction cell for one of our CRADA partners.

As a benchmark for this work, a calculation demonstrated that our three-dimensional results (Fig. 1) are consistent with a prior one-dimensional study. This figure quantifies how the sheet resistance of a lateral current-spreading layer between the top and bottom subcells affects the performance of a GaInP/GaAs tandem cell under chromatic aberration. If the typical sheet resistance value of 200–1000 ohm/square could be reduced significantly, chromatic aberration from lower-quality (less-expensive) optics could be mediated. This sort of three-dimensional modeling helps quantify the performance compromises inherent to a CPV module.

Simulation of III-V multijunction solar cells: During the validation work, we found that although both the Silvaco and the Crosslight codes could simulate well the performance of single-junction GaInP and GaAs solar cells and stand-alone tunnel junctions, only Crosslight could adequately handle a GaInP/GaAs dual-junction solar cell with tunnel junction interconnect (TJIC). As a result, we ended the work on the Silvaco code.

We successfully simulated the two-dimensional operation of a dual-junction GaInP/GaAs (with TJIC) under uniform and nonuniform high-irradiance conditions. For uniform irradiance, we demonstrated the expected gradual (then abrupt) roll-off of fill factor (FF) and efficiency as the photocurrent Jsc approaches (then exceeds) the peak tunneling current Jpeak of the GaAs tunnel junction interconnect. For Jsc > Jpeak, the simulated IV of the tandem device reflects the IV curve of the embedded tunnel junction. For nonuniform irradiance, we can now simulate current spreading in the vicinity of the tunnel junction as shown in Figure 2, as well as the accelerated fall-off of efficiency and FF with average irradiance, relative to the case of uniform irradiance.

3.5 Milestones Achieved

- Evaluate use of BSR in IMM triple-junction cells (level 3; achieved 09/09).
- Improve understanding of growth effects on LMM cell growth (level 4, achieved 09/09).

4. Planned FY 2010 Activities

- Design 3J IMM cell for high-temperature operation, and initiate temperature-dependent measurement (09/10).
- Develop diffusion barriers for enhanced tunnel-junction manufacturability (09/10).
- Measurement of degradation-induced change in cell parameters as a function of misfit / defect density (09/10).
- Use in-situ characterization techniques to characterize strain relaxation mechanisms as a function of III-V materials compositions (09/10).
- Extend numerical modeling to include non-uniform illumination and non-uniform heating of multijunction solar cells (09/10).

5. FY 2009 Special Recognitions and Awards

2009 Federal Laboratory Consortium Award for Excellence in Technology Transfer, for the development and transfer of the inverted metamorphic multijunction solar cell.

6. Major FY 2009 Publications

M.A. Steiner, L. Bhusal, J.F. Geisz, A.G. Norman, M.J. Romero, W.J. Olavarria, Y. Zhang, and A. Mascarenhas, "CuPt Ordering in High Bandgap GaxIn1-xP Alloys on Relaxed GaAsP Step Grades," *J. Appl. Phys.* **106**, 063525 (2009).

J.F. Geisz and D.J. Friedman, "Engineering the World's Most Efficient Solar Cells," *SPIE Newsroom* 1645 (2009). doi: 10.1117/2.1200906.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
RF Micro Devices	Greensboro, NCrfmd.com	IMM technology transfer / high-volume, low-cost production	*	Funds-in
Dupont-DARPA	Wilmington, DE James.McCambridge@ usa.dupont.com	DARPA VHESC-Very High Efficiency Solar Cell Program	*	Funds-in
Several additional industry partners	Varied	IMM technology transfer and CPV development	*	Funds-in
		*TOTAL:	>$2.5M	

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Organic Photovoltaics

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Dave Ginley (NREL, Primary Contact), 303-384-6573, david.ginley@nrel.gov
Dana Olson (NREL), 303-384-6575, dana.olson@nrel.gov

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

FY 2009 Budget: $1,751K (NREL)

Objectives

- Develop state-of-the-art active layer materials using modeling and synthesis to improve absorption and open circuit voltage, thus improving conversion efficiency and lifetime.
- Develop contact materials with tailored properties for carrier selectivity and low contact resistance for a variety of active layer materials to optimize device performance.
- Investigate degradation mechanisms in organic photovoltaic devices and develop materials as well as device architectures that improve device lifetime.
- Demonstrate scalable processes to organic solar cell fabrication.

Accomplishments

- Demonstrated 5% conversion efficiency for organic solar cell on 1-cm^2 device area.
- Completed initial degradation and lifetime studies on organic solar cells using the NREL-developed combinatorial degradation system.
- Demonstrated greatly enhanced device lifetime in inverted devices versus traditional devices that use low work function metal cathodes.
- Demonstrated the active layer is very stable if proper encapsulation is employed.
- Enhanced the electric field and charge extraction at the anode interface in hybrid solar cells through gradient doping of the ZnO electron transport layer material with Ga or Li.
- Assembled a materials design and synthesis team that proposed new materials with enhanced absorption and band alignment for enhanced conversion efficiency.
- Developed solution-deposited multilayer inorganic barrier films with barrier properties >1 order of magnitude better than current industrial food packaging barriers.
- Maintained Cooperative Research and Development Agreements (CRADA) interactions with Konarka, Plextronics, and TDA Research; started CRADA work with Luna Innovations; and initiated CRADA interactions with Solarmer, Nano-C, and ConocoPhillips. Collaborating with ECN, Stanford, and University of Queensland.
- Published more than 20 papers, gave more than 30 invited talks, and helped organize international conferences based on these efforts.

Future Directions

- Design and synthesize new absorber materials to improve light absorption and band offset in organic photovoltaic (OPV) devices.
- Continue to develop new contact layers for optimized charge extraction from new donor/acceptor materials systems as well as continued improvement in device lifetime.
- Explore further degradation mechanisms in OPV devices, including studies on the contribution of contacts and active layer lifetime.
- Develop next-generation encapsulation with processes scalable to roll-to-roll processing.

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1. Introduction

The OPV effort develops new materials and device architectures needed to improve conversion efficiency and lifetime in organic solar

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cells. It supports the industry directly through CRADA interactions and through research on new active layer and contact materials. Our OPV program has gained national and international attention because of our integrated approach to new acceptor and donor development coupled with our developments in new process technology, new characterization tools specific to OPV, and initial results to improve the lifetime (intrinsic and extrinsic) of OPV devices.

2. Technical Approach

- Develop next-generation OPV devices and investigate scalability and lifetime.
- Design and synthesize new donor/acceptor systems to improve performance and lifetime.
- Develop a program to understand and optimize hybrid interfaces in OPV devices.
- Improve contacts by collaborating with the TCO program to develop OPV devices using non-ITO TCOs.
- Support our CRADAs with Konarka, Plextronics, TDA, Luna Innovations.

3. Results and Accomplishments

We continued to develop the infrastructure and assembled a team with the skills and tools to design and synthesize high performance donor/acceptor materials. This effort is producing materials by design, which allows a down-selection of target systems prior to synthesis. New IP has already resulted from this approach. This allows for a focused and efficient program for new organic materials development.

Previous work focused on developing the phenyl-cored thiophene-based dendrimers as electron donors in OPV devices. They often have the lowest unoccupied molecular orbital (LUMO) localized on the core, which likely hinders photo-induced electron transfer to the fullerene acceptor and in turn the performance in BHJ devices. As such, we designed several new materials that tune the bandgap and band offset to fullerene acceptors used in OPV devices. One donor system is based on triphenylamine, known for excellent hole-transport properties. It employs a benzothiadiazole moiety shown to decrease the LUMO, thereby reducing the bandgap of the material as well as the energy lost in the electron transfer process from donor to acceptor. This results in increased absorption without loss in V_{OC} and the LUMO localized on the arms to facilitate electron transfer (Fig. 1).

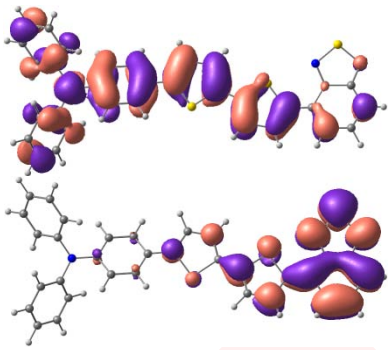

Fig. 1. DFT-calculated HOMO (top) and LUMO (bottom) orbitals of 1-arm molecule. The remaining arms show degenerate states equal in energy and electron density.

The calculations allow us to reasonably predict the material properties before the time- and resource-intensive synthesis process. These methods are being used to develop conjugated polymer donor systems as well based on novel chromophores that allow for tailoring the band structure of the donor material. Predicted values indicate that these materials are capable of very high absorption coefficients, bandgaps near 1.4 eV, and V_{OC} greater than 0.8 V. Such systems are being prepared, and productivity in materials preparation will accelerate soon with the completion of the new synthesis lab for OPV materials scheduled to be open in a few weeks time. This capability coupled to our ability to make new materials is unique and can serve the solar community.

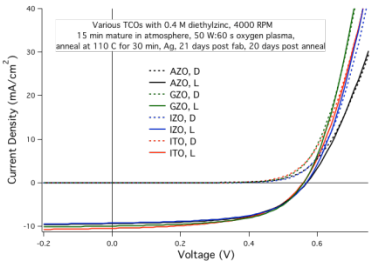

Fig. 2. J-V curves for inverted OPV devices with different dopants incorporated into the ZnO electron transport layer.

Work in developing new contact materials for OPV devices continued on ZnO-based inverted device architectures because of their potential for improved stability. We developed a low-temperature solution deposition method that results in very high quality ZnO films after processing at only 100°C. This allows for processing on flexible substrates and eliminates any dependence of device performance on the underlying TCO material (Fig. 2).

We demonstrated that doping gradients in the ZnO electron contact enhance the field at the front interface with the active layer. Gradients in carrier concentrations were achieved using both gallium and lithium doping. This results in enhanced diode quality, fill factor, and efficiency in inverted OPV devices (Fig. 3).

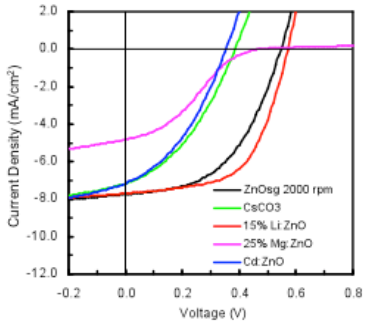

Fig. 3. J-V curves for inverted ITO/doped ZnO/P3HT:PCBM/Ag devices with different dopants incorporated into the ZnO layer.

As we had determined, electrode materials selection is critical for determining the lifetime of OPV devices. We showed that inverted device architectures dramatically improve the shelf life of devices in the dark in air without encapsulation. The completed combinatorial degradation system allows us to evaluate 360 devices concurrently. We used this system to evaluate the performance of unencapsulated inverted devices under continuous illumination. In Figure 4 we show the current density (J_{SC}) versus illumination time. The V_{OC} and fill factor remain constant during this time, and therefore the efficiency mirrors the J_{SC}. We also demonstrate that the lifetime can be dramatically improved by increasing the Ag metal electrode thickness. When the electrode thickness is increased, T_{80} is not yet reached after 1500 hours of light soaking in air for unencapsulated inverted devices.

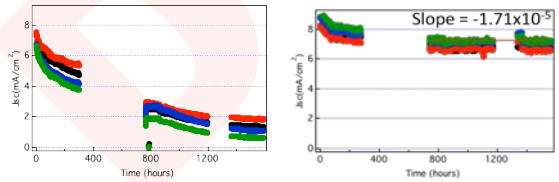

Fig. 4. Current density vs. time curves for four inverted OPV devices with 100-nm Ag anode thickness (left), and with 100-nm Ag + 100-nm Al electrode (right).

Although we made progress on understanding and reducing OPV device degradation, the intrinsic stability of the active layer upon illumination will determine the ultimate stability limit. We used characterization methods specific for OPV to evaluate the intrinsic stability of the active layer under 1 sun intensity for 1000 hours without contacts or electrodes in both inert atmosphere (N_2-filled glove box) and ambient conditions.

Under inert atmosphere, we observed no photo-induced degradation after 1000 hours of illumination. In contrast, some devices did degrade under inert atmosphere, indicating that it can be largely attributed to other components of the device, such as interfaces with electrical contacts.

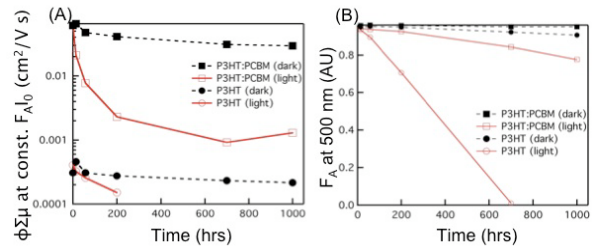

Fig. 5. (A) The product of the yield for free carrier generation times the mobility of free carriers (extracted from the photoconductivity data) vs. degradation time in air, for a P3HT:PCBM blend under illumination (red squares) and a control sample that was kept in the dark (black squares). Same results shown for a pure P3HT film in air and in the dark. (B) Absorbance of the films from A at 500 nm.

Under ambient conditions, strong bleaching or pure P3HT was observed under illumination. The presence of PCBM in the bulk heterojunction, however, stabilized the polymer and strongly mitigated the bleaching (Fig. 5B). The photoconductivity of the blend decreased by almost two orders of magnitude, despite the apparent stability of the polymer (Fig. 5A). The results in Figure 5 indicate that a photo-induced structural change of PCBM may be present that has an adverse effect on the mobility of electrons in the blend. We performed TOF-MALDI experiments to probe the species present in a degraded P3HT:PCBM film. This leads to new efforts to develop new acceptors.

This is the first complete study that effectively combines contactless photoconductivity, structural characterization, and theory to identify the dominant mechanisms for degradation in organic bulk heterojunctions. A manuscript has been submitted to *Nature Materials*; it is the first in a series of studies to identify general mechanisms of degradation and to design mitigation schemes. The methods developed here can also serve as a

screening tool for candidate materials from our CRADA partners.

We accomplished these milestones:

- Achieved 5.0% OPV device with 1-cm^2 device area (Fig. 6; 9/09).
- Dramatically enhanced device lifetime and understanding of degradation mechanisms in OPV devices (8/09).
- Established and employed models with synthesis for developing new donor/acceptor systems.

These accomplishments have the potential for tremendous impact on enhancing OPV device performance and lifetime.

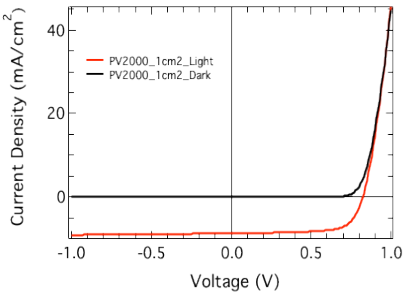

Fig. 6. Current density–voltage curves for 5% OPV devices with 1 cm^2 device area.

4. Planned FY 2010 Activities

- Develop state-of-the-art active layer materials to improve absorption properties, enhance open circuit voltage, and thus improve conversion efficiency (09/10).
- Develop contact materials with tailored properties for carrier selectivity and low contact resistance to a variety of active layer materials to optimize device performance (09/10).
- Investigate degradation mechanisms at play in organic solar cells and develop materials as well as device architectures that improve device lifetime (09/10).

5. FY 2009 Special Recognitions and Awards

David Ginley will serve as president of the MRS in 2010.

David Ginley is editor of a Springer book on TCOs to be published this year. Dana Olson is a chapter author.

David Ginley was organizer for MRS symposia on combinatorial materials.

Dana Olson was co-chair of Organic Photovoltaics 2009, held in Philadelphia.

Dana Olson was chair of Organic Photovoltaics Summit 2009, held in Boston.

David Ginley is a co-chair of the 3rd Intl. Summit on OPV Stability.

More than 15 invited talks on OPV in 2009.

6. Major FY 2009 Publications

Lloyd et al., "Impact of Contact Evolution on the Shelf Life of Organic Solar Cells," *J. Mater. Chem.* **19**, 7638 (2009).

Lloyd et al., "Improved Efficiency in Poly(3-hexylthiophene)/Zinc Oxide Solar Cells via Lithium Incorporation," *J. Phys. Chem. C* **113**, 17608 (2009).

Reese et al., "Photoinduced Degradation of P3HT and P3HT:PCBM Active Layers for Organic Photovoltaic Devices," submitted *to Nature Materials*.

White, M.S. et al., Control of Charge Separation by Electric Field Manipulation in Polymer-Oxide Hybrid Organic Photovoltaic Bilayer Devices, *Physica Status Solidi A* (2009). doi:10.1002/pssa.200925591.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Konarka Technologies Russel Gaudiana	Lowell, MA rgaudiana@konarka.com	Development of solution deposited inorganic multilayer barriers for roll-to-roll processing	400	100
Plextronics Darin Laird	Pittsburgh, PA dlaird@plextronics.com	Research on contacts, TCOs, and lifetime of OPV devices	150	150
TDA Research Michael Diener	Wheat Ridge, CO mikee@tda.com	Development of new fullerene acceptors for OPV devices	105	42
Luna Innovations Steven Joslin	Danville, VA joslins@lunainnovations.com	Research on carbon nanosheets as electrodes in OPV devices	150	

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Sensitized Solar Cells

Performing Organization: National Renewable Energy Laboratory (NREL)

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

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

FY 2009 Budget: $694 K (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 device stability and performance in collaboration with DOE/OS/BES.

Accomplishments

- Demonstrated 5.8% efficient device with <10% power loss over 1000 hours under light soaking.
- Developed a process for forming inorganic p-type semiconductors in n-type nanotube (NT) arrays.
- Developed a general synthetic approach for preparing transparent TiO_2 NT films on transparent conducting oxide (TCO).
- Established a characterization tool set to study degradation of devices under light soaking.
- Demonstrated use of atomic layer deposition (ALD) for preparing an inorganic semiconductor sensitized solar cell (SSC).

Future Directions

- Demonstrate devices with improved efficiency and durability under continuous light soaking.
- Develop nonvolatile charge-conducting phases for solid-state devices.
- Demonstrate performance of devices with newly developed charge-conducting phases and film architectures.
- Investigate principal fundamental parameters governing device stability and efficiency.

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1. Introduction

This agreement applies to SSCs, covering both liquid/solid and solid/solid electron- and hole-conducting materials. Both dyes and inorganic semiconductor nanostructures are used as light-absorbing materials. Our primary objectives are to evaluate cell stability at different performance levels, to identify the causes of efficiency loss, and to develop more effective cell materials and configurations for improved device durability and efficiency.

2. Technical Approach

This project focused on designing and developing photoelectrode architectures, solid/liquid charge-conducting phases, and assembly/sealing techniques for enhancing device stability and performance. A significant fraction of the research effort was aimed at developing photoelectrodes with oriented nanostructured architectures (e.g., NT arrays) having enhanced charge-collection and light-harvesting capabilities compared with conventional nanostructured architectures. Another aspect of this work was to increase cell stability by developing more robust and effective charge-conducting phases.

3. Results and Accomplishments

- Demonstrated 5.8% efficient device with <10% power loss over 1000 hours under light soaking (09/09).

We made major upgrades to our diagnostic setup to improve the reliability of long-term measurements of cell stability and performance. Using a low volatile ionic electrolyte, we demonstrated a 5.8% efficient device with less than 10% degradation (power loss) over 1,000 hours under simulated AM 1.5 light soaking (Fig. 1).

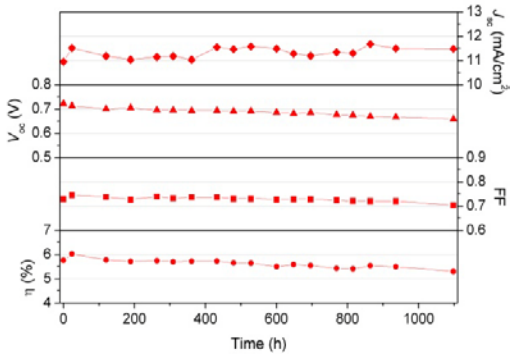

Fig. 1. Stability test of TiO_2 nanoparticle (NP)-based dye-sensitized solar cells (DSSCs).

- Developed a process for forming inorganic p-type conducting phase in n-type NT arrays (11/08).

We constructed an ordered sensitized heterojunction using a novel, low-cost bottom-up electrochemical synthesis approach. p-$CuInSe_2$ was grown within the nanopores (pore diameters < 100 nm) of electrically conducting n-type TiO_2 NT and NP films. Such solid-state film architectures could potentially extend operating temperatures and increase the stability and efficiency of SSCs.

- Developed a general synthetic approach for preparing transparent TiO_2 NT films on TCO (09/09).

High solar conversion efficiency in oriented TiO_2 NT-based DSSCs requires that the incident light enters the cell from transparent electron-collecting substrates. There are technological challenges with current methods for depositing NT films on TCO. We discovered that adding a special thin layer between Ti metal and TCO enables reproducible fabrication of transparent NT films on TCO. This approach is applicable to preparing other metal oxide electrodes on TCO.

- Developed characterization tool set to study degradation effects of devices under light soaking (09/09).

We developed a characterization tool set to study the energy losses owing to electron dynamics. The initial studies based on time- and frequency-resolved electro-optical techniques showed that the charge-collection efficiency exhibits a simple but nontrivial correlation with light soaking. Such studies will provide important insight into the effects of long-term light soaking on the degradation of SSCs.

- Demonstrated the use of ALD for preparing inorganic semiconductor SSCs (08/09).

We developed (with Steven George at CU Boulder) an ALD route for fabricating inorganic semiconductor SSCs. This approach is applicable to a variety of semiconducting materials.

4. Planned FY 2010 Activities

- Develop 6.5% efficient device with <10% power loss over 1,000 hours under continuous light soaking.
- Develop nonvolatile, charge-conducting phases for solid-state devices.
- Demonstrate performance of devices with newly developed charge-conducting phases and film architectures.
- Investigate principal fundamental parameters governing device stability and efficiency.

5. FY 2009 Special Recognitions and Patents

K. Zhu, et al. *Nano Lett*. 2007, **7**, 69 on NT based DSSCs has become the eighth most cited paper in chemistry from 2007 <http://science-watch.com/ana/hot/che/09mayjun-che/>.

Provisional patent (Frank, Neale, Zhu) "Nanowire Sensitized Solar Cells," filed 2008.

6. Major FY 2009 Publications and Presentations

A.J. Frank, "Science, Technology and the Future of Sensitized Solar Cells," Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Beijing, P.R. China, January 7, 2009.

A.J. Frank, "Recent Advances in Sensitized Solar Cells," WOLEDs and Organic Photovoltaics Workshop, University of Hong Kong, January 8–11, 2009.

Q. Wang, K. Zhu, N.R. Neale, and A.J. Frank, "Constructing Ordered Sensitized Heterojunctions: Bottom-Up Electrochemical Synthesis of p-Type Semiconductors in Oriented n-TiO2 Nanotube Arrays." *Nano Lett.* **9**, 806 (2009).

Cross-Cutting Transparent Conducting Oxides

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Dave Ginley (NREL, Primary Contact), 303-384-6573, dave.ginley@nrel.gov
John Perkins (NREL), 303-384-6606, john.perkins@nrel.gov

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

FY 2009 Budget: $618K (NREL)

Objectives

- Develop new transparent conducting oxides (TCOs) for improved PV performance
- Use and improve combinatorial methods to accelerate materials advances for TCOs
- Develop solution-based processes and precursors to enable functional TCOs synthesized at atmospheric pressure.

Accomplishments

- Increased conductivity of amorphous In-Zn-O (a-IZO 25% to 3,750 S/cm by mixed RF/DC sputtering; environmentally stable at 85°C, 85% relative humidity (RH) for >40 days; a-IZO finished copper indium gallium selenide (CIGS) solar cell with 16.4% efficiency; first demonstration of a-IZO finished silicon heterojunction cell
- Provided new deposition systems on line (Process Development and Integration Laboratory [PDIL]) with in situ diagnostics resulting in large area uniform coating for IZO and ZnO to other photovoltaic (PV) groups at NREL and externally
- Gave significant support to the organic photovoltaics (OPV) effort through materials and interlayer development
- Improved conductivity of Ga-doped ZnO (GZO) to > 3,000 S/cm by sputtering; also improved J_{SC} in OPV by 75%using GZO interfacial layer.
- Used atmospheric pressure synthesis to produce smooth, dense a-IZO with conductivity >30S/cm
- Developed sputtered SnO_2:F with conductivity of 1,000 S/cm (subject of two records of invention).

Future Directions

- Increase conductivity of a-IZO to 4,000–5,000 S/cm
- Optimize a-IZO TCO top contact for CIGS PV and Si heterojunction PV
- Research high conductivity, sputtered, SnO_2-based TCOs
- Develop TCOs with functionally independent control of conductivity and work function
- Transfer new TCO technologies to PV manufacturers.

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1. Introduction

Nearly every solar technology uses TCOs. Because the needs are commensurate, an integrated approach to TCO development with high-throughput methods is employed to rapidly develop materials for internal and external partners, specifically with Si, a-Si, CIGS, and OPV.

2. Technical Approach

High-throughput discovery and optimization are coupled with very controlled single composition deposition to optimize TCO material properties. We used newly developed tools to incorporate these TCOs into prototype PV devices, resulting in fundamentally new materials science and optimized materials for PV applications.

3. Results and Accomplishments

Using combinatorial approaches, we determined that high conductivity transparent a-IZO can be made with indium content down to 60%,

significantly less than the industry standard of 84%.

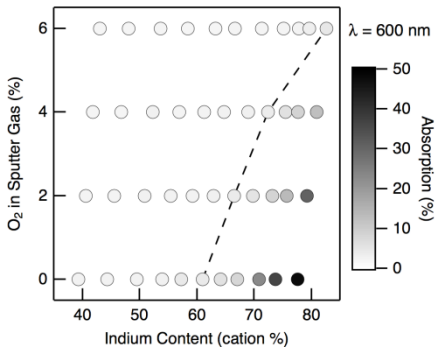

Fig. 1. Absorption in a-IZO. Dashed line is contour of maximum conductivity.

Using our new mixed RF/DC sputtering capability, we improved conductivity of a-IZO by 25%, from 3,000 to 3,750 S/cm (world best). The TCO a-IZO (Fig. 1) is being optimized for and incorporated in CIGS PV applications. Also, we accomplished the first demonstration of an a-IZO finished Si heterojunction cell. In addition, we increased the conductivity of sputtered Ga-doped ZnO by a factor of 10 to 3,200 S/cm for OPV applications.

We are now testing a-IZO TCOs as the top TCO in CIGS PV with the NREL CIGS team and Heliovolt because of the improved stability of this material. The TCO a-IZO is being optimized for CIGS and HIT cell PV, and GZO is being optimized for OPV; a-IZO has demonstrated optical and electrical stability in damp heat (85°C, 85% RH) for 40 days.

4. Planned FY 2010 Activities

- State-of-the-art TCO materials: Develop a-IZO with conductivity > 4,000 S/cm; Zn(Ga, Mg, Cu) for TCOs with independent bandgap, work function, and conductivity control; high conductivity sputtered SnO_2.
- TCOs for PV technologies: Optimize a-IZO for CIGS and Si heterojunction PV; Zn(Ga, Mg, Cu)O for OPV.
- Scale up new TCO materials to large-area deposition (using PDIL): Atmospheric pressure synthesis of TCOs from liquid precursors.

5. FY 2009 Special Recognitions and Patents

Project staff are active in leading professional organization activities, conference symposia organization (5), invited talks (8), and book chapters (3).

Completed TCO book now at Springer for publication.

Three records of invention (one joint with Corning).

6. Major FY 2009 Publications

M.P. Taylor et al., "The Remarkable Thermal Stability of Amorphous In-Zn-O Transparent Conductors," *Adv. Funct. Mater.* **18**, 3169 (2008).

J.D. Perkins et al., "Conductivity and Transparency in Amorphous In-Zn-O Transparent Conductors," M.F.A.M. van Hest, M.P. Taylor, and D.S. Ginley, *Int. J. Nanotechnol.,* **6**, 850 (2009).

J.D. Perkins et al., "Transparent Conducting Oxides for Advanced Photovoltaic Applications," *Photovoltaics International,* 3rd edition, First Quarter, 94 (2009).

J.D. Perkins et al., "Optical Absorption and Electrical Conductivity in Amorphous In-Zn-O: A New TCO for CIGS PV," *Proc. 34th IEEE PVSC* (2009).

T. Gennett et al., "Humidity-Resistant High-Conductivity Amorphous-InZnO Transparent Conductors," *Proc. 34th IEEE PVSC* (2009).

R. Sundaramoorthy et al., "Comparison of Amorphous InZnO and Polycrystalline ZnO:Al as a Conductive Layer for CIGS PV Solar Cells," *Proc. 34th IEEE PVSC* (2009).

R. Pasquarelli et al., "Solution Deposition of Amorphous IZO Films by Ultrasonic Spray Pyrolysis," *Proc. 34th IEEE PVSC* (2009).

7. University and Industry Partners

Organization/PI	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
University of Colorado Prof. Charles Rogers	Boulder, CO Charles.Rogers@colorado.edu	Properties of sputtered amorphous InZnO TCOs	80	0
Colorado School of Mines Prof. Ryan O'Hayre	Golden, CO rohayre@mines.edu	Deposition of InZnO TCO from liquid precursors	40	0
Heliovolt	Austin, TX leldada@heliovolt.com	Development of improved TCO for CIGS	75	25
Plextronics	Pittsburgh, PA DLaird@plextronics.com		50	30

DRAFT

Theory & Computational Science

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Bill Tumas (NREL, Primary Contact), 303-384-7955, bill.tumas@nrel.gov
Suhuai Wei (NREL), 303-384-6666, suhuai.wei@nrel.gov
Alex Zunger (NREL), 303-384-6672, alex.zunger@nrel.gov
Angelo Mascarenhas (NREL), 303-384-6608, angelo.mascarenhas@nrel.gov
Wesley Jones (NREL), 303-275-4070, wesley.jones@nrel.gov

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

FY 2009 Budget: $915K (NREL)

Objectives

- Enhance and accelerate advances in photovoltaic (PV) technology; perform fundamental research to establish the basic knowledge infrastructure of PV materials using state-of-the-art computational tools; explain experimental results, give guidance for future experimental investigation, and predict properties of novel materials that are potential candidates for future PV applications
- Accelerate the pace of PV materials and device understanding and development using data management systems, advanced data analyses with data mining, and statistical optimization approaches to guide experiments.

Accomplishments

- Systematically searched possible quaternary chalcogenides for potential PV absorber; gave theoretical insights about suitability of these materials for PV applications
- Explained why IZO has good optical and transport properties even in the amorphous phase
- Proposed new quantum dots for potential hybrid organic-inorganic solar cell applications
- Produced physical insights on growing covalent Si on ionic oxides with clean interfaces
- Gave insight about the suitability of (Mg, Zn, Cd)Te alloys for tandem solar cell applications
- Proposed new approaches to overcome doping difficulty in wide gap semiconductors
- Advanced theory and models for solar energy materials, both foundational and applied, leading to new capabilities for accurate prediction of PV materials properties and to results directly relevant in materials of current solar cell technologies
- Demonstrated the capability of the ultrafast measurement of defect study
- Developed informatics-aided methods for maximally extracting quantitative processing-structure-property relationships
- Initiated data modeling and development of data aggregation systems for correlation, querying, and analysis of multiple local repositories of deposition records
- Implemented a new data aggregation tool into the silicon data system for the P-System.

Future Directions

- Compare the electronic and defect properties of quaternary chalcogenides ($Cu_2ZnGeSe_4$, Cu_2ZeSnS_4, and $CuGa(Sn\square)Se_4$) with CIGS to investigate their suitability as PV absorbers
- Study physical properties of homologous IZO, GZO, and AZO for low-cost TCO applications
- Understand impurity diffusion and related stability issue in CdTe-based solar cell
- Search oxide substrate that has the optimal interface properties for growth of c-Si
- Understand the crystal structures and passivation mechanism of c-Si/a-Si heterojunction
- Search new nano materials for SSC and hybrid OPV applications
- Establish collaboration between BES-sponsored Energy Frontier Research Center (EFRC) at NREL and the Solar Energy Technologies Program (SETP)

- Predict doping and carrier transport properties in TCOs used in current PV technologies
- Predict effect of defects on performance of In-free solar cells absorbers from $Cu_2(II,IV)VI_4$ family and ways to overcome them
- Initiate data aggregation, analysis and mining for CIGS reliability testing
- Develop informatics tools to integrate, correlate, and visualize composition spread, crystalline and amorphous phases, property, and performance for future p-type TCO
- Enhance collaborations with groups concerning advanced characterizations
- Develop new reliability-testing methods for PV modules and devices (CIGS and encapsulation).

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1. Introduction

This agreement integrates PV-related cross-cutting NREL capabilities in computational, theoretical, and fundamental materials studies at the Basic Science directorate. These capabilities are (1) theory of PV materials, (2) solid state theory, (3) ultrafast imaging of defects in PV materials, and (4) PV materials informatics. This agreement plays a key role in building a strong link between fundamental study and applied technologies.

2. Technical Approach

The Theory of PV Materials task applies state-of-the-art computational methods such as density functional theory, molecular dynamics, and Monte Carlo simulation to study critical issues in design and development of novel PV materials. The studies are done in close collaboration with NCPV experimental groups.

The hallmarks of the SST work are that we use state-of-the-art, quantum-mechanical theoretical methods to address contemporary translational materials challenges in Type II PV; (we leverage methods developed under our BES programs; and we work primarily with PV experimentalists at NCPV as well as SETP subcontractors.

The ultrafast measurement is based on a new PL mapping direct-imaging technique in which the entire two-dimensional sample surface can be imaged onto an electron-multiplying-CCD camera.

In PV Informatics, we build sophisticated data management models and multivariant analysis tools to relate deposition, characterization, and process data and enable mining of related data. We apply state-of-the-art material informatics techniques to design experiments and optimization techniques in collaboration with researchers.

3. Results and Accomplishments

- Searched systematically quaternary compounds for PV absorber applications using sequential atomic mutation approach. Suggested that $Cu_2ZnGeSe_4$ in the kesterite structure may be the best quaternary PV absorber material (Chen et al. 2009a, 2009b; Walsh et al. 2009a) .
- Demonstrated and explained that ternary oxides formed from zinc and indium compounds (IZO) have good electrical and optical properties even in the amorphous phase (Walsh et al. 2009b, 2009c).
- Predicted that zincblende (Mg, Zn)Te [(Mg, Cd)Te] alloys have accessible direct band gaps in the ranges of 2.39(1.48)–3.25(3.02) eV, suitable for tandem solar cell applications (Yang et al. 2009).
- Calculated electronic structures of polymers. Suggested that InSb quantum dots or quantum wires could be good materials for hybrid organic-inorganic solar cells applications (Arantes et al. 2009, Xiang et al. 2009b).
- Explained why Si and Al_2O_3 can form clean interface. Provided criterion on searching optimal oxide substrate for growth of c-Si (Xiang et al. 2009a).
- Suggested new approaches such as surfactant-enhanced doping to overcome doping difficulty in PV materials (Gai et al. 2009, Zang et al. 2009).
- Performed first theoretical study of n-type doping by transition metals in the currently used TCOs ZnO and In_2O_3 (Raebiger et al. 2009).
- Developed and applied a novel method to predict quantitatively hole binding energies of acceptors in p-type TCO, useful for multiple PV applications. Applied this method to all metal-site acceptors in ZnO, In_2O_3, and SnO_2, and showed that the acceptor levels are too deep to produce p-type conductivity, contrary to previous claims based on conventional theories (Lany and Zunger 2009).

- Developed and tested computational method needed for calculating defects in complex PV materials (Lany and Zunger 2008).
- Measured glass/SnO_2/CdS/CdTe samples, showing that after treatment a higher concentration of the Te-rich CdS_xTe_{1-x} alloy exists in the grain-boundary region and that $CdCl_2$-treatment can reduce nonradiative recombination at the grain boundary (Dhere et al. 2009).
- Initiated and continued work in data aggregation, analysis, and mining (i.e., informatics). Began developing data models for integrating local data aggregation systems into a common platform.
- Implemented a new data aggregation tool into the silicon data system for the P-System. It is focused on a user-friendly data entry and record display (Jones et al. 2009).
- Continued updates and support for the data aggregation tool for FTIR characterization focusing on data access and reporting.
- Demonstrated an effective way of screening and visualizing myriad information by providing the effect of composition of Co of Co:ZnO thin films on the structural properties and linked it processing conditions.
- A new accelerated reliability testing technique was developed in terms of experimental economics and statistical accuracy.

4. Planned FY 2010 Activities

The PV Materials Theory project will continue its work on critical issues related to PV materials. In FY 20110, the focus will be on studying the electronic and defect properties of quaternary chalcogenides ($Cu_2ZnGeSe_4$, Cu_2ZeSnS_4, and CuGa(Sn□)Se_4) to investigate their suitability as PV absorber materials; studying crystalline and amorphous phases of homologous GZO and AZO for low-cost TCO applications; and understanding impurity diffusion and related stability issues in CdTe-based solar cells. If funding permits, we will also extend our study to include searching an oxide substrate for growth of c-Si and understanding the passivation mechanism of the c-Si/a-Si heterojunction.

The SST research activity will further address p-type doping in TCOs and wide-gap semiconductors. We will also apply our unique capabilities to predict doping and carrier transport properties in TCOs of current technologies, like TiO_2, to identify and resolve bottlenecks on the basis of an accurate theory. We further plan to investigate the impact of defects on In-free Cu_2ZnSnS_4 absorber materials, and to identify the trade-offs for optimal performance. If funding permits, we will further study charge separation mechanisms in Si nanowire based solar cell, and the design of intermediate band solar cells.

The Ultrafast Measurement activity will use and perfect the apparatus for the study of defects in thin-film solar cell and build new apparatus to extend the current capabilities. We apply this technique to understand the relationship of the microstructure and individual defects to optical behavior of thin-film PV materials.

The PV Materials Informatics task will initiate new and continued data aggregation activities with film silicon, OPV, thin films, TCOs, and measurements and characterization researchers. It will begin collaborations on applying state-of-the-art material informatics techniques with PV program researchers. We will begin data aggregation, analysis, and mining for CIGS reliability testing. We will review requirements and maintain capability compatible with DOE requirements for scientific and technical data access and distribution. We will enhance collaborations with groups concerning advanced characterizations such as auger electron spectroscopy and X-ray photoelectron spectroscopy for elemental and chemical mapping for CIGS devices and PDIL.

5. FY 2009 Special Recognitions and Awards

S.-H. Wei, “First-Principles Design of Functional Materials for Energy Applications,” *Arizona Workshop for Renewable Energy*, Tempe, AZ, November 2008.

S.-H. Wei, “Overcoming the Doping Asymmetry Problem in Wide Gap Semiconductors,” *CECAM Workshop on Electronic Structure Method for the Study of Defects*, Lausanne, Switzerland, June 2009.

S.-H. Wei, “Computational Study of Material Properties of Metal Oxides,” *International Conference on Materials for Advanced Technologies*, Singapore, July 2009.

S.-H. Wei, “First-Principles Investigation of Unusual Materials Properties of Oxides,” *CECAM Workshop on Computer Simulation of Oxides*, Dublin, Ireland, September 2009.

S. Lany, “Theory of Doping, Defects, and Non-stoichiometry in Transparent Conducting Oxides,” *2nd Intl. Symp. Transparent Conductive*

Oxides, Hersonissos, Crete, Greece, October 2008.

S. Lany, "Predicting p-orbital Hole-polarons in DFT Supercell Calculations," *CECAM Workshop on Electronic Structure Method for the Study of Defects,* Lausanne, Switzerland, June 2009.

S. Lany, "Material-intrinsic efficiency limitations in CIGS absorbers due to metastable defects," *MRS Spring Meeting*, San Francisco, CA, April 2009.

A. Zunger, Invited talk on novel PV materials in *MRS*.

A. Zunger, Invited talk on theory applications to PV at *BES* panel.

6. Major FY 2009 Publications

J.T. Arantes, S.-H., Wei, et al., "Effects of Side Chain and Electron Correlation on the Band Structure of Perylene Diimide Liquid Crystals: A Density Functional Study," *J. Phys. Chem. B* **113**, 5376 (2009).

S. Chen, S.-H. Wei, et al., "Crystal and Electronic Band Structure of Cu_2ZnSnX_4 (X = S and Se) Photovoltaic Absorbers: First-Principles Insights," *Appl. Phys. Lett.* **94**, 041903 (2009a).

S. Chen, S.-H. Wei, et al., "Electronic Structure and Stability of Quaternary Chalcogenide Semiconductors Derived from Cation Cross-Substitution of II-VI and I-III-VI_2 Compounds," *Phys. Rev. B* **79**, 165211 (2009b).

R. Dhere, A. Mascarenhas, et al., "Investigation of Effects of Processing and Impurities on the Properties of CdTe Using Microscopic 2D PL Imaging Technique," *Proc. 34th IEEE PV Specialists Conf. Philadelphia, PA, 2009*.

Y. Gai, S.-H. Wei, et al., "Design of Shallow Acceptors in ZnO through Compensated Donor-Acceptor Complexes: A Density Functional Calculation," *Phys. Rev. B* **80**, 153201 (2009).

W.B. Jones, et al., "Tools for Aggregating, Analyzing and Mining Combinatorial Data," *Mater. Res. Soc. Symp. Proc.* **1159**, G03-08 (2009).

D. Korytina, W.B. Jones, et al., "Ad hoc Structured Search over Complex, High-Throughput Data Sets, Expressed in a Restructurable, Integrated Form," *Proc. IKE 2009* **143** (2009).

S. Lany and A. Zunger, "Assessment of Correction Methods for the Band Gap Problem and for Finite-Size Effects in Supercell Defect Calculations: Case Studies for ZnO and GaAs," *Phys. Rev. B* **78**, 235104 (2008).

S. Lany and A. Zunger, "Polaronic Hole Localization and Multiple Hole Binding of Acceptors in Oxide Wide-Gap Semiconductors," *Phys. Rev. B* **80**, 085202 (2009).

H. Raebiger, S. Lany, and A. Zunger, "Electronic Structure, Donor and Acceptor Transitions, and Magnetism of 3d impurities in In_2O_3 and ZnO," *Phys. Rev. B* **79**, 165202 (2009).

A. Walsh, S.-H. Wei, et al., "Design of Quaternary Chalcogenide Photovoltaic Absorbers through Cation Mutation," *Proc. 34th IEEE PV Specialists Conf., Philadelphia, PA, 2009a*.

A. Walsh, S.-H. Wei, et al., "Electronic and Optical Analysis of Ternary $In_2O_3(ZnO)_n$ Transparent Conducting Oxides," *Phys. Rev. B* **79**, 073105 (2009b).

A. Walsh, J.L.F. Da Silva, and S.-H. Wei, "Interplay between Order and Disorder in the High Performance of Amorphous Transparent Conducting Oxides," *Chem. Mater.* **21**, 5119 (2009c).

H.J. Xiang, J.L.F. Da Silva, H.M. Branz, and S.-H. Wei, "Understanding the Clean Interface between Covalent Si and Ionic Al_2O_3," *Phys. Rev. Lett.* **103,** 116101 (2009a).

H. Xiang, S.-H. Wei, and X. G. Gong, "Identifying Optimal Inorganic Nanomaterials for Hybrid Solar Cells," *J. Phys. Chem. C* **113**, 18968 (2009b).

J.-H. Yang, S.-H. Wei, et al., "Electronic Structure and Phase Stability of MgTe, ZnTe, CdTe and their Alloys in the B3, B4 and B8 Structures," *Phys. Rev. B* **79**, 245202 (2009).

L. Zhang, Y. Yan, S.-H. Wei, "Enhancing Dopant Solubility via Epitaxial Surfactant Growth," *Phys. Rev. B* **80**, 073305 (2009).

Measurement & Characterization Summary

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 SETP supported PV companies. 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.
The M&C project is designed to help the SETP meet their 2015 targets. Research 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.

	NREL	SNL	Solar
	Total $K	Total $K	Total $K
Measurement & Characterization	**10025**	**0**	**10025**
Analytical Microscopy	**2545**	**0**	**2545**
Electro-Optical Characterization	**2590**	**0**	**2590**
Surface Analysis	**1800**	**0**	**1800**
Cell and Module Performance	**2200**	**0**	**2200**
M&C Management	**890**	**0**	**890**

DRAFT

Analytical Microscopy Characterization

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Mowafak Al-Jassim (NREL), 303-384-6602, mowafak.aljassim@nrel.gov

DOE HQ Technology Manager: John Lushetsky, 202-586-8064, john.lushetsky@hg.doe.gov

FY 2009 Budget: $2,545K

Objectives

- Provide routine and specialized measurement and characterization support for photovoltaics (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 our industrial partners, including pre-incubator, incubator, and Technology Pathway Partnership projects; maintained cutting-edge support and acceptable turnaround time despite the large increase in sample volume
- In support of the Process Development and Integration Laboratory (PDIL) operation, commissioned and further developed a scanning probe microscope and a scanning electron microscope with environmental control and pod compatibility
- Studied the reliability of CdTe/CdS solar cells, investigated the effects of stress on these cells, and studied the influence of Cu on their electrical properties
- Investigated surface electronics of CIGS thin films and role in junction formation of solar cells
- Developed a scanning luminescence microscopy technique to investigate exciton transport in organic solar cells
- Studied the reliability of III-V solar cells and the relaxation behavior and atomic ordering behavior in lattice mismatched III-V layer structures
- In collaboration with in-house black Si project, investigated the microstructure, chemistry, and electronic properties of the porous Si oxide layer before and after thermal treatment
- In collaboration with in-house Si heterojunction project, investigated microstructure, chemistry, and electronic properties of a-Si/c-Si interface of initial SHJ cells grown on industrial Si cells
- In collaboration with in-house CdTe project, investigated barrier layer for Na diffusion from soda lime glass.

Future Directions

- Provide priority analytical microscopy support to our industrial partners
- Investigate the influence of the deposition rate on the defect physics in copper indium gallium diselenide (CIGS) films
- Investigate the amorphous/crystalline Si interface in industrial Si heterojunction cells
- Develop a better understanding of the role of grain boundaries and intragrain defects in affecting transport properties of CdTe films
- Continue the studies of the degradation of multijunction cells
- Investigate defect type, density, and distribution as a function of casting conditions of upgraded metallurgical grade Si wafers.

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1. Introduction

The Analytical Microscopy Team provides measurement and analysis support and research for the National Photovoltaics Program. It 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 understand and direct work on their research and commercial product development. We also serve as one of the test and evaluation facilities used to evaluate subcontract and stage-gate deliverables for preincubator and incubator projects.

These activities address one or more of the three areas crucial to meeting the EERE 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. This is accomplished by selecting projects that address key issues for a broad spectrum of technologies, including c-Si, a-Si, thin Si, copper indium diselenide (CIS), CdTe, III-Vs, organic photovoltaics (OPV), and other future-generation materials.

2. Technical Approach

We use a wide variety of microscopy-based techniques to characterize PV materials and devices. Electron probe microanalysis (EPMA) makes compositional measurements using either energy dispersive or wavelength dispersive X-ray analysis. We use transmission electron microscopy (TEM) and high resolution scanning transmission electron microscopy (STEM) to perform structural and defect analyses. Scanning electron microscopy (SEM) in its various modes, such as secondary electron imaging, cathodoluminescence (CL), and EBIC imaging, provides wide support for measuring the topographical, luminescent, and microelectrical properties of PV materials and devices.

Additionally, this task gives extensive support to the PV program in the nanoscale characterization area. Atomic force microscopy (AFM)-based techniques examine the morphology, surface structure, and electrical properties on the nanoscale of semiconductor and PV materials and devices.

3. Results and Accomplishments

Supporting our SETP industrial partners:
The highest priority in FY 2009 was supporting the PV industry projects. Considerable time and resources were devoted to supporting preincubator, incubator, and TPP projects. Such projects resulted in a significant increase in our workload from the previous year. Despite this dramatic increase in analysis volume, we supplied state-of-the-art measurements at an acceptable turnaround time. The industry work falls into three categories: measurement support, verification of deliverables, and research support. An example of the last is the light-induced degradation study of Si cells.

PDIL tool development:
In support of the PDIL, we finished installing and testing the scanning probe microscopy (SPM) system for large-area samples and environmentally controlled measurements. The sample transfer station was tested with the pod and achieved the expected performance. Further, the glove box was installed, tested, and approved. We demonstrated the benefits of the glove box by analyzing Si samples by C-AFM in air and in the controlled ambient of the glove box. We also finished commissioning the large-sample environmental SEM and its sample transfer station in the PDIL. We applied these new environmentally controlled and vacuum capabilities to characterizing several solar cell materials and devices. One example is investigating the electrical potential profiles on the junction of III-V devices. We previously studied the potential profile in air, and demonstrated a surface Fermi-level pinning on cross-sections of the device. This Fermi-level pinning made the measured potential value smaller than that of the bulk, a crucial parameter in device performance. With cleaving the device in the glove box, we demonstrated clean surface and a minimal effect of surface Fermi-level pinning.

Investigation of light-induced degradation in UMG mc-Si cells:
We studied the reliability of upgraded metallurgical grade (UMG) Si cells. Light-induced degradation (LID) in these cells was the main degradation mechanism observed. LID in these UMG mc-Si cells was investigated using I-V, QE, diffusion length, and lifetime measurements. A meta-stable regenerated state with finite time factor was further investigated for the UMG cells. E_{ff}, V_{oc}, and J_{sc} degraded logarithmically with time, and the J_{sc} is the dominant factor for the efficiency degradation. QE measurements showed that the J_{sc} degradation happened mainly in the long wavelength range, indicating the degradation is in the bulk absorber. Diffusion length maps (Fig. 1a) as deduced from light-beam induced current (LBIC) show grain structures with degradation at grain boundaries and intragrain defects. The

diffusion length is longer on the [111]-oriented grains than in other orientations. With LID, the diffusion length on the defect-free regions was significantly reduced (Fig. 1b), regardless of the grain orientations. The diffusion length on the defects, however, did not change significantly with LID, indicating that the recombination of carriers on the defects is dominated by the defects themselves. Lifetime measurements by micro-photoconductance decay (u-PCD) also showed overall decrease consistent with the LBIC and QE measurements. All these measurements indicate that LID induces defects that are dispersed in the bulk absorber with micro- or atomic scales.

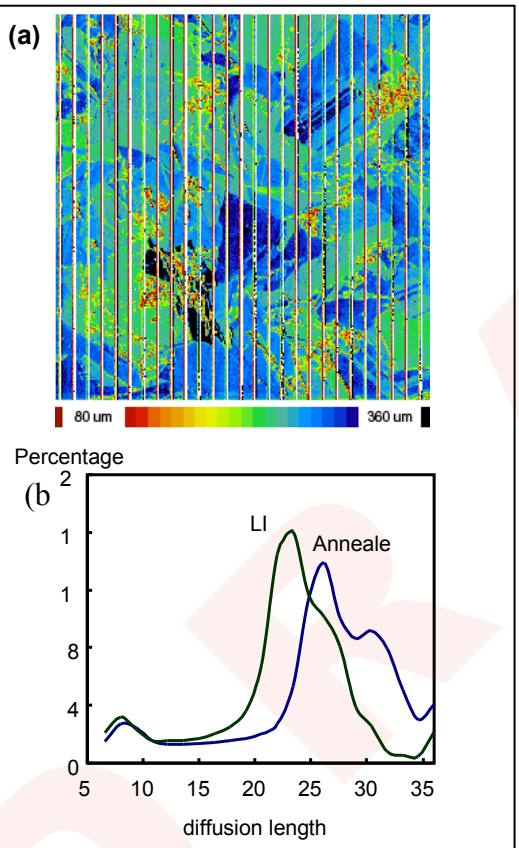

Fig. 1. (a) A diffusion length map of a UMG mc-Si cell, and (b) histograms of the diffusion length of a cell at the annealed and LID states.

Resolution of the nanoscale exciton transport in organic solar cells by a new SPM:
We observed excitonic luminescence from P3HT blended with PCBM in tunneling luminescence measurements based on AFM. The plasmon excitation confined to the metallic tunneling gap at the tip is responsible for the large enhancements in the intensity of the molecular luminescence. This effect allows for dramatic improvement in the detection sensitivity and, in combination with AFM, the acquisition of photon intensity images of the excitonic luminescence with nanometer resolution. For a series of P3HT:PCBM annealed at different temperatures, we found excellent correlation between the nanoscale morphology and the predicted exciton transport properties reflected in the photon intensity images of the molecular luminescence. This scanning luminescence microscopy can thus be applied to investigating the exciton transport, dissociation across donor-acceptor interfaces, and evaluation of the exciton diffusion length, all with nanometer resolution. Developing such a powerful technique will produce critical information on the performance of OPV devices.

Defect physics in CIGS thin films:
Defect physics includes the study of atomic structure, chemical composition, electrical potential, and recombination behaviors of point defects and their complexes, grain boundaries, dislocations, stacking faults, twins, and interfaces. In FY 2009 we focused on surface defects, which are long thought to be a fundamental aspect of CIGS films that is critically involved in the formation of the junction of the solar cell. We developed a luminescence spectroscopy based on the STM, in which tunneling electrons are responsible for the excitation of luminescence. Such tunneling luminescence is excited at the surface and, consequently, the tunneling luminescence spectrum reveals the electronic states near the surface. In combination with cathodoluminescence, the transition from the grain interior to the surface can be investigated. We observed a red-shift in the emission spectrum at the surface of the CIGS that can be explained by the distinct defect structure of the surface caused by its deviations in stoichiometry. The <112> orientation is a special case in which there is no discontinuity at the surface. The surface electronics is controlled by the relative Cu deficiency, and most of the time is spatially more uniform than the underlying CIGS. We applied these measurements to CIGS thin films with different selenium regimes (from deficiency to overpressure) and investigated the electron transport across individual grain boundaries for films with increasing <Se>/<M> ratios. This technique produced much needed information on the characteristics of our best-efficiency CIGS cells and the key to achieving the 20% efficiency.

The influence of grain misorientation on grain boundary recombination in thin-film Si cells:

The film silicon roadmap puts a high priority on developing large-grained c-Si films on low-cost substrates that must be high quality to be used in 15% solar cells. The effects of residual grain boundaries (GBs) and dislocations must be understood, and it is a roadmap priority to develop passivation techniques for them. This project aimed to develop the fundamental understanding and needed techniques for imaging GBs and for evaluating the recombination activity of GBs and dislocations and the efficacy of passivation techniques. In collaboration with the in-house thin film Si project, we studied seed/epitaxy Si films to understand which grain boundaries dominate the recombination statistics. We (1) mapped the misorientation of various GBs over selected areas on prepatterned films using electron backscattered diffraction (EBSD); (2) measured selected areas with the multiple techniques from AFM and SEM; and (3) selected specific grain boundaries in the focused ion beam (FIB) and examined the atomic structure of the boundaries by TEM. We observed (Fig. 2) that (1) carrier concentrations are lower around the GBs than on center regions of the grains; (2) the depletion width at the GBs varies considerably, between 0 and 100 nm, depending on individual GBs; and (3) intragrain carrier depletion existed at point and line defects. Directly measuring the carrier depletion on the GBs demonstrates that the GBs in Si thin films indeed create charged gap states. The nonuniformity of the carrier depletions suggests that the gap states depend on specific GB structures, which should relate directly to the grain orientations and grain facets adjacent to the GB. The depletion around the intragrain defects indicates that the defects are charged and can be recombination centers and, thus, harmful to device performance.

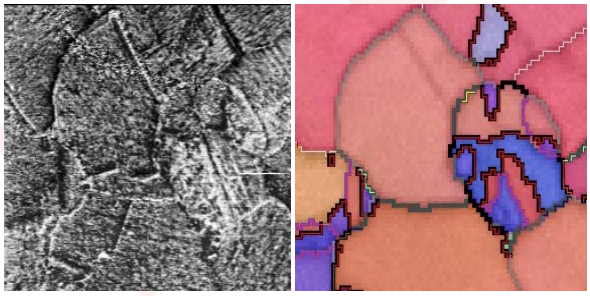

Fig. 2. Scanning capacitance image (left) and EBSD image (right) of GBs in thin-film Si solar cell.

4. Planned FY 2010 Activities

- Provide priority analytical microscopy support to our SETP industrial partners
- Investigate shunting in industrial Si cells
- Study the reliability of UMG Si cells and modules
- Complete the reliability study of CdTe/CdS cells, investigate the effects of stress on these cells, and study the influence of Cu on their electrical properties
- Continue the studies of the degradation of III-V multijunction cells
- Develop further understanding of the interfaces of Si heterojunction cells on large Si wafers.

5. FY 2009 Special Recognitions and Awards

One NREL Staff Award and several NREL Directors Awards.

6. Major FY 2009 Publications

C.-S. Jiang, A. Ptak, B. Yan, H.R. Moutinho, J.V. Li, and M.M. Al-Jassim, "Microelectrical Characterizations of Junction in Solar Cell Devices by Scanning Kelvin Probe Force Microscopy," *Ultramicroscopy* **109**, 952 (2009).

H. Moutinho, R. Dhere, C.-S. Jiang, and M. Al-Jassim, "Scanning Kelvin Probe Microscopy of CdTe Solar Cells Measured Under Different Bias Conditions," *MRS Proceedings* **1165**, M08-28 (2009).

A.G. Norman, "Defects and Strain Relaxation Behavior in Compositionally Step Graded Layer Structures for High Efficiency, Metamorphic, Multi-junction Solar Cells," invited talk at the 17th American Conference on Crystal Growth and Epitaxy, Lake Geneva, WI, August 2009.

M.J. Romero, M.A. Contreras, I. Repins, C.-S. Jiang, and M.M. Al-Jassim, "Recent Advances in the STM-based Luminescence Microscopy of Cu(In,Ga)Se2 Thin Films," *MRS Proceedings* **1165**, M09-11 (2009).

M.J. Romero, A.J. Morfa, T.H. Reilly III, J. van de Lagemaat, and M.M. Al-Jassim, "Nanoscale Imaging of Exciton Transport in Organic Photovoltaic Semiconductors by Tip-enhanced Tunneling Luminescence," *Nano Lett*. **9**, 3904 (2009).

Electro-Optical Characterization

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Dean Levi (NREL), 303-384-6605, dean.levi@nrel.gov

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

FY 2009 Budget: $2,590K (NREL)

Objectives

- Help SETP subcontractors succeed by giving top priority support through collaborative R&D projects, technique development, and standard measurements
- Bring six new PDIL tools to full operational capability, including vacuum-integrated spectroscopic ellipsometry, vacuum-integrated minority carrier lifetime, vacuum-integrated photoluminescence imaging, PV reflectometer, optical processing furnace, and wafer processing station
- Continue ongoing advancement of measurement techniques, including imaging of lifetime and cell performance, minority carrier lifetime, minority carrier diffusion length, and fundamental PV device properties
- Help NREL in-house PV technology projects succeed through collaborative R&D projects, technique development, and standard measurements.

Accomplishments

- Gave priority support for numerous SETP-supported companies, including 1366 Technologies, Innovalight, Solexel, Abound (formerly AVA) Solar, Calisolar, MicroLink Devices, PrimeStar Solar, SoloPower, BP Solar, Dow Chemical, General Electric, Miasole, Nanosolar, and United Solar Ovionic
- Achieved substantial completion of all PDIL tools, including vacuum-integrated spectroscopic ellipsometry, vacuum-integrated minority carrier lifetime, vacuum-integrated photoluminescence imaging, PV reflectometer, optical processing furnace, and wafer processing station
- Made significant advances in imaging techniques for solar cell diagnostics, including electro-luminescence imaging, forward and reverse bias dark lock-in thermography, and illuminated lock-in thermography
- Transferred NREL-developed technology to two industrial partners through CRADAs: GT Solar ha developed the GT Fabscan 6000 based on NREL's PV reflectometer technology, and 2) Applied Optical Sciences developed a highly efficient optical processing furnace for PV applications based on NREL's cavity-type optical furnace
- Developed a robust computational model of triple-junction PV devices that included the first accurate simulation of tunnel junctions; used this model to study the effects of concentration and provided a new explanation for fill factor drop at high concentrations
- Developed a transient ion drift measurement using slow capacitance transients to study dopant migration in CdTe, CIGS, and organic photovoltaic (OPV) devices.

Future Directions

- Give top priority support for SETP subcontractors through collaborative R&D projects, technique development, and standard measurements
- Integrate six new PDIL tools into collaboration and support projects. Seek opportunities to partner with PV industry and in-house NREL research groups using these new capabilities
- Continue ongoing advancement of measurement techniques for minority carrier lifetime, minority carrier diffusion length, thin film optical properties, and fundamental PV device properties
- Determine the viability of time-resolved photoluminescence (TRPL) as an online diagnostic for PV manufacturing (contingent on capital equipment funding)
- Initiate studies of CIGS material growth using real-time spectroscopic ellipsometry

DRAFT

- 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 agreement supports SETP by developing and applying measurement and analysis techniques to solve scientific and technical problems that arise when developing and commercializing PV technologies. Our expertise and capabilities cut across all technologies to facilitate research, development, and T&E in support of the PV technology roadmaps: wafer-silicon, film-silicon, concentrator PV, CIGS, CdTe, OPV, intermediate-band PV, multiple-exciton-generation PV, dye-sensitized solar cells, and reliability.

2. Technical Approach

We bring extensive experience and advanced experimental capabilities to solving technical challenges in PV R&D. Our technical staff are experts in applying and interpreting a wide range of electro-optical measurement techniques. A major focus area is developing and applying methods for measuring 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 for rapid imaging of MCL. We apply several spectroscopic techniques: photoluminescence spectroscopy; spectroscopic ellipsometry; near-, mid-, and far-infrared spectroscopy; and diffuse reflectance spectroscopy. We use several electrical device characterization methods to determine defect properties and fundamental junction parameters: deep level transient spectroscopy (DLTS), capacitance-voltage (C-V), admittance spectroscopy (AS), drive-level capacitance (DLCP), and in-plane impedance spectroscopy. We also have expertise in 2D and 3D computer modeling of solar cell structures, including modeling the measurements themselves, enabling our scientists to “look inside” the measurement process to gain greater insight and understanding of the measurement results.

3. Results and Accomplishments

- *Supported SETP subcontractors at the highest level possible*
- *Achieved significant advances in imaging techniques for solar cell diagnostics.*

Support for solar companies comprises a major portion of our work. In FY 2009 we performed hundreds of measurements and analyses for 14 different SETP-supported companies. One emphasis for our group in recent years has been developing advanced imaging metrology techniques for the PV industry. We began to extensively use these techniques to support SETP contractors, e.g., our collaboration with an SETP-supported company to help optimize their multicrystalline Si wafer processing. The company was concerned with cell series resistance. We used a modified version of our standard PL imaging (PLI) technique, where a CCD camera is used to image the PL emission from a Si wafer that is excited using an 810-nm laser diode. In this case the mc-Si PV cell is connected through a resistive load while illuminated by 810-nm light. Areas of high resistance show up brighter in the image because of higher carrier densities resulting from poor carrier collection. Figure 1 shows an image of one of their cells where the crosshatched pattern in the lower left matched the pattern of a belt furnace used in wafer processing. The company was then able to modify the furnace to eliminate this problem and produce higher efficiency cells. We also made significant advances using dark lock-in thermography to image shunts, began applying imaging techniques to CIGS solar cells, and transferred the technical knowledge for imaging to multiple SETP-supported companies.

- *Achieved substantial completion of six new PDIL tools*
- *Transferred NREL-developed technology to two industrial partners.*

The electro-optical characterization group was unique among NREL agreements responsible for tool development in the PDIL in terms of the number and complexity of tools that fell within its agreement. Of the six PDIL tools we were responsible for in FY 2009, only one was an “off the shelf” unit from an outside vendor. The rest were completely custom designed and constructed at NREL, designed at NREL and built by an outside contractor, or based on

NREL-developed IP and designed and constructed under a CRADA with a commercial partner under license with NREL. In FY 2009 we substantially completed all six PDIL tools: vacuum-integrated spectroscopic ellipsometry, vacuum-integrated minority carrier lifetime, vacuum-integrated photoluminescence imaging, PV reflectometer, optical processing furnace, and wafer processing station.

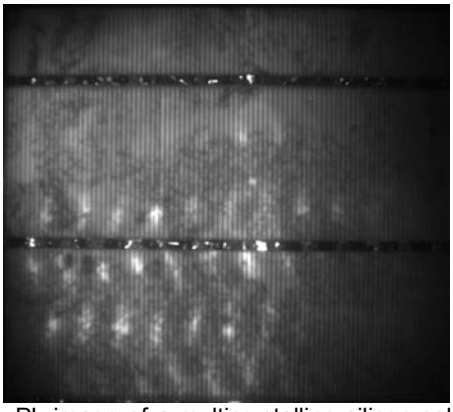

Fig. 1. PL image of a multicrystalline silicon solar cell under load showing areas of high resistance (bright areas) that correlated to the pattern of a belt furnace.

Two of these tools, the PV reflectometer and the optical processing furnace, or OPF, are excellent examples of technology transfer from NREL to the PV industry. Both are based on NREL intellectual property and licensed to a commercial partner. The PV reflectometer and OPF now in the PDIL are the first commercial prototypes, and were designed and assembled by our commercial partners in collaboration with NREL scientists under a CRADA agreement. The PV reflectometer, or GT-Fabscan 6000, as it is now known, is based on a patented measurement concept developed at NREL. It uses reciprocal optics to rapidly acquire the diffuse reflectance spectrum of a large-area sample. It can also use spectrally filtered images to produce parameter maps. This capability is illustrated in Figure 2, which shows a dislocation density map of an mc-Si wafer. We made extensive use of this capability to help several PV wafer suppliers better understand and optimize their ingot growth process. In addition to dislocation density, the reflectometer can measure wafer thickness, grain orientation maps, grain size distribution, texturing etching, antireflection coating thickness, front metallization (metal height and metallization area), and back reflectance. Because GT-FabScan 6000 can make measurements very rapidly (typically in < 40 ms) and without physically contacting the wafer, it can be used to monitor various process steps in the commercial production of solar cells. This tool is now available to NREL and visiting industry researchers to help understand and optimize their solar cell processing.

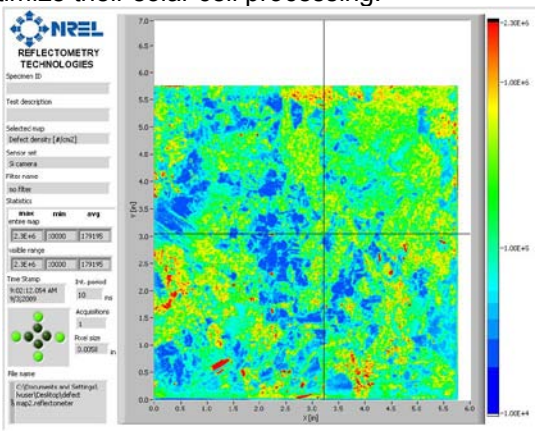

Fig. 2. Dislocation density in mc-Si wafer mapped by NREL's GT Fabscan. This map is acquired in 10 ms.

- *Developed a robust computational model of triple junction PV devices and applied it to understand device performance under high concentration.*

One of the goals in concentrating photovoltaics (CPV) is operating at very high levels of concentration (500–1000x). This reduces the amount of expensive semiconductor required in a CPV module and also increases the conversion efficiency of the triple-junction solar cell. It has been experimentally shown that device efficiency increases with concentration but saturates as concentration exceeds 300x.

We have been working for the past 2 years to develop robust computational models of the GaInP/GaAs/Ge triple-junction solar cells that are used in CPV modules. In FY 2009 we succeeded in achieving convergence of these highly complex models and used them to study the effects of concentration on triple-junction solar cell performance. Our simulations found that the fill-factor reaches a peak near 300x and then starts decreasing. Because of the fill-factor decrease, the efficiency saturates at high concentrations. These are the same trends observed experimentally, but not fully explained so far.

In addition to the commonly accepted explanation that the impact of series resistance on device performance increases under concentration, the simulations pointed to an additional effect. The valence-band offset (VBO) at the GaAs/GaInP interface for the GaAs middle cell back contact creates a barrier for majority holes. To study the impact of this barrier, we performed simulations on an isolated GaAs middle cell. Under high

concentration, the high density of photogenerated minority electrons will cause the recombination rate at the barrier to increase, reducing the density of holes to values below the levels needed to produce high photocurrents through the tunnel junction. It follows that a lower VBO at the GaAs/GaInP interface will reduce the FF drop at high concentrations. Figure 3 illustrates this concept, showing FF dependence on concentration for three different VBOs. For a VBO of 0.35eV, the FF drop significantly decreased, and our simulations show that efficiency keeps on increasing with concentration beyond 1000x. It follows that the FF decrease can be eliminated by substituting GaInP with other materials. A research group in Spain used $Al_xGa_{1-x}As$ ($0.2 < x < 0.3$) instead of $Ga_{0.5}In_{0.5}P$, and obtained peak efficiency at higher concentrations, essentially confirming the results of our calculations.

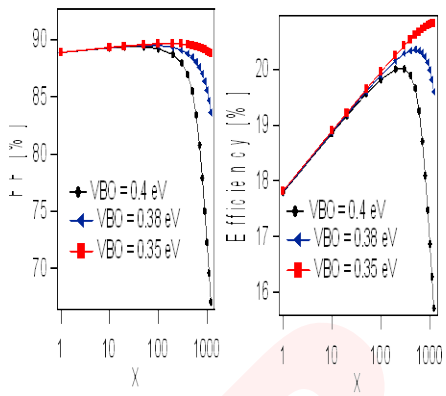

Fig. 3 Calculated fill factor as a function of concentration X for three different values of the valence band offset at GaInP/GaAs interface.

4. Planned FY 2010 Activities

See "Future Directions" section on first page.

5. FY 2009 Special Recognitions, Awards, and Patents

PV workshops

- Organized the 19th Crystal Silicon Workshop August 5-9, 2009 in Vail, CO; very well attended and successful; 184 PV specialists attended
- Organized symposium "Materials and Manufacturing Issues in Photovoltaics" at the MRS 2008 Fall Meeting. MRS has requested that we organize a 3.5-day, annual workshop of the same title for next 5 years.

Invited talks

- Bhushan Sopori, "Limitations of Multicrystalline Si Solar Cells: Potential Approaches to Reach Monocrystalline Si Efficiencies," TMS Annual Meeting, San Francisco, CA (02/09)
- Steve Johnston, extended oral presentation: "Applications of Imaging Techniques for Solar Cell Characterization," IEEE PVSC Philadelphia, PA, (06/09)
- Bhushan Sopori, "Limitations of Multicrystalline Solar Cells Caused by Defect Clusters," ECS-Asia, Shanghai, China, (03/09)
- Bhushan Sopori and Przemyslaw Rupnowski, "Breakage Mechanism(s) of Photovoltaic Silicon Wafers: Theory and Experiment," International Photovoltaic Reliability Conference II, Tempe, AZ, (07/09).

Awards

- B. Sopori, V. Budhraja, P. Rupnowski, S. Johnston, N. Call, H. Moutinho, and M. Al-Jassim, "Defect Clusters in Multicrystalline Silicon: Their Nature and Influence on the Solar Cell Performance," IEEE PVSC Philadelphia, PA June 2009, Best Poster Award.

Invention disclosures

- B. Sopori, Optical technique for measurement of Pt content in PMEA electrodes.
- B. Sopori, A new chuck for cross sectioning wafer silicon solar cells.

6. Major FY 2009 Publications

R.K. Ahrenkiel and S.W. Johnston, "An Optical Technique for Measuring Surface Recombination Velocity," *Solar Energy Mater. Solar Cells* **93**(5) 645 (2009).

D.S. Albin, R.G. Dhere, S.C. Glynn, and W.K. Metzger, "Direct Correlation of CdTe Solar Cell Stability with Mobile Ion Charge Generation During Accelerated Lifetime Testing," *34th IEEE PVSC, June 2009, Philadelphia, PA*.

S.W. Johnston, N.J. Call, B. Phan, and R.K. Ahrenkiel, "Applications of Imaging Techniques for Solar Cell Characterization," *34th IEEE PVSC, June 2009, Philadelphia, PA.*

A. Kanevce and W.K. Metzger, "The Role of Amorphous Silicon and Tunneling in Heterojunction with Intrinsic Thin Layer (HIT) Solar Cells," *J. Appl. Phys.* **105** (9) 094507 (2009).

I.L. Repins, W.K. Metzger, C.L. Perkins, J.V. Li, and M.A. Contreras, "Measured Minority Carrier Lifetime and CIGS Device Performance," *34th IEEE PVSC, June 2009, Philadelphia, PA*.

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: Scott Stephens, 202-586-0565, scott.stephens@hq.doe.gov

FY 2009 Budget: $1,800K (NREL)

Objectives

- Take 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 on 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 R&D.

Accomplishments

- Gave surface analysis measurement support to researchers and manufacturers funded by the Solar Energy Technologies Program (SETP)
- Completed development of thermodynamics-based models describing impurity migration and surface/interfacial segregation in PV materials and heterostructure devices under processing and field-deployed conditions
- Completed installation and acceptance tests of the Process Development and Integration Laboratory (PDIL) measurements and characterization sample transfer robot
- Completed installation and acceptance tests of the large-platen AES tool in PDIL; demonstrated large-area mapping capabilities
- Completed installation of the large-platen XPS tool and flipping station in PDIL
- Installed and integrated into program activities a new, state-of-the-art, dynamic secondary ion mass spectrometer (SIMS)
- Developed unique capabilities for synthesizing and studying the novel thin-film PV absorber material Cu_2ZnSnS_4 (CZTS)
- Developed methods using XPS and dynamic contact angle to establish glass-washing protocols, screening methods for clean glass, and metrics for glass cleanliness of substrates intended for Mo deposition for subsequent CIGS device fabrication.

Future Directions

- Give high level surface analysis support to SETP-supported PV companies and researchers, making all reasonable attempts to maintain maximum 2-week turn-around time for requests
- Examine textured crystalline silicon surfaces intended for heterojunction cells; explore surface composition as a function of the conditions used for texturing; and relate the findings to the resultant electronic properties of finished cells
- Investigate the chemical interactions occurring at interfaces of organic semiconductors
- Measure CIGS thermal decomposition and equilibrium vapor pressure; compare results with process conditions used in various NREL CIGS deposition systems
- Map uniformity of ink jet printed top contacts and underlying metal contact/adhesion layer or metal contact/AR coating interface using the PDIL XPS tool
- Develop combinatorial mapping capabilities for the large-platen AES and XPS tools.
- Enhance existing capabilities of the STF 140 Surface Analysis cluster tool by developing the ability to deposit one or more layers of a typical organic photovoltaic (OPV) device.

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1. Introduction

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) giving analytical support to SETP research participants, conversion technology researchers, and researchers in reliability; (2) collaborating and leading research on the chemistry and physics of surfaces and interfaces of PV materials; and (3) advancing the utility and understanding of our measurements by improving analytical methods and by developing new tools for in situ study of surface and interface properties.

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 we use in our work are detailed at www.nrel.gov/pv/measurements/surface _analysis.html. The group received three new pieces of equipment in FY 2009, adding significant new capabilities for surface science research: a small-spot XPS/UPS, a large-platen Auger, and a low-energy depth profiling dynamic SIMS. The group was also responsible for the M&C PDIL sample transfer robot.

During FY 2009, we continued our focus on activities related to supporting DOE SETP funded partners, and to our collaborative interactions with in-house PV conversion technology researchers. We also worked with multiple instrument manufacturers to ensure all four of our new tools were installed safely, and that they met the performance specifications listed in the contracts. This included suggesting and testing modifications to the new equipment when it did not to perform to specification. We also spent significant time integrating these new tools into program activities. Finally, we continued to conduct research leading to better understanding of various PV materials, and also work that improved our analytical results.

3. Results and Accomplishments

3.1 Support for DOE SETP Funded Partners

- CaliSolar—We continued work described in FY 2008 report developing their process for upgraded metallurgical silicon.
- 1366 Technologies—We studied phosphorous depth distribution on and between contact regions on silicon solar cells; produced scanning ion image maps of the surface showing contact regions; and also provided depth profile analysis for light element contaminants.
- Innovalight—We studied phosphorous depth distribution on and between contact regions on silicon solar cells; produced scanning ion image maps of the surface showing contact regions; and also provided depth profile analysis for light element contaminants.
- United Solar—We studied nanocrystalline cell structures grown under various conditions; we also produced light element and dopant depth distributions.
- MicroLink—We studied III-V high-efficiency cell structures and compared inverted and noninverted cell structures; we used depth profile analysis to look for diffusion of dopants, matrix elements, and light element contaminants.
- GA Tech—We collaborated with GA Tech researchers to study phosphorous and boron diffusion in belt furnace fired silicon solar cells; performed depth profiles to study metallic and light element contamination; and used SIMS to perform trace element analysis of gold remaining after black silicon texturing.
- We also collaborated with PrimeStar Solar, Ampulse, Plextronics, Global Solar Energy, and EPV Solar.

3.2 Chemical Interactions of Organic Semiconductors and Contact Materials

- Using ultraviolet photoelectron spectroscopy, we determined the band alignments for the components in a solar cell based on a new perylene-based polymer synthesized by Gregg and coworkers. The work is a key part of an article submitted to *Chemistry of Materials*.
- Collaboration with Plextronics led to a better understanding of chemical interactions between their cathode materials and active layers and resulted in changes in some of their deposition processes.
  - An innovation report was filed describing a completely new class of cathode materials for devices based on organic semiconductors.

3.3 Surface Modification of Oxides for Improved Dye-Sensitized Cells

- We quantitatively compared molecular linking schemes used in dye-sensitized cells and in

OPV devices that use ZnO using XPS, contact angle measurements, and a new technique based on a homebuilt quartz crystal microbalance-based flow reactor.

- A novel means of using ammonium chloride as a probe of self-assembled monolayer quality was introduced and used in this study.
- The phosphonic acid moiety was found to be substantially superior to the thiol group for linking organic molecules to the ZnO surface. A manuscript detailing this work was published 9/09.

3.4 Studies of Cu_2ZnSnS_4, a Novel Thin-Film Absorber Material for TW-level PV

- We initiated a project funded by the NCPV Seed-Fund Program to synthesize and study CZTS, a material that has recently attracted a great deal of interest because of its potential as a thin-film absorber based on abundant elements.
- We developed experimental capabilities that include the ability to deposit either uniform or combinatorially graded thin-film samples, and to perform in situ thermal-desorption mass spectrometry (TDMS) studies of thermodynamics and growth kinetics. We used TDMS quantify the thermal stability of thin films in the Cu-Zn-Sn ternary system, which might be used for CZTS synthesis via precursor sulfurization.
- In addition, we deposited a series of combinatorially graded Cu-Zn-Sn thin-film precursor library films in preparation for sulfurization and baseline device-processing studies.

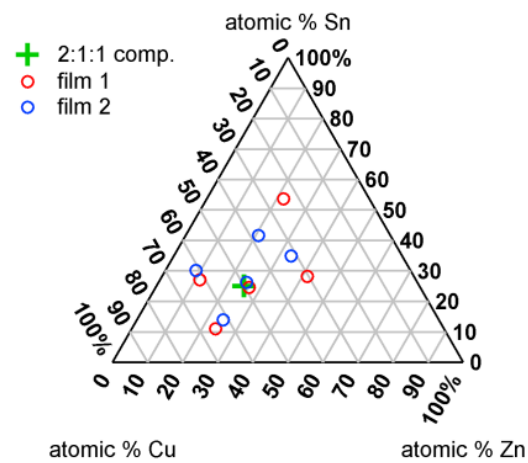
3.5 Installation and Testing of New Surface Analysis Tools

- We installed and tested the new large-platen PDIL Auger tool, and discovered errors in the stage motion and locating routines. We discussed problems and potential solutions with DCA, leading to removal and repair of the stage. After its return and reinstallation on the tool, we were able to produce large-area maps using the tool.
- Major issues reading data files into existing NREL processing software were finally resolved with the help of the software manufacturer, CasaXPS. The Auger is currently connected to the CIGS cluster tool and is awaiting growth activities to begin on this tool.
- Installed and tested the new small-spot PDIL XPS/UPS tool with flipping station.

Unfortunately there have been numerous problems with the installation and integration of these two tools, and the XPS has still not reached levels of performance necessary to attain acceptance by NREL. Most issues involve either the base pressure in the sample chamber or the reliable handling of platens. In addition, there are difficulties with the flipping/transfer station that limit the ability to move platens easily from one system to the other. Both manufacturers have worked with NREL to solve most of the problems; however, further redesigns will probably be necessary to fully resolve the issues.

- We installed and tested the new dynamic SIMS instrument. The installation was smooth and the tool was accepted after the specification tests were concluded. Subsequent, more thorough testing by NREL staff, however, revealed a significant problem with primary optics focusing under certain analytical conditions. The manufacturer acknowledged an unforeseen design flaw existed, after NREL brought the problem to their attention. They have been cooperating with NREL staff to reach a workable solution.

Fig. 1. Combinatorially graded Cu-Zn-Sn metal



precursor films.

4. Planned FY 2010 Activities

The Surface Analysis team will focus on several activities. Many of these activities will employ the new PDIL tools to relate changes in surface chemistry and composition across a large area to variations in material quality or device performance or both.

- Give Surface Analysis support to DOE SETP supported PV companies and researchers; make all reasonable attempts to maintain maximum two-week turn-around time for analytical requests
- Examine textured crystalline silicon surfaces intended for heterojunction cells to explore optimal surface preparation as a function of the conditions used for texturing, and relate the findings to the resultant electronic properties of finished cells
- Investigate the chemical interactions occurring at interfaces of organic semiconductors
- Measure CIGS thermal decomposition and equilibrium vapor pressure. Time permitting, compare results with process conditions used in various NREL CIGS deposition systems
- Map uniformity of ink jet printed top contacts and underlying metal contact/adhesion layer or metal contact/AR coating interface using PDIL XPS tool
- Develop combinatorial mapping capabilities for large-platen AES and XPS tools
- Enhance existing capabilities of STF 140 Surface Analysis cluster tool by developing ability to deposit one or more layers of a typical OPV device.

5. FY 2009 Special Recognitions, Awards, and Patents

NREL Innovation Report #IN 09-19 was filed describing a completely new class of cathode materials for devices based on organic semiconductors.

NREL is developing terms for "license to technology" with industrial partner and co-inventor Beneq. The license will guarantee royalty income to NREL from ALD tools built by Beneq that use our joint invention for production of moisture barriers.

6. Major FY 2009 Publications

T.A. Gessert, W.K. Metzger, P. Dippo, S.E. Asher, R.G. Dhere, and M.R. Young, "Dependence of Carrier Lifetime on Cu-Contacting Temperature and ZnTe:Cu Thickness in CdS/CdTe Thin Film Solar Cells," *Thin Solid Films* **517**(7), 2370 (2009).

C.S. Jiang, H.R. Moutinho, R. Reedy, M.M. Al-Jassim, and A. Blosse, "Two-Dimensional Junction Identification in Multicrystalline Silicon Solar Cells by Scanning Kelvin Probe Force Microscopy," *J. Appl. Phys*. **104**(10), Article No. 104501 (2008).

X. Li, J. Pankow, and Y. Yan, "Impurity Study of Optical Properties in Fluorine-Doped Tin Oxide for Thin-Film Solar Cells," *Materials Research Society Symposium Proceedings (Thin-Film Compound Semiconductor Photovoltaics), 2009.*

C.L. Perkins, "Molecular Anchors for Self-Assembled Monolayers on ZnO: A Direct Comparison of the Thiol and Phosphonic Acid Moieties," *J. Phys. Chem. C* **113**, 18276 (2009).

C.L. Perkins, B. Egaas, I. Repins, and B. To, "Quantitative Analysis of Graded Cu(In1-x,Gax)Se_2 Thin Films by AES, ICP-OES, and EPMA," submitted to *Surface and Interface Analysis*.

I. Repins, W.K. Metzger, C.L. Perkins, J.V. Li, and M.A. Contreras, "Measured Minority-Carrier Lifetime and CIGS Device Performance," *Proc. 34th IEEE Photovoltaics Specialists Conference, Philadelphia, PA, June 7-12, 2009.*

G. Teeter, "A Model for Bulk-Diffusion-Coupled Surface Segregation Kinetics and Equilibria," to be submitted.

G. Teeter, "A Model for Dopant or Impurity Migration in Device Heterostructures," to be submitted.

D.L. Young, H.M. Branz, F. Liu, R. Reedy, B. To, and Q. Wang, "Electron Transport and Band Structure in Phosphorus-Doped Polycrystalline Silicon Films," J. Appl. Phys. **105**(3), Article No. 033715 (2009).

G.D. Yuan, Z.Z. Ye, J.Y. Huang, L.P. Zhu, C.L. Perkins, and S.B. Zhang, "X-ray Photoelectron Spectroscopy Study of Al- and N- Co-doped p-type ZnO Thin Films," *J. Crystal Growth* **311**(8), 2341 (2009).

M. Woodhouse, C.L. Perkins, M.T. Rawls, R.A. Cormier, Z. Liang, A.M. Nardes, and B.A. Gregg, "Non-Conjugated Polymers for Organic Photovoltaics: Physical and Optoelectronic Properties of Poly(perylene diimides)," submitted *J. Phys. Chem. C*.

Cell and Module Performance

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Keith Emery (NREL), 303-384-6632, keith.emery@nrel.gov

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

FY 2009 Budget: $2,200K (NREL)

Objectives

- Support contact technical monitors, SETP partners, and the photovoltaic (PV) industry by furnishing 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 solar 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

- Gave measurement support in cell and module performance to more than 260 PV research partners in industry, academia, and NREL; even more groups were supported via phone conversations, emails, and visits detailing all aspects of cell and module PV I-V and QE measurement technology
- Assisted Newport in becoming a certified secondary cell calibration facility
- Gave site visit and tutorials to UL to assist in PV testing procedures at their San Jose, CA, plant; continue to support, at highest possible level, all current and future U.S. based certified cell and module testing groups
- Maintained ISO 17025 accreditation for primary and secondary cell and module calibrations
- Chaired the November 2008 ASTM E44.09 PV standards meetings, and served as the secretary for the E44 main committee as well as the chair of the PV technical subcommittee; member of IEC TC82 working groups 2 and 7; active in writing, shepherding, and developing the technical basis for all ASTM and IEC standards related to cell and module performance evaluation
- Supported the U.S. terrestrial PV community by transferring performance measurement technology via emails, tours, day-long technical visits at NREL, visits to partner sites, phone conversations, and publications.

Future Directions

- Continue to support SETP subcontracted program at the highest possible priority and level
- Continue to support the U.S. terrestrial PV community by transferring performance measurement technology and furnishing 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 multijunction technologies
- Maintain ISO 17025 accreditation for primary and secondary cell and module calibrations.

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1. Introduction

This agreement has been performing PV performance measurements for the U.S. terrestrial PV community since 1980. We have kept that community "on the same page" in terms of performance ratings and efficiency measurements by providing these groups with

calibrations upon request. PV performance measurement technology relating to algorithms, procedures, and equipment capabilities and limitations have been routinely transferred to academia, PV cell and module manufacturers, and equipment suppliers. This project has supported, directly or indirectly, nearly all EERE activities relating to PV cell and module development. This project has advanced the state of the art in performance characterization in many areas, and has been active in ASTM and IEC PV standards development.

2. Technical Approach

This agreement employs six different solar simulator based current versus voltage test beds illuminated by different light sources with different but complementary capabilities for evaluating prototype cells, concentrator cells, commercial cells, flat plate modules, and concentrator modules of any conceivable size and technology. The test beds are designed to be able to evaluate performance with respect to standard reporting conditions defined by total irradiance (1-sun = 1000 Wm^{-2}), spectral irradiance (IEC 60904-3 / ASTM G173), and temperature (25°C). The group has two outdoor test beds for taking single-point measurements on flat plate modules and for evaluating performance of concentrator modules over time.

The unique contributions of the project include giving PV manufacturers and research labs accurate certified PV performance calibrations; offering extensive consulting on performance measurement procedures, equipment, and software; and developing the measurement science and methods that allow for state-of-the-art cell and module performance characterization. For example, we have led the community in multijunction measurement procedures and procedures to evaluate high-efficiency, multijunction concentrator cells and modules.

The major scientific and technical issue is that, despite being the most capable PV performance characterization lab in the world, our measurement uncertainties are still too large for some customers.

3. Results and Accomplishments

- *Furnish routine and specialized measurement and characterization support for PV program research and industry teams:*

During FY 2009, the team evaluated numerous contract deliverables and stage-gate milestones at the cell and module level. We evaluated stage-gate milestones consistently in less than 1 week from arriving in the lab (2 weeks for concentrator cells) by giving these requests the highest possible priority at the expense of other requests in the queue. During FY 2009, independent efficiency measurements and reference cell and module calibrations were performed on 2,631 cells and modules for 261 groups. There were 5,140 cell I-V, QE, and linearity measurements on 1,496 samples, and 3,839 I-V measurements on 905 modules. All of these measurements were subjected to the team's rigorous ISO 17025 quality system of data collection and review. The team also performed on-site stage-gate measurements on a prototype concentrator module following ASTM E2527 for the Skyline Solar PV-Incubator subcontract. The prototype concentrator module test bed took 78,618 I-V curves on nine modules, including SAI partners Amonix, Boeing, Solfocus, and Spectrolab. Multijunction prototype concentrator modules from Semprius Solar, Greenvolts, Daido Steel, and Fraunhofer ISE were also evaluated.

To improve the calibration accuracy and traceability of key DOE partners, the team calibrated 10 primary reference cells with formal ISO 17025 accredited calibration certificates for Sandia and FSEC.

We completed internal and external audits by A2LA to verify the team's compliance with ISO 17025 requirements regarding our quality system, equipment calibrations, software, and documentation. This is critical for other DOE labs like Sandia, industry, and research partners to have an accurate and formal calibration traceability path so the peak watt rating for PV is a useful rating. This lab is the only one in the nation that has formal primary reference cell calibration capability. The other three labs worldwide are PTB in Germany, AIST in Japan, and The EU Joint Research Center in Italy. Intercomparisons with these labs are conducted annually to document how the team's calibrations compare with values from around the world.

- *In-House Support and Collaborative R&D:*

In support of the NCPV, the team maintained

user facilities for IV and QE measurement calibrations and trained users in procedures to minimize measurement errors. We also maintained our 35-year-old simulator and 15-year-old test bed, which required frequent maintenance, and updated system software to meet changing research requirements. The in-house reliability program was also supported with the highest possible priority measurements to minimize the time the samples are not being stressed. During FY 2009, we evaluated more than 1,320 modules in support of the reliability group, as well as hundreds of samples of all cell technologies for in-house groups for independent efficiency measurements reported on samples fabricated at NREL.

- *Large-Area Module Solar Simulator Installation and Certification:*

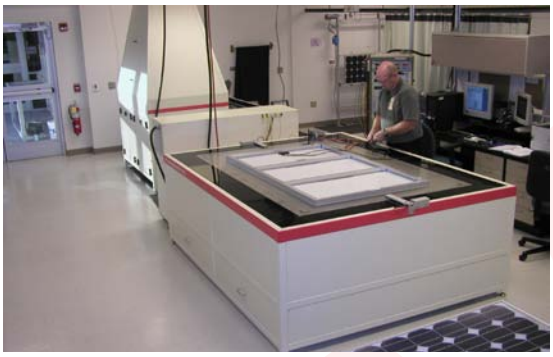

Fig. 1. The Spire 4600 long pulse solar simulator was delivered in May 2008.

After acceptance testing and development of the software to meet the team's standards, the Spire 4600 long pulse solar simulator was certified as operational and customers' samples were being measured beginning in August 2009. Several significant software issues in Spire's code were identified and communicated to Spire. The spatial nonuniformity of the simulator meets ASTM and IEC guidelines for a Class A simulator but meets only class C non-uniformity specifications for small pixel sizes complicating the procedures and uncertainty analysis. The manufacturer was alerted that this issue could be a serious problem for thin-film modules where the cells are long and narrow. This is also being discussed in the standards arena because the uniformity specification in the IEC and ASTM simulator standard did not account for a simulator with large uniformity differences as the pixel area changes from 4 to 100 or 200 cm^2.

- *Multisource Concentrator Solar Simulator Development:*

The Spectrolab THIPSS spectrally adjustable concentrator solar simulator purchase order was placed on October 2008, and the unit is scheduled to be delivered May 2010. The delivery was delayed for several reasons, including expanded range and software capabilities required to meet the needs of the PV concentrator community.

- *Multisource 1-Sun Solar Simulator Development*:

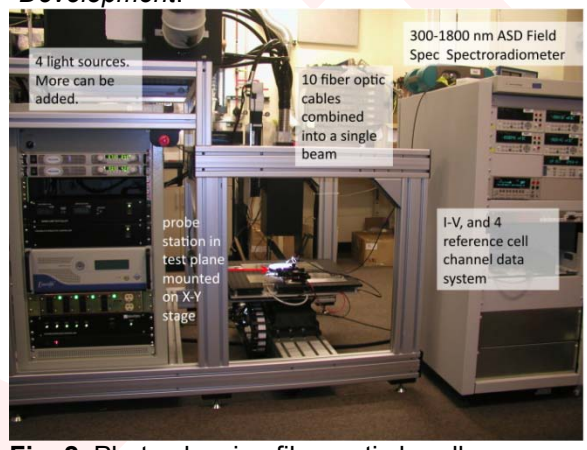

Fig. 2. Photo showing fiber optic bundle delivering light in nine spectrally adjustable bands to the test plane.

A new multisource 1-sun solar simulator, designed by Sphere Optics (now Labsphere), was delivered in July 2008, four months behind schedule. The unit failed to meet multiple critical performance criteria detailed in the specifications, including beam size (15 x 15 cm), ability to match the reference spectrum in selected bands, and failure of the Xe lamps to operate at Denver's elevation. We are working closely with Labsphere, and they are devoting significant resources to resolve these problems. Before this purchase, the largest fiber optic based simulators (research or commercial) had beam sizes of only a few square centimeters and were not spectrally adjustable. This unique simulator will be able to map out the spectral sensitivity at or below 1-sun for any conceivable multijunction technology. The data acquisition system, probe station, and temperature-controlled plates were purchased and installed. The software was written and debugged to the extent possible without a working simulator.

4. Planned FY 2010 Activities

- Furnish routine and specialized measurement and characterization support for PV program research and industry teams; support subcontractors (Technology Pathway Partnerships and PV Incubator) at the highest level possible
- Maintain full ISO 17025 accreditation for primary reference cell, secondary reference cell, and secondary module calibrations
- Continue active membership and participation in ASTM and IEC WG2 and WG7 PV cell and module standards activities
- Include the SPI4600 long pulse simulator in the team's scope of ISO 17025 accreditation
- Resolve the failures to meet specifications and bring the spectrally adjustable 1-sun simulator to an operational status
- Accept delivery of concentrator multisource simulator, verify that the unit meets performance specifications, and bring to an operational status.

5. FY 2009 Special Recognitions and Awards

NCPV received the 2009 Colorado Governor's Award for Research Impact in the area of renewable energy for its work on thin film solar cells; gave presentation showcasing the team's contribution to this award.

6. Major FY 2009 Publications

A. Barnett, D. Kirkpatrick, C. Honsberg, D. Moore, M. Wanlass, K. Emery, R. Schwartz, D. Carlson, S. Bowden, D Aiken, A. Gray, S. Kurtz, L. Kazmerski, M. Steiner, J. Gray, T. Davenport, R. Buelow, L. Takacs, N. Shatz, J. Bortz, O. Jani, K. Goossen, F. Kiamilev, A. Doolittle, I. Ferguson, B. Unger, G. Schmidt, E. Christensen, and D. Salzman, "Very High Efficiency Solar Cell Modules," *Prog. Photovoltaics Res. Applicat.* **17**, 75 (2009).

J.A. del Cueto, C.A. Deline, D.S. Albin, S.R. Rummel, and A. Anderberg, "Striving for a Standard Protocol for Preconditioning or Stabilization of Polycrystalline Thin Film Photovoltaic Modules," *SPIE 2009 Conference 7412, San Diego, CA, Aug. 2009*.

K. Emery, "Cell and Module Level Testing Procedures and Intercomparisons," *International Photovoltaic Reliability Workshop II, Tempe, AZ, July 29-31, 2009*.

K. Emery, *Uncertainty Analysis of Certified Photovoltaic Measurements at the National Renewable Energy Laboratory*, NREL/TP-520-45299, Golden, CO: NREL (August 2009).

M.A. Green, K. Emery, Y. Hishikawa, and W. Warta, "Solar Cell Efficiency Tables (version 33)," *Prog. Photovoltaics Res. Applicat.* **17**, 85 (2009).

M.A. Green, K. Emery, Y. Hishikawa, and W. Warta, "Solar Cell Efficiency Tables (version 34)," *Prog. Photovoltaics Res. Applicat.* **17**, 320 (2009).

A. Kimber, T. Dierauf, L. Mitchell, C. Whitaker, T. Townsend, J. NewMiller, D. King, J. Granata, K. Emery, C. Osterwald, D. Myers, B. Marion, A. Pligavko, A. Panchula, T. Levitsky, J. Forbess, and F. Talmud, "Improved Test Method to Verify the Power Rating of a Photovoltaic (PV) Project," *Proc. 24th IEEE PVSC, Philadelphia, PA, June 8–12, 2009*.

M.A. Steiner, M.W. Wanlass, J.J. Carapella, A. Duda, J.S. Ward, T.E. Moriarty, and K.A. Emery, "A Monolithic Three-Terminal GaInAsP/GaInAs Tandem Solar Cell," *Prog. Photovoltaics Res. Applicat.* **17**, 587 (2009).

X. Wang, N. Waite, P. Murcia, K. Emery, M. Steiner, F. Kiamilev, K. Goossen, C. Honsberg, and A. Barnett, "Improved Outdoor Measurements for Very High Efficiency Solar Cell Sub-modules," *Proc. 24th IEEE PVSC, Philadelphia, PA, June 8–12, 2009*.

7. University and Industry Partners

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

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PDIL Development & Integration Laboratory Summary

The Process Development and Integration Laboratory (PDIL) is a collaborative facility that provides specially designed and unique research tools to accomplish the following vision for the U.S. Solar Program:

- Shorten the time necessary to transfer a PV technology from the laboratory to pilot production by facilitating an improved understanding of process integration issues that are critical to successfully scaling a technology.
- Assist the U.S. industry by providing access to state-of-the-art capabilities and scientific expertise in the areas of materials deposition, processing, and characterization.
- Facilitate the development of next-generation PV technologies by providing a dynamic research capability that encourages innovation and helps develop the scientific foundation necessary to commercialize a new technology.

The PDIL will provide the largest known collection of integrated PV-specific capabilities supporting multiple PV technologies. It is operated as a collaborative facility between research partners and core NCPV research staff.

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
PDIL Development & Utilization	**2692**	**0**	**0**	**2692**
PDIL Hardware Development	**1692**	**0**	**0**	**1692**
PDIL Software Integration	**660**	**0**	**0**	**660**
PDIL Project Management	**340**	**0**	**0**	**340**

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Process Development and Integration Laboratory Hardware Development, Software Integration, & Management

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Brent Nelson (NREL), 303-384-6407, brent.nelson@nrel.gov

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

FY 2009 Budget: $1,692K (NREL)

Objectives

Hardware Development

- Ensure hardware standards are followed in equipment design and implementation.
- Ensure DOE and NREL EHS requirements are followed
- Coordinate acquisition, site preparation, equipment installation, and optimization
- Install hardware into the Process Development and Integration Laboratory (PDIL).

Software Integration

- Furnish the necessary file structures and database schema supporting the PDIL data products
- Create a data technology bridge allowing PDIL researchers to access the high-level analysis tools of the Computational Sciences Center (CSC)
- Develop or improve automation systems for sample handling, data acquisition, and equipment diagnostics
- Develop intuitive user interfaces to access raw data, derive logical data sets, and support knowledge extraction
- Furnish security to ensure that the PDIL network is protected and monitored and that all data products are encrypted, transferred, and stored securely.

Management

- Give financial (acquisition) guidance to the core groups and tool owners
- Furnish project management support for tool installations
- Communicate PDIL capabilities to the photovoltaics (PV) community at large
- Continue ongoing management of the physical assets of the PDIL

Accomplishments

Hardware Development

- Delivered and installed the CIGS cluster tool
- Delivered and installed the Atmospheric Processing Platform (APP)
- Enhanced the thin-film silicon cluster tool with VHF capabilities
- Designed and specified the silicon wafer replacement tool (thin crystal silicon film).
- Designed and specified the CdTe cluster tool
- Installed the Auger electron spectroscopy (AES) tool.
- Installed the X-ray photoelectron spectroscope (XPS)
- Installed the scanning electron microscope (SEM)
- Installed the atomic force microscope (AFM)
- Installed the wet chemistry processing station
- Installed the reflectance spectroscopy tool
- Installed the spectroscopic ellipsometry tool.

Software Integration

- Completed a PDIL network, file structure, and database schema
- Established a data interface and strong personnel working relationship with the CSC, giving us access to their high-end analysis tools
- Made the PDIL data infrastructure fully DOE cyber security compliant
- Gave data access at project level need-to-know and controlled by project PIs

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- Created software development process to monitor changes and documentation
- Developed methods and techniques of PV informatics to be used on actual PDIL data.

Management

- Gave financial (acquisition) guidance to the core groups and tool owners
- Furnished project management support for tool installations
- Communicated PDIL capabilities to the PV community at large
- Continued ongoing management of the physical assets of the PDIL.

Future Directions

Hardware Development

- Furnish hardware support to optimize tool operation
- Install the optical processing furnace
- Oversee fabrication of the silicon wafer replacement tool
- Oversee fabrication of the CdTe cluster tool
- Fully integrate the resonance-coupled photoconductive decay (RC-PCD) tool on the measurements and characterization (M&C) vacuum robot
- Fully integrate the photoluminescence (PL) imaging on the M&C vacuum robot
- Fully integrate the sputtering / plasma etching tool on the M&C vacuum robot
- Fully integrate the plasma-enhanced chemical vapor deposition (PECVD) tool on the M&C vacuum robot.

Software Integration

- Automate scientific and process data extraction so that researchers have access to meta- and derived data on the atmospheric processing tool and the CIGS cluster tool important to science
- Integrate arrays of spectral data for extracting information to surface analysis and analytical microscopy tools in the PDIL, especially related to CIGS data
- Continue to integrate PDIL data, via applied informatics, into a PV Informatics Toolkit.

Management

- Give financial (acquisition) guidance to the core groups and tool owners
- Furnish project management support for tool installations
- Communicate PDIL capabilities to the PV community at large
- Continue ongoing management of the PDIL physical assets

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1. Introduction

The PDIL is a unique collaborative facility where industry and universities can work closely with NREL scientists on integrated equipment to answer pressing questions related to PV material and device development. It is the only fully integrated R&D laboratory dedicated to resolving the unique challenges of PV applications. The facility includes complementary deposition, processing, and characterization tools that can share 157 x 157 mm (~6-inch) samples in a controlled atmosphere. We work with a wide range of PV materials from wafer silicon to organics, including the various thin films (e.g., crystalline Si, amorphous Si, microcrystalline Si, copper indium gallium diselenide, and cadmium telluride). Integrated characterization techniques allow us to probe chemical compositional, morphological, and structural properties of materials and interfaces immediately after material growth without exposing a surface to air. The ability to transport a device part way through cell fabrication, in a controlled ambient environment, to a large number of characterization tools, and then return the sample to complete the device, allows us to gain knowledge about how material properties and interface characteristics affect cell performance.

2. Technical Approach

The PDIL directly supports industrial collaborations as well as in-house research. Support for the PV industry presents unique challenges. Although essentially all PV devices share a common circuit design (one or more p-n junctions in series), an immense range of materials and processes are manufactured and investigated. It is useful to compare the associated challenges with the microelectronics industry, which shared a single material and geometry (round silicon wafers). This commonality greatly facilitated cooperation between manufacturers, equipment fabricators, material suppliers, and

researchers. In contrast, the PV industry lacks standardization or even standard product sizes. To have an integrated toolset, we implemented a size, geometry, and transfer standard that enables cooperation but is flexible enough to accommodate the unique needs of multiple PV technologies. The standard chosen consists of a 178 x 178 mm (7 x 7 in.) frame, or platen, capable of handling samples up to 157 x 157 mm. The PDIL Hardware Agreement supports the efforts of the core groups in developing their PDIL tool sets.

Fig. 1. The CIGS cluster tool in Bay 1 of the PDIL.

3. Results and Accomplishments

Hardware

The central robot and three sputtering chambers for ZnO, CdS, and Mo were added to the CIGS MBE chamber and are installed in PDIL Bay 1 (Fig. 1). This cluster tool gives the PDIL the functionality to fabricate a full CIGS device with all dry processes.

Fig. 2. The APP in Bay 2 of the PDIL.

The APP was installed in PDIL Bay 2 (Fig. 2); it consists of both a spray-jet and an ink-jet printer for depositing metals, semiconductors, transparent conducting oxides, and other solar cell materials. These deposition capabilities are in controlled ambient glove boxes and supported by a rapid thermal annealer, XRF, and XRD, also in glove boxes. The platform also has a vacuum robot to interface to the PDIL intertool transport pod and evaporation and sputtering capabilities. Added to the existing M&C tools during FY 2009 were the SEM, XPS, and reflectance spectrometer in PDIL Bay 5 (Fig. 3).

Fig. 3. Standalone M&C equipment in Bay 5 of the PDIL.

Much of the integrated M&C cluster tool was installed in PDIL Bay 6: the central vacuum robot (Fig. 4), the spectroscopic ellipsometer tool (Fig. 5), the RC-PCD, and PL imaging tools (Fig. 6).

For complete details of PDIL capabilities, see (http://www.nrel.gov/pv/pdil/capabilities.html). The intertool mobile transport pods underwent several design changes in FY 2009 because of inconsistencies in floor levelness from tool to tool. This project is behind schedule, but is a top priority for FY 2010.

Software

The necessary file structures and database schema was developed; it is the key architecture for proper archiving and data handling for PDIL tools. This was a level 4 milestone for FY 2009. It supports the creation of automated data pipelines for the heterogeneous PDIL assets, methods for system monitoring, and automated acquisition of the data products across the network. Significantly, it also is the infrastructure for moving and storage of the data to the CSC data archives by establishing data formats and files structures that work in concert with their advanced parallel computing systems and analysis codes. A file download portal was added to facilitate the scientists' ability to download their files.

Fig. 4. Central robot and load lock on the integrated M&C cluster tool in Bay 6 of the PDIL.

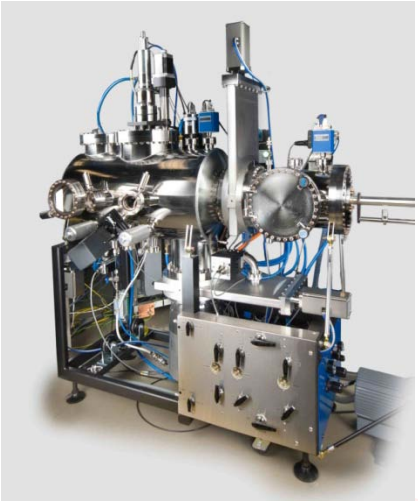

Fig. 5. Spectroscopic ellipsometer tool on the integrated M&C cluster tool in Bay 6 of the PDIL.

The PDIL group continued integrating PDIL data products into the established infrastructure. An intuitive user interface was developed to access the raw data, derive logical data sets, and furnish knowledge extraction capabilities to researchers in the PDIL. We also wrote a data user manual to educate users on how to use these tools. This interface will undergo continuous improvement based on feedback from data generators and data analysis collaborators.

The PDIL software architecture was expanded to include a fully compliant web and application server on the NREL moderate enclave, separating test and development systems from production systems. The development process was then enhanced to include software path-to-production concepts, enabling future development in a robust, industry-standard methodology, where new software and database concepts are fully tested and processed through change control procedures before being moved to production.

Fig. 6. Photoluminescence imaging tool on the integrated M&C cluster tool in Bay 6 of the PDIL.

The PDIL data infrastructure was made fully DOE cyber security compliant, protecting proprietary data products from inadvertent and targeted losses.

4. Planned FY 2010 Activities

Hardware

The PDIL group will continue to support acquiring and installing the thin-crystal silicon film (a.k.a., silicon wafer replacement) cluster tool, the CdTe cluster tool, and both the sputtering/plasma diagnostic and PECVD chambers on the integrated M&C cluster tool.

Software

This task will fully integrate the operational equipment of the PDIL into the automated data services of the PDIL. This includes the CIGS, atmospheric processing, silicon cluster, TCO, SEM, AFM, XPS, Auger, reflectometer, and ellipsometry. It will ensure that the acquisition and data system of the CdTe and Si-wafer replacement tools is compatible with PDIL data standards. It will also automate the actual operation of the electro-optical and surface analysis tools on the M&C central robot. This task continues work to develop a data technology bridge to the CSC.

Systems Development Highlights

A significant portion of the photovoltaic (PV) subprogram R&D budget falls into the Systems Development category. The goal of Systems Development is to rapidly advance the maturity and performance of commercial and near commercial PV manufacturing technologies.

Systems Development comprises the following areas:

- PV Systems Development
- PV Component Development
- Operations and Planning.

Within PV Systems Development is a major program initiated in 2007. Technology Pathway Partnerships (TPPs) are industry-led projects that emphasize the development, testing, demonstration, validation, and interconnection of new PV components, systems, and manufacturing equipment. TPPs focus on technologies at the more advanced stage of maturity that are closer to the market but still face significant technological hurdles that can be overcome through partnership based research and development. TPPs are developed with clear levelized cost of energy (LCOE) metrics that helps focus awardees to address Total System Costs. TPPs have a minimum cost share requirement of 50%.

Within the PV Component Development area is an innovative program that supports small companies in the development of new PV technologies. The PV Incubator Program supports the transition of verified PV devices to prototype products and early pilot production by leveraging National Renewable Energy Laboratory (NREL) R&D resources and mitigating risk through fixed firm pricing contracts.

	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Systems Development	**15204**	**591**	**50522**	**66342**
PV Systems Development	**964**	**200**	**45450**	**46614**
PV Component Development	**13726**	**50**	**0**	**13776**
Operations & Planning	**514**	**341**	**5072**	**5952**

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Technology Pathway Partnerships

Performing Organizations: Amonix; The Boeing Company; BP Solar, Inc.; Dow Chemical Company; GE Global Research; GreenRay, Inc.; Konarka Technologies, Inc.; Nanosolar, Inc.; Soliant Energy, Inc.; Sunpower, Inc.; United Solar Ovonic LLC, 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
Leon Fabick, DOE/GO, 303-275-4958, leon.fabick@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: Scott Stephens, (202) 586-0565, Scott.Stephens@ee.doe.gov

FY 2009 Budgets: $42,339K TPP Recipients, $964K (NREL), $200K (SNL)

Objectives

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

Accomplishments

- Continued 11 Technology Pathway Partnership (TPP) awards into FY 2009
- Assessed TPP Program Progress against objectives; Evaluated technology viability and ability to meet program critical criteria for 2010 objectives
- Completed six Phase I Stage-Gate Reviews and three Phase II Stage Gate Reviews in FY 2009; remaining reviews anticipated for FY 2010 completion.

Future Directions

- Develop PV systems that by 2015 produce electricity at parity with the cost of electricity in select grid-tied target markets across the nation and expand the U.S.-installed domestic capacity of PV systems to 5 to 10 GW.

1. Introduction

The TPP is an integral part of the Solar Energy Technologies Program (SETP). The TPP represents a significant enhancement of the U.S. Department of Energy's (DOE's) business strategy of partnering with entities in the industry to accelerate commercialization of PV system R&D to meet ambitious cost and installed-capacity goals.

The TPP program will accelerate commercialization of solar PV systems by 2015.

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

- Accelerate development of U.S.-produced PV systems substantively, so that PV-produced electricity reaches parity with the cost of electricity in select grid-tied target markets across the nation (see Table 1)
- Expand the U.S.-installed domestic capacity of PV systems to 5 to 10 GW.

The cost basis of electric energy in these markets is the kilowatt hour; therefore the 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. Table 1 lists the overall cost goals for the TPP projects.

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

Market Sector	Current U.S. Market Range (¢/kWh)[1,2]	Solar Electricity Cost—Current and Projected (¢/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 program focuses 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 kW 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 CCT plants) for wholesale. Utility systems typically are ground-mounted and range in size from 1 to 100 MW, although much larger systems are being developed. Designs include both fixed and tracking configurations.

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

- *Industry-led*: Applicants formulate all technical details regarding approach, timelines, milestones, and system integration. The national laboratories give critical support to DOE in monitoring technical progress, conducting tests and evaluations, and directly supporting TPPs on specific R&D tasks.
- *Focused on near- and mid-term results*: Emphasis is on technologies with the greatest potential for cost-competitiveness in the period leading up to 2015.
- *System focus*: The primary metric for the TPP program is the LCOE, based on the complete PV system rather than any component. TPP is working toward novel, integrated, PV systems.
- *Partnerships*: Industry participants are strongly encouraged to formulate partnerships to address the spectrum of possible technical improvements in the PV-system value chain.
- *Market-based*: All technical objectives established through SETP directly affect the market-based goals for cost, penetration, and job creation..

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

- 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 intensity of manufacturing scale-up through targeted investments in such areas as equipment/feedstock suppliers and distribution channels.

The 11 awards must demonstrate the benefits of their project based on the 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.

Total 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 costs.

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 milestones or decision points. After the stage-gate review, DOE makes a determination about the continuation of the project into the next budget period.

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 DOE LCOE cost targets for their technology. The LCOE values depend on system performance and manufacturing costs; therefore these quantities are evaluated independently (performance evaluated by NREL/Sandia and cost evaluated by an independent contractor to DOE) to ensure that they are sufficient to demonstrate the stage-gate criteria were met. DOE conducts a programmatic review and decision to continue to the next phase as proposed, continue to the next phase with modifications, hold the project until more information is available, or discontinue the project. Figure 1 shows the steps of the stage-gate process.

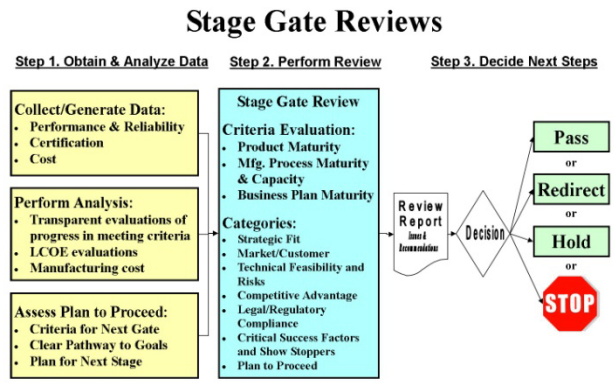

Fig. 1. Stage-gate review process.

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 provided by NREL and SNL.

This management approach uses a technical monitor who is cognizant of the technology being developed. Technical monitors are from one of the National Center for Photovoltaics laboratory partners (NREL or SNL). 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 progress of TPP projects.

In this capacity, they give substantial technical assistance and guidance, facilitate interactions with additional technical experts as needed, and ensure timely access to DOE-funded laboratory resources when required for the project (e.g., test facilities). The technical monitors also perform technical 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 participate in, and make recommendations from, the stage-gate reviews.

3. Results and Accomplishments

Amonix Inc.: Fielded the Amonix 7700 Solar Power Generator equipped with III-V, multijunction solar cells.

Boeing Co.: Increased average production lot cell efficiency to 28.5% and demonstrated cell

efficiency > 39% using experimental metamorphic cells; completed proof of design for CPV system deployed and under test at multiple locations.

BP Solar Inc.: Demonstrated 18.35% Mono^{2TM} top performing cell.

GreenRay Inc.: Verified 50-year inverter lifetime with in-house stress testing.

Konarka Technologies Inc.: Demonstrated the utility of adhesive fillers for stabilizing modules that allow > 1,000 hours of stable performance at 65°C/85% humidity.

Nanosolar Inc.: Completed TUV panel certification and also passed the requirements for a UL Class A fire rating.

Soliant Inc.: Designed and built pilot plant capable of producing more than 1 MWp per year of manufactured tracking/concentrating solar panels.

SunPower Inc.: Achieved world-record panel efficiency at 20.4%, as verified by NREL.

United Solar Ovonic LLC: Obtained NREL-confirmed 11.7% stable total-area efficiency on a-Si:H/nc-Si:H/nc-Si:H triple-junction device.

3.1 Stage-Gate Reviews

Six Phase I stage-gate reviews were completed during FY 2009. Results of the reviews are as follows.

- Dow Chemical Co. (11/06/08); Hold, pending revised testing results of flexible roofing product.
- GE Global Research Inc. (11/29/08); Project not continued. Met Phase I technical objectives. See OSTI database (http://www.osti.gov/) for detailed technical results.
- Nanosolar Inc. (11/29/08): Pass to Phase II; on track to meet project targets, proceed as planned.
- SunPower Inc. (11/30/08): Pass to Phase II, continue to fund project at a reduced level of effort.
- BP Solar Inc (01/27/09): Pass to Phase II; on track to meet project targets, proceed as planned.
- Soliant Energy Inc. (02/10/09): Pass to Phase II; on track to meet project targets, proceed as planned.

Three Phase II stage-gate reviews were completed during FY 2009. Results of the reviews are as follow:

- The Boeing Co. (07/15/09): Pass to Phase II; on track to meet project targets, proceed as planned.
- Konarka Technologies (08/25/09): Pass to Phase I; on track to meet project targets, proceed as planned.
- GreenRay Inc. (08/27/09): Pass to Phase II; on track to meet project targets, proceed as planned.

3.2 TPP Awardee Progress

Progress for each TPP awardee is summarized in this report.

4. Planned FY 2010 Activities

Stage gates anticipated for FY 2010 are shown in Table 2.

Table 2. TPP Award Recipients, FY 2009 Funding, Stage-Gate Schedule

TPP Recipient	FY 2009 Obligation	Start Date	Stage-Gate I Date	Stage-Gate II Date
Amonix Inc.	$5,740,496	5/14/07	6/24/08	10/20/09
The Boeing Co.	$4,216,900	7/1/07	6/26/08	7/15/09
BP Solar Inc.	$3,934,505	9/1/07	1/27/09	1/26/10
Dow Chemical Co.	-	8/1/07	11/06/08	Pending

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GE Global Research Inc.	$1,265,464	9/1/07	11/19/08	*
GreenRay Inc.	$1,149,515	1/1/07	6/18/08	8/27/09
Konarka Technology Inc.	$866,421	7/1/07	9/4/08	8/25/09
Nanosolar Inc.	$8,096,247	9/1/07	11/29/08	11/4/09
Soliant Energy Inc.	$1,081,928	9/1/07	2/10/09	4/10
SunPower Corp.	$9,552,817	9/1/07	11/30/08	11/5/09
United Solar Ovonics LLC	$5,434,499	4/30/07	8/27/08	11/13/09

*Project completed 6/30/09.

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TPP Awardee: Amonix Inc.

"Low Cost High Concentration Photovoltaic Systems for Utility Power Generation"
Total Award Amount: $33,635,272; DOE/Recipient Share: $15,605,631/$18,029,642

Objectives

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

Accomplishments

- Fielded the Amonix 7700 Solar Power Generator equipped with III-V multijunction solar cells
- Developed a parameter model well correlated to more than 12 months of field performance
- Compiled energy performance data for a proposed IEC energy rating specification for concentrating photovoltaics (CPV)
- Conducted accelerated life tests under an NREL CRADA for validating and improving cell package designs
- Sent representative test modules to UL for certification to IEC 62108 and UL 8703
- TUV conducted tests on representative modules to obtain CEC listing
- Sandia measurements of MegaModule performance exceeded stage-gate milestones for Phase II and Phase III
- Completed Amonix LCOE roadmap out to 2015 with SAM results falling within LCOE goal ranges set out by the DOE SETP
- Based on TPP accomplishments, Amonix identified a major investor for the next round of funding needed to commercialize Amonix' CPV systems.

Future Directions

- Complete IEC 62108 qualification and UL 8703 safety certification
- Demonstrate 25 MW/year manufacturing facility
- Expand reliability studies through system deployment, compilation of reliability data, and investigation of lifetime determination methods.

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1. Introduction

The principal objectives of this project are to meet DOE's LCOE goals for 2015 and enable Amonix to successfully compete in large-scale utility markets with its CPV systems. The project consists of tasks leading to reduced material costs, system performance increases, improvements in reliability. and, most important, cost reductions owing to high-volume manufacturing.

2. Technical Approach

Amonix expanded its production capacity to 25MW/year by building a production line for automated manufacturing of all components of the MegaModule, including cell packages, receiver plate, and module structure.

During the first phase, all effort shifted from silicon to III-V multijunction cells to more quickly meet the TPP LCOE goals. Although this shift entailed additional risk, a significant payoff was realized by incorporating these much higher efficiency solar cells into the Amonix MegaModules.

During FY 2009, the project continued to develop all non-solar-cell components of the Amonix MegaModule by redesigning them for low-cost and high-volume manufacturing. For example, the MegaModule depth was reduced in the project's first phase to reduce steel costs. A fast-cure adhesive for lens attachment was also developed in the project's first phase. During Phase II, Amonix reviewed designs for the pedestal, drive, and torque tube and identified high-volume suppliers. The drive, controls, and installation processes were improved for high-volume installation and lower cost. Optimized III-V

multijunction cells were produced for field use in the MegaModules. The cell packages were adapted to accommodate the III-V Multijunction cells and began extensive field, qualification, and accelerated tests to ensure reliability. Amonix fabricated and tested HCPV systems, leading to its new 7700 product consisting of a seven MegaModule array on a single pedestal.

Amonix worked with suppliers and partners for lens fabrication, III-V multijunction cells, and cell packaging; MegaModule manufacturing equipment, pedestals, trackers, and inverters; and installation, testing, and system demonstration with interested customers. The outcome was new suppliers identified that can meet the performance, reliability, and cost requirements for manufacturing Amonix's 7700 product.

3. Results and Accomplishments

In March 2009, Amonix announced its latest product, the Amonix 7700 HCPV solar-powered generator. The 7700 is powered by the world's most efficient III-V multijunction solar cells and is rated at 53 kW AC under PVUSA test conditions.

Researchers developed a multijunction parameter model to predict power and energy generation of the Amonix systems. This model demonstrates a strong correlation between prediction and more than 12 months of energy generation. The model incorporates soiling as well as atmospheric variation using meteorological data from the TMY3 database. The only adjustable parameter is the schedule for cleaning the lenses. The parametric model was also used to generate peak power and annual energy predictions for five prospective deployment locations.

Daily energy (kWh) generated and plotted as a function of the direct normal solar radiation (kWh/m^2/day) shows a strong linear correlation over 6 months. The data were presented to IEC TC82 WG7 for its consideration as an IEC Technical Specification for CPV energy performance rating.

Results from Highly Accelerated Life Testing (HALT) studies conducted at NREL allowed one major failure mode to be addressed and revealed a second failure mode, which led to an improved design.

A set of 14 representative modules, each about 1 m^2, was prepared and sent to UL in San Jose, CA, for testing to IEC 62108 (qualification standard) and UL 8703 (safety standard). Amonix sent a full-size test MegaModule and control MegaModule to UNLV for witness testing by UL. TUV conducted tests on another set of representative modules to obtain CEC listing for the Amonix 7700 to qualify for California Solar Initiative programs.

Sandia measured the performance of the Amonix MegaModule in September 2009. Sandia determined that the MegaModule surpassed the stage-gate review efficiency milestones for both Phase II and Phase III. The efficiency was measured to be 28.7% at STC (DNI = 1000 W/m^2, AM1.5D, T_{cell}=25°C) or 28.9% at CPV-STC (DNI = 850 W/m^2, AM1.5D, T_{cell}=25°C).

Performance projections from the Amonix power waterfall and the pricing assumptions from the business plan were used to complete the LCOE roadmap for Amonix through 2015. The LCOE projections for Amonix fall within the LCOE goal ranges set out by DOE's SETP.

Despite the difficult economy in 2009, Amonix found potential investors, project developers, and customers were quite interested in Amonix' new MegaModule technology developed as a result of this TPP. This interest bodes well for 2010.

4. Planned FY 2010 Activities

- Demonstrate operation of 25 MW/year production rate in Seal Beach
- Qualify MegaModule system to IEC 62108, UL 8703 and obtain CEC listing.
- Compile reliability data on deployed HCPV systems.

5. Major FY 2009 Publications

R. McConnell, M. Symko-Davies, and S. Kurtz, Conference Co-Chairs of *5th International Conference on Solar Concentrators, Palm Desert, CA,* Proceedings CD, ISBN: 978-0-615-29119-2 (November 2008)

G. Kinsey and K. Edmondson, "Spectral Response and Energy Output of Concentrator Multijunction Solar Cells," *Prog. Photovoltaics* (December 2008)

G. Kinsey, P. Pien, P. Hebert, and R. Sherif, "Operating Characteristics of Multijunction Solar Cells," *Solar Energy Mater. Solar Cells* (June 2009).

R. McConnell, V. Garboushian, J. Brown, C. Crawford, K. Darban, D. Dutra, S. Geer, V.

Ghassemian, R. Gordon, G. Kinsey, K. Stone, and G. Turner, "Assuring Long-Term Reliability of Concentrator PV Systems," *Reliability of Photovoltaic Cells, Modules, Components and Systems II*, N. Dhere, J. Wohlgemuth, and D. Ton, editors, *Proc. SPIE 7412*, 741208 (2009).

6. University and Industry Research Partners

Organization	Location	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
University of Nevada, Las Vegas	Las Vegas, NV	Installation and testing of Amonix MegaModules	247	0
NREL	Golden, CO	Cooperative R&D agreement for HALT studies	30	0
State Engineering University of Armenia	Yerevan, Armenia	DLC coatings	27	0

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TPP Awardee: The Boeing Co.

"Concentrator Photo Voltaic Power System"

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

Objectives

- Develop a new CPV system, incorporating high-efficiency multijunction cells, for the utility-scale PV power market
- Employ a novel nonimaging optical design to optimally use cell performance while addressing the reliability and cost of the tracker and balance of systems equipment
- Increase the efficiency of production multijunction solar cells for high-concentration terrestrial applications from 36% to 40% by 2010
- Reduce the cost of such cells by more than 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

- Increased average production lot cell efficiency to 28.5%
- Demonstrated cell efficiency > 39% using experimental metamorphic cells (9 months ahead of schedule)
- Increased cell production throughput to > 20 MW/year (more if market demand warrants)
- Demonstrated production of C4MJ metamorphic cells with efficiencies > 39%
- Deployed one full-size panel (15 m^2) and four remote test sites with minimum two modules supporting life testing in real world environments
- Selected site for 100-kW demonstration power plant and started construction
- Demonstrated greater than 30% module active-area efficiency
- Validated the cost reduction efforts required to hit the $0.15/kWh LCOE target
- Started construction of a demonstration 1-2 MW/year robotic assembly factory
- Completed mechanical design for a Boeing tracker
- Started debugging Boeing controller software
- Completed qualification of PV powered 260-kW inverter with an industry-best, 10-year warranty
- Selected licensee and signed commercialization agreement ensuring the future of the products developed on the SETP-TPP program.

Future Directions

- Deploy C4MJ cells in real-world applications
- Deploy 100 kW power plant at California State University, Northridge (CSUN)
- Install Boeing trackers and controllers at the CSUN site
- Design next-generation module to ensure path toward LCOE < $0.15/kWh
- Investigate protective coatings for the first surface mirror and antireflective coatings for the cover glass and secondary lens
- Continue developing relationship with licensee to ensure future commercialization of the SETP-TPP developed products.

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1. Introduction

Boeing has long been a leader is solar cell technology through its wholly owned subsidiary, Spectrolab. The Boeing TPP Concentrator PV project is intended to leverage this technical leadership and to expand Spectrolab's market in terrestrial solar power. Spectrolab's leadership is in multijunction (III-IV) gallium arsenide solar cells. This project uses multijunction cells and unique optics to concentrate solar radiation by 700x. By concentrating the solar energy, it is possible to reduce the area (and cost) of the semiconductor per watt of power produced. This project has a dual focus: first to increase the efficiency of Spectrolab's cells while reducing cost and second to develop the concentrator system that uses those cells to produce power.

2. Technical Approach

During FY 2009, Boeing and its team partners continued their TPP activities started in 2007.

Spectrolab continued to lead the industry with the development of C4MJ advanced metamorphic cells. Cell efficiencies > 39% have been demonstrated.

The Boeing Research and Technology team completed the design of the off-axis CPV panel. One full-size panel and four remote test systems were built, each employing a minimum of two modules at each site. To date, the full-size panel has been on sun for 9 months with no measurable degradation in performance. Boeing also supplied one module to NREL for testing. That module continues to perform as expected. The 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. The 260 kW inverter is the second inverter product to receive UL certification under this program.

3. Results and Accomplishments

- Produced 38.5% average production efficiency cells during the engineering confidence run for the production C3MJ cell design and completed that generation's Final Design Review
- Implemented automated tooling at Spectrolab for cell manufacturing and demonstrated annualized production rate of 20 MW/year
- Completed installation of one full-size array and remote test systems in four locations
- Demonstrated a module acceptance angle greater than 1.9° and measured a panel acceptance angle greater than 1°, within the expected value based on our tolerance analysis
- Demonstrated active-area efficiency of greater than 30%.

Fig. 2. Production module

Two-axis array trackers were purchased and evaluated. The evaluation result was a decision to pursue a Boeing tracker solution. The mechanical design is complete for a new tracker and the control software is being tested. The tracker control algorithm is innovative and will offer a significant cost savings.

Team member PV Powered obtained UL certification of their new 260-kW inverter. Reliability improvements resulting from this program allowed PV Powered to offer a 10-year standard warranty, the first in the industry, for a nominally increased cost. This should be viewed as a singular success for the TPP programs.

- Completed power plant system for the initial deployment at CSUN, to augment the green energy programs already in place there
- Validated the detailed LCOE model and established a path to meeting the $0.15/kWh LCOE target
- Participated in various IEC WG7 standards committees, particularly the CPV tracker committee and the system energy rating committee.

4. Planned FY 2010 Activities

- Demonstrate production mean cell efficiency of at least 38.5% (06/09)
- Perform module environmental test using C4MJ cells and criteria consistent with IEC 62108 (06/09)
- Install 100 kW capacity at CSUN
- Demonstrate pilot production of inverter and tracker (06/09)
- Begin planning for a 1–2 MW reference power plant to begin construction in early 2011 in conjunction with our licensee.

5. FY 2009 Special Recognitions, Awards, and Patents

Two patent applications were filed in 2009:

61/091,284 Flexible Thermal Cycle Test Equipment for Concentrator Solar Cells (provisional)

12/258,321 Flexible Thermal Cycle Test Equipment for Concentrator Solar Cells

6. Major FY 2009 Publications

"Electric Energy Generation using Concentrating Photovoltaic III-V Solar Cell Technology," Presentation will be given at the Printed Electronic USA 2009, San Jose, CA, Dec. 2–3, 2009.

N.H. Karam, "Ultrahigh Efficiency Multi-junction Solar Cells for Terrestrial Applications," to be presented at Arizona State University, Tempe, Nov. 6, 2009.

R.W. Morris and J.M. Fife, "Using Probabilistic Methods to Define Reliability Requirements for High Power Inverters,"

N. Karam, R. King, R. Jones, P. Pien, and J. Ermer, "Recent Progress in Concentrating Photovoltaic Solar Cell Technology and Manufacturing," presented at *SPIE Conf., August 2009*.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009

Organization	Location	Description or Title of research	FY2009	Cost Share
SPL	Sylmar, CA	Solar cell performance improvements	$5,329,278	$2,982,321
LPI	Los Angeles/Madrid SP	Optics development and parts for demonstration hardware	$1,456,210	$458,408
PV Powered	Bend, Or	Qualify 260 kW inverter	$548,661	$548,661
Comau	Detroit, MI	Automated factory optimization	$424,108	$0
UCI	Irvine, CA	Solar tracker mechanical structure study	$4,500	$0
UC-Boulder	Boulder, CO	Low-cost CPV tracker	$65,082	$0
CSUN	Northridge, CA	Conceptual design: Solar track	$24,331	$0

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TPP Awardee: BP Solar International Inc.

"Reaching Grid Parity Using BP Solar Crystalline Silicon Technology"

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

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
- Optimize and implement Mono^{2TM} casting technology to improve material quality
- Develop BIPV products designed for specific value-added applications.

Accomplishments

- Completed pilot trial of Mono^{2TM} ingots, transferring the full process into production and producing 650,000 wafers (1.5 MW worth)
- Demonstrated contaminant reduction in the casting process
- Developed process for wafering 156 mm square, 180 µm thick wafers and transitioned newer production saws to this process
- Demonstrated 18.35% Mono^{2TM} top performing cell
- Demonstrated an advanced metallization process developed by PARC realized an efficiency gain of +1.0% absolute driven by Isc and FF improvements
- Performed a 520 module pre-production run at BP Solar with the half-cell module design; average power for the modules was 245 W (module efficiency 14.5%)
- Completed a pilot run of 5 kW of silicone encapsulated modules
- Completed development of TPO membrane supermodule and built samples for qualification testing and demonstration on a roof
- Demonstrated remote dispatchability of stored energy from SMUD House of the Future.
- Completed fabrication of HV-MPPT charge controller prototypes and conducted full HALT- Multi-Environment Over Stress Test (MEOST).

Future Directions

- Demonstrate 16% cell efficiency using silicon cast with 100% solar grade material
- Continue to develop the Mono^{2TM} and demonstrate 15% module efficiency
- Complete development of a roof integrated PV module and submit for certification
- Define a module production process that achieves cost reductions to 67% of the 2006 BP Solar baseline
- Verify that both the residential and commercial systems under development will meet the DOE LCOE 2010 target goals.

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1. Introduction

BP Solar's TPP program is based on accelerated development of multicrystalline silicon 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 the 2006 cost by 2010 and to 50% of the 2006 costs by 2015; and 2) system costs to 60% of 2006 cost by 2010 and to 36% of 2006 costs by 2015. These are projected to result in LCOE of 8¢–10¢/kWh for residential systems and 6¢– 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 silicon through installation of the systems at the customer site. To achieve parity with the grid and growth to gigawatt levels of production requires involving the entire product chain. Partners in this effort include:

- Key materials vendors (Dow Corning for silicon, encapsulants, and pottants; Ceradyne for crucibles; STR for EVA; and AGC Flat Glass North America for glass) to assist in lowering cost, improving quality and performance, and ensuring that the material will be available in the volume necessary

- Equipment vendors (Komax and ATS) to assist in developing the next generation of equipment for automated production at high volumes
- Vendors of balance of systems equipment (Xantrex for inverters, Comverge for energy dispatchability) 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 (PARC) to support research.
- A utility (SMUD) will supply customer interface, demonstration sites, and the utility prospective on the value of PV electricity.

Key components of the program include:

- Silicon purification process development of solar grade silicon to increase the availability of silicon feedstock for the PV industry
- Casting: Implementation of Mono$^{2™}$ technology (single crystal quality at multi cost)
- Wafering: thinner wafers down to 160 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 a 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

Results are described by topic.

3.1 Silicon Feedstock

Solar grade silicon (SGS) purchased from a commercial vendor was mixed in a ratio of 93% SGS to 7% semiconductor grade Si, cast into multicrystalline ingots, and processed on the cell line. The cells from the three ingots matched the cell efficiency and yields of standard ingots processed with 100% semiconductor grade, except for slightly higher levels of shunt rejects. Ten cells, each measuring > 16% efficiency were delivered to DOE.

3.2 Casting

A large Mono$^{2™}$ trial was run with 55 ingots produced. Process procedures were documented and operators trained beforehand to allow operation personnel to learn all production aspects. A total of 650,000 wafers were cut. Cell fabrication is now under way. Process economics were carefully tracked

3.3 Wafering

Production trials were undertaken with 120 μm diameter wire used to cut 160 μm wafers. The yields were considerably lower for the thinner wafers with the largest yield loss due to cleaning and separating after the actual cutting process. Improvements to the cleaning and handling equipment and process are necessary before 160 μm thick wafers can be implemented in production.

3.4 Cell Process

Efforts during Phase II included implementing processes developed during Phase I as well as identifying future processes for high efficiency. Processes optimized on the cell line included:

- Improved back print design achieving a 0.6% relative gain in average cell efficiency and a 1% gain in module efficiency
- Optimized SiN deposition process and co-fire, resulting in a 0.6% relative gain in average cell efficiency
- Improved control over process to eliminate visual stains, resulting in a 2% increase in yield.

Laboratory efforts to improve processing of Mono$^{2™}$, including texturing, selective emitter, diffusion/SiN optimization, and rear passivation, resulted in best cell efficiencies of 18.3% with a group average of approximately 17%.

3.5 Module Development

New product development included work on a residential roofing tile, a module that integrates into a commercial roofing material, a half-cell module that increases module efficiency, and an encapsulant that helps reduce module temperature.

3.6 Manufacturing

BP Solar implemented statistical process control in the production line to improve control and reduce yield loss. A new method for measuring and

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controlling the SiN color, thickness, and index of refraction was implemented.

3.7 Inverter
Partner Xantrex completed design of a charge controller for high-voltage PV systems for use with battery storage. The full prototype design was successfully tested via MEOST, a new extension to HALT with the addition of voltage stress cycles.

3.8 Monitoring and Control
Partner Comverge installed a cellular gateway in the SMUD House of the Future and verified its operation via remote server. During the summer, web-enabled battery charging and discharging was successfully tested and a battery discharge schedule was developed that coincided with SMUD's peak usage period.

3.9 System Engineering
The mounting system for the Generation 2 BIPV residential roofing product passed in-house wind uplift testing. The mounting design was modified to improve the spread of lame test results.

3.10 System Installation and Maintenance
A trial installation of the residential roofing product was completed in conjunction with ASU Design Center, a roof tile manufacturer, and a home builder. Carlisle supplied details on the installation procedures for roofing membranes and assisted BP Solar in designing an integrated PV roofing membrane product.

3.11Deployment
BP has been assessing some commercially available software tools designed to predict PV system performance. The initial results indicate that various tools give significantly different results and that they all have trouble duplicating actual performance under some sets of operating conditions.

3.12 Collaboration
BP participated in Solar ABCs, IEC, ASTM, and UL efforts in PV standards and codes development.

4. Planned FY 2009 Activities

- Demonstrate processes and cost model for lowest cost purification of UMG Si to make SoG Si
- Demonstrate full commercial production of SoG Silicon
- Demonstrate efficiency boost from contaminant reduction in casting process
- Define and demonstrate process for lowest possible cost per kg of Mono$^{2\text{™}}$ manufacturing
- Complete development of equipment and processing with new station and make decision to expand capacity using this design
- Demonstrate wafering, cleaning, and demounting of 100 µm thick wafers
- Select and prototype a preferred process for passivated rear point contacts
- Achieve 18% average cell efficiency using processes compatible with 160µm wafers
- Complete development and qualification of two residential and one commercial roofing products and begin commercialization
- Complete development and offer charge controller along with inverter for commercial sale
- Complete development and testing of monitor and control unit and make decision to commercialize
- Complete three residential demonstrations
- Complete one commercial building demonstration.

5. FY 2009 Special Recognitions, Awards, and Patents

Five disclosures related to this program were submitted in FY 2009. Three patent applications were submitted to the US Patent Office in FY 2009.

6. Major FY 2009 Publications

D.W. Cunningham, D. Amin, A. Nguyen, J. Miller, Z. Xia, and J. Wohlgemuth, "Key Aspects of Module Design That Influence Energy Generation," *24th European PVSEC, September 2009*.

N.G. Stoddard, R. Sidhu, J. Creager, S. Dey, B. Kinsey, L. Maisano, C. Phillips, R. Clark, and J. Zahler, "Evaluating BP Solar's Mono$^{2\text{ TM}}$ Material: Lifetime and Cell Electrical Data," *34th IEEE PVSC, 2009*.

J. Wohlgemuth, R. Clark, J. Posbic, J. Zahler, M. Gleaton, D. Carlson, and D. Cunningham, "Reaching Grid Parity Using BP SOLAR Crystalline Silicon Technology," *34th IEEE PVSC, 2009*.

Z. Xia, D. Cunningham, and J. Wohlgemuth, A "New Method for Measuring the Cross-link Density in Ethylene Vinyl Acetate Based Encapsulant," *PV International,* 5th edition, 2009.

Z. Xia, D. Cunningham, and J. Wohlgemuth, "A Non-solvent Extraction Method for Measuring the

Gel Content of Ethylene Vinyl Acetate as PV Encapsulant," *34th IEEE PVSC, 2009*.

Z. Xia, J.H. Wohlgemuth, and D.W. Cunningham, "A Semi-empirical Method of Predicting the Lifetime of EVA Encapsulant and Polyester Based Backsheet Materials," *SPIE Solar Energy and Technology Conference, August 2009*.

Z. Xia, J.H. Wohlgemuth, and D.W. Cunningham, "Lifetime Prediction of PV Encapsulant and Backsheet via Time Temperature Superposition Principle," *34th IEEE PVSC, 2009*.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization	Location	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Dow Corning	Midland, MI	Solar-grade Si feedstock for the casting process; develop alternative silicone encapsulation system	1,300	1,300
AGC Flat Glass NA	Kingsport, TN	Develop solar glass with AR coatings	75	137
ATS-Ohio	Lewis Center, OH	Develop automated thin wafers and cells handling equipment	197	0
Arizona State University	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	284	66
Ceradyne Thermo Materials	Clarkston, GA	Develop large-area, high purity crucibles for silicon casting	152	152
Georgia Institute of Technology	Atlanta, GA	Design, optimize, and fabricate high-efficiency solar cells on BP Solar cast silicon wafers	70	0
Komax Systems York	York, PA	Develop screen print and tabbing/stringing equipment for thin PV cells	135	183
PARC	Palo Alto, CA	Develop, qualify a gridline printing system	12	12
BASF	Wyandotte, MI	Design, develop residential BIPV molded module frames	49	49
Sacramento Municipal Utility District	Sacramento, CA	Supply utility prospective to and demonstration sites for residential and commercial PV systems	5	
STR	Enfield, CT	Develop of low-cost, high-performance encapsulants	70	70
University of Central Florida	Coco, FL	Study module energy collection, PV connector performance, and module leakage current	140	0
Xantrex Technology Inc.	Burnaby, BC	Develop high-reliability, battery-backed, grid-tie inverter power conversion system	0	400
North Carolina State University	Raleigh, NC	Evaluate BP cast multicrystalline and mono^2 silicon	92	0
Comverge	Kennett Square, PA	Development of data acquisition systems for PV systems with remote deployment of stored energy	58	58

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TPP Awardee: Dow Chemical Co. Inc.

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

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

Objectives

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

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 meet LCOE targets.

Future Directions

- Scale up pilot line for low-cost manufacturing of shingles
- 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 offer residential and commercial customers 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 working on 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 resolved to be applied in the full-size shingle.

Shingle design was affected by a change in cell supplier. We were able to rapidly qualify another CIGS manufacturer to aid our development. This manufacturer, Global Solar, Inc., operates two large-scale CIGS PV manufacturing sites, one in Tucson, AZ, and one in 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 using 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 (03/08)
- Produced full-scale shingle (07/08)
- 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 from both 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 ensure cell stability and long shingle life. They also needed to acquire and qualify

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equipment for a test lab, which is now fully functional.

Dow is developing the BIPV product materials structure using a multigeneration plan to ensure continuous progress in terms of cost reduction while maintaining successful product performance. Many different approaches to achieving adequate barrier performance that will enable CIGS-based PV shingles to perform for 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 toward a simple yet rugged and reliable interconnection design for the Dow Solar Shingle that 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 reducing installation costs, Dow validated their design with a test build using standard roofing contractors.

4. Planned FY 2010 Activities

- Develop equipment modifications to fit product design (GSE; Q1)
- Build pilot line and start-up (Q1)
- Install turnkey systems and collect data (Q2)
- Develop commercial roofing analog product (Q1).

5. FY 2009 Special Recognitions, Awards, and Patents

Provisional 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 2009.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2009 ($K)
Global Solar Energy Jeffery Britt	Tuscon, AZ	Cell supplier	3
Prost Construction Vaughn Prost	Columbia, MO	Install demonstration unit with Columbia Water and Light to initiate rate structure study for solar PV electricity production	35

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TPP Awardee: GE Global Research Inc.

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

Total Award Amount: $21,225K; DOE/Recipient Share $9,184K/$12,041K

Objectives

- Investigate multiple technical pathways for producing modules and system components that will meet the TPP LCOE goals and be successful in the U.S. marketplace
- Address the segments of the U.S. PV market where GE's technical and system integration competencies can have the largest effect on PV system cost and performance
- Deliver into the residential and commercial markets a complete system of components consisting of a 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

- Completed the moisture-ingress-degradation model for flexible packaged CIGS devices and ran it for a variety of conditions, packages, and cells
- Proved that modified barrier coatings for CIGS-based devices improve by ~10x the number of visible defects generated during damp heat testing
- Built and tested mini-modules to validate the interconnect electrical model; model predictions are generally within 3&–6% of these measurements
- Expanded the temperature/humidity test matrix for cell degradation kinetics to include 100% humidity testing; the results indicate some amount of electrical contact degradation combined with CIGS device degradation
- Studied power loss for three system level interconnect strategies.

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1. Introduction

General Electric's (GE) DOE Solar Energy Technologies Program (SETP) TPP encompassed development in critical areas of the photovoltaic value chain that affected the LCOE for systems in the United States. This was a complete view across the value chain, from materials to rooftops, to identify opportunities for cost reductions to realize the Department of Energy's cost targets for 2010 and 2015. GE identified several strategic partners with proven leadership in their respective technology areas to accelerate along the path to commercialization. GE targeted both residential and commercial rooftop scale systems.

During FY 2009, GE and its partners investigated two photovoltaic pathways that included low-cost multicrystalline silicon cells and modules and flexible thin film modules. The balance of system for residential and commercial installations were also investigated. GE pursued innovative system installation strategies as an additional avenue for cost reduction.

2. Technical Approach

GE focused on two distinct technical pathways for the module, as well as a technical pathway that addresses the inverter/balance of system and installation. Each pathway was self-contained, spanned the value chain to include materials, solar device, and system, and included critical technologies and partners. An internal stage-gate process was used to down-select to the most favorable approach or partnership.

2.1 Low-Cost Multicrystalline Silicon Module

GE developed a solar cell based on a molded silicon wafer fabricated 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 also developed a low-cost silicon feedstock based on a carbothermic reduction process that would be easier to scale than other processes currently in use. This process takes advantage of GE Global Research's knowledge of high-quality quartz manufacturing.

2.2 Flexible Thin Film Module

GE worked with vendors 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. A weakness of CIGS (and all other thin films using a thin conductive oxide) is sensitivity to moisture, limiting life well below that of a silicon module. GE developed packaging technologies for flexible organic light emitting diodes (OLEDs) that have been 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 forms the basis for a moisture-tight package that provides four orders-of-magnitude better protection than the Teflon-based materials currently being used.

A moisture-ingress-degradation model was completed and run for a variety of conditions, packages, and cells. Key predictions are 1) a barrier of WVTR < 10^4 g/m^2/day is required for 20-year life in Miami; 2) 20years in Miami is roughly equivalent to 12,000 hours of "damp heat" (85°C/85%RH) for a barrier-packaged cell; 3) cells of less-robust structure (obtained from a second vendor) require 25X this barrier; 4) cells must degrade at < 0.07X this rate to require no barrier; and 5) two-sided compared with one-sided module heat transfer (freestanding compared with BIPV) has little effect on module degradation rate.

2.3 Balance of System

GE and Xantrex Technology, Inc. intend to lower inverter cost and improve performance by developing innovative new circuit designs, implementing high-performance components, and 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 worked with top PV installers to identify internally driven cost elements related to time and materials and external factors such as local codes and regulations that influence costs nonuniformly, and to develop a streamlined process flow. Additionally, in a partnership with GAF, GE intends to market and develop new solar systems and roofing systems for residential and commercial customers.

4. Major FY 2009 Publications

D.J. Coyle, H.A. Blaydes, J.E. Pickett, R.S. Northey, and J.O. Gardner, "Degradation Kinetics of CIGS Solar Cells," *34th IEEE PV Specialists Conference, Philadelphia, PA, June 2009.*

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TPP Awardee: GreenRay Inc.

"Development of an AC Module System"

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

Objectives

- Develop a fully integrated plug-and-play PV system by integrating power electronics with a 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 the life-cycle cost of PV energy to meet DOE goals.

Accomplishments

- Began safety certification testing of inverter and AC module at UL
- Stress testing in house verifies 50-year inverter lifetime
- Completed AC module system demonstrations in Massachusetts, New Jersey, and Texas.

Future Directions

- Complete thorough testing of the inverter, including final safety certification
- Begin pilot production and market launch.

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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 creating a true plug-and-play AC system, with advantages of simplicity, safety, performance and cost. GreenRay focuses 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: a high-reliability inverter, a simple residential mounting system, and a 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 experienced PV installers.

The inverter has been designed to achieve a 30-year lifetime, to improve system reliability, and reduce maintenance. Consultants reviewed 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 produce module-level information.

3. Results and Accomplishments

- AC Module System submitted to UL for safety certification (07/09)
- In-house stress testing shows inverter lifetime greater than 50 years (08/09)
- Cost projections of the AC Module System show the potential to achieve the targeted lifecycle cost of energy (08/09).

GreenRay completed the design of its novel inverter in a form factor optimized for integration with a PV module. The beta prototype of the inverter operated successfully. Updated reliability analysis was completed using standard tools and methods to model the circuit. Results indicate the potential to achieve the targeted lifetime and reliability. In-house stress tests demonstrate a 50+year lifetime for the inverter.

Demonstration systems were completed in Massachusetts, New Jersey, and Texas. The installation labor cost savings were validated, and the GreenRay AC Module System is roughly half that of the conventional system.

GreenRay tested and demonstrated imbedded data acquisition and communication capability.

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The user interface features were reviewed with key stakeholders and refined.

4. Planned FY 2010 Activities

- Complete AC module safety certification (04/10)
- Begin pilot production of 2,000 AC modules and launch product in market. (04/10).

5. FY 2009 Special Recognitions, Awards, and Patents

One patent was filed in FY 2009:

- Modified ZVT Converter.

Two provisional patents were advanced to the PCT level and filed in the United States in FY 2009:

- AC Module Wiring Method
- AC Module and Inverter Assembly.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization	Location	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
SANYO Energy	San Jose, CA	Testing to support inverter and AC module development	$25,062	$25,062

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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 using water and oxygen barriers that include barrier films, coated barrier films and adhesives that have barrier properties
- Improve performance by creating and using n-type materials in the active layer
- Improve performance and lower cost by using a highly conductive, highly transparent, printed metal grid.
- Reach performance objective of 10% cell efficiency and module efficiency 7%–8%
- Reach rooftop module lifetime objective of 10years and cost objective of < $0.2/kWh.

Accomplishments

Stability

- Demonstrated the utility of adhesive fillers in stabilizing modules
- Demonstrated that solution coatable barriers have potential for improving stability
- Delineated molecular details regarding degradation.

Performance: n-type materials

- Produced many fullerene derivatives per specification, but none showed performance improvement over the standard PCBM.

Performance: Printed metal grids

- Developed silver grid top electrode that exhibits performance equal to a solid silver electrode
- Identified silver formulation for the bottom grid electrode that has the correct set of properties and surface roughness.

Future Directions

- Transfer clay/adhesive formulations to manufacturing
- Develop solution coatable barriers
- Investigate new family of n-type fullerenes
- Optimize silver formulations for the top grid and bottom grid.

1. Introduction

Konarka Technologies is dedicated to producing low-cost organic photovoltaic modules that are flexible, lightweight, and with low manufacturing costs. This can be accomplished because the modules are made using a roll-to-roll coating process on inexpensive polymer substrates in a high-speed, wide-roll coating process.

2. Technical Approach

Konarka concentrated all work on organic photovoltaics. They are simultaneously creating new materials and investigating advanced concepts while pushing the best performers through development and into manufacturing. The latter is making products for portable applications centered on battery charging.

Konarka is also investigating the environmental factors that are responsible for instability while creating, evaluating, and using new barrier materials.

Regarding performance, researchers are investigation new polymeric donors; several new families of polymers have been developed and are being optimized. N-type materials, e.g., fullerene derivatives and new polymers, are also being investigated. The concept behind this investigation centers on imparting better absorption properties and better matched device energy levels.

Regarding the grid electrodes, the expensive ITO bottom electrode will be replaced with an electrode that has higher transmission, higher conductivity, and lower cost. Using a silver grid as the top electrode replacing the solid silver electrode also lowers the cost (~10%) of the silver.

3. Results and Accomplishments

Stability

During the second year of the program, Konarka focused on devising and optimizing the formulas for a new adhesive/clay combination. Konarka demonstrated that stability was significantly improved when this adhesive/clay combination was used in combination with improved barrier material films. Several examples were produced that are stable for several thousand hours at 65°C/85%RH; 85/85 testing has begun with resultant formulations being incorporated into the product line.

NREL is developing solution coatable barriers. Experiments with these materials on our Research Test Coater pilot line have begun.

Performance—N-Type Materials
Konarka created two sets of fullerene derivatives: one set with deeper LUMOs and the other with shallower LUMOs relative to PCBM. Thus far these have not exhibited better performance than PCBM. Konarka continues to investigate these new materials from the standpoint of their effect on morphology.

Performance—Grids
We experimented with a wide variety of silver inks and have used various printing techniques, including inkjet in the December timeframe. For the bottom grid, upon which the active layers of the cell will be coated, target surface roughness is < 5nm RMS, and we achieved this level of roughness. In addition, the surface of the grids and the leveling layer are equal. There is still a very low density of 50–100 nm spikes in the silver grid, and we are working on this problem. We developed a grid for the top electrode, and modules are in development.

4. Planned 2010 Activities

The Konarka manufacturing line is now fully operational, and continued improvement of product performance is expected.

Stability
- Incorporate new adhesive and improved commercial barriers into the product line
- Improve barrier properties and coat NREL's solution coatable barriers.

Performance
- Demonstrate 8%–9% cell efficiency
- Demonstrate 5%–6% module efficiency
- Use printed silver grids in both top and bottom electrodes target cell efficiency equal to that of ITO and solid silver electrodes.

5. FY Awards, Special Recognition, Patents

Patent 7,622,667, Photovoltaic fibers
Patent 7,612,367, Photovoltaic component and production method therefor
Patent 7,586,035, Photovoltaic cell with spacers
Patent 7,572,974, Gel electrolytes for dye sensitized solar cells
Patent 7,572,396, Patterned photovoltaic cell
Patent 7,544,747, Photoactive materials and related compounds, devices, and methods
Patent 7,522,329, Displays with integrated photovoltaic cells
Patent 7,476,278, Roll to roll manufacturing of organic solar modules

6. Papers

C.N. Hoth, S.A. Choulis, P. Schilinsky, and C.J. Brabec, "On the Effect of Poly(3-hexylthiophene) Regioregularity on Inkjet Printed Organic Solar Cells," *J. Mater. Chem.* **19**(30), 5398 (2009).

C.N. Hoth, P. Schilinsky, S.A. Choulis, and C.J. Brabec, "Printing Highly Efficient Organic Solar Cells," *Nano Lett.* **8**(9), 2806 (2008).

C.N. Hoth, R. Steim, P. Schilinsky, S.A. Choulis, S.F. Tedde, O. Hayden, and C.J. Brabec, "Topographical and Morphological Aspects of Spray Coated Organic Photovoltaics," *Organic Electron.* **10**(4), 587 (2009).

M. Koppe, C.J. Brabec, S. Heiml, A. Schausberger, W. Duffy, M. Heeney, and I. McCulloch, "Influence of Molecular Weight Distribution on the Gelation of P3HT and Its Impact on the Photovoltaic Performance," *Macromolecules* **42**(13), 4661 (2009).

M.R. Lee, R.D. Eckert, K. Forberich, G. Dennler, C.J. Brabec, and R.A. Gaudiana, "Solar Power Wires Based on Organic Photovoltaic Materials," *Science* **324**(5924), 232 (2009).

M.R. Lee, R.D. Eckert, K. Forberich, G. Dennler, C. Brabec, R.A. Gaudiana, P. Calvert, and A. Agrawal, "Optical and Electronic Properties of Organic Photovoltaic Wires and Fabrics," *J. Macromol. Sci., Part A: Pure Appl. Chem.* **46**(12), 1238 (2009).

A. Seemann, H.-J. Egelhaaf, C.J. Brabec, and J. A. Hauch, "Influence of Oxygen on Semi-transparent Organic Solar Cells with Gas Permeable Electrodes," *Organic Electron.* **10**(8), 1424 (2009).

R. Steim, P. Schilinsky, S.A. Choulis, and C.J. Brabec, "Flexible Polymer Photovoltaic Modules with Incorporated Organic Bypass Diodes to Address Module Shading Effects," *Solar Energy Mater. Solar Cells* **93**(11), 1963 (2009).

R. Steim, S.A. Choulis, P. Schilinsky, U. Lemmer, and C.J. Brabec, "Formation and Impact of Hot Spots on the Performance of Organic Photovoltaic Cells," *Appl. Phys. Lett.* **94**(4), 043304/1 (2009).

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization	Location	Description/Title of Research Activity	FY 2009 ($K)	Cost Share

				($K)
Institute for Energy Conversion, University of Delaware	Newark DE	Determination of the stability of modules under various conditions of temperature, humidity, and light. Investigation of the instability mechanism.	103	76
NREL	Golden, CO	Improving barrier properties of perimeter seals by adding rodlike fillers to the adhesives. Year 2, converted to solution coatable barriers.	450	–

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TPP Recipient: Nanosolar Inc.

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

Total Award Amount: $42,616K, DOE/Recipient Share $19.991K/$22,626K

Objectives

- Achieve grid-parity economics for the commercial market based on an integrated suite of innovations in module, inverter, and mounting technology
- Achieve a 2010 real LCOE target of 6.3¢/kWh and a 2015 real LCOE target of 5.5¢/kWh.

Accomplishments

- Demonstrated successful achievement of all technical milestones for Phase II of the project
- Completed TUV certification for our initial panel product, and passed the requirements for a UL Class A fire rating
- Retained more than 95% of initial power output after 200 thermal cycles, and more than 90% of power output after 450 thermal cycles, when Nanosolar panels were tested per standard IEC protocols .
- Showed, using the Sunlink mounting system, that the installation process is highly streamlined by minimizing mounting components, standard tool usage, and a plug-in installation strategy.

Future Directions

- Demonstrated successful deployment of both 100-kW and 1-MW commercial rooftop systems.

ABSTRACT

Nanosolar optimized the manufacture of an inexpensive solar panel enabled by the rapid roll-to-roll production of solar cells, which are then assembled into modules in a high-throughput automated process. The economics of the Nanosolar cell and module production enables a substantial reduction in panel cost. The Nanosolar panel also successfully achieved TUV and UL certification. The panel design enables reduced balance of system costs for mounting and installation. Further, SunLink LLC, a Nanosolar team partner, developed an inexpensive and rapidly assembled mounting system optimized for Nanosolar panels. A test installation with Nanosolar panels and a Sunlink mounting system was deployed.

1. Objectives

Nanosolar developed a new generation of solar electricity cell technology based on a printed semiconductor, which permits substantially improved cost efficiency. To translate this cell advance into grid-parity PV systems economics, however, the panel mounting system was also optimally redesigned, allowing for a redefinition of the interfaces and component functions from a systems-optimized perspective. Nanosolar is leading a team to develop an optimized solar system for the key market of corporate customers with flat-roof commercial buildings.

2. Technical Approach

2.1 Solar Cell Technology

Nanosolar developed proprietary technology based on CIGS absorber technology that allows printing this semiconductor material onto metal foil using a high-speed, high-throughput roll-to-roll manufacturing process. Cells are then assembled and placed between two glass panes to form a panel.

2.2 Mounting System Technology

o further reduce the cost of deploying solar systems on rooftops, Sunlink has developed a low-cost and durable mechanical structure to rapidly assemble modules on a flat commercial rooftop using a system that comprises only seven components and requires only two standard tools for installation.

Taking input from structural analysis, roof interface requirements, Nanosolar panel mounting guidelines, and typical installation practices, researchers designed a mounting system that is responsive to the needs of the installation crews. The system was then built and assessed using both wind-tunnel testing and mechanical load tests.

Figure 1 shows the installation of a Nanosolar panel in the Sunlink mounting system, and Figure 2 shows an array of Nanosolar panels attached using a Sunlink mounting system. The integrated system permits rapid array assembly.

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Fig. 1. Installation of Nanosolar panel in Sunlink mounting system on simulated rooftop. Upper panel, placement of panel onto mounting structure. Lower panel, rapid plug-in installation into mounting system.

Fig. 2. Nanosolar panels mounted on Sunlink system on a flat roofing structure.

3. Results

3.1 Certification of Nanosolar Panel

Nanosolar completed TUV certification for our initial panel product, and also passed the requirements for a UL Class A fire rating. In particular, Nanosolar successfully completed all of the mechanical and electrical tests, including IEC61646 Section 10.1 (visual inspection), IEC61646 Section 10.2 (Max Power Determination), IEC61646 Section 10.3 (Insulation Test), IEC61646 Section 10.16 (wet leakage current test), IEC61646 Section 10.8 (outdoor exposure test, 60 kWh/m^2, IEC61646 Section 10.4 (Measurement of Temperature Coefficients), IEC61646 Section 10.5 (NOCT), IEC61646 Section 10.6 (Performance at STC and NOCT), IEC61646 Section 10.7 (Performance at Low irradiance), IEC61646 Section 10.9 Hot-Spot Endurance test, and IEC61646 Section 10.15 (wet leakage current test). Further, Nanosolar has successfully passed IEC61646 Section 10.10 (UV Protection test at 15 KWh/m^2), IEC61646 Section 10.11 (Thermal Cycling Test, 200 cycles, -40C to +85C), IEC61646 Section 10.12 (Humidity Freeze Test, 10 cycles, -40C to +85C, 85% RH), IEC61646 Section 10.13 (Damp Heat Test, 1000 hours, 85C, 85% RH), IEC61646 Section 10.14 (Robustness of Termination Test), IEC61646 Section 10.15 (Wet Leakage Current Test), IEC61646 Section 10.16 (Mechanical Load Test), IEC61646 Section 10.17 (Hail Test), and IEC61646 Section 10.19 (Light Soaking). Based on the TUV data, Nanosolar also received a UL equivalency listing.

3.2 Demonstration of Nanosolar Panel Performance under Thermal Cycling

Nanosolar panels were tested under the IEC61646 testing protocols for thermal cycling, and retained more than 95% of initial power output after 200 thermal cycles, and more than 90% of power output after 450 thermal cycles (Fig. 3), twice the number of required thermal tests per IEC.

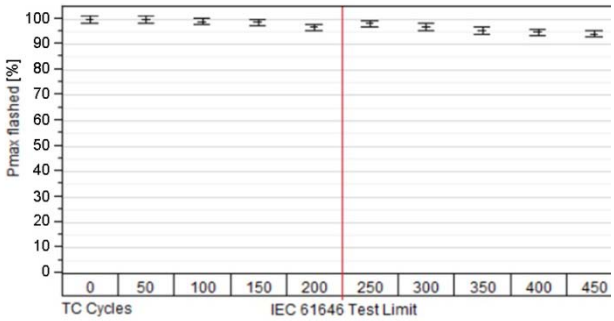

Fig. 3. Power output (%) for Nanosolar panels vs. number of thermal cycles as per IEC61646 testing. Red line depicts testing limit for standard IEC testing.

3.3 Demonstration of Installation of Nanosolar Panel with Sunlink Mounting System

Figure 2 shows a Nanosolar panel array deployed using a Sunlink mounting system. The installation process was measured in time and motion studies and is highly streamlined by using a small number of mounting components, standard tool usage, and a plug-in installation strategy.

4. Significance

In addition to lower panel cost, the Nanosolar panel design drives balance-of-system and deployment cost efficiency in several other ways relative to other thin-film products, including cost savings on mounting materials, mounting labor, cabling materials length, cabling labor, and shipping cost. For example, using dual panes of tempered glass, substantially increased panel strength, allowing a 2-m mounting span (relative to a 1.2-m span for typical thin film), a 41% decrease in mounting material. Using high-current carrying conductive metal foils in the cell design allows assembly of longer panel arrays, and Nanosolar uses only 1.6 km of cabling per megawatt compared to 20 km per megawatt for typical thin-film panels, a 92% savings in cabling cost per panel. Using dual "edge box" connectors optimally positioned for landscape-mode inter-connection means that cabling interconnection is 85% faster than that of thin-film panels with standard junction box designs.

Balance of system cost has been further reduced through the Sunlink mounting system for commercial rooftops, where, in addition to low materials cost, the mounting system provides high component efficiency (with little hardware required for installation) and versatile build "as you go" installation (using 2 by 1 m subarrays). This subarray modularity gives a solar system layout designer the flexibility to maneuver around rooftop obstructions.

5. Patents

Patent 359,246, "Methods for Thermal Processing Flexible Substrates," 1/23/09

Patent 369,524, "Improved Solution Deposition System," 2/11/09

Patent 176,902, "Roll-to-Roll Manufacturing of Back-Contacted Solar Cells," 5/9/09

Patent 180,814, "Solar Cell Interconnection" 5/22/09

Patent 180,815, "Material Additive" 5/22/09Patent 180,817, "Structure and Process for Solar Cell Electrodes" 5/22/09

Patent 559,451, "Methods for Thermal Processing Flexible Substrates," 9/1/09.

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 DOE Funding ($K)	Cost Share ($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

Program Objectives

- Develop a tracking/concentrating solar module that has the same geometric form factor as a conventional, flat roof-mounted PV panel, producing more power and cost less than conventional panels of the same size
- Reach target LCOE: $0.079/kWh in 2010
- Reach target efficiency: 26% in 2010 (22% for 2008 prototype, 24% for 2009 pilot)
- Reach target performance: equivalent to 650 Wp in 2010 (490W for 2008 prototype, 540W for 2009 pilot).

2009 Accomplishments

- Designed and built pilot plant capable of producing more than 1 MWp[1] per year of manufactured tracking/concentrating solar panels that mount to standard racking systems on commercial rooftops, with standard output electrical connections
- Expanded earlier system on Soliant HQ rooftop to full 4.4 kWp; system operated within specifications for most of 2009 until decommissioned for research purposes
- Installed two 2.0 kWp beta systems on customer rooftops
- Internally tested units with energy output equivalent to 449Wp flat plate.

Future Directions

- Improve efficiency and power output
- Reduce manufacturing cost
- Ensure that delivery volume manufactured units are establishing path to goal LCOE.

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[1] Beginning in Phase 2 of the project, Soliant discontinued use of the descriptive but nonstandard "watts equivalent" in favor of the emerging CPV Wp STC standard that is emerging from IEC TC82 WG7. In this report the phrase "equivalent to Wp" is used where necessary to maintain a link to the original proposal; in all other places Wp means CPV Wp STC.

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1. Introduction

Soliant Energy is a venture-capital-backed startup focused on bringing advanced concentrating solar panels to market. The fundamental innovation of this approach a racking solar concentrator developed specifically for commercial rooftop applications, resulting in the lowest LCOE for rooftop electricity generation.

Today, the commercial rooftop segment is the largest and fastest-growing market in the solar industry. Soliant Energy concentrating panels can make a major contribution to the TPP program objectives of reducing the cost of solar electricity and rapidly deploying capacity.

Soliant's commercialization focus was reshaped in 2009, shifting from an emphasis solely on panel efficiency to LCOE. Since the inception of the TPP program, LCOE has become the de facto standard for comparing commercial photovoltaic systems. Although estimation and prediction models still differ, the emergence of performance-based incentive and feed-in tariff systems, as well as power purchase agreement financing structures, makes LCOE the natural metric for photovoltaic systems.

During 2009, Soliant made progress on several fronts, including manufacturing capacity, technology development, market awareness, and sales.

2. Technical Approach

Because the Soliant effort is intended to produce capital equipment with high reliability under harsh conditions, the technical approach is borrowed from the automotive industry. The first phase of the effort, from 9/07 through 3/08, was engineering validation, with a goal of demonstrating a working product design. This phase was completed with delivery of a prototype unit validated by Sandia to meet all key objectives.

The second phase is design validation (DV), which further refines the design and readies it for manufacturing. Substantial progress has been made toward completing this phase by establishing a pilot manufacturing line in an existing facility in Monrovia, CA. This phase was to be completed in December 2008. Product improvements identified during the initial part of the DV, however, prompted Soliant to undertake a second DV iteration.

The third phase is production validation and will culminate in the first large-scale deliveries of our product to customers in 2011.

The technical approach of the original proposal included a strong but largely separate task of receiver packaging development.

3. Results and Accomplishments

- Worked with UL to define draft 8703 for photovoltaic concentrators
- Designed product revisions to ensure UL certification; passed critical UL tests
- Expanded earlier system on Soliant HQ rooftop to full 4.4 kWp; system operated within specifications until decommissioned in late 2009 for research purposes
- Outfitted second Soliant facility for 1 MWp per year production capacity
- Installed two 2.0 kWp beta systems on customer rooftops
- Continued long-term reliability testing
- Received important customer commitments toward purchase of product.

The major focus of effort in 2009 was to ramp up manufacturing capacity of a panel that passes UL and meets customer needs. With a few modifications, this goal was accomplished. A pilot-scale manufacturing plant was specified, designed, equipped, and validated that, running at full capacity, could produce in excess of 600 kWp of Soliant SE-500X concentrating solar panels. The Soliant SE-500X produces an annual power equivalent to 449 Wp flat plate, or 416 kWh/m^2/year in Phoenix. The energy output of the beta SE-500X was verified by Sandia in early 2009. Figure 1 shows the Soliant rooftop array at full power from the early morning sun.

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Fig. 1. The 4.4 kWp array at Soliant HQ.

In April 2009 an additional building adjacent to the Monrovia headquarters was leased and outfitted as a module- and panel-assembly line. The ribbon-cutting for this facility took place in August and first panels were delivered from it in September. Congressman David Dreier is third from right in Figure 2.

Fig. 2. Ribbon-cutting for pilot plant.

Important progress was made in 2009 toward UL listing of the SE-500X product. Soliant worked closely with UL to define the UL8703 draft safety standard for photovoltaic concentrators. Soliant passed the fire testing elements of this standard in 2009 and at year end was accumulating hours toward the long-term tests such as outdoor exposure.

The subcontract with MIT has seen further progress. A model for impacts of various alternatives in a multi-echelon supply chain has been developed. Mechanisms for three-dimensional articulation of the optical element is also being investigated as part of this effort.

Fig. 3. Beta system installed.

In December 2009, beta systems of approximately 2 kWp each to third party evaluators were delivered. One of these (Fig. 3) is grid-connected, and the other is awaiting municipal approvals for grid connection that is expected in 1Q10.

4. Planned Calendar 2010 Activities

Three to five beta-sized systems of approximately 2kWp each are expected to be installed. We also plan to sell ten 10 kWp systems. UL listing is expected in 2Q10.

5. 2009 Special Recognitions, Awards, and Patents

Two U.S. patents applications were filed in this period. One U.S. patent was issued.

6. 2009 Publications

N. Fromer, R. Johnson, S. Missirian, and J. Bobruk, “Soliant Energy Concentrator Module Performance and Comparison To Silicon Flat Panel Performance,” poster session, *34th Annual IEEE Photovoltaic Specialists’ Conference (PVSC34), 2009*. A similar paper was presented in a poster session at the *SPIE Solar Energy + Technology 2009 San Diego, August 2009*.

Organization	Location	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)

Spectrolab, Inc.	Sylmar, CA	Development and supply of III-V concentrator PV cells	18	0
Massachusetts Institute of Technology	Cambridge, MA	Advanced research in manufacturing engineering	56	0
SunEdison, Inc.	Beltsville, MD	Customer-perspective review of proposed panel specification	0	0

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

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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 turn-key, high-efficiency residential and commercial systems that are cost-effective in delivering electricity at grid parity
- Decrease LCOE values to 9–12¢ cents/kWh and 13–18¢ cents/kWh, respectively, for the commercial and residential markets
- Achieve target LCOE values through development of 20% efficient modules and reduced system development and installation time.

Accomplishments

- Achieved world-record panel efficiency at 20.4%, as verified by NREL
- Demonstrated pilot manufacturing capability to produce 23%+ cells
- Released large-format modules into production for commercial markets
- Demonstrated production ramp and deployment through installation of 2 MWp of innovative commercial rooftop product
- Completed design for 75-MW automated module line
- Integrated automated design and simulation software for commercial applications.

Future Directions

- Implement domestic manufacturing capacity for modules
- Demonstrate pilot manufacturing and field deployment of next-generation tracker technology
- Demonstrate development of a fully equipped systems kit that is delivered as a unit to the site of residential installations.

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1. Introduction

As a participant in the DOE TPP Program, SunPower Corporation is developing turn-key PV systems that are designed to be cost-effective in delivering electricity at grid parity. Taking advantage of its vertical integration strategy, SunPower is addressing cost reduction throughout the value chain, from wafer technology through installation deployment. In addition to internal resources, SunPower, as the prime TPP contractor, is partnering with Dow Corning, Tigo Energy, Solar Bridge, and NREL to investigate new materials, develop innovative inverter designs, and validate efficiency and performance characteristics, respectively.

2. Technical Approach

The SunPower project examines multiple levels of the value chain. Internal efforts focused on developing integrated system-level products and leveraging improvements in the wafer and cell technologies.

3. Results and Accomplishments

The SunPower project includes tasks focused on (1) wafering; (2) back-contact cells; (3) module design; (4) system product design; (5) manufacturing implementation; (6) enabling software; (7) residential-installation tools; (8) performance modeling and monitoring; and (9) inverter design and reliability. Summary results from a subset of these tasks follow.

3.1 Wafering Technology Development

SunPower focused efforts on reducing final wafer thickness and increasing wafer diameter. Work included changes to the manufacturing processes and equipment set to enable use of the thinner and larger wafers. SunPower successfully processed wafers, cells, and modules using 145-µmthickness. The production of cells at this thickness has been fully implemented in the SunPower large-scale manufacturing operations.

3.2 High Performance Back-Contact Solar Cells

Solar cell conversion efficiency leverages cost savings throughout the value chain. Today SunPower manufactures cells with nominal efficiency of 21.2% in full production.

Under this program, SunPower pursued a variety of options for improving on this cell efficiency and lowering manufacturing cost. This work has included evaluating the geometry effects, optimizing the collecting junction, using long lifetime silicon, and studying the effects of surface passivation.

SunPower demonstrated pilot production capability to produce 23%+ cells, which enabled the world-record panel efficiency of 20.4%.

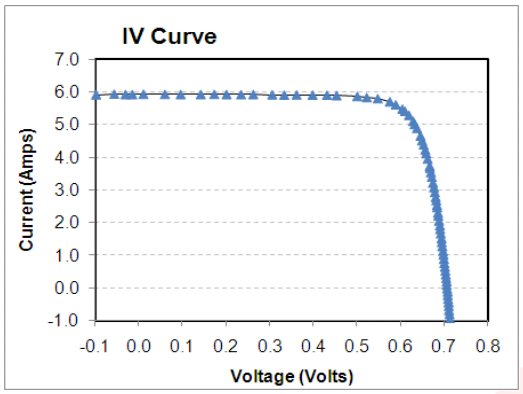

Fig. 1. IV curve of next-generation solar cell from the prototype line indicating an efficiency of 23.4%.

3.3 Low Cost, High Performance Modules for Easy System Integration

SunPower developed and released two new commercial laminates and modules for integration with rooftop and ground-mounted system solutions. These new formats incorporate lower cost materials, improved shipping features, and innovative materials that improve overall performance. Both formats have been UL certified on the TPP program.

Fig. 2. Delivery of SunPower 96-cell modules to commercial rooftop site.

SunPower also worked on developing bifacial and Class A fire-rated modules. In parallel, Dow Corning evaluated polymer materials to replace the front glass on conventional modules.

3.4 Unitary Product Design

Building on its vertical integration, SunPower is designing system-level solutions that integrate module and system design elements to optimize material use, performance, and overall product design to deliver a turnkey system for either rooftop or ground applications. The development of a complete set of system components will radically reduce installation time, eliminate redundant materials and labor, and improve system aesthetics.

In this phase of the program, SunPower has released the T5 commercial rooftile. This product builds on the 96-cell module platform with a polymeric frame that integrates mounting hardware, stacking features, wiring guides, and interconnection points. This integrated frame design reduces the BOS costs and parts count.

Fig. 3. T5 commercial rooftile units installed at 1.1-MW site in Santa Clara, CA.

For ground-mount applications, SunPower designed and released the next-generation tracker built around the 96-cell and 128-cell module formats. In addition to the improved PV capacity, this design achieves LCOE cost reduction through optimized steel and concrete materials, as well as improved packing densities and installation methods to reduce deployment costs.

3.5 Cells-to-Systems Factory

The work under the TPP program is geared toward enabling implementation of a domestic

cells-to-systems factory. This activity has been divided into production lines for cells-to-laminates and laminates-to-systems conversion. In the future, SunPower plans to integrate the assembly lines.

In this phase of the program, SunPower installed and ramped a 24-MWp manufacturing line of the T5 commercial rooftop product in Richmond, CA. Laminates are assembled into T5 units on this new line. During FY 2009, SunPower manufactured and installed 1.3 MW of this product.

Fig. 4. Manufacturing line of T5 commercial rooftile units in Richmond, CA.

For the cells-to-laminates line, SunPower completed the design of an automated, 75-MWp laminate/module line. Equipment orders were placed with vendors, and negotiations concerning site selection were initiated.

3.6 Engineer to Order Software

To reduce deployment-related expenses, SunPower worked to significantly reduce the time and effort to design a PV system. SunPower successfully developed and implemented an engineer-to-order system that takes system design inputs and semi-automatically generates optimized and engineering correct designs, drawing sets, bills-of-materials, and cost and energy simulation that accounts for site-specific obstructions. Typical commercial solar projects take several weeks to design, analyze, simulate, and contract. Through a comprehensive set of design automation improvements, the design time is being reduced to about one hour.

During FY 2009, SunPower expanded the internal software to cover all rooftop solutions, including the newly released T5 product. SunPower issued the first release of a web-based energy simulation engine that is linked to the design software. In addition, SunPower also issued the release of a comprehensive, parametric-based cost engine that will eventually link to the design tools.

3.7 15-Year Warranty Inverter

During this phase, SunPower initiated partnerships with Tigo Energy and Solar Bridge to develop a 15-year warranty inverter.

4. Planned FY 2010 Activities

- Implement domestic manufacturing capacity for modules
- Demonstrate pilot manufacturing and field deployment of next-generation tracker technology
- Develop fully equipped systems kit that is delivered as a unit to residential installations
- Expand engineer-to-order tools for use with ground-mount systems applications.

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5. FY 2009 Special Recognitions, Awards, and Patents

During FY 2009, SunPower filed 20 U.S. patent applications and 12 international applications. No patents were issued during this period.

6. Major FY 2009 Publications

J. Botkin and M. Culligan, "The Unitary Ideal in Commercial PV System Product Design," *34th IEEE PVSC, Philadelphia, PA, June 7–12, 2009.*

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
SunPower Corporation	San Jose, CA	Prime contractor: addressing wafer, cell, module, and system design and deployment	$15,774	$8,241
Dow Corning Corporation	Midland, MI	Subrecipient: new material investigations	$166	$83
Tigo Energy, Inc.	Los Gatos, CA	Subrecipient: 15-year warranty inverter	$55	$28
Solar Bridge	Champaign, IL	Subrecipient: 15-year warranty inverter	$162	$81
NREL	Golden, CO	FFRDC: device measurement and characterization	-	-
Ribbon Technology*	Cupertino, CA	Subrecipient: wafering technology	$64	$32
Xantrex*	Livermore, CA	Subrecipient: 15-year warranty inverter	$102	$102
SiGen*	San Jose, CA	Subrecipient: wafering technology	$254	$204
Solaicx*	Santa Clara, CA	Subrecipient: ingot growth technology	$227	$163

* Subcontract ended during FY 2009.

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TPP Awardee: United Solar Ovonic LLC

"Low Cost Thin Film Building-Integrated PV Systems"

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

Objectives

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

Accomplishments

- Obtained NREL-confirmed 11.7% stable total-area (0.268 cm^2) efficiency on an a-Si:H/nc-Si:H/nc-Si:H triple-junction device, using a small-area MVHF batch reactor on a Ag/ZnO back reflector with production time constraints; achieved world-record stable total-area efficiency of 12.5% at same deposition rate but longer deposition time than the current production deposition time
- Obtained NREL-confirmed 9.5%–9.8% stable total-area (0.268 cm^2) efficiency on a-Si:H/a-SiGe:H/a-SiGe:H triple-junction solar cells on Al/ZnO back reflectors with production time constraints and with a-Si:H and a-SiGe:H cells deposited at ≥ 0.6 nm/s
- Obtained NREL-confirmed 10.1% stable aperture-area (~400 cm^2) efficiency on an a-Si:H/nc-Si:H/nc-Si:H triple-junction device on a Ag/ZnO back reflector, using large-area MVHF batch reactor with production time constraints
- Obtained NREL-confirmed 8.7% stable aperture-area (~400 cm^2) efficiency on an a-Si:H/a-SiGe:H/a-SiGe:H triple-junction device, using a large-area MVHF batch reactor on a Al/ZnO back reflector with production time constraints
- Demonstrated cost saving of 7¢/W using grid wire produced in-house
- Developed and installed in-line monitors in roll-to-roll deposition machines to measure efficiency of solar cells and thicknesses of individual layers and demonstrated excellent agreement with corresponding off-line post-deposition measurements
- Developed standard PV system installation design and interface with utility grid
- Achieved power rating of 144 W on > 80% of 22L laminates
- Attained power rating of 158 W on prototype 22L laminate product using a Ag/ZnO back reflector
- Conducted qualification tests on new sources of stainless steel substrate, EVA, ETFE, and back lamination materials that will lead to substantial cost reduction of our commercial product.
- Developed low-cost solution for a removable solar module for EPDM and TPO roofs that will reduce the overall installation cost.
- Designed and installed two 75-kW PV systems with wireless data acquisition capability: (i) direct bond application of our field-applied PV laminates to a metal roof and (ii) removable solution deployed on a membrane roof (TPO).

Future Directions

- Advance the state-of-the-art technology for nc-Si:H, and a-Si:H and a-SiGe:H materials and solar cells for both small-area and large-area deposition and attain higher conversion efficiency with production-compatible parameters
- Investigate new light trapping schemes in solar cells
- Insert new deposition technology and increase the power rating of prototype 22L laminate on Ag/ZnO back reflector with increased power rating
- Investigate new module designs, assembly processes, and materials to reduce module, installation, and systems level costs.

1. Introduction

United Solar Ovonic (United Solar) is working to develop a low-cost solution for the commercial BIPV and BAPV markets. 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 goal of 2010. 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 United Solar team includes experts from universities, NREL, and industry.

2. Technical Approach

Based on the analysis of all the cost centers associated with providing a complete BIPV/BAPV solution, the company divided the project into five tasks: solar module improvement, inverter and balance system, system engineering and integration, deployment, and project management and TPP collaborative activity.

Work on the module represents the largest portion of the program and underscores a multipronged thrust to reduce module cost. One subtask focuses on materials and process optimization of the current manufacturing lines to improve the current manufacturing process to increase the efficiency of the current 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 is being developed for deposition of a-Si:H, a-SiGe:H, and nc-Si:H materials and cells to obtain higher efficiency and reduce capex. The MVHF deposition technology has shown promise for possible deployment in future roll to roll production machines. There is also an effort to improve the back reflector and associated deposition technologies.

Another effort is directed toward bringing down the cost of stainless steel substrate, grid wires, packaging materials, and miscellaneous materials that go into the module. Innovative detachable module solutions are being developed that are more appealing and will reduce installation cost.

Within the inverter and 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 learnt from test arrays in different locations on different types of roofs.

This project coordinates the efforts of several partners including equipment manufacturers, academia, national laboratories, 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

United Solar achieved target performance with both potential device designs and processes as listed under Accomplishments.

Another goal was the performance against target LCOE (for 2010). United Solar's average module price and total system cost decreased significantly in 2009. Using projected costs of inverter and balance of systems, United 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 multijunction 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 II, the product rating increased to 144 W.

4. Planned FY 2010 Activities

- Attain ≥12% stable total -area (0.268 cm^2) efficiency on multijunction device

incorporating nc-Si:H on Ag/ZnO back reflector

- Attain ≥10.5% stable aperture-area (~400 cm^2) efficiency on multijunction device incorporating at least one nc-Si:H layer at rate ≥ 1nm/s on Ag/ZnO back reflector
- Attain ≥10.2% stable total-area (0.268 cm^2) efficiency on multijunction cells on Ag/ZnO back reflector incorporating a-Si:H and a-SiGe:H deposited at ≥ 0.6 nm/s
- Attain 9.5% stable aperture-area (~400 cm^2) efficiency on multijunction cells, using large-area MVHF batch reactor on Ag/ZnO back reflector incorporating a-Si:H and a-SiGe:H deposited at ≥ 0.6 nm/s
- Using RTR machines, attain 22L laminates having power ratings of 155 W on Ag/ZnO, using new, inexpensive, back reflector deposition techniques
- 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 grid wire for current collection and alternative packaging materials
- Conduct systems engineering and integration to develop novel and advanced application processes that will reduce the overall installation cost of United Solar roofing laminate modules
- Continue to advance in-line diagnostic technology for in situ monitoring of device parameters
- Continue to work with inverter companies to bring down the cost further
- Obtain certification for new installation schemes.

5. FY 2009 Special Recognitions, Awards, and Patents

Subhendu Guha, principal investigator of this program, received the PVSEC 2009 award for his contribution to science and technology of photovoltaic.

Eight patent applications were filed.

6. Major FY 2009 Publications

A. Banerjee, G. DeMaggio, K. Lord, B. Yan, F. Liu, X. Xu, K. Beernink, G. Pietka, C. Worrel, B. Dotter, J. Yang, and S. Guha, "Advances in Cell and Module Efficiency of a-Si:H Based Triple-Junction Solar Cells Made Using Roll-to-Roll Deposition," *34th IEEE PVSC, 2009*.

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X. Xu, Y. Li, S. Ehlert, G. Yue, B. Yan, T. Su, J. Zhang, A. Banerjee, J. Yang, and S. Guha, "Comparative Study of MVHF and RF Deposited Large Area Multi-junction Solar Cells Incorporating Hydrogenated Nano-Crystalline Silicon," *Mater. Res. Soc. Symp. Proc*. *1153, 2009.*

X. Xu, T. Su, D. Beglau, S. Ehlert, G. Pietka, D. Bobela, Y. Li, K. Lord, G. Yue, J. Zhang, B. Yan, C. Worrel, K. Beernink, G. DeMaggio, A. Banerjee, J. Yang, and S. Guha, "High Efficiency Large Area Multi-Junction Solar Cells Incorporating a-SiGe:H and nc-Si:H Using MVHF Technology," *34th IEEE PVSC, 2009*.

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B. Yan, G. Yue, X. Xu, J. Yang, and S. Guha, "High Efficiency Amorphous and Nanocrystalline Silicon Solar Cells," *Proc. 23rd ICANS, Netherlands, 2009*; *Phys. Status Solidi A* (2010).

B. Yan, G. Yue, L. Sivec, J. Yang, and S. Guha, "Extraction of Carrier Transport Parameters from Hydrogenated Amorphous and Nanocrystalline Silicon Solar Cells," *SPIE, 2009*.

J. Yang and S. Guha, "Status and Future Perspective of a-Si:H, a-SiGe:H, and nc-Si:H Thin Film Photovoltaic Technology," *SPIE, 2009* (invited).

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G. Yue, L. Sivec, B. Yan, J. Yang, and S. Guha, "High Efficiency Amorphous and Nanocrystalline Silicon Based Multi-junction Solar Cells Deposited at High Rates on Textured Ag/ZnO Back Reflectors," *Mater. Res. Soc. Symp. Proc. 1153, 2009*.

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G. Yue, B. Yan, L. Sivec, J. M. Owens, S. Hu, X. Xu, J. Yang, and S. Guha, "Improvement of a-Si:H and nc-Si:H Multi-junction Solar Cells by optimization of Textured Back Reflectors," *34th IEEE PVSC, 2009*.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009* ($K)	Cost Share* ($K)
University of Oregon/ J. David Cohen	Eugene, OR	Electronic and optical characterization of materials for a-Si:H, a-SiGe:H, and nc-Si:H materials and solar cells	150	0
Syracuse University/ 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	148	37
Colorado School of Mines/ P. Craig Taylor	Golden, CO	Defect characterization of materials and devices using NMR, ESR, and PL	150	31
NREL/ Pauls Stradins	Golden, CO	Full material characterization and modeling of high rate materials using various characterization methods	150	0

* Phase II awarded amounts.

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University Process & Product Development 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) (2); University of Florida (UF); University of Toledo (UT) (2)

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 2009 Budget: $2,892K (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

- Demonstrated >20% efficiency using local back-contact structure formed by dielectric etching and laser ablation (ASU)
- Demonstrated back-surface recombination velocity of 125 cm/s and back-surface reflectance of 93% using local back contact structure (GIT)
- Achieved a small-area device efficiency of 15.5% (AR coated, measured at NREL) on Na doped $Cu(InGa)Se_2$ films deposited in the roll-to-roll system (UD).

Future Directions

- Fabricate and characterize In_xGaAs_{1-x}/InP /Si and $In_xGaAs_{1-x}P$/InP /Si solar cells (CalTech)
- Fabricate 19%–20% efficient cells with dielectric passivated rear contact with screen-printed local BSF (GIT)
- High-temperature XRD studies of base-CIGS thin films multi-layer precursors (UF).

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1. Introduction

The University PV Process and Product Development Support research area is part of the system development and manufacturing phase of the Solar Energy Technologies Program, restricted to U.S. universities. 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 to leverage their knowledge in assisting the transition of PV technology from laboratory to marketplace. Additionally, market-oriented research offers students exposure to the growing PV-related commercialization efforts and supplies industry with a stream of qualified scientists.

2. Technical Approach

University PV Process and Product Development Support awarded 11 projects in six topic areas in FY 2008. The topic areas and awards were CdTe (1), CIGS (2), CPV (3), Thin Silicon (1), Organic PV (1), and Wafer-Silicon (3). Agreements are listed in the table that follows. Progress for each award is described in Section 3.

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Agreement Title	FY 2009 Budget ($K)
ASU—G. Tamizhmani Reliability Evaluation of Concentrator Photovoltaic Modules per IEC Qualification Specifications	33
Caltech—H.A. Atwater 100-mm Engineered InP-on-Si Laminate Substrates for InP-based Multijunction Solar Cells	273
GIT—A. Rohatgi Development of Rear-Contact Technologies for Next-Generation High-Efficiency Commercial Silicon Solar Cells	344
MIT—A. Buonassisi Defect Engineering, Cell Processing, and Modeling for High-Performance, Low-Cost Crystalline Silicon PV	499
NCSU—S. M. Bedair Tunable Narrow Bandgap Absorbers for Ultra High Efficiency Multijunction Solar Cells	256
Penn State—C. A. Grimes TiO2 Nanotube Array-Organic Semiconductor Heterojunction Solar Cells for Efficient, Low-Cost, Large Area Scalable Solar Energy Conversion	297
UD—E. Eser Development of a Low-Cost Insulated Foil Substrate for Cu(InGa)Se2 PV	299
UD—U. Das High-Efficiency Back-Contact Silicon Heterojunction Solar Cells	292
UF—T. Anderson Routes for Rapid Synthesis of CuGaxIn1-xSe2 Absorbers	83
UT—X. Deng High-Rate Fabrication of a-Si-Based Thin-Film Solar Cells Using Large-Area VHF PECVD Processes	260
UT—R. Collins Improved CdTe PV Modules by Atmospheric Pressure Vapor Deposition	256

3. Results and Accomplishments

3.1 Reliability Evaluation of Concentrator Photovoltaic Modules per IEC Qualification Specifications (ASU)

Testing cost and time for the CPV partners will be reduced by as much as 65%. ASU accomplished the following:

- Performed thermal cycling tests with pulsating current on the CPV receivers
- Initiated long-term outdoor testing of CPV modules on two-axis trackers
- Ordered an environmental chamber
- Modified the building to install the chamber.

3.2 100-mm Engineered InP-on-Si Laminate Substrates for InP-based Multijunction Solar Cells (Caltech)

This work is to advance III-V/Si laminate substrate development for multijunction solar cell technology, and to achieve low-cost, high-efficiency multijunction solar cells fabricated on 100-mm InP/Si laminate substrates. Caltech fabricated InP laminate substrates for III-V multijunction cell fabrication on 100-mm-diameter Si substrates, and together with partner Spectrolab developed high-quality InAlAs epitaxial alloys for application as a top cell in InP-based multijunction cells. Caltech also developed a "virtual template substrate" process for fabricating laminate substrates at different lattice constants, using the In_xGaAs_{1-x}/InP system. Caltech is also focusing on developing a robust process for fabricating 100-mm InP/Si substrates. Work to establish and validate a wafer specification for an InP/Si substrate that is commercially manufacturable at high volumes continues, using prototype InGaAsP/InGaAs and InAlAs/InGaAsP/InGaAs multijunction solar cells.

3.3 Development of Rear-Contact Technologies for Next-Generation High-Efficiency Commercial Silicon 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%) silicon solar cells. GIT accomplished the following:

- Modeled effect of amorphous silicon heterojunction on solar cell efficiency
- Developed dielectric with low fixed-charge density and optimized local back-contact geometry
- Deposited silane-free SiC_X and evaluated passivation quality
- Demonstrated back-surface recombination velocity of 125 cm/s and back-surface reflectance of 93% using local back-contact structure
- Demonstrated > 20% efficiency using local back-contact structure formed by dielectric etching and laser ablation.

3.4 Defect Engineering, Cell Processing, and Modeling for High-Performance, Low-Cost Crystalline Silicon PV (MIT)

The objective is to close the efficiency gap between industrial multicrystalline silicon (mc-Si) and monocrystalline silicon solar cells and conserve the economic advantage of low-cost, high-volume substrates inherent to mc-Si. MIT accomplished the following:

- Identified and decoupled the lifetime limiting defects types in "good" and "bad" regions of ingot multicrystalline silicon solar cell material
- Used equivalent lifetime modeling to estimate the impact of each characteristic region on device performance
- Determined the distribution and states of impurities in raw feedstock material (quartz and woodchips/charcoal)
- Reduced dislocation densities in mc-Si via high-temperature annealing.

3.5 Tunable Narrow Band Gap Absorbers for Ultra High Efficiency Multijunction Solar Cells (NCSU)

The objective is to reduce LCOE by improving the efficiency of III-V multijunction solar cell and lead to a practical and achievable efficiency > 45% through a four-junction cell. Using organometallic chemical vapor deposition at 600°C and 625°C, epitaxial structures for the fabrication of simple GaAs test cells and similar structures with superlattices were fabricated into test cells. The structures have high doping back-surface fields (BSFs) and are unpassivated on the front surfaces, but no high bandgap window layer. Researchers compiled the spectral response results to find the effect of barrier width on the barrier transmission probability (internal quantum efficiency of the single wells). Results indicate that structures with barrier widths less than 30 Å demonstrated an I_{sc} equal to or better than that of our GaAs standard cell, illustrated in Figure 1. Because the superlattices have more than 20 periods, a blue response of greater than 80% of the GaAs response shows that we have exceeded 99% transmission through the barriers. Major accomplishments are as follows:

- Grew InGaAs-GaAsP strain balanced superlattices
- Incorporated strain-balanced superlattice in GaAs p-i-n device
- Observed spectral response from superlattices <1,3 eV
- Exceeded 99% transmission through the thin GaAsP barriers.

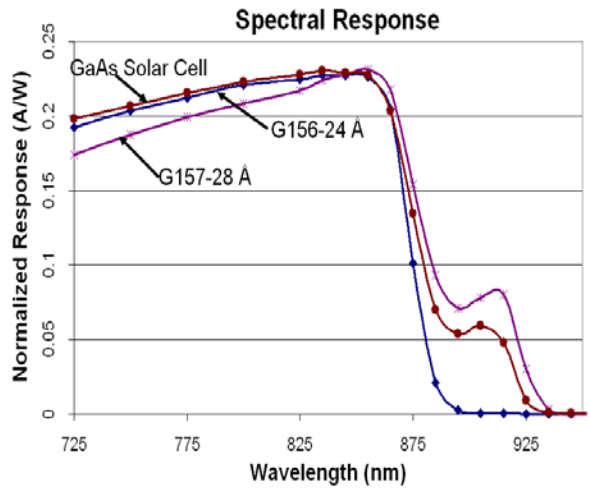

Fig. 1. Effect of barrier thickness on spectral response

3.6 TiO_2 Nanotube Array-Organic Semiconductor Heterojunction Solar Cells for Efficient, Low-Cost, Large-Area Scalable Solar Energy Conversion (Penn State)

The grant's purpose is 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% to 8%. Penn State accomplished the following:

- Developed new acene molecules that serve as both dye and hole-transporter
- Developed optimal routes for intercalation of hole transporting p-type polymers within the pores of one-dimensional electron transporting transparent TiO_2 nanotube array films
- Achieved photostable dye-sensitized heterojunction solid-state solar cells of 6% photoconversion efficiency
- Achieved Förster resonance energy transfer in solid-state dye-sensitized solar cells, enabling enhanced solar spectrum capture and utilization.

3.7 Development of a Low-Cost Insulated Foil Substrate for Cu(InGa)Se^2 PV (UD—Eser)

The goal is to develop low cost stainless-steel flexible-substrate coated with high-temperature silicone-based resin (SBR) dielectric for use in processing $Cu(InGa)Se_2$-based PV. UD accomplished the following:

- Reduced defects in the SBR coatings shorting Mo layer to the stainless-steel foil substantially; the remaining defects were

burned away with an applied voltage of less than 3 V

- Showed, using SIMS depth-profiling data, that SBR coatings were robust diffusion barriers for elements in the stainless steel base.
- Characterized the NaF evaporation source, which is being used routinely in the R2R process system to dope $Cu(InGa)Se_2$ films
- Achieved a small-area device efficiency of 15.5% (AR coated, measured at NREL) on Na-doped $Cu(InGa)Se_2$ films deposited in the R2R system
- Showed small-area device average efficiency over 9 feet of a $Cu(InGa)Se_2$ web of 10.8%, with a maximum of 13.2%.
- Showed small-area end-point efficiencies of 11.9% (at 2 feet from the leading edge) and 11.5% (at 29 feet from the leading edge) on 30 feet of $Cu(InGa)Se_2$ web
- Achieved small-area device efficiency of 8.5% on $Cu(InGa)Se_2$ films prepared by precursor selenization
- Demonstrated $Cu(InGa)Se_2$ laser scribing on small area samples.

3.8 High-Efficiency Back Contact Silicon Heterojunction Solar Cells (UD—Das)

The objective is to implement an interdigitated back-contact (IBC) silicon solar cell using low-temperature heterojunction (HJ) depositions. The use of silicon HJs allows a simpler design of rear-contact solar cells and higher performance at lower deposition temperatures. Results and accomplishments in FY 2009 include the following:

- Demonstrated lowtemperature stack layer (2 nm a-Si:H/60 nm SiN_X/20 nm SiC_X) for c-Si front surface passivation and antireflection (AR) structure with surface recombination velocity (SRV) < 7 cm/s.
- Achieved highly transparent evaporated ZnS films for c-Si front surface passivation with SRV ~ 30 cm/s.
- Implemented a-Si:H-based stack layer as a robust, process-compatible front surface passivation, and AR structure leads to V_{OC} > 700 mV in IBC-SHJ solar cells on thin (<150 μm) n-type Fz wafer
- Modified and prepared various interfaces between c-Si and thin a-Si:H layers essential to improve solar cell FF and were demonstrated by two-dimensional numerical simulation and in experimental front SHJ solar cells.
- Front SHJ solar cells with improved interfaces exhibited FF > 79% on thin (< 150 μm) polished Fz and FF > 75% on 150 μm SunPower textured wafers.

3.9 Routes for Rapid Synthesis of $CuGa_xIn1\text{-}xSe_2$ Absorbers (UF)

The objective is to develop predictive models that quantitatively describe reaction pathways to synthesize CIGS for increased throughput as a result of shortened reaction time for absorber synthesis. Additional cost reductions owing to process scale-up will be realized with quantitative rate data. The target is a synthesis time of 2 minutes or under. Progress to date includes the following:

- Performed high-temperature X-ray diffraction (HT-XRD) studies of the Ga-Se and In-Se binary systems using both codeposited and bilayer precursors: the Ga-based reactions were much faster than In-based ones, and pathways for stacking sequence of Cu/Ga/In/Se and Ga/In/Cu/Se layered structure were compared
- Using a sublattice model, assessed the metal-Se binary phase diagrams and evaluated the pseudo-binary CIS-CGS phase diagram; also assessed the Cu-Ga binary system using the sublattice model framework
- Performed detailed high-temperature XRD studies on samples provided by two of our industrial collaborators; these studies provided valuable insight into their processes
- Validated a low-temperature route to grain growth of CIS nanoparticles using peritectic decomposition of $CuSe_2$ or CuSe in temperature ramp experiments; initiated a study of the effect of Na addition on the nanoparticle growth pathway and rate.
- Reviewed available data and performed a preliminary analysis of CALPHAD-based diffusion mobility descriptions for phases in the 3 metal-Se, 3 metal-metal, and CIS systems.

3.10 High-Rate Fabrication of a-Si-Based Thin-Film Solar Cells Using Large-Area VHF PECVD Processes (UT—Collins)

Two clear objectives of this effort are (1) to develop and improve a large area (3 × 3 ft) PECVD system for high rate fabrication of 8 Å/s a-Si and 20 Å/s nc-Si or 8 Å/s a-SiGe absorber layers with high uniformity in film thicknesses and in material structures, and (2) develop and optimize large-area PECVD processes to achieve high-performance a-Si/nc-Si or a-Si/a-SiGe tandem-junction solar cells with >10% stable efficiency. Accomplishments include the following:

- Systematically studied a-Si and a-SiGe solar cells deposited in lab-scale (4 × 4 in.) and large-area (3 × 3 ft) PECVD systems at elevated pressures of 1 ~ 4 Torr and power density
- Achieved high deposition rate of >8 Å/s for a-Si and a-SiGe absorber layers without compromising the cell performance
- Modified the large-area PECVD cathode to improve the discharge stability and uniformity
- Developed a-SiGe cells with graded Ge profile; the efficiency of a-Si/a-SiGe tandem cells deposited at a high rate reached >10%
- Fabricated full-laminated a-Si/a-SiGe modules of 1.5 × 1.5 in. window area; the module efficiency reached 10.28% from NREL measurement results
- Optimized the front transparent conductive oxide films to improve light absorption and current collection
- Conducted numerical simulation of gas distribution in a large-area PECVD system
- Installed multichannel RTSE on small-area (4 × 4 in.) PECVD system; demonstrated the phase diagrams of PECVD a-SiGe cells deposited at high rate.

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 manufacturing cost advantages of APVD. Accomplishments include the following:

- Achieved an average efficiency of greater than 12% for CdTe cells as thin as 1 micron with the appropriate post-deposition treatment and optimized back contact scheme
- Obtained a map of the CdS bulk layer thickness from spectroscopic ellipsometry measurements over a 120 x 60 cm area of a glass plate coated with TEC-15 and HRT layers
- Optimized a dual electrochemical/photochemical treatment process for CdTe cells.

4. Planned FY 2010 Activities

ASU

- Install and commission the first environmental chamber, order second chamber
- Collect and report test data on the outdoor exposure tests
- Install and commission the second environmental chamber
- Perform two qualification tests for each of the two partners.

CalTech

- Fabricate and characterize In_xGaAs_{1-x}/InP /Si and $In_xGaAs_{1-x}P$/InP /Si solar cells
- Fabricate and characterize In_xAlAs_{1-x}/InP /Si solar cells
- Develop comprehensive laminate substrate wafer specification and defect characterization protocol.

GIT

- Develop and optimize technology to open local contact windows using screen printable dielectric etching paste and laser patterning technique
- Develop Al paste and firing technique to form high-quality Al BSF through the contact windows without warping thin wafers
- Fabricate 19%–20% efficient cells with dielectric passivated rear contact with screen printed local BSF
- Develop the technology for the local plated contacts and inkjet printing to form local rear contacts
- Fabricate cells with the plated and inkjet rear contacts with efficiency of 18%–20%

NCSU

- Achieve reflectivity of > 80% with Bragg reflector
- Optimize full cell structure (passivation, windows) for incorporation into multijunction cell
- Optimize strained-layer superlattice composition for current and voltage
- Begin technology transfer to Spectrolab.

UD—Eser

- Demonstrate 12% or higher efficiency devices on $Cu(InGa)Se_2$ films prepared by precursor selenization
- Optimize laser scribing of the $Cu(InGa)Se_2$ films and of the top contact ITO
- Fabricate prototype 3 x 3 in. minimodule.

MIT

- Evaluate which defects are and are not passivated during hydrogenation in cell processing, and explore low-temperature annealing to improve solar cell device performance
- Develop and release an impurity simulation tool to predict the effect of impurities on silicon material performance
- Transfer to industrial partners by 2011.

Penn State

- Optimize the performance of solid-state solar cells comprising dye-sensitized TiO_2 nanotube films intercalated with p-type polymeric blends
- Synthesize functionalized pentacene derivatives and incorporate them into TiO_2 nanotube array hybrid solar cells to decrease bandgap, increase stability, and improve compatibility with oxide surfaces
- Explore high-throughput fabrication techniques to form the active layer organic semiconductor films on TiO_2
- Quantify and overcome the limiting parameters affecting solar cell performance.

UD —Das

- Investigate effect of different front-surface passivation and AR layer on optical and electrical performances of IBC-SHJ solar cells
- Characterize and modify different interfaces to achieve high V_{OC} (>700 mV) and FF (>80%) of SHJ solar cells
- Fabricate IBC-SHJ solar cells on thin wafers (~ 150 μm) with improved interface quality.

UF

- Perform high-temperature XRD studies of base-CIGS thin-film multilayer precursors
- Perform high-temperature XRD studies of grain growth using nanoparticles
- Complete assessment of the ternary Cu-In-Ga system
- Perform DICTRA modeling of binary Se couples to extract diffusion mobilities: Cu-Se, In-Se, and Ga-Se.

UT—Deng

- Improve gas distribution and discharge uniformity in a large-area 3 × 3 ft PECVD system in combination with theoretical simulation
- Further improve the deposition rates and stability of a-Si, a-SiGe, nc-Si, and nc-SiGe solar cells grown at high pressure
- Fabricate a-Si/a-SiGe or a-Si/a-SiGe/nc-SiGe multi-junction solar cells at a high deposition rate.

UT—Collins

- Select the best advanced solar tuned glass for further study of CdTe solar cells
- Evaluate the performance of spatial scanning SE for CdTe solar cells
- Continue studies of rapid thermal on-line activation
- Select optimum atmospheric pressure metallization procedure
- Perform scribing on cell structures with the optimized thicknesses chosen after Year 1
- Perform testing on minimodules (interconnected and encapsulated) to identify possible issues.

5. FY 2009 Special Awards and Patents

U.S. provisional patent application, R.W. Birkmire et al., "Methods for Fabricating All-Back-Contact Heterojunction Solar Cells," serial number 61/187,812 filed on June 17, 2009.

Penn State

U.S. patent application, X. Feng, K. Shankar, and C.A. Grimes, "Single-Crystal Nanowires and Liquid Junction Solar Cells."

6. Major FY 2009 Publications

UD—Das

U.K. Das, D. Xu, O. Jani, M. Lu, S. Bowden, and R.W. Birkmire, "Designing Rear Surface for Carrier Transport in all Back Contact Silicon Heterojunction Solar Cells," *Tech. Digest, 18th International Photovoltaic Science and Engineering Conference & Exhibition, Jan. 19–23, 2009, Kolkata, India*.

UT—Collins

J. Li, J. Chen, M. Sestak, C. Thornberry, and R.W. Collins, "Spectroscopic Ellipsometry Studies of Thin Film CdTe and CdS: From Dielectric Functions to Solar Cell Structures," *34th IEEE PV Specialists Conference, June 7-12, 2009, Philadelphia, PA,* Invited Paper 505.

MIT

D.P. Fenning, M.I. Bertoni, and T. Buonassisi, "Insights Into the Optimal Phosphorus Diffusion Profile for Silicon Solar Cells," *Proc. 24th European Photovoltaic Solar Energy Conference*, *Hamburg, Germany, 2009*.

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7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location	Description/Title of Research Activity
ASU/ G. Tamizhmani Solfocus, Inc. Warren Nishikawa Soliant Energy, Inc. Brad Hines	Mountain View, CA Pasadena, CA	Perform thermal cycling test of receivers with current injection; outdoor exposure testing of the modules / assemblies
Caltech/ H.A. Atwater Spectrolab Dr. Daniel C. Law	Sylmar, CA	Assist with cell processing, $In_xGa_{1-x}As$ cell fabrication
GIT/ A. Rohatgi SiXtron Advanced Materials, Inc.	Varennes, Quebec, Canada	Furnish silane-free solid source for SiN-/SiC-based AR-coatings and passivation layers for Si cells
NCSU/ S.M. Bedair Spectrolab Ken Edmondson	Sylmar, CA	Support integration of NCSU subcell into multijunction cell
Penn State/ C.A. Grimes University of Kentucky	Lexington, KY	Assist in the design and synthesis of organic semiconductors
UD/ E. Eser Dow Corning Corp. Elizabeth McQuiston	Midland, MI	Develop silicone-based dielectric coated stainless-steel foils
UD/ U. Das SunPower Richard Swanson	Sunnyvale, CA	Produce textured thin wafers and participate in technical discussions
UT/ X. Deng Xunlight Corporation X. Deng	Toledo, OH	Furnish materials, labor, and equipment for Xunlight's roll-to-roll production line
UT/ R. Collins Solar Fields Dr. Norm Johnston University of Nevada, Las Vegas Dr. Clemens Heske University of Michigan Kai Sun NSG Pilkington David Stricklert	Perrysburg, OH Las Vegas, NV Ann Arbor, MI Northwood, OH	Supply large-area thin-film deposition processing Provide electron and photon spectroscopies Provide high resolution electron microscopy Supply ASTG plates

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PV Component Development Summary

The PV Systems and Component Development agreement for subcontracted R&D activities includes the PV Incubator Solicitation, the Pre-Incubator (device and development evolution) solicitation and the Industry Thin Film Partnerships.

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
PV Component Development	**137226**	**50**	**0**	**13776**
PV Incubator Solicitation	**11664**	**50**	**0**	**11714**
Industry Thin Film Partnerships	**2062**	**0**	**0**	**2062**

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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 2009 Budget: $11,664K (NREL)

Objectives

- Shorten the timeline for companies to transition prototype and precommercial photovoltaic (PV) technologies into pilot- and full-scale manufacture
- Move companies into commercial production quickly and successfully
- Position companies to be competitive for market entry by 2012.

Accomplishments

- Completed merit review and analysis to select negotiations for third round of Incubator subcontracts in August 2009
- Began stage-gate reviews for the second round of Incubators; six companies are in this round, one to date was down-selected
- Completed the first round of Incubator subcontracts, October 2009; seven of 10 companies completed the Incubator successfully within 18 months.

Future Directions

- Issue a fourth letter of interest (LOI) for the PV Technology Incubator in fiscal year FY 2010. This will combine the Pre-Incubator and the Incubator with merit criteria updated to better represent the maturity levels for small businesses that will be competitive for this upcoming procurement
- Complete merit review for responses to the fourth Incubator/Pre-Incubator LOI by September 2010
- Complete stage-gate reviews of round 2 Incubators of progress, deliverables, and ability for commercialization by January 2010
- Begin negotiations with the companies selected under the third Incubator solicitation. Complete awards by March 2010.

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1. Introduction

The primary objective of the PV Technology Incubator project is to shorten the timeline for companies to transition PV technologies into pilot and full-scale manufacture. Companies selected are diverse and are able to meet the objectives set out by the SETP program. Incubator companies should be able to achieve market entry by 2011.

This 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 focus 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 subcontract duration will be 18 months, and each award will be $3 million under this solicitation. Entrance opportunities for the Incubator project are anticipated every 9–12 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 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. The guidelines will be revisited in FY 2010.

The success of the PV Technology Incubator project is attributable to the financial resource supported fully by the DOE and the capabilities and the experience the researchers bring to each project. Kick-Off meetings begin the dialogue with the Companies and NREL researchers. Involvement begins immediately and is very effective in this program.

2. Technical Approach

2.1. PV Incubator Management

The Project Management and Support subtask manages the Incubator project, manages subcontracts awarded, and coordinates NREL in-house activities in support of the small businesses.

Table 1. PV Incubator Project Tasks and Budget

Task Title	FY 2009 Budget ($K)
PV Technology Incubator Management	1,170
PV Technology Incubator Subcontracts	10,434

2.2. 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 2011 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.

Table 2. FY 2007 PV Incubator Subcontractors Round 1. Successful companies completed early FY 2009.

Subcontractor	Title of Subcontract
Abound Solar	Advanced CdTe PV Technology
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
SolFocus	Reflective Optics CPV Panels Enabling Large-scale, Reliable Generation of Solar Energy Cost-competitive with Fossil Fuels
SoloPower	CIGS Technology based on Electroplating

Table 3. Subcontractors Selected in Response to the FY 2008 PV Incubator Solicitation. Subcontracts will be completed during FY 2010

Subcontractor	Project Title
1366 Technologies, Inc.	Self Aligned Cell – Scaling Up Manufacture of a Cost Effective Cell Architecture for Multi-Crystalline Silicon Photovoltaics
Innovalight, Inc.	High-Efficiency, Low-Cost Solar Cells Manufactured Using "Silicon Ink" On Thin Crystalline Silicon Wafers
Skyline Solar, Inc.	Accelerating the Transition of Skyline Solar's Module to Manufacturing: Medium Concentration onto Silicon = Low Cost × Explosive Scalability
Solexel, Inc.	Productization and Manufacturing Scaling of High-Efficiency Solar Cell and Module Products Based on a Disruptive Low-Cost, Mono-Crystalline Technology
Spire Semiconductor Corporation, LLC	Manufacturing of High-Efficiency Bi-Facial Tandem Concentrator Solar Cells

3. Results and Accomplishments

1366 Technologies is focusing efforts on a self aligned cell, scaling pp manufacturing of a cost-effective cell architecture for multicrystalline silicon photovoltaics. During the Incubator project,

1366 invented a patterning machine that makes a structured texture on multicrystalline cells that improves the cell efficiency. 1366 also developed a dispensing machine that created front metallization with three times the conductivity and one-third the width of screen-printed fingers. The dispensing machine makes it possible for cell manufacturers to switch from silver conductors to copper conductors. Copper is two orders of magnitude cheaper than silver.

Innovalight is focusing on increasing the efficiency of crystalline silicon solar cells and modules by developing low-cost manufacturing processes using ink-jet printing of "silicon ink" onto thin crystalline silicon wafers. During 2009, they exceeded their efficient target for 25 x 25 mm crystalline silicon cells incorporating optimized antireflection coating, metallic contact grid, and optimized front surface texturing by achieving more than the required 17% on all 125 x 125 mm cells. They also demonstrated a less than 10% degradation in the efficiency, Jsc, Isc, Voc, Pmax, and FF on (nonpackaged) 125 x 125 mm cells after exposure to 85°C/85% relative humidity for 250 hours.

Skyline Solar is focusing on manufacturing linear CPV concentrators designed for medium concentration (10–50X) on silicon solar cells. Their project emphasizes a low-cost CPV product using aluminum reflectors, optics with flexible tolerances, lightweight structures to minimize installation costs, and standard industrial manufacturing processes to maximize scalability. Skyline Solar achieved an array efficiency of 12.5% $\pm$ 0.4% with their 12-m^2 prototype module.

Solasta's project emphasizes optimizing and scaling up solar cells that incorporate a unique nanocoax architecture with an a-Si absorber layer. Nanocoax solar cells consist of arrays of vertical nanopillars coated by a layer of a-Si, followed by a conformal layer of a transparent conductive oxide (TCO). They achieved 8% initial efficiency on 1-cm^2 nanocoax cells and plan to submit 1-cm^2 nanocoax cells with 10% initial efficiency to NREL by February 2010. Solasta intends to achieve 100-cm^2 nanocoax solar cells with > 15% efficiency and prepare for pilot production by the end of the 18-month subcontract.

Solexel is focusing on fabricating epitaxially grown monocrystalline silicon thin-film solar cells and incorporates these cells into a module designed to reduce efficiency loss. The epitaxial silicon is grown on and lifted off of a crystalline silicon template that can be reused numerous times to yield many thin film silicon substrates (TFSS), which are then processed into solar cells. By the end of their 18-month subcontract, Solexel intends to achieve a 3-MW pilot manufacturing line that produces 156 x 156 mm TFSS cells with > 19%.

The focus of the Spire Semiconductor Corporation research activities is to develop a manufacturable, 42.5% efficient, bifacial, tandem CPV solar cell suitable for 500X concentration. This multijunction approach is highly innovative and can achieve greater than 43% efficiency during the project. The results to date include developing the InGaP top cell with a bandgap of ~1.9 eV, the InGaAs bottom cell with bandgap of ~ 1.0 eV, and low-absorption TJs suitable for > 500X device fabrication. Cell results to date are a 39.3% tandem cell at 218X and 35.6% tandem cell at 500X, independently verified by NREL.

The round 3 Incubators solicitation was released in May 2009 with selections during FY 2009 and announced into FY 2010. These companies are Alta Devices, Semprius, Solar Junction, and TetraSun. The subcontracts are anticipated to be completed by March 2010. The subcontracts will mostly use ARRA funding.
The Pre-Incubator solicitation was released in January 2009, and 11 selections were made. These awards were completed by late November 2009. The selections are Crystal Solar, TiSol, Banyan, Microlink, EPIR, Vanguard, Ascent, 1366 Technologies, Lightwave, Spectrawatt, and Luna Innovations. These 1-year subcontracts will complete with a finished prototype ready to apply for the Incubator solicitation.

4. Planned FY 2010 Activities

The Round 3 Incubators selected during FY 2009 and announced in January 2010 will be awarded by March 2010. These companies are Alta Devices, Semprius, Solar Junction, and TetraSun. These will mostly use ARRA funding.

A fourth solicitation incorporating the Incubator and Pre-Incubator will be released in Spring 2010. Updates to the solicitation will include such items as the merit criteria. This type of change is to better represent the maturity levels for small businesses that will be competitive for this upcoming procurement. Typically we expect 8–10 Incubators and 12–16 Pre-Incubators to be funded under this solicitation. These subcontracts will

then undergo a stage-gate review in late 2010. At that time their progress will be evaluated we will decide whether to continue with the second 9-month phase of the subcontract.

Additionally, we will track the potential in terms of megawatts, job creation, and other quantitative metrics to better evaluate the success of the program.

5. Industry Partners

The following organizations partnered in the Incubator project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title Research Activity	FY 2009 ($K)	Cost Share ($K)
1366 Technologies, Inc. Frank Van Mierlo	16 Outlook Dr. Lexington, MA 02421 Phone: 617-818-6996 Email: mierlo@1366tech.com	Self Aligned Cell – Scaling Up Manufacture of a Cost Effective Cell Architecture for Multi-Crystalline Silicon Photovoltaics	1,500	330
Innovalight Inc. Nick Cravalho	Innovalight, Inc. 965 East Arques Avenue Sunnyvale, CA 94085 Email: ncravalho@innovalight.com	New Metallization Technique Suitable for 6-MW Pilot Production of Efficient Multicrystalline Solar Cells Using Upgraded Metallurgical Si	1,509	972
Skyline Solar, Inc. Scott McHugo	Skyline Solar, Inc. 185 East Dana St. Mountain View, CA 94041 Phone: 650-864-9770 x2122 Email: smchugo@skyline-solar.com	Accelerating the Transition of Skyline Solar's Module to Manufacturing: Medium Concentration onto Silicon = Low Cost × Explosive Scalability	1,300	820
Solasta, Inc. **Mike Naughton**	Pittsburgh, PA swilliams@plextronics.com	Nanocoax Solar Cells	1,431	315
Solexel, Inc. Mehrdad Moslehi	1530 McCarthy Blvd. Milpitas, CA 95035-7405 Phone: 408-715-9554 x222 Email: moslehi@solexel.com	Productization and Manufacturing Scaling of High-Efficiency Solar Cell and Module Products Based on a Disruptive Low-Cost, Mono-Crystalline Technology	1,400	397
Spire Semiconductor Corporation, LLC Steven Wojtczuk	25 Sagamore Park Rd. Hudson, NH 03051 Email: swojtczuk@spiresemi.com	Manufacturing of High-Efficiency Bi-Facial Tandem Concentrator Solar Cells	1,382	278

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Industry Thin Film Partnerships

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 2009 Budget: $985K (NREL)

Objectives

- Support the Technology Partnership Pathway project to achieve levelized cost of electricity (LCOE) by 2015
- Support the near-term transition to first-time manufacturing and commercial introduction of reliable copper indium diselenide (CIS) and cadmium telluride (CdTe)
- Build a technology base on 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 can 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 LCOE and grid parity electricity.

Accomplishments

- Achieved a production cost of $0.92/Wto $1.14.W for thin film PV technology and then further reduced it to $0.85/W in FY 2009 (First Solar)
- Provided support to assist two technology partners, U.S. manufacturing facilities, to expand: First Solar, 159 MWp (1,200 MW worldwide) and Global Solar, 40 MWp (75 MWp worldwide)
- 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 300 MWp in 2009.

Future Direction

- The three subcontracts, two industries and one university, are being or have been phased out.

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1. Introduction

Thin-film PV technologies have good potential to meet ambitious cost and performance goals, such as achieving long-term goals for a levelized cost of electricity by 2015. The Thin Film PV Partnership Program is designed to accelerate progress toward meeting those goals. The partnership includes subcontracted R&D in CIS and CdTe. 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 2009 Presentations and Publications

We published several subcontract reports and presentations. Other important publications and presentations include the following:

H.S. Ullal, "Polycrystalline Thin Film Solar Electric Technologies," presented at the 18th International Photovoltaic Science and Engineering Conference, Kolkata, West Bengal, India, January 19–23, 2009.

H.S. Ullal, "The Great Thin Film Debate," panelist and speaker at Solar Power International 2008, Oct 13-16, 2008, San Diego, CA.

H.S. Ullal, "Thin Film Debate," panelist and speaker at Solar Power International 2009, October 27-29, 2009, Anaheim, CA.

3. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
First Solar, LLC Scotty Gilmore	Perrysburg, OH sgilmore@firstsolar.com	Development of robust high efficiency thin film CdTe PV modules	270	270
Global Solar Energy Scott Wiedeman	Tucson, AZ swiedman@globalsolar.com	Cost and reliability improvements for CIGS based on flexible substrates	660	660
University of South Florida Chris Ferekides	Tampa, FL ferekide@eng.usf.edu	High efficiency CdTe cells by CSS	55	4

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Evaluation, Validation & Analysis Summary

As the market for solar energy systems grows, the energy produced by solar systems (kWh) and the value of the energy (¢/kWh) are replacing capacity (watts) and cost ($/W) as primary metrics. Modeling and analysis tools and accompanying data are needed that accurately estimate both the energy output and the cost of energy from solar systems. This information is critical not only to system design and project management, but also to setting research priorities based on the potential impact of various technology development options.

The solar community was surveyed in 2006 to identify specific modeling priorities. The data show broad support, especially among industry (manufacturers and integrators) for reliability/lifetime modeling for components and integrated systems, better solar resource data, and performance algorithms for PV components and systems. Manufacturers supported development of design optimization tools, but the likely users of such tools, the integrators, did not support this area. Customers were especially interested in financing algorithms.

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
Evaluation, Validation & Analysis	**6720**	**4495**	**2045**	**13260**
System Modeling	**678**	**615**	**0**	**1293**
Systems Analysis	**1740**	**0**	**650**	**2390**
Reliability R&D	**2970**	**1555**	**1000**	**5525**
Test & Evaluation	**1332**	**2275**	**0**	**3607**
Regional Experiment Stations	**0**	**50**	**395**	**445**

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Systems Performance 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
Chris Cameron (SNL, Primary Contact), 505-844-816, cpcamer@sandia.gov

DOE HQ Technology Manager: Kevin Lynn, 202-586-1044, kevin.lynn@hq.doe.gov

FY 2009 Budgets: $678K (NREL), $615K (SNL)

Objectives

- The system modeling efforts of this project seek to enhance the U.S. Department of Energy (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.
- These efforts also will validate SAM and, potentially, other solar models for a variety of technologies, applications, and locations.
- These tools can be used by industry and government to guide research and development (R&D) prioritization and to provide credible energy production and cost data using a common platform for project development, evaluation, and due diligence.
- These efforts also will provide additional tools to industry to meet their planning, R&D, siting, and other modeling needs to help accelerate market penetration.
- These efforts will support progress evaluation at Stage-Gate assessments for the Technology Pathway Partnerships (TPPs).
- This project also will maintain and advance the online PV tool called PV-Watts.

Accomplishments

- Reconstruction of the entire Solar Advisor Model (SAM) core code in C++ for these reasons:
  - It is significantly faster
  - Allows greater interaction with risk-assessment tools such as @Risk and CrystalBall
  - Incorporates Monte Carlo analysis (in conjunction with SNL)
  - Enables SAM as a WebApp and a Apple Mac version
  - Allows easier interaction with Excel, Matlab and other Web tools
  - Improved maintainability
- Release new SAM versions with:
  - PV-Watts Model as perfoption
  - Simple shading
  - Enhanced graphical capabilities
  - Simple PV electric storage
  - Physically different PV subsystems can be combined in a single financial analysis
  - Enhanced graphic user interface (GUI) and greater graphical output capability including Tornado-chart analysis
  - Added time-of-use utility rates and automated independent power producer (IPP) financing optimization
  - Updated databases of component performance parameters
- Conducted multiple in-person and Web-based trainings for SAM.
- Provided analysis and review of levelized cost of energy calculations for TPP Stage Gates.
- Install system to collect data in diffuse climate for use in performance model validation.
- Began development of an analytical tool to assess performance model accuracy and uncertainty.

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Future Directions

- Continue DOE and user support, including analysis for TPP Stage Gate reviews, and hold a full-day user forum.
- Acquire additional data sets, including thin-film and concentrating photovoltaic (CPV) system data, for use in model validation.
- Complete an assessment of performance model accuracy and uncertainty.
- Convene an industry workshop on performance modeling tool development and validation.
- Support grid-integration work including the incorporation of complex utility-rates and electric loads for residential and commercial systems.
- Continue support to SETP analysis activities at NREL and SNL.

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1. Introduction

The objective of this project is to combine PV, CSP, and thermal solar technologies into a single model making use of high-quality performance models developed by NREL, SNL, and other partners. This will facilitate comparison by handling performance, costs, and financing consistently across technologies. There will be a high emphasis on a quality user interface to promote greater usage of quality tools by industry and DOE. This project also captures several smaller activities such as PV-Watts and (starting in FY 2010) In My Back Yard (IMBY).

2. Technical Approach

The system modeling task consists of systems performance and cost modeling and validation projects. The primary function of the 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, levelized cost of energy, and system capital and operation and maintenance (O&M) costs. SAM is used not only by DOE, laboratory management, and research staff, but also is widely-used 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 PV-Watts, which is a popular model for simple performance estimates for PV systems. For FY 2010, this activity also covers the IMBY model.

3. Results and Accomplishments

There was a great deal accomplished for SAM development in FY 2009. The primary activity was the development and release of a rebuilt code base for SAM. This was done for a variety of reasons including ongoing issues with the original platform chosen and its ongoing speed issues. While not a planned deliverable, this activity was accomplished while still accomplishing the other planned deliverables (and some originally slated to be enhanced activities).

Planned FY 2009 activities for the SAM can be broken into two general groupings – core activities (jointly funded by PV and CSP funds) and PV-specific activities.

With more than 11,000 individuals having downloaded SAM, user-support continues to be a growing issue especially as some long-time users delve ever deeper into the capabilities. Documentation has been greatly improved across all aspects of SAM with multiple avenues to access help both within the tool and online.

Specific PV SAM Accomplishments:

- A specific annual one-day workshop was held at Solar Power International (SPI).
- Added PV-Watts as a PV Option in SAM
- Shading: simple module shading as an option was added to the model.
- Electric Storage: The ability to model electric storage (either on-grid or off) likely in the form of batteries was added.
- Support the needs of the PV program by sponsoring university-level development of enhanced PV modeling capabilities relevant to the current systems. This should result in an enhanced CEC model.
- Added capability to sum different system outputs and do financial analysis at an aggregate level.
- Continued to add components to the module and inverter databases.

- In collaboration with Navigant Consulting, perform cost and levelized cost of energy (LCOE) reviews at all TPP Stage Gates.

Performance Model Validation:
It is essential that PV performance models have validated accuracy.

- An approach to model validation has been developed in collaboration with industry that involves collection of data sets for diverse technologies and in diverse climates; input of system design data as well as measured weather and irradiance data into a range of widely-used performance models; and comparison of model predictions with measured results to assess model accuracy.
- To supplement data sets from NREL and SNL, both located in sunny climates, an automated weather and irradiance data system was installed on the roof of DOE Headquarters to gather data on five systems, including three thin-film systems, located in a diffuse climate.
- Development of an automated tool to permit rapid assessment of model accuracy and uncertainty was begun. This tool also will provide insight into the steps needed to improve model accuracy.

4. Planned FY 2010 Activities

Task #1: DOE and Industry User Support-SAM. This activity involves providing user support for SAM via an e-mail address supported by a subcontractor. With more than 11,000 individual users (obviously some more active than others) this is a significant effort. This activity also involves reworking the SAM Web site to incorporate the capabilities of our current Google Group site.

TPPs are supported in the use of SAM at stage gates and in parametric analysis to highlight development opportunities. In FY 2010, we will begin to apply stochastic techniques to permit multivariate parametric analysis.

Task #2: SAM Model Enhancement (Core).

- Incorporate direct access to DSIRE incentive Web feed.
- Complete SAM code restructuring:
  - Documentation
  - Sample files for working with Excel/other tools
  - Examples of sub-system aggregation

Task #3: SAM Model Enhancement (PV-Specific). The specific goals for FY 2010 are:

- Enable detailed modeling to support grid integration work
  - Work with grid integration team to implement detailed algorithms for building load management, storage management and dispatch and inverter control.
  - Use new software structure to call SAM from distribution model (Dew) to enable more complex PV production profiles within their distribution grid models.
  - This should allow accurate modeling of local high-penetration of PV systems.
- Incorporate improvements from 5-parameter model improvements currently under development by subcontractor.
- Incorporate algorithmic improvements for new technologies (CIGS, Organics). These could come fromSNL's efforts or from industry input. The chosen modeling options have yet to be determined.

Task #4: Model Validation.
Additional data sets to enable model validation will be collected, including data on CPV systems. Development of the model validation and assessment tool will be completed and will be used to evaluate modeling of crystalline-silicon, thin-film, and CPV systems.

Task #5: PV-Watts (Support and Model development). Under this task, NREL will continue to maintain and provide user support to the PV-Watts community as well as the various tools that incorporate the PV-Watts algorithms. This also will include setting up version control for the code and rebuilding the online interface for PV-Watts to be more user-friendly.

Task #6: IMBY Support. This activity was supported in FY 2009 by Solar America Cities (SAC). The primary activities for this year would be to incorporate more appropriate building load data, database driven utility rates, and incentives, as well as potentially incorporating the new SAM as the calculation engine for both performance and financial analysis.

Task #7: Convene Industry Workshop. An industry workshop will be held on modeling and analysis tools development and integration needs. We will present key results from model validation, progress in model enhancements, and uncertainty analysis. The workshop will set the stage for transfer of important model enhancements and will collect industry input to guide further model development and technology transfer.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
Janzou Consulting Steve Janzou	Evergreen, CO Steve.janzou@nrel.gov	Steve's efforts were to program the front-end and basic engine of the Solar Advisor Model	140
University of Wisconsin-Madison Prof. Sanford Klein	Madison, WI Klein@engr.wisc.edu	Development of an advanced PV module model	105
Paul Gilman	Chicago, IL PaulGilman@earthlink.net	Paul provides user support and technical writing support	40
Clean Power Research Tom Hoff	Napa, CA tomhoff@cleanpower.com	Satellite-based Irradiance Data and Analysis	50
Precision Solar Technologies Tim Leonard	Tijeras, NM TMLeonard@TapTheSun.com	Automated Portable Weather and Irradiance Data System	39

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Systems 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
Ryan Wiser (LBNL), 510-486-5474, RHWiser@lbl.gov

DOE HQ Technology Manager: Kevin Lynn, 202-586-1044, kevin.lynn@hq.doe.gov

FY 2009 Budgets: $1,740K (NREL), $300K (LBNL)

Objectives

- Give a broad range of analytical support to the U.S. Department of Energy's (DOE) Solar Energy Technologies Program (SETP)
- Conduct analysis to provide key research contributions in market, value, policy, financial, and market transformation analysis
- Develop resources such as publications, data sources, and models to support the ongoing informational, decisional, and strategic planning needs of the SETP.

Accomplishments

- Launched the solar vision study, a major research and modeling activity involving industry-wide collaboration, to assess the feasibility of high solar energy deployment scenarios
- Launched the manufacturing cost model project to fill a critical R&D gap
- Began market transformation analysis, including workforce development analysis
- Conducted research for and drafting of the 2008 annual solar market trends report
- Completed numerous solar financing reports and briefs on feed-in tariff policy design and implementation, solar photovoltaics (PV) financing for the residential, nonresidential, and federal government sectors, and the impacts of policies on solar PV financing and deployment
- Completed core development of the SolarDS (Solar Deployment System) PV market penetration model, presented the model to SETP, and published documentation and sample results
- Released the Open PV Mapping database and web site, a collaborative repository and analysis tool for all available U.S. PV installation data: http://openpv.nrel.gov/
- Completed collecting data and analyzing the installed cost of solar PV installations, including publishing reports detailing findings for data through 2007 and 2008 (LBNL)
- Continued to analyze and publish research in PV system integration (LBNL)
- Provided short-term analysis support to SETP to respond to information requests from Congress, the Office of Energy Efficiency and Renewable Energy (EERE) corporate office, NREL, and other stakeholders.

Future Directions

- Continue and expand analysis in the market, value, policy, financial, and market transformation areas
- Conduct research and modeling to follow the analysis and findings of the solar vision study
- Continue PV manufacturing cost modeling
- Give analysis support for DOE SETP's strategic planning efforts
- Publish the 2009 annual solar market trends report
- Continue to analyze and publish on topics pertaining to solar financing, and support the WebView as an online resource for solar (and renewable energy) financing information and tools
- Continue to develop and enhance modeling tools and online resources such as the SolarDS model, the Open PV Mapping database, and the PV value clearinghouse
- Develop a strong foundation for market transformation analysis, including workforce development

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- Produce topical reports and give general analytic support to meet the needs of DOE SETP and to fill analysis gaps for the solar industry.

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1. Introduction

The primary objectives of the systems analysis activity are to 1) give a broad range of analytical support to SETP; 2) develop resources such as publications, data sources, and models to support the ongoing informational, decisional, and planning needs of the SETP; and 3) conduct analysis to contribute key research in market, value, policy, financial, and market transformation analysis. Analysis in these areas consists of:

- Market analysis: Analyze existing and emerging solar energy markets, prepare an annual solar market trends report, give solar technology roadmap support, and continue to develop and implement models such as the SolarDS PV market penetration model.
- Value analysis: Give inputs, support, and review for SETP's annual benefits analysis (GPRA) process, develop methods and tools for improving quantification of the benefits and costs of distributed PV, and maintain the PV Value Clearinghouse.
- Policy analysis: Conduct research that examines the impacts of existing and potential policies on solar technology development and deployment.
- Financial analysis: Conduct research and analysis pertaining to solar financing in all sectors. Support the WebView as an online resource for solar (and renewable energy) financing information and tools.
- Market transformation analysis: Serve as a foundation for analysis on market transformation issues, including workforce development and other critical topics.

2. Technical Approach

Market, value, policy, financial, and market transformation analysis relies on two main technical approaches.

The first is to use and improve existing models and to build new models and tools that can be employed to develop long-term market-penetration projections for solar technologies. Current emphasis is on developing and enhancing new and existing models, as well as integrating models and model results, such as for the solar vision study. Model development involves examining both the system and policy drivers of solar technologies in various markets in the short and long term. A general emphasis has been and continues to be improving the representation of solar technologies in all models. Modeling efforts are a foundation for other solar analysis activities and inform the SETP and the broader solar industry by serving as an analytical basis for projecting the economic and environmental benefits and costs of solar technology deployment. Examples of models are NREL's Regional Energy Deployment System (ReEDs), SolarDS, the DOE Energy Information Administration's NEMS, MARKAL, and others.

The second approach is to use a range of policy analysis tools and techniques to evaluate policies and other factors that affect the value of PV technologies in various markets. These include existing models, spreadsheets, and other tools (such as implementing 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 affected or will affect the value of solar technologies to consumers, utilities, governments, and other players.

3. Results and Accomplishments

Accomplishments resulting from market, value, policy, financial, and market transformation analysis in FY 2009 include:

- Launched the solar vision study, including establishing a schedule, industry-wide working groups, concepts and scenarios, a report outline, meetings, an overall study workshop, and making progress on chapter outlines and resource gathering
- Launched the manufacturing cost model project to fill a critical R&D gap, starting with modeling for wafer silicon PV
- Conducted research and drafting of the 2008 version of the annual Solar Market Trends report
- Conducted and published an analysis of solar market forecasts and the impact of the financial crisis on these forecasts
- Supported EERE program benefits analysis (GPRA) for SETP

- Completed core development of the SolarDS PV market penetration model, presented the model to SETP, and published documentation and sample results
- Released the Open PV Mapping database and web site, a collaborative repository and analysis tool for all available U.S. PV installation data: http://openpv.nrel.gov/
- Completed data collection and analysis of the installed cost of solar PV installations, including publication of reports for data through 2007 and 2008 (LBNL)
- Completed preliminary analysis of the value of net metering for residential PV customers in California, with forthcoming publication (LBNL)
- Updated the PV value clearinghouse: http://www.nrel.gov/analysis/pvclearinghouse/
- Published work on the PV Carbon Wedge—Pathways for U.S. Growth and Sensitivity to Manufacturing Emissions
- Completed analysis on key drivers and sensitivities for grid parity analysis for residential PV, publication forthcoming
- Conducted research and analysis on solar financing, resulting in completion of numerous solar financing reports on the following topics: 1) feed-in tariff policy design and implementation, 2) solar PV financing for the residential sector, 3) solar PV financing for deployment by Federal government agencies, 4) financing non-residential PV projects (LBNL), 5) implications of ITC changes on the residential PV market (LBNL), 6) solar leasing for residential PV (fact sheet), 7) potential regulatory and legal challenges to the third party PPA model (11/09), 8) insurance for PV systems (12/09)
- Continued to develop the WebView project, a forthcoming on-line resource for solar and other renewable energy financing, in preparation for FY 2010 release
- Launched market transformation analysis efforts, especially in workforce development and state technical support
- Updated analysis on state-level renewable portfolio standard developments for input into the solar vision study, market report, and other analysis products (LBNL)
- Hosted PV variability workshop with Utility Wind Integration Group, SEPA, and DOE; published summary of lessons learned; and continued to collaborate with labs, DOE, utilities, and solar industry to obtain access to short-time-scale PV output data (NREL/SNL/LBNL)
- Continued to analyze spatial and temporal scales of PV variability and the benefit of geographic diversity in reducing short-time-scale ramps, with forthcoming report (LBNL)
- Published response to an article in *Environmental Science & Technology* that concluded that operational integration constraints would reduce CO_2 offset benefits and lead to net increase in NO_x emissions from wind and solar generation (LBNL)
- Gave short-term analysis support to SETP to respond to information requests from Congress, the EERE corporate office, the public, and other stakeholders.

4. Planned FY 2010 Activities

As solar markets grow at a record pace and solar technologies continue to evolve rapidly, the need for targeted analysis will be critical to inform decisions affecting the solar industry. Ongoing activities and expansions of current activities under this task include 1) conducting research and modeling in followup to the solar vision study, 2) continuing PV manufacturing cost modeling, 3) giving analysis support for DOE SETP's strategic planning, 4) publishing the 2009 annual solar market trends report, 5) continuing analysis and publication on solar financing topics and release of the WebView as an online resource for financing information and tools, 6) continuing to develop and enhance modeling tools and online resources such as the SolarDS model, the Open PV Mapping database, and the PV value clearinghouse, 7) developing a strong foundation for market transformation analysis, including analysis on workforce development, and 8) producing topical reports and giving general analytic support to meet the needs of DOE SETP and to fill analysis gaps for the solar industry.

5. Major FY 2009 Publications

J.E. Bartlett, R.M. Margolis, and C.E. Jennings, *Effects of the Financial Crisis on Photovoltaics: An Analysis of Changes in Market Forecasts from 2008 to 2009*, NREL TP-6A2-46713, Golden, CO: NREL (2009).

M. Bolinger, *Financing Non-Residential Photovoltaic Projects: Options and Implications*, LBNL-1410E, Berkeley, CA: LNBL (2009).

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DRAFT

Reliability Research & Development

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
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DOE HQ Technology Manager: Kevin Lynn, 202-586-1044, kevin.lynn@hq.doe.gov

FY 2009 Budgets: $4,200K (NREL), $2,198K (SNL)

Objectives

- Help industry develop more reliable photovoltaic (PV) systems and make increasingly confident predictions of performance, degradation, lifetime, and associated costs for system operation and maintenance
- Develop a suite of tools, which enable reduced LCOE through improved product reliability and improved predictions of LCOE
- Develop best practices specific to the PV industry that enhance reliability.

Accomplishments

- Completed the first two rounds of the test-to-failure protocol for module reliability at NREL; this protocol moving toward more quantitative predictions for PV modules
- Gave multiple presentations describing studies of CPV reliability related to understanding the stress related to concentrated light, testing of the die-attach, and application of concentrated UV light
- Documented the thermal exposure of modules within the context of how to design for thermal endurance adequate to avoid safety issues
- Completed baseline failure modes and effects analyses (FMEAs) for crystalline silicon modules, CdTe modules, CIGS modules, and residential inverters; in addition, Sandia facilitated company-specific FMEAs for two companies focusing on systems-level effects
- Demonstrated the PV Reliability and Availability Predictive Model (PVRAM) initial capability based on 5 years of operations, maintenance, and field failure data from Tucson Electric Power's Springerville 4.6 MW PV plant
- Established the database and web-based interface to collect PV systems field O&M data for reliability assessments and predictions (SNL)
- Produced 20 publications, presentations, and webinars on results.

Future Directions

- Combine the PVRAM with weather, performance, and cost-predictive models in a user-friendly environment
- Develop accelerated test methods and correlate with field data
- Standardize fully developed accelerated test methods to gain acceptance for industry use
- Collect accurate field data in a cost-effective manner to empower the community to use the exponentially growing supplies of data
- Quantify effects of weather to estimate acceleration factors relevant to various weather patterns.

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1. Introduction

Reliability is an essential element of reaching the Solar Energy Technologies Program's cost goals. It complements other parts of the program by studying the long-term performance, degradation, and failure of PV modules and systems, and how to design short-term tests to predict these.

2. Technical Approach

Real-time Reliability Studies (NREL & SNL)—Deployment, monitoring, and analysis of data for PV modules/systems outdoors at the labs and elsewhere, using experiments designed to quantify degradation rates and identify failure modes/mechanisms for deployment in different locations.

Accelerated & Diagnostic Reliability (SNL)—Studies of accelerated stress testing, diagnostic studies of failure mechanisms, and development of new diagnostic tests. This work includes environmental chamber testing, IR imaging, adhesion measurements, I-V testing, other electrical testing, and transmission/reflectance measurements.

Module Accelerated Testing (NREL)—Studies of accelerated stress testing on modules. This work includes environmental chamber testing, I-V testing, and other testing that is associated with module qualification tests. Notably, this effort supports DOE contract deliverables, as needed.

Component/Material Accelerated Testing (NREL)—Studies of accelerated stress testing, diagnostic studies of failure mechanisms, and development of new diagnostic tests. This work includes IR imaging, adhesion measurements, I-V testing, other electrical testing, and transmission/reflectance measurements. Testing components, materials, and subassemblies can give more direct information while still being directly relevant to module testing. Although collaborations are fruitful, cell-level reliability work is primarily funded by the technology areas.

Predictive Model Development (SNL & NREL)—Discussions with industry to develop FMEAs, develop/validate PVRAM, and collect relevant operations, maintenance, and field failure data into a database.

Industry Workshop and Standards Support (SNL & NREL)—Plan and host an industry workshop and participate in writing/discussion of standards. Note: Technical support of standards work is supported in other tasks as well.

3. Results and Accomplishments

Level 3 and 4 milestones:

- Completed testing/assessments scheduled for reliability stage-gates for the TPPs (09/09)
- Expanded predictive model development to include operating data from APS and TEP (09/09)
- Developed accelerated UV testing method to more quickly diagnose CPV problems (06/09)
- Completed baseline FMEAs for c-Si, CdTe, CIGS, CPV systems, and residential inverters; documented highest level reliability concerns (available on NREL website) (08/09)
- Started developing techniques, designs, and processes to apply and assess reliability of conductive adhesives for interconnecting PV (09/09)
- Initiated long-term system exposure of three technologies in three locations in collaboration with SunPower (09/09)
- Completed first iteration of test-to-failure protocol (06/09).

Real-time Reliability Studies (NREL & SNL)—A study was initiated in partnership with SunPower to deploy nine small systems in three locations to study system degradation rates. Baseline testing for two locations was completed in FY 2009. Further baselines and deployment will occur in FY 2010. At NREL, the array field was repaved, communications lines updated, and plans made for installing several new products for monitoring.

Accelerated & Diagnostic Reliability (SNL)—Sandia developed and exercised an accelerated life test for conductive tapes used in place of soldering in PV modules. The initial results led an industry partner to change its design. Two publications documented the results.

Sandia implemented CT scanning and advanced X-ray techniques for advanced failure analysis diagnostic work. These techniques helped three companies improve their designs for CPV cell assemblies, modules, and microinverters. Results were published.

Systems-level reliability assessments were completed for TPP and incubator partners, including Soliant, Dow, and Abound Solar.

Sandia completed an accelerated testing chamber and performed initial testing on conductive oxides for thin-film module use. The accelerated test capability allows varying humidity, temperature, light, and oxygen levels while testing the conductivity of the sample in situ.

Module Accelerated Testing (NREL)—The first two rounds of the test-to-failure protocol were

completed. Results were discussed with members of Solar ABCs and "Application of the NREL Test-to-Failure Protocol for PV Modules" was presented by Peter Hacke at the Si Workshop in August 2009. This protocol is moving toward more quantitative predictions for PV modules.

Accelerated module stress testing was completed in support of stage-gate reviews and other support of TPP and incubator projects, including Dow, PrimeStar, CaliSolar, BP Solar, 1366, Skyline, and Spectrolab.

Component/Material Accelerated Testing (NREL)—Testing of CPV components and materials included assessing transmission of concentrated sunlight through various CPV optical designs to assess the use environment of the various component materials; developing the capability to apply concentrated UV and application of this stress to various encapsulant materials; and performing quantitative studies of the effects of thermal cycling on the CPV die attach. Results from these studies were presented to the community.

Predictive Model Development (SNL & NREL)—Sandia facilitated the development of system-level FMEAs for two companies with new technologies. The PVRAM initial capability was demonstrated based on 5 years of operations, maintenance, and field failure data from Tucson Electric Power's Springerville 4.6-MW PV plant. Results were published in two conference proceedings.

XFRACAS was chosen as the O&M and field failure data collection tool to be used in conjunction with PVRAM. Two utility partners, Tucson Electric Power and Arizona Public Service, began beta-testing the XFRACAS tool for three large PV systems.

Industry Workshop and Standards Support (SNL & NREL)—Support of standards development included completing a first draft for an IEC Power Rating for CPV, and participating in a SEMI-DOE workshop on c-Si Terrestrial Photovoltaic Cells and ASTM and IEC standards meetings.

To better define how to test for safety issues related to thermal aging, a study documented the expected thermal exposure to modules deployed in hot locations.

The importance of reliability to the long-term success is becoming evident to the community. When given the opportunity, this project strived to educate the PV community about reliability issues; for example, Sarah Kurtz presented an invited talk on "Reliability Challenges for Solar Energy" at the IEEE IRPS conference, introducing many reliability engineers to PV reliability issues; and Jennifer Granata and Michael Quintana gave a webinar hosted by SEPA entitled, "Reliability of PV Systems – How Long Can We Expect Them to Last?" This webinar had more than 100 virtual attendees.

4. Planned FY 2010 Activities

- Complete stage-gate reliability assessments and testing for TPPs, incubators, and other DOE SETP participants
- Assess performance of modules/systems fielded at NREL and SNL to identify those that have degraded
- Perform at least three sensitivity studies using PVRAM and publish results
- Hold industry workshop to facilitate industry dialogue
- Publish aggregated degradation data/high level predictive model results from SLTE and PVRAM
- Propose details of new accelerated test for a specific technology to correlate with real-time field degradation.

5. FY 2009 Special Awards and Patents

NREL Patent: M.O. Reese, A. Dameron, T. Moricone, and M.D. Kempe, "Electrical Calcium Test," Patent application filed 08/09.

6. Major FY 2009 Publications

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E. Collins, M. Dvorack, J. Mahn, M. Mundt, and M. Quintana, "Reliability and Availability Analysis of a Fielded Photovoltaic System," *34th IEEE Photovoltaic Specialists Conference, Philadelphia, 2009*.

A.A. Dameron, M.O. Reese, T.J. Moricone, and M.D. Kempe, "Understanding Moisture Ingress and Packaging Requirements for Photovoltaic Modules," *Photovoltaics Intl.* **13**, 121 (2009).

J.A. delCueto, C.A. Deline, D.S. Albin, S.R. Rummel, and A. Anderberg, "Striving for a Standard Protocol for Preconditioning or Stabilization of Polycrystalline Thin-Film

Photovoltaic Modules," *SPIE, San Diego, CA, 2009*.

J.E. Granata and M.A. Quintana, "Reliability of PV Systems – How Long Can We Expect Them to Last?" *SEPA Webinar, June 2009*.

J.E. Granata and M.A. Quintana, "System Level Reliability Methodologies," *International Asia-Pacific Partnership Reliability Workshop, July 2009*.

P. Hacke, D. Trudell, K. Terwilliger, N. Bosco, E. Gelak, and S. Kurtz, "Application of the NREL Test-to-Failure Protocol for PV Modules," *19th Crystalline Silicon Workshop, Vail, CO, 2009*.

M.D. Kempe, "Design Criteria for Photovoltaic Back-Sheet and Front-Sheet Materials," *Photovoltaics Intl.* **10**, 100 (2008).

M.D. Kempe, M. Kilkenny, T.J. Moricone, and J.Z. Zhang, "Accelerated Stress Testing of Hydrocarbon Encapsulants for Medium-Concentration CPV," *34th Photovoltaic Specialists' Conference, Philadelphia, PA, 2009*.

M.D. Kempe, T. Moricone, and M. Kilkenny, "Effects of Cerium Removal from Glass on Photovoltaic Module Performance and Stability," *SPIE, San Diego, CA, 2009*.

S. Kurtz, J. Granata, and M. Quintana, "Photovoltaic-Reliability R&D Toward a Solar-Powered World," *Proc. SPIE Optics and Photonics, San Diego, CA, 2009*.

S. Kurtz, K. Whitfield, D. Miller, J. Joyce, J. Wohlgemuth, M. Kempe, N. Dhere, N. Bosco, and T. Zgonena, "Evaluation of High-Temperature Exposure of Rack-Mounted Photovoltaic Modules," *34th IEEE Photovoltaic Specialists Conference, Philadelphia, 2009*.

D.M. Miller, M.D. Kempe, C.E. Kennedy, and S.R. Kurtz, "Analysis of Transmitted Optical Spectrum Enabling Accelerated Testing of CPV Designs," *Proc. SPIE Optics and Photonics, San Diego, CA, 2009*.

M. Mundt, E. Collins, M. Dvorack, J. Mahn, and M. Quintana, "Reliability and Availability Analysis of a Fielded Photovoltaic System," presented at June 2009 International Applied Reliability Symposium.

C.R. Osterwald and T.J. McMahon, "History of Accelerated and Qualification Testing of Terrestrial Photovoltaic Modules: A Literature Review," *Progress PV* **17**(1), 11 (2009).

F.J. Pern, S.H. Glick, X. Li, C. DeHart, T. Gennett, M. Contreras, and T. Gessert, "Stability of TCO Window Layers for Thin-Film CIGS Solar Cells upon Damp Heat Exposures: Part III," *SPIE, San Diego, CA, 2009*.

E.C. Quintana, M.A. Quintana, K.D. Rolfe, K.R. Thompson, and P. Hacke, "Exploring Diagnostic Capabilities for Application to New Photovoltaic Technologies," *34th IEEE Photovoltaic Specialists Conference, Philadelphia, 2009*.

M.A. Quintana, "Photovoltaic Module Reliability and Photovoltaic System Reliability," *International Photovoltaic Reliability Workshop, Shanghai, China, December 2008* (Invited Presentation).

N.R. Sorensen, M.A. Quintana, J.D. Puskar and S.J. Lucero, "The Effect of Metal Foil Tape Degradation on the Long-Term Reliability of PV Modules," *34th IEEE Photovoltaic Specialists Conference, Philadelphia, 2009*.

N.R. Sorensen, M.A. Quintana, J.D. Puskar and S.J. Lucero, "The Effect of Metal Foil Tape Degradation on the Long-Term Reliability of PV Modules," *SPIE, San Diego, CA, 2009*.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Arizona State Univ. A. Cronin	Tucson, AZ cronin@physics.arizona.edu	Evaluation of data from Tucson Electric Power field	20	5
Arizona State Univ. G. Tamizhmani	Gilbert, AZ manit@asu.edu	O&M Database Data Entry for APS	15	0
BEW Engineering	Richmond, CA Ray.hudson@bewengineering.com	Inverter Reliability Assessment Support	20	0
ReliaSoft	Phoenix, AZ Doug.Ogden@ReliaSoft.com	Development of Reliability Software tools specific to PV	35*	0
South Dakota State Univ.	Brookings, SD Michael.Ropp@SDSTATE.EDU	Outdoor Module Exposure Testing	40	0

* Multiyear contract; $35K in FY 2009 funds.

Test & Evaluation

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

Key Technical Contacts: Jennifer Granata (SNL, Primary Contact), 505-844-8813, jegrana@sandia.gov
Bill Marion (NREL, Primary Contact), 303-384-6793, bill.marion@nrel.gov

DOE HQ Technology Manager: Kevin Lynn, 202-586-1044, kevin.lynn@hq.doe.gov

FY 2009 Budgets: $2,775K (SNL), $1,750K (NREL)

Objectives

- Develop, employ, validate, and furnish industry with test and evaluation (T&E) methodologies to measure, understand, predict, and certify the performance of PV components and systems.
- Provides test and evaluation of PV modules, arrays, inverters/balance of systems (BOS), and systems to TPP participants, other PV industry, labs, and universities in support of work sponsored by DOE's Solar Energy Technologies Program (SETP).
- Supports testing and evaluation of the integration of PV systems into the electric power grid by working with system integrators and utilities.

Accomplishments

- Completed all stage-gate evaluations for TPPs, Incubators, SEGIS, and other DOE contract participants (NREL—Boeing, Skyline, Plextronics; SNL—Amonix, Greenray, United Solar, Soliant)
- Awarded the subcontract for transfer of SNL's PV Module Database maintenance and routine outdoor PV module testing to populate the database to TUV-PTL (05/09)
- Completed CPV testbed and summary report on CPV modules tested (NREL)
- Wrote SPIE paper on precondition and stabilizing methods of thin-film PV modules, and the use of capacitance-voltage (C-V) measurements as an indication of stability (NREL)
- Designed a multi-irradiance sensor array at SNL and began to procure the equipment needed to develop a network of irradiance sensors to study modeling and performance issues
- Enhanced SNL's laboratory capabilities to evaluate SEGIS stage-gate deliverables that include energy management capabilities, load shedding capacities, and voltage support capabilities
- Developed several contractual partnerships with industry and utilities to develop system performance enhancements that include advanced battery technologies and utilization capabilities, advanced automated controls, and reliability prediction algorithms
- Produced 11 publications and presentations on FY 2009 results.

Future Directions

- Develop protocols and capabilities for test and evaluation of new components and systems, including systems-level technologies such as CPV ; develop more efficient and more accurate methods to characterize large-scale fielded systems
- Enhance capabilities to define and conduct tests to provide information/data for validation and improvement of systems-level models, including reliability and other performance models as well as developing data/information for input to performance and economic models
- Transfer improved test procedures and methods to standards committees
- Evaluate PV systems with enhanced energy management capabilities
- Conduct pre-production and production evaluations on inverters with an emphasis on interoperability, controls, and arc fault detection/mitigation
- Develop solutions related to integration of high levels of PV systems into electric power grids
- Implement high-resolution irradiance data for high penetration of PV distributed generation systems
- Investigate the possibilities of power smoothing capabilities using storage systems.

1. Introduction

T&E is a cross-cutting activity that supports the SETP areas of Reliability, Modeling and Analysis, Concentrating PV, PV Grid Integration, Codes and Standards, and Solicitations. T&E support is critically important to DOE and industry participants to determine if cost and performance stage-gate criteria are met for DOE contracts with an emphasis on bringing new products to the U.S. market. T&E spans the product development cycle, from early proof-of-concept devices to prototypes and commercial products.

2. Technical Approach

The FY 2009 funding agreement consisted of eight activities: (1) Lab-Based Industry Support, (2) Lab T&E Data Collection, (3) Standards Development and Industry Transfer, (4) Field T&E, (5) Grid Integration T&E, (6) Inverter/BOS R&D, (7) PV Module Database, and (8) Energy Ratings Method Validations. Depending on the activity, SNL and NREL had either shared or sole responsibility. They had shared responsibility for activities 1–5, SNL had sole responsibility for activities 6 and 7, and NREL had sole responsibility for activity 8.

T&E work includes characterizing the performance and reliability of TPP and other DOE-funded projects; developing protocols and capabilities for test and evaluation of new components and systems; and developing and maintaining capabilities to define and conduct tests to provide information/data for validation and improvement of reliability and performance models. All test data are acquired using calibrated instruments (e.g., radiometers, meteorological sensors, data acquisition systems).

3. Results and Accomplishments

- All stage-gate evaluations completed for TPPs, incubators, and other DOE contract participants (09/09)
- Summary report on CPV modules tested (09/09)
- Test technology transfer to TUV-PTL test lab (initiated 05/09)
- SEGIS evaluation procedure completed and implemented (on-going into FY 2010)
- Completed report on systems level testing for Grid Integration (09/09)
- Completed NREL technical report and IEEE PVSC paper on results from the Anatolia Subdivision with SMUD (09/09)
- Began collecting high-resolution data at Nellis AFB and Lanai PV systems (09/09).

3.1 Lab-Based SAI and Industry Support

We completed testing for several stage-gate evaluations for TPPs, incubators, and other DOE contract participants. Testing was performed both onsite and at the participant's facility. Many of these evaluations were used to verify LCOE targets during stage gate assessments.

Performance and energy production testing of CPV modules representing various concentrating technologies began in January 2009 at NREL. The data are used for stage-gate evaluations and for characterization of CPV performance. A technical report was completed outlining initial performance results, lessons learned, and recommendations for establishing this type of test facility, including testing protocols.

Fig. 1. Two-axis tracker at NREL with CPV modules from 5 manufacturers.

3.2 Lab T&E Data Collection

Quality-assessed hourly and 15-minute interval data sets of measured meteorological and PV system performance data for a 1-year period were developed using data from existing PV systems at NREL and SNL. These data sets are available to interested parties for model validation of system performance models.

At NREL, this activity also supports the operation and maintenance of the Performance and Energy Rating Testbed (PERT). This test bed measures performance for up to 45 PV modules, with test

durations of weeks to years, depending on the stage-gate, energy rating, or reliability activity it supports.

SNL developed a new cell test capability for multijunction solar cells using laser beam induced current techniques and presented a paper at the 2009 PVSC.

3.3 Standards Development and Industry Transfer
Current standards lack specifics on how to precondition CdTe and CIGS modules so that when tested for reporting conditions the results are well coordinated with subsequent field performance. This work examined existing and proposed methods. Using capacitance-voltage measurements was discovered to be a useful indicator of stability. A record of invention of this measurement method was submitted by NREL. This work continues in FY 2010.

SNL trained eight companies on site for Module and Cell Test Technology Transfer and participated in Codes and Standards development: IEC 62108, UL 8703 for CPV.

3.4 Field T&E
For a PV system, both snow and shadowing losses may be difficult to predict. To address these issues, a heated pyranometer for accurate irradiance measurements and digital images to detect snow coverage on the PV array were demonstrated to be useful for assessing performance losses from snow. The results of a literature survey, in conjunction with experiments, were used to present methods for determining performance losses from shading.

The Field Test Protocol draft was completed in FY 2009. It was exercised for feedback during simultaneous field testing of two generations of Amonix MegaModules (~5 kW) in Las Vegas, NV.

3.5 Grid Integration T&E
Grid Integration T&E focused on systems level testing to determine the effect of PV systems on the electrical grid. NREL and SNL coordinated activities to evaluate different types of PV systems. NREL T&E activities included monitoring the Anatolia with Sacramento Municipal Utility District and Alamosa with Xcel Energy/SunEdison. SNL Grid activities included monitoring the Nellis AFB and Las Vegas Valley Water District with SunPower and NV Energy, and the Lanai PV system with SunPower. Confidentiality concerns on the part of system owners have made it difficult to widely disseminate the data and analysis results, particularly for large PV systems. Some of these issues are being addressed through the PV Variability Working Group that SNL and NREL lead.

3.6 Inverter/BOS R&D
Power controls and microgrid control schemes were of particular importance in FY 2009. SNL collaborated with industry to implement real and reactive power control in inverters, and implemented a three-phase microgrid control scheme. In support of DOE contracts, SNL implemented laboratory enhancements necessary to validate SAI/SEGIS developments.

3.7 PV Module Database
The subcontract for transfer of SNL's PV Module Database maintenance and routine outdoor PV module testing to populate the database was awarded to TUV-PTL in May 2009. Work began on the transfer process, with expected completion of test capability transfer in June 2010. In addition, SNL doubled the number of modules in SNL's PV Module database to 422 and updated the database used in the Solar Advisor Model.

3.8 Energy Ratings Method Validation
Two types of methods were evaluated for correcting the short-circuit current of PV modules for variations in the solar spectrum under clear skies: (1) empirical relationships based on air mass, and (2) use of spectral irradiance models and PV module spectral response data. Methods of the first type were the SNL absolute air-mass function, or $f(AM_a)$, and the CREST air-mass function, or f(AM). The second type used SEDES2 and SMARTS spectral irradiance models.

For predicting the short-circuit current under clear skies for a multicrystalline silicon PV module and an amorphous silicon PV module, the methods using spectral irradiance models and PV module spectral response data performed better than the empirical air mass methods. This work continues in FY 2010 to assess performance under both clear and cloudy skies.

4. Planned FY 2010 Activities

- Complete all stage-gate evaluations for TPPs, incubators, SEGIS, and other DOE SETP participants (09/10)
- Report on effect of aerosol and water vapor variations on CPV performance at NREL (09/10)

- Document procedure for AC module performance testing (09/10)
- Provide Executive Summary to DOE of thin-film system tests (09/10)
- Draft stabilization procedure for testing thin-film PV modules (09/10)
- Complete two Round Robin module tests with TUV-PTL to prepare for hand-off of outdoor baseline module testing (07/10)
- Document standard SNL test protocols to support test technology transfer (09/10)
- Report on shade mitigation performance of "Solar Magic" devices (03/10)
- Provide Field Test Protocol to industry (09/10)
- Report on effect of long-term inverter operation and exposure of SWTDI and SNL located inverters (09/10)
- Document results of PV AFCI testing of PV systems and develop arc fault generator and test bed for PV AFCI (09/10)
- Document cloud cover evaluation data sets for use by dynamic models and PV power ramping control capabilities development (09/10)
- Report on procedures for correcting for spectrum for energy rating standards (09/10)
- Evaluate procedures for determining PV module nominal operating cell temperatures (NOCTs) and participate in round robin validation efforts (09/10).

5. Major FY 2009 Publications

J.A. del Cueto, Deline, Albin, Rummel, and Anderberg, "Striving for a Standard Protocol for Preconditioning or Stabilization of Polycrystalline Thin Film Photovoltaic Modules," *2009 SPIE Conference*.

C. Deline, "Partially Shaded Operation Of A Grid-Tied PV System," *2009 PVSC*.

J.E. Granata, "Cell and Indoor PV Module Measurements," and "Outdoor PV Module and System Measurements," *International Photovoltaic Reliability Workshop, Shanghai, China, Dec. 2008*.

J.R. Finn, Hansen, and Granata, "Multiple Junction Cell Characterization Using the LBIC Method: Early Results, Issues, and Pathways to Improvement," *34th IEEE PVSC, 2009*.

J.E. Granata, Boyson, Kratochvil, and Quintana, "Long-Term Performance and Reliability Assessment of 8 PV Arrays at Sandia National Laboratories," *34th IEEE PVSC, 2009*.

S. Gonzalez, Kuszmaul, and Ellis, "Long-Term Inverter Operation Demonstration at Sandia National Laboratories," *34th IEEE PVSC, 2009*.

A. Kimber, Dierauf, Mitchell, Whitaker, Townsend, NewMiller, King, Granata, Emery, Osterwald, Myers, Marion, Pligavko, Panchula, Levitsky, Forbess, and Talmud, "Improved Test Method to Verify the Power Rating of a Photovoltaic (PV) Project," *2009 PVSC*.

S.S. Kuszmaul, Gonzalez, Ellis, and Serban, "Commanding Inverters to Establish Coordinated μ-grid Functionality at Sandia National Laboratories," *34th IEEE PVSC, 2009*.

B. Marion, "Instrumentation for Evaluating PV System Performance Losses from Snow," *2009 ASES Conference*.

M. Muller, *Development of an Outdoor Concentrating Photovoltaic Module Testbed, Module Handling and Test Procedures, and Initial Energy Production Results*, NREL/TP-520-46569, Golden, CO: NREL (2009).

M. Muller, Rodriguez, and Marion, "Performance Comparison Of A BIPV Roofing Tile System In Two Mounting Configurations," *2009 PVSC*.

P. McNutt, Hambrick, Keesee, and Brown. "Effects of Photovoltaics on Distribution system Voltage Regulation", *34th IEEE PVSC, 2009*.

P. McNutt, Hambrick, Keesee, and Brown. *Impact of SolarSmart Subdivisions on SMUD's Distribution System."* NREL/TP-550-46093, Golden, CO: NREL (July 2009).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Ametek Power Systems	San Diego, CA tony.ng@ametek.com	PV Simulator Development	60	13
TUV-PTL	Phoenix, AZ gtamizhmani@tuvptl.com	Transfer of SNL's Outdoor Module Test Technology and PV Module Database maintenance	173	40.4

Regional Experiment Stations

Performing Organizations: Southwest Regional Experiment Station (SWRES)
Southeast Regional Experiment Station (SERES)

Key Technical Contacts: Steve Palmeri (DOE/GO), 303-275-4832, steve.palmeri@go.doe.gov
Holly Thomas (DOE/GO), 303-275-4818, holly.thomas@go.doe.gov

DOE HQ Technology Manager: Charlie Hemmeline, 202-586-6646, Charlie.hemmeline@hq.doe.gov

FY 2009 Budgets: $1,136K (SWRES), $855K (SERES)

Objectives

- Ensure that education, training, outreach, and technical support required to accelerate the rate of nation's photovoltaic (PV) deployment are available and effectively implemented to support growth of the PV market
- Lead and support industry and national laboratories in (1) testing systems, modules, and inverters; (2) creating and implementing procedures, codes, and standards for quality, safe, and cost-effective installed systems; (3) certifying hardware; and (4) resolving system engineering issues observed in fielded systems
- Furnish technical support to the Department of Energy (DOE), national laboratories, Solar America Cites, Showcase Projects, and industry in executing and validating stage gates for Technology Pathway Partnerships (TPP).

Accomplishments

- Completed second-period requirements of 3-year award and began the final period work
- Conducted product testing, system evaluations, and 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 participants
- Furnish 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
- Continue 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 developing and disseminating 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, the University of Central Florida for SERES, and New Mexico State University for SWRES.

The ongoing work by these organizations entails a wide range of technical work in such areas as:

- Module reliability R&D
- Inverter and balance of system (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 comprising 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.

Organization/ Principal Investigator	Description/ Title of Research Activity
University of Central Florida/Florida Solar Energy Center/ Bob Reedy/Stephen Barkaszi	PV System Research and Technical Assistance
Southwest Technology Development Institute/ Andrew Rosenthal	PV System Research

2.2 Infrastructure Development

Both organizations conduct training, design review and approval, and codes and standards development.

2.3 Long-Term Component Testing

RES supply 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

3.1 SERES

- Participated as a Tiger Team lead in the Solar America Program; in this capacity, furnished extensive technical support through bid specification development, design review, engineering design, policy support and development, and training
- Continued the partnership with ETL-Intertek to conduct performance testing of PV modules in accordance with UL-1703 and IEC standards; assisted ETL-Intertek in entering the commercial testing arena as a Nationally Recognized Testing Laboratories (NRTL)
- Conducted comprehensive design reviews for numerous small-scale PV systems installed in Florida, evaluating for code compliance and basic functional performance criteria
- Conducted the week-long course *Installing PV Systems* at the Florida Solar Energy Center (FSEC) monthly; the course was also held for Solar America City participants
- Evaluated module performance versus module nameplate numerous PV module makes and models; this information is the basis for determining stabilized module performance information and long-term performance
- Installed several additional PV systems in Florida for disaster relief applications, primarily at schools that serve as emergency shelters to ensure power availability during grid outages at these critical locations; SERES performed design review, acceptance testing, and performance monitoring
- Continued data collection for side-by-side comparison of utility interactive inverters, using identical arrays and monitoring performance continuously under real-world conditions in a hot-humid climate
- Transferred system certification/design review to Miami-Dade and Broward counties as part of the expedited solar permitting process; several major utilities require certification for interconnection.

3.2 SWRES

- Served as Tiger Team lead or participant Solar America Cities: Tucson, AZ; Santa Rosa, CA; San Jose, CA; Austin, TX; and Pittsburgh, PA; performed modeling and site assessment for Solar America Showcase Forest City (Oahu, HI)
- Participated in merit reviews when requested to support DOE
- Designed special inverter power quality data acquisition systems (DASs) and operated six for 5-year tests for inverter long-term reliability with Sandia National Laboratories and FSEC with 100% data availability
- Inspected and approved all 2009 Solar Decathlon PV systems; supplied immediate support to NREL with modeling system performance of several systems affected by grid outages during judging, enabling the competition to be judged accurately and on time
- Participated in developing and planning the system long-term exposure tests that will take place at three different regions around the country over the next several years; took responsibility for all DAS development, construction, and installation for the project
- Continued to perform on-site exposure testing and monitoring for innovative concentrating PV technologies, emerging CIGS modules, and innovative PV-assisted heat pump development for one of the nation's largest heating and cooling manufacturers (Lennox)
- Consulted with electrical inspectors nationwide on major code concerns

- Conducted Internet-based training and Webinar for more than 60 electricians, inspectors, and installers
- Trained more than 1,440 designers, inspectors, and installers in National Electrical Code® (NEC) workshops during 12-month reporting period.

4. Planned FY 2010 Activities

- Continue to lead or participate as a member of technical outreach Tiger Teams for Solar America Cities and Showcases, cross-cutting activities, and training courses
- Continue testing and evaluating fielded PV systems for general system benchmarking PV systems and component performance, cost, and reliability characterization
- Continue training and participate in the developing and disseminating codes and standards
- Continue to support market transformation activities with needs that capitalize on the SERES research and technology transfer work
- Continue to increase capabilities in field-test and outdoor validation activities for hot-humid climates, including high voltage testing
- 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 and expand small residential inverter testing facilities
- Continue workforce development efforts through course offerings in PV system design and installation.

5. Major FY 2009 Publications

SERES

W. Young, *Florida's Emergency Shelter Program*, FSEC-CR-1812-09, Cocoa, FL: Florida Solar Energy Center, Aug. 11, 2009.

W. Young, *Solar 2009: Deploying Mobile PV Emergency Power Systems in a Disaster*, FSEC-PF-446-09, Cocoa, FL: Florida Solar Energy Center, Sept. 18, 2009.

SWRES

A. Rosenthal, "Esthetically Designed Municipal PV System Maximizes Energy Production and Revenue Return," *38th ASES National Solar* Conference, May 11-16, 2009, Buffalo, NY.

J. Wiles, "Array to Inverter and Things in Between," *Home Power* **131,** Mar/Apr (2009).

J. Wiles, "Combiner to DC Disconnects," *Home Power* **129,** Jan/Feb (2009).

J. Wiles "Connecting Inverters to the Grid—Part I," *Home Power* **134,** Sep/Oct (2009).

J. Wiles, "New Grounding Methods," *Home Power* **127,** Oct/Nov (2008).

J. Wiles, "Inverter Grounding," *Home Power* **133,** Jul/Aug (2009).

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Grid Integration Summary

The PV Grid Integration efforts address both the technical and analytical challenges that need to be overcome to enable the incorporation of high amounts of PV into the electrical power system. By combining PV with storage, controls, and other appropriate technologies, the PV grid integration projects build the foundation for realizing high-penetration scenarios while enhancing the operation of the electricity grid.

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
Grid Integration	**475**	**5415**	**200**	**6090**
PV Grid Integration	**475**	**725**	**200**	**1400**
Solar Energy Grid Integration Systems (SEGIS) Solicitation	**0**	**4690**	**0**	**4690**

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Photovoltaic Grid Integration Support

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

Key Technical Contacts: Abraham Ellis (SNL, Primary Contact), 505-844-7717, aellis@sandia.gov
Ben Kroposki (NREL, Primary Contact), 303-275-2979, benjamin.kroposki@nrel.gov

DOE HQ Technology Manager: Kevin Lynn, 202-586-1044, kevin.lynn@hq.doe.gov

FY 2009 Budgets: $725K (SNL), $475K (NREL), $200K (Other)

Objectives

- Resolve the technical and analytical challenges that need to be overcome 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 *IEEE Power and Energy* Special Issue on Solar Integration
- Completed report on IEA Task 11: PV Hybrid Power Systems and Task 14: High Penetration PV Systems
- Started PV Variability working group
- Completed analysis of PV variability using data from PV systems of several sizes
- Organized several industry workshops to disseminate information and collect industry input: High Penetration PV workshop, Ontario, CA; SEGIS-ES and Inverter Communications Workshop, Albuquerque, NM; PV Variability Workshop, Cedar Rapids, IA
- Started planning 4th International Conference on Integration of RE and DER
- Organized Renewable Energy Modeling Task Force under WECC to analyze industry requirements for PV system planning models.

Future Directions

- Continue support of IEA PVPS Task 11 and Task 14
- Continue to support PV Variability working group
- Continue to support industry activities aimed at overcoming barriers to high-penetration PV. This includes collaborating with WECC, NERC, IEEE, and similar organizations
- Continue to leverage federal investment through industry partnerships
- Improve modeling of short circuit, power flow, and dynamic models for PV systems
- Quantify and model PV output variability from large PV systems.

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1. Introduction

Improved PV efficiencies and lower costs have rapidly expanded the PV market to include utility, distributed generation, and building-integrated applications. The commercial and residential market continues to be the fastest-growing market segment for solar energy, with significant growth potential forecasted. As this market share grows, however, concern about potential impacts on the stability and operation of the electricity grid may create barriers to future expansion. PV Grid Integration investigates the technical and analytical challenges that need to be overcome to enable high amounts of PV to penetrate the electrical power system. By combining PV with

storage, controls, and other appropriate technologies, our research builds the foundation for realizing high-penetration scenarios while enhancing electricity grid operation.

2. Technical Approach

The technical approach in the PV grid integration area emphasizes three main tasks:

The Grid Integration Support task supports the overall PV Grid Integration agreement. This includes developing the FY 2010 planning documents, annual reports, program reviews, and multiyear research plan input. This task also supports work on the International Energy Agency (IEA) PVPS tasks that relate to grid integration and support of the PV Variability working group.

The System Level Testing task supports work conducted at field test sites examining the issues with integrating high penetrations of PV into the electric power system. NREL currently works with SMUD on testing and evaluating a residential distribution circuit with a large amount of installed PV and with Xcel Energy/SunEdison on deploying a large 8 MW plant. SNL is working with a large 1 MW plant integrated into the electric power system of the island of Lanai and the large 14 MW PV plant at Nellis Air Force Base (AFB).

The Distributed Renewable Energy System Analysis task includes developing analysis, modeling, and simulation tools; conducting technical analysis on high-penetration scenarios for PV systems; and understanding their effect on the electric power system. This task will develop enhanced component and system models for distributed renewable energy systems (e.g., sources, energy storage units).

3. Results and Accomplishments

For Grid Integration Support, in FY 2009 we compiled and published a special issue of *IEEE Power and Energy* magazine. The issue contained six articles on various aspects of integrating solar into the electric power system.

NREL hosted the Task 11: PV Hybrid and Minigrid working group to discuss progress on the IEA-sponsored program. NREL staff presented the state of research in PV hybrid and microgrid research and projects in the United States. NREL is working on a report to describe the current state of more than 40 PV hybrid power systems that have been installed in the nation over the last 30 years. The Task 11 group reviewed the status of its various topics, including design issues, control issues, penetration of PV into minigrids, and sustainability.

SNL organized or hosted several industry workshops to disseminate information and obtain industry input:

- Renewable Energy Grid Integration Systems, Lanai, HI, with participation from APEC.
- High-Penetration PV workshop, Ontario, CA.
- PV Inverter Communication workshop, Albuquerque, NM, in partnership with EPRI.
- SEGIS-ES, Albuquerque, NM, focusing on energy storage for PV applications.

SNL and NREL organized the PV Variability workshop, held in Cedar Rapids, IA, in collaboration with UWIG and SEPA. Analysis of high-resolution PV data, including large PV plants, was presented, some for the first time. A public report summarizing the key findings was compiled.

As part of the Industry Support task, SNL and NREL lead or play a technical support role in several key activities. Some examples are:

- SNL and NREL lead and facilitate the PV Variability working group, where many key stakeholders are collecting and analyzing data related to PV variability and grid integration challenges.
- SNL is participating in NERC's Integration of Variable Generation Task Force (IVGTF), to recommend standards specifically addressing variable generation.

For Distributed Renewable Energy System Analysis, we worked on developing higher temporal resolution PV output sets as part of the Western Wind and Solar Integration Study (WWSIS). We developed an algorithm based on measured PV system performance that produces 10-min PV output values at sites with hourly irradiance data.

An analysis of 1-min power output histories from six PV plants in Las Vegas and 1-s output from a SNL PV array and an anonymous multi-megawatt plant allowed SNL to characterize the effect of geographic dispersion on output variability at a variety of temporal and spatial scales. Preliminary results were presented at UWIG meeting in Cedar Rapids on 10/7/09, and included in a paper submitted to *Electricity Journal*.

Better simulation models for PV systems (both distributed and large scale) continue to be a critical industry need. In FY 2009, SNL partnered with Northern Plains Power Technologies to improve PV inverter dynamic models for the Matlab platform. The models allow for adjustment of voltage and frequency trip thresholds, and SEGIS functionality (ramp rate limits and dynamically adjustable power factor). These models enable more detailed analysis of high-penetration PV deployment scenarios.

In FY 2009, SNL organized the WECC Renewable Energy Modeling Task Force, an industry group whose specific mission is to develop models for interconnection and planning of distributed and utility-scale PV systems.

4. Planned FY 2010 Activities

The Grid Integration Support task supports U.S. representation on the IEA PVPS Task 11 and the new IEA PVPS Task 14: High Penetration of PV Systems in Electricity Grids. The intention of the new task is to discuss and report on high-penetration grid-connected scenarios in a number of PVPS countries and solve the problems and issues associated with this development with in-country experts.

SNL and NREL will work with industry stakeholders to write the Grid Integration chapter of the Solar Vision study. SNL will continue to support several tasks of the NERC IVGTF efforts, emphasizing PV grid integration aspects.

This task also supports the PV Variability working group. NREL and SNL co-lead this ad hoc group of industry and laboratories that was formed in FY 2009 as a forum to discuss the variability of PV caused by clouds. In FY 2010, the first face-to-face workshop will be held.

We will continue to collaborate with EPRI and other partners in Europe and Asia to organize and execute the 4th International Conference on Integration of Renewable and Distributed Energy Resources. SNL leads the scientific committee for the conference, and DOE is a sponsor.

For the System Level Testing task, in FY 2010, NREL will continue working with SMUD on their Anatolia III Solar Subdivision and with Xcel Energy/SunEdison on the Alamosa system. Data from these systems will help identify potential issues with large penetrations of PV on distribution feeders as well as quantify the effect these systems are having on actual operating electrical distribution systems.

SNL will continue to work on data collection and analysis of the Lanai and the Nellis AFB PV systems, and will produce a report documenting the operating experience of large PV systems, focusing on grid impacts. High-resolution data collection is already under way at both locations. In FY 2010, SNL will begin to collect and analyze data at the DeSoto PV plant in Florida, and will install irradiance sensor networks at Lanai and DeSoto to support modeling and analysis.

The Distributed Renewable Energy System Analysis task includes developing analysis, modeling, and simulation tools and conducting technical analysis on high-penetration scenarios for PV systems and understanding their impact on the electric power system. This task will develop enhanced component and system models for distributed renewable energy systems (e.g., sources, energy storage units). In FY 2010 we will develop inverter fault current models to help understand the effect of PV systems under short circuit conditions.

SNL will focus on developing and validating generic, nonproprietary, positive-sequence dynamic models for central-station and distributed PV systems. This work will be done through the WECC Renewable Energy Modeling Task Force that SNL leads. This effort will also produce guidelines for power flow and dynamic representation of PV systems in planning and interconnection studies. Laboratory testing of PV inverters conducted at SNL and NREL will support the modeling.

In FY 2010, SNL will quantify PV output variability of large PV systems and develop models that can predict statistical characteristics of PV output variability as a function of, e.g., PV system size, tracking system. Data from existing and planned irradiance sensor networks will be used to develop and validate the models. This work will lay the foundation to significantly increase the time and spatial resolution of existing solar resource data,

For technology development, SNL plans to demonstrate how imaging can be used to forecast short-term PV output. Several technical challenges such as cloud segmentation will need to be solved. SNL will also demonstrate using advanced batteries to mitigate PV output variability. The

demonstration will also quantify the effect of regulation duty on advanced battery degradation. The experiment will compare the effectiveness of several smoothing algorithms.

For codes and standards, NREL and SNL will organize a workshop on standards for high-penetration PV, in close collaboration with SEPA. SNL will develop test protocols for standards being developed through the EPRI/SNL Inverter Communications activity. This work will directly benefit the DOE and EPRI Smart Grid Demonstration projects.

5. Major FY 2009 Publications

J. Bebic, R. Walling, K. O'Brien, and B. Kroposki, "The Sun Also Rises—Planning for Large-Scale Solar Power," *IEEE Power and Energy Magazine*, May/June 2009.

S. Gonzalez, S. Kuszmaul, and A. Ellis, "Long-Term Inverter Operation Demonstration at Sandia National Laboratories," *34th IEEE Photovoltaic Specialists Conference, Philadelphia, 2009.*

T. Key, "Finding a Bright Spot—Utility Experience, Challenges, and Opportunities in Photovoltaic Power," *IEEE Power and Energy Magazine*, May/June 2009.

B. Kroposki, R. Margolis, and D. Ton, "Harnessing the Sun—An Overview of Solar Technologies," *IEEE Power and Energy Magazine*, May/June 2009.

E. Liu, J. Bebic, B. Kroposki, J. de Bedout, and W. Ren, "Distribution System Voltage Performance Analysis for High-Penetration PV," *IEEE 2030 Conference, Atlanta, GA, November 2008*.

A. Mills, M. Ahlstrom, M. Brower, A. Ellis, R. George, T. Hoff, B. Kroposki, C. Lenox, N. Miller, J. Stein, and Y. Wan, *Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System*, LBNL-2855E. Berkeley, CA: Lawrence Berkeley National Laboratory, December 2009.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Sacramento Municipal Utility District (SMUD)	Sacramento, CA	Evaluation of SolarSmart Subdivisions	50K	50K
Xcel Energy and SunEdison	Alamosa, CO	Evaluation of the Alamosa 8 MW PV system	50K	50K
BEW	San Ramon, CA	PV inverter interconnection and planning models	$15K	Contract
Northern Plains Power Technologies	Brookings, SD	Development of detailed models of PV inverters with SEGIS capability	$25K	Contract
SunPower	Richmond, CA	Evaluation of Lanai PV system data, installation of wireless irradiance sensor network	$25K	$25K
NV Energy	Las Vegas, NV	Analysis of PV system data from Las Vegas Valley Water District	$10K	$10K
EPRI	Knoxville, TN	Inverter communications standards and test protocols	$10K	$10K

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Solar Energy Grid Integration Systems Industry Projects

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contacts: Ward Bower (SNL), Primary, 505-844-5206, wibower@sandia.gov
Scott Kuszmaul (SNL), 505-844-5401, sskuszm@sandia.gov

DOE HQ Technology Manager: Kevin Lynn, 202-586-1044, Kevin.Lynn@ee.doe.gov

FY 2009 Budgets: $7,092K (SNL Program), $4,800K (SNL ARRA)

Objectives

- Lay the groundwork for high levels of photovoltaic (PV) electrical grid penetration
- Advance the power electronics, controls, energy management, and communications for grid integration and microgrid applications for PV technologies
- Enable PV systems to meet the goal of making solar power cost-competitive with today's conventional sources of electricity while improving other values such as time-of-day metering
- Integrate PV systems to use energy management, energy storage, and communications for total system optimization that also meets the Solar Energy Technologies Program (SETP) levelized cost of energy (LCOE) goals
- Commercialize and deploy advanced, integrated, PV-system technologies that will enhance our nation's energy security and confront the serious challenges of environmental responsibility and global climate change.

Accomplishments

- Completed an extremely aggressive schedule to move the Solar Energy Grid Integration Systems (SEGIS) solicitation from Stage 1 (conceptual designs and market analysis) into Stage 2 (prototype development) with a project downsize to five promising industry contractor teams
- Completed quarterly, final, and critical reviews to track progress and select high likelihood of successful commercialization
- Gave progress technical feedback to contractors to help ensure successful prototype development with DOE program-compatible cost goals related to LCOE and system integration.

Future Directions

- Complete Stage 2 prototype development involving five SEGIS contractors
- Complete witness testing of prototypes with evaluation of performance, functionality, and compliance with required and upcoming interconnect rules
- Evaluate Stage 2 progress and determine "Best Value" contractor proposals to move into Stage 3 (toward commercialization)
- Guide SEGIS Stage 3 to bring commercialized developments to a focused demonstration site and to evaluate interconnection functionality with multiple disciplines.

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1. Introduction

The SEGIS project promotes the development of advanced PV smart-grid-ready technologies allowing increased penetration of PV into the utility grid while maintaining or improving the power quality and reliability of the utility grid. Highly integrated, innovative, advanced inverters, controllers, balance-of-system (BOS), and associated BOS elements for residential, commercial, and utility-scale solar energy applications are the critical components being developed. Fully integrated inverters, controllers, and communications components will incorporate energy storage and management functions and communicate with other energy management systems that are increasingly used for building energy conservation. Complete and fully integrated systems will include utility energy and communication portals to pioneer PV system interfaces with emerging products such as Advanced Metering Infrastructure (AMI).

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Products and interconnection methodologies are being developed to support the move from the electrical grid of today, which was designed for one-way power flow, to the grid of tomorrow, which will seamlessly accommodate two-way power flows as required by wide-scale deployment of solar and other distributed resources. The interconnect methods being developed are to work with what is allowed today for interconnections and what may likely be adopted as future options. The work is often the first of its kind but likely will be used to help guide the needs of evolving standards and the new Smart Grid.

Figure 1 shows a pictorial representation of a fully interactive system with the SEGIS developments located in the central box with communications between all elements of the intertied system.

Fig. 1. Representation of SEGIS in the electrical load, resource information, and utility infrastructure.

2. Technical Approach

The SEGIS project is based on a very aggressive competitive solicitation with three stages of work: (1) Market Analysis and Concept; (2) Prototype Development and Evaluations, and (3) Toward Commercialization. Each stage must be completed and show significant progress toward the goals of the project and SETP. To advance to the next stage, contractors must compete with progress and final reports for the stage, presentations at critical review meetings, and a next-stage proposal update.

The SEGIS solicitation serves both evolutionary and revolutionary advances in PV BOS and intelligent connections to the utility grid and microgrids. The project covers PV systems from 100 W through 1 MW where 1 MW size systems will use a modular approach to build the system.

The SEGIS solicitation strongly encourages and has resulted in strong teaming with the primary contractor, electric utilities, communications firms, energy storage, energy management, and energy conservation experts to ensure bottom-up integration of developed systems. Stage 3 is a commercialization effort requiring either in-house manufacturing capabilities or partnerships with firms ensuring high quality manufacturing with quality control plans. All SEGIS contractors must have designs for long lifetime and high reliability and are required to participate in programs that improve likelihood for longevity and reliability such as the Highly Accelerated Lifetime Testing (HALT®) or equivalent. SEGIS contractors are also required to participate in pertinent codes and standards making processes.

3. Results and Accomplishments

Placing Stage 2 contracts with project downsizing was a level 3 milestone and was completed on schedule on June 26, 2009. Level 3 milestones for FY 2009 include completion of project reviews, project critical reviews at SNL and final Stage 1 reports by 12 contractors. Milestones for SEGIS contracts are set to specific program dates and must be completed on time and linked to the competitive schedule to the next stage.

Table 1. FY 2009 SEGIS Milestones and Accomplishments

Milestones	Accomplishments
1st Stage 1 Quarterly Reports (12 contractors)	Updated market analysis and concept designs (9/09)
2nd Stage 1 Quarterly Reports (12 contractors)	Completed with technical feedback (12/09)
DOE Solar Program Review Presentations.	Open overview presentations completed at DOE (2/09)
Final Stage 1 Reports (12 contractors)	Completed and used in selection criteria for downsize (3/09)
Project Critical Reviews (12 contractors)	Completed contractor full-day review presentations (4/09)
Complete Stage 1 Contractor Reviews	Completed by evaluation team for down-select process (4/09)
Stage 2 downsize (5 Contracts)	Contracts completed (6/26/09) for Best Value advances
1st Stage 2 "Quarterly Reports" (5 contractors)	Completed with webinars to review progress since kickoff meetings (8/09)

Figure 2 shows the setup and measurement of advanced maximum power point tracking being developed through SEGIS. It has been determined

that the communications aspects of connecting PV to an intelligent grid will require communications to monitor the grid, communications to the electrical utility command and control, communications to the owner of the system, and communications to provide the required safety. The communications studied through SEGIS included power line carrier (PLC), internet and Ethernet, fiber optics, wireless, available SCADA (Supervisory Control And Data Acquisition), and connections to the many AMI units being deployed by utilities.

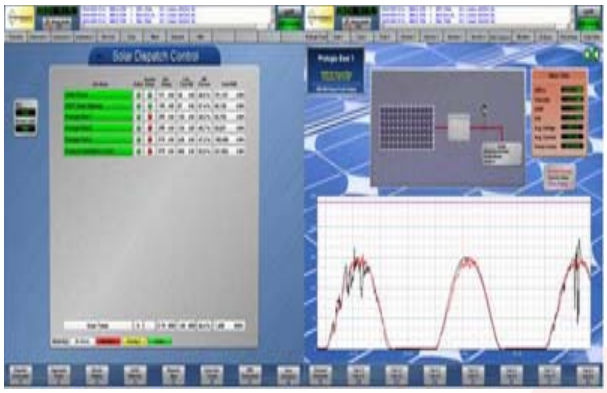

Fig. 2. Demo of PV Powered advanced max power point tracking for all PV technologies.

4. Planned FY 2010 Activities

FY 2010 work will complete Stage 2 of the SEGIS solicitation with five contractors. The progress of each contractor will be evaluated through witness testing of the prototype deliverables, a one-day critical review at SNL, delivery and evaluation of final Stage 2 reports, and evaluations of the proposed Stage 3 work. Evaluations will be based on "Best Value" for the SEGIS program and SETP goals. Figure 3 shows the project schedule.

Stage 3 will be completed in FY 2011. SNL is developing plans to deploy the commercialized products, where real-time grid-tied or microgrid installations will be installed and evaluated for performance working with intelligent grids.

An added activity in FY 2010 will be to address the need for arc-fault detection by PV systems installed on roofs of buildings. Current activities include collaborating with Underwriters Laboratories to develop a standard for arc-fault detection devices. This work is preliminary and will eventually cover detection and mitigation methods for arcs within PV modules, intermodule wiring, junction boxes, and inverter input circuits.

Table 2. FY 2010 Activities

Activity	Date	Results/Impact
Bill of Material Memo	9/09	Helps ensure steady progress by each contractor
Workforce Buildup Memo	9/09	Logs anticipated job creation through developing and manufacturing systems
Mid Year Report	1/10	Reports progress analysis and feedback to contractors
Testing and Prototype Readiness Review	2/10	Reviews preparation and readiness for testing, equipment needed, and priorities
Stage 2 Progress Report	2/10	Evaluates progress in Web meeting (contractor and SNL)
DOE Program Review	5/10	Serves as a communications pathway to DOE and PV community
Witness Evaluation Test on Prototypes	4-5/10	Measures performance and functionality of SEGIS advances and prototypes: a stage-gate input
Stage 2: Final Report – Stage 3 Update	6/10	Is a proprietary report on progress, findings, lessons learned, and stage-gate input
Evaluate and Select Stage 3 Contractors	6/10	Uses selection criteria for the SEGIS project and combines critical reviews, witness testing, and Stage 3 likelihood of success
Kickoff Meetings for Stage 3 Contractors	8/10	Serve as sanity check on anticipated work for the commercialization stage for SEGIS

5. FY 2009 Special Recognitions

The SEGIS solicitation moved from the conceptual design and market analysis stage to the prototype development stage. Various publications are recognizing the SEGIS solicitation and contractors and their work. The article "Year of Energy 2009" from Sigma Xi, the Scientific Research Society, stated, "Such SEGIS research is also critically important to improving utilities' management of traditional energy generation and demand-side resources for improving the utilization of their existing infrastructure."

6. Major FY 2009 Publications

W. Bower, "Grid-tied Inverter Technology and Functionality Options for Intelligent Grid Applications," *Intersolar North America Conference, San Francisco, CA, July 14–16, 2009*.

A. Ellis and W. Bower, "The US DOE Solar Energy Grid Integration Systems Program 'SEGIS'," *REGIS Workshop, Lanai, HI, February 14, 2009*.

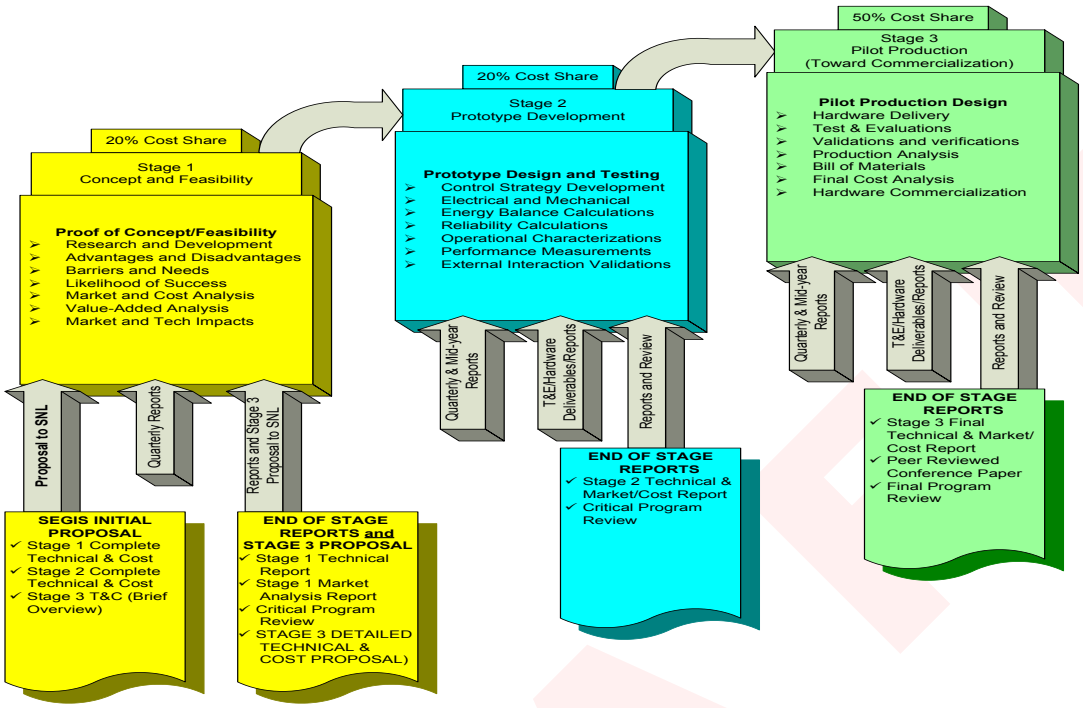

Fig. 3. Timetable for SEGIS solicitation.

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($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 or management, and a portal for communication. The gateway provides communication with utility portals to control two-way power flows.	$864
Petra Solar/ Adje Mensah	Somerset, NJ Adje.Mensah@petrasolar.com	"Development of Economically Viable, Highly Integrated, Highly Modular SEGIS Architecture." Multilayer control/communication with PV systems to interconnectivity, cost reduction, system reliability, and safety resulting in a cost-competitive, easy to install, modular and scalable system.	$1,657
Princeton Power/ Paul Heavener	Princeton, NJ	"Demand Response Inverter." A complete design for a 100-kW "Demand Response Inverter System with proprietary technology. The design will be optimized for low-cost, high-quality manufacture and integrates control capabilities including dynamic energy storage and demand-side load response.	$1,553
PV Powered/ Mesa Scharf	Bend, OR	"MPPT and EMS Advancements." Develop a suite of maximum power point tracking (MPPT) algorithms for all available and emerging PV module technologies. State-of-the-art two-way communications and integration with building energy management and utility management networks.	$1,612
University of Central Florida/ Robert Reedy (FSEC)	Orlando, FL reedy@fsec.ucf.edu	"Grid-Smart Inverters." Grid integration concepts for PV that incorporate battery storage, utility control, communication, monitoring functions, and building energy management. Validate "anti-islanding" strategy for PV inverters to maintain PV during grid disturbances, while meeting safe operation rules.	$770
Total Program Funds			**$6,456.***

ARRA Funds amounting to $4.8M total was expended with delivery of the Readiness Review deliverable in 3/10.

DRAFT

Resource & Safety R&D Summary

Accurate knowledge of quantity and quality of solar/optical radiation is essential to determine solar renewable energy system performance, substantiate progress in manufacturing and device development, and validate measurements and models of available solar resources. The task provides technical foundation for high quality optical/solar radiation sensor calibrations, measurements, data, and solar radiation resource models for solar energy system engineering applications and performance testing.

	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Resource & Safety R&D	**1630**	**0**	**470**	**2100**
Solar Radiometry and Modeling	**880**	**0**	**0**	**880**
Resource Assess & Character	**750**	**0**	**0**	**750**
ES&H/Lifecycle Research	**0**	**0**	**470**	**470**

DRAFT

Solar Radiometry & Metrology

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Daryl Myers (NREL), 303-384-6768, daryl.myers@nrel.gov

DOE HQ Technology Manager: Kevin Lynn, 202-586-1044, kevin.lynn@hq.doe.gov

FY 2009 Budget: $880K (NREL)

Objectives

- Support Measurements and Characterization ISO 17025 accreditation scope
- Provide ISO 17025 compliant broadband and spectral radiometric calibrations traceable to international and national reference standards
- Participate in consensus standards by American Society for Testing and Materials (ASTM) and International Lighting Commission and CIE standards development on solar system testing
- Reduce uncertainties in solar radiometric data and solar radiation models
- Transfer technology to the solar industry related to optical and solar measurements and data.

Accomplishments

- Verified NREL reference standard stability relative to World Radiometric Reference (WRR) at 10/08 NREL Pyrheliometer Comparison (NPC): NREL, Sandia, and 21 other participants
- Performed 32 spectral and 280 broadband solar broadband radiometer calibrations for NREL and solar industry partners
- Classified 3 industrial partner and 3 NREL flash solar simulators with respect to ASTM E927
- Transferred NREL Pulse Analysis Spectroradiometer System (PASS) technology to Newport Corp. through Technical Partnership Agreement TSA-08-202
- Published NREL technical report, ASES paper on relative performance of radiometric instrumentation for 15 models of solar radiometer (see publications)
- Published spectral model to convert hourly (TMY2) broadband solar data to hourly spectral distributions for all sky conditions. Need for further modifications identified. (see publications)
- Responded to 301 requests for technical information from industry, university, and DOE inquiries.
- Author or co-author on 1 journal article, 1 report, and 5 conference papers (see publications).

Future Directions

- Prepare for International Pyrheliometer Comparison, 10/10, Davos Switzerland
- Improve broadband to spectral conversion model (extend wavelength range; improve accuracy)
- Deploy and analyze instrument systems for high spatial, (~0.5 km) temporal (less than 5 s) resolution data collection for PV grid integration applications
- Expand scope of ISO 17025 accreditation to include broadband/spectral radiometer calibrations.

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1. Introduction

Accurate solar radiometric measurements and models reduce uncertainties associated with solar energy conversion systems, ultimately influencing the levelized cost of energy (LCOE). Accurate solar data are needed for solar research and bankable industry resource data. We provide traceable transfer chain from the World Meteorological Organization World Radiometric Reference (WMO/WRR) and the National Institute of Standards and Technology (NIST) spectral irradiance scale for Photovoltaic (PV) Measurements and Characterization task ISO 17025 accreditation. We conduct measurement and modeling research that provides expertise and quantifies bankable data for project proposals results for industry.

2. Technical Approach

We conduct measurement research and publish results and respond to technical assistance requests. We maintain NREL optical radiation

reference standards and conduct research to identify and quantify bankable data for solar projects. We serve with consensus standards groups to develop useful industry standards. See **www.nrel.gov/solar_radiation**.

3. Results and Accomplishments

Established uncertainty limits for PVUSA test condition (PTC) rating methodology for several PV technologies. See Table 1 and publications.

Table 1. Limits of uncertainty NREL 1.6-kWp dual junction system using PTC approach.

POA kWm^{-2}	Note: e_I=25 Wm^{-2}, e_W = 1 ms^{-1}, and e_T= 1° C. PTC Rating = 1480 W. $(ei*\partial/\partial i)^2$	$(ew*\partial/\partial w)^2$	$(\partial/\partial t)^2$	Ps RSS ERROR	% error wrt 1480
0.5	781.39	1.3	0.033	28.0	1.9%
0.6	942.90	1.9	0.047	30.7	2.1%
0.7	1119.57	2.6	0.064	33.5	2.3%
0.8	1311.41	3.4	0.084	36.3	2.5%
0.9	1518.40	4.3	0.106	39.0	2.6%
1.0	1740.56	5.2	0.131	41.8	2.8%
1.1	1977.87	6.3	0.158	44.5	3.0%

Mean residual when 990 Wm^{-2}<POA<1010 Wm^{-2} is 2.5 W

Modified SEDES2 spectral model to convert hourly broadband data into spectral distributions. Figure 1 is example of cloudy day measured and modeled spectra.

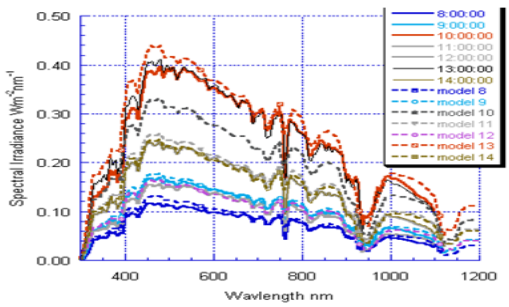

Fig 1. Measured and modeled cloudy sky spectra

4. Planned FY 2010 Activities

- Deploy and analyze high time resolution (<5 s samples) and high spatial (~0.5 km) resolution radiometric sensors for PV grid integration support
- Extend wavelength range, improve accuracy spectral conversion model
- Extend ISO 17025 accreditation to spectral calibrations.

5. Major FY 2009 Publications

C.A. Gueymard and D.R. Myers, "Evaluation of Conventional and High-Performance Routine Solar Radiation Measurements for Improved Solar Resource, Climatological Trends, and Radiative Modeling," *Solar Energy* **83**(2), 171-185 (2009).

D. Myers, "Comparison of Historical Satellite Based Estimates of Solar Radiation Resources with Recent Rotating Shadowland Radiometer Measurements," R. Campbell-Howe, ed., *Proc. Solar 2009 Conf., 11-16 May 2009, Buffalo, NY*. NREL CP-550-46806 (2009).

D. Myers, "Evaluation of the Performance of the PVUSA Rating Methodology Applied to Triple Junction PV Technology," R. Campbell-Howe, ed., *Proc. Solar 2009 Conf., 11-16 May 2009, Buffalo, NY*. NREL CP-550-46799 (2009).

D.R. Myers, "Terrestrial Solar Spectral Distributions Derived from Broadband Hourly Solar Radiation Data." Paper No. 74100A. Tsai, B.K. ed., *Optical Modeling and Measurements for Solar Energy Systems III: Proceedings of SPIE Conference, 2-4 August 2009, San Diego, CA*. NREL CP-550-46254 (2009).

Myers, D.; Wilcox, S. M. "Relative Accuracy of 1-Minute and Daily Total Solar Radiation Data for 12 Global and 4 Direct Beam Solar Radiometers." R. Campbell-Howe, ed., *Proc. Solar 2009 Conf., 11-16 May 2009, Buffalo, NY*. NREL CP-550-46803 (2009).

S. Wilcox and D. Myers, "Joint Solar Power Industry and Department of Energy Solar Resource and Meteorological Assessment Project (SOLRMAP)." Paper No. 741006, Tsai, B.K., ed., *Optical Modeling and Measurements for Solar Energy Systems III: Proceedings of SPIE Conference, 2-4 August 2009, San Diego, CA*. NREL CP-550-46537 (2009).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Z. Li	Stratford, CT yun.li@newport.com	PASS for flash solar simulator tests TSA-08-202	$15.8 NREL Labor	$35 Newport Equipment

Solar Resource 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: Kevin Lynn, 202-586-1044, kevin.lynn@hq.doe.gov

FY 2009 Budget: $750K (NREL)

Objectives

- Develop reliable and accurate methods for estimating solar resources over large areas with high temporal and spatial resolution
- Continue providing updates to the National Solar Radiation Database (NSRDB) and typical meteorological year version 3 (TMY3) data sets
- Evaluate the impacts of cloud characteristics on resource and grid-integrated system variability
- Evaluate short-term solar resource forecasting methods
- Provide technical and Operating Agent (OA) support to IEA/SHC Task 36 Solar Resource Knowledge Management.

Accomplishments

- Developed further in-house capability of modeling solar resources using satellite imagery
- Undertook a roadmapping exercise to identify research priorities over the next 5 years in modeling, forecasting, measurement capabilities, and photovoltaic (PV) variability analysis
- Analyzed data sets to evaluate ramp rates and other characteristics of grid-tied PV outputs
- Developed field campaign designs to further evaluate resource variability under various climatic and cloud cover conditions
- Through IEA/SHC Task 36 continued work in evaluating various methods for determining 1–3-day ahead solar resource forecasting
- Gave presentations on PV variability analysis and IEA/SHC Task 36 outcomes at various conferences and workshops
- Made a strategic new hire (Manajit Sengupta) to lead our in-house capabilities in resource modeling, forecasting, and benchmarking.

Future Directions

- Develop various empirical and physically based satellite modeling and solar resource forecasting capabilities (in combination with CSP)
- Undertake 2-3 field measurement campaigns to gather critical data on resource variability at time scales of 15 minutes or less, for PV grid integration studies
- Provide effective information dissemination and public outreach mechanisms
- Continue to provide technical and OA support to IEA/SHC Task 36 and future tasks
- Produce periodic updates to the NSRDB (in combination with CSP).

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1. Introduction

This project focuses on developing and disseminating more reliable and accurate measurements and estimates of the solar resource, including high temporal and spatial resolution data sets for evaluating the performance of a significant amount of PV systems interconnected to a grid distribution or transmission system. The scope includes the validating short-term solar forecasts in formats suitable for large-scale utility operations of solar systems, and updating and disseminating the National Solar Radiation Data Base.

2. Technical Approach

To accomplish these goals, we undertook four technical tasks (some of this work was cost-

shared through funds from the CSP Market Transformation efforts):

Solar Resource Model Development and Application: Using geostationary satellite imagery, we are developing an empirical model to produce high spatial (5–10 km) and temporal (15–30 min) data sets for the North American region.

Test and Evaluate Solar Resource Forecasting Methodologies: Adopting procedures deployed by European researchers in IEA/SHC Task 36, we examine the suitability of various 1–3 day ahead and 0–6 hour ahead solar forecasting capabilities based on National Weather Service (NWS) forecast products, numerical mesoscale weather models, and satellite-derived cloud vector motion analysis.

Conduct PV Variability Assessments: Using existing high-resolution solar resource data as well as PV output data from developers from actual projects, we examine PV ramp rates and other resource characteristics that result from cloud passages and other short-term weather phenomena.

Stakeholder Support: There are increasing demands for public dissemination of high quality resource data and data products. This task provides web-based and personalized technical assistance to our stakeholders to ensure that the most appropriate data products are used for specific applications.

3. Results and Accomplishments

In the solar resource modeling task, through our consultant Bernard Walter Consulting, we established procedures to access geostationary satellite data (both visible and IR channels), and are finalizing a procedure for converting this imagery into high resolution solar resource estimates, both GHI and DNI. The empirical modeling approach is nearing completion and will be tested in FY 2010. We are also developing a more physically based satellite model, to be used for research and benchmarking, collaborating with NOAA, University of Wisconsin, and Colorado State University (CSU). In FY 2009 we focused on developing a scope of effort and establishing partnerships with the key researchers involved in NOAA's Geostationary Satellite Installation Project (GSIP). A prototype of the GSIP algorithm is currently being run at CSU, and we expect to team with our university partners to produce high temporal and spatial resolution GHI datasets in 2010.

We obtained a number of data sets from project developers operating grid-tied PV systems, and are analyzing these data to develop statistical relationships on PV ramp rates and other resource variability characteristics. These results are used to devise models to create PV data on subhourly time steps, for use in high-penetration PV grid integration evaluations. These studies are also being used to design field campaigns, to be undertaken in FY 2010, on gathering key data sets to evaluate and model the impacts of partly cloudy conditions and cloud passages across large scale and distributed grid-tied PV arrays.

Through IEA/SHC Task 36 we are gaining critical information and data on solar resource forecasting techniques being examined in several regions around Europe. NASA/LaRC in this country previously evaluated some of these techniques, and this work will continue under support from the SETP later in FY 2009 and in FY2010. Although mesoscale model input improves the result of solar resource forecasts using NWS forecast products, considerable work needs to be done to obtain sufficient reliability of these forecasts for utility-scale operations.

4. Planned FY 2010 Activities

Work in all four task areas will continue in FY 2010, in some cases with continued support from the CSP subprogram. The PV and CSP tasks will be consolidated into a single agreement under the Systems Integration subprogram in 2010. Specific work will include:

- Finalize and benchmark an empirically-based satellite-derived solar modeling capability
- Begin work on a physically based satellite-derived modeling capability, in cooperation with NOAA and universities
- Carry out two or three field campaigns to gather high temporal resolution solar and PV output data for determining PV variability characteristics based on various weather and climatic conditions
- Update the NSRDB (through 2007 for hourly data and through 2009 for monthly data)
- Further benchmark and identify research priorities of solar resource forecasting schemes
- Give ongoing technical assistance to data users through web-based data dissemination,

publications, and participation in workshops and lab visits.

5. Major FY 2009 Publications

D. Renné, *IEA/SHC Task 36: Solar Resource Knowledge Management: Annual Report to the IEA Solar Heating and Cooling* ***Program*****, IEA/SHC.**

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Bernard Walter Consulting	Seattle, WA bwalter@cablespeed.com	Develop empirical satellite-derived high spatial and temporal resolution satellite-derived solar resource model	100	50*
State University of New York/Albany: R. Perez	Albany, NY perez@asrc.cestm.albany.edu	Analyze cloud motion vectors for 0-6 hour ahead solar forecasting	60	0
State University of New York/Albany: R. Perez	Albany, NY perez@asrc.cestm.albany.edu	Test and evaluate various 1–3 day ahead solar forecasting methodologies	50***	25**
University of Oregon: F. Vignola	Eugene, OR Ned.Money@idea.com	Provide data collection and analysis of legacy Pacific Northwest solar network	50****	0

* Partial funding from Western Wind and Solar Integration Study.
** Partial funding from CSP Market Transformation Program.
*** To be awarded in FY 2010.
**** Carryover from FY 2008.

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Environmental Health & Safety/Lifecycle Research

Performing Organization: Brookhaven National Laboratory (BNL)

Key Technical Contact: Vasilis Fthenakis, 631-344-2830, vmf@bnl.gov

DOE HQ Technology Manager: Kevin Lynn, 202-586-1044, kevin.lynn@ee.doe.gov

FY 2009 Budget: $470K

Objectives

- Assist in preserving the safe and environmentally friendly nature of photovoltaics and in minimizing environmental health and safety (EH&S) risks and associated costs, to ensure the public support and economic viability of photovoltaic (PV) systems
- Identify potential EH&S barriers of PV materials, processes, or applications and define strategies to overcome such barriers
- Maintain the 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

- Published leading articles and gave keynote addresses on PV sustainability
- Promoted international collaborations on life-cyle assessment (LCA) of PV energy technologies
- Hosted a PV Industry Recycling Scoping workshop and led an International Energy Agency (IEA) PVPS task
- Assisted several companies on site-specific EH&S issues
- Answered several requests for EH&S information from the public and the industry.

Future Directions

- Perform comparative LCA of additional solar technologies to guide toward safe and environmentally friendly alternatives
- Research recycling separations and cost optimization.

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1. Introduction

The activities of the Environmental, Health and Safety Research Center focus on minimizing potential EH&S impacts associated with current and future PV energy systems and applications. This objective is accomplished by proactive research, rigorous industry outreach, and technical communications.

The overall goal is to preserve the safe and environmentally friendly nature of PV and minimize EH&S risks and associated costs, to ensure the public support and economic viability of PV systems. Also, the Center serves as the world's best source on PV EH&S, providing accurate information related to EH&S issues and perceptions. This activity supports the overall communications and outreach objectives of the Solar Energy Technologies Program.

2. Technical Approach

The major areas of BNL's activities are hazard identification and characterization, hazard management, industry outreach, and information dissemination. Ongoing efforts are required because the PV industry is undergoing changes in type and quantities of materials, in manufacturing processes, and in scale, and because continuous vigilance is required in safety and loss prevention.

Task Title	FY 2009 Budget ($K)
1. Hazard Identification/Characterization	220
2. Hazard Management/Recycling	60
3. Industry Outreach/DOE/NCPV Information Dissemination	120
4. IEA Task 12	70

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3. Results and Accomplishments

Task 1: Conducted leading research on PV sustainability metrics, resources of minor metals, land use, and economic-environmental feasibility of large-scale PV penetration.

Task 2: Organized and conducted a Recycling Industry Scoping workshop, IEEE PVSC, June 2009.

Started recycling cost optimization studies. Conducted studies on the environmental impacts of large-scale PV deployment.

Task 3: Provided facility-specific assistance to PV manufacturing companies, and advised PV companies, universities, public utilities, and concerned citizens on EH&S issues.

Task 4: -Answered several requests for EH&S information from different agencies, business partners, citizen organizations, and the media. Led the IEA Task 12, a collaborative effort by specialists from 10 countries, creating a unified expert front on PV EH&S, LCA, and recycling. Published and presented extensively (8 journal papers, 11 presentations [4 keynote]).

4. Planned FY 2010 Activities

Task 1: This task is part of BNL's proactive research to overcome EH&S barriers to support for large-scale implementation of PV. Activities planned for FY 2010 include:

- LCA of additional PV technologies (e.g., CIGS, HCPV)
- end-of life in LCA
- harmonization of LCA results
- Solar vision siting and environmental tasks.

Task 2: These activities are pivotal in preserving the safe and environmentally friendly nature of the PV industry as it moves toward large-scale manufacturing. In FY 2010, research at BNL will focus on:

- Improving technical and economic feasibility
- Collaborating with PVCycle.

Task 3: In FY 2010, BNL will:

- Serve as the lead organizer and US representative to IEA PV EH&S Task 12
- Guide the industry and R&D labs on accident prevention and pollution prevention
- Support DOE and NCPV as needed.

Task 4: The results of BNL's research will be disseminated with new publications, e-mail and the web. The PV EH&S Research Center serves as a clearinghouse for EH&S information requested by potential customers, business partners, citizen organizations, and the media.

5. Major FY 2009 Publications

J.K. Choi and V.M. Fthenakis, "Economic Feasibility of Photovoltaic Module Recycling: Survey and Model," *Journal of Industrial Ecology*, in press.

V.M. Fthenakis, "Sustainability of Photovoltaics: The Case for Thin-Film Solar Cells," *Renewable and Sustainable Energy Reviews* **13**, 2746 (2009).

V.M. Fthenakis, and H.C. Kim, "Land Use and Electricity Generation: A Life Cycle Analysis," *Renewable and Sustainable Energy Reviews* **13**, 1465 (2009).

V.M. Fthenakis and H.C. Kim, "Prospective Life Cycle Assessment of Nanotechnology: Multi-junction a-Si Photovoltaics," *Progress in Photovoltaics Research and Applications*, in press.

V. Fthenakis, J. Mason, and K. Zweibel, "The Technical, Geographical and Economic Feasibility for Solar Energy to Supply the Energy Needs of the United States," *Energy Policy* **37**, 387 (2009).

V.M. Fthenakis, W. Wang, and H.C. Kim, "Life Cycle Inventory Analysis in the Production of Metals used in Photovoltaics," *Renewable and Sustainable Energy Reviews* **13**, 493 (2009).

V. Fthenakis, H. Kim, S. Gualtero, and A. Bourtsalas, "Nanomaterials in PV Manufacture: Some Life Cycle Environmental and Health Considerations," *Proc. 34th IEEE PV Specialists Conf., Philadelphia, June 2009*.

V. Fthenakis, M. Raugei, M. Held, H.C. Kim, and J. Krones, "An Update of Energy Payback Times and Greenhouse Gas emissions in the Life Cycle of Photovoltaics," *Proc. 24th European Photovoltaic Solar Energy Conf.*, *Hamburg, Germany, September 21–25, 2009*.

6. University and Industry Partners

Several, through EPIA and IEA Task 12, at no cost to our project.

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Market Transformation Highlights

Fiscal year 2009 saw a continued development of the Market Transformation portfolio, now in its third year of expanded effort.

Market Transformation activities seek to reduce the barriers to solar implementation and complement the program's R&D portfolio by focusing on the non-hardware costs associated with installation. Combined with technology improvements, Market Transformation aims to support the delivery of cost-competitive solar electricity by 2015.

Market Transformation activities target a wide range of decision-makers who affect the deployment of solar energy technologies. These include states, local governments, utilities, the educational community, codes and standards bodies, and the solar industry.

Key activities in FY 2009 included supporting 25 Solar America City partnerships, the Solar America Board for Codes and Standards (Solar ABCs), the Solar Electric Power Association (SEPA), and multiple state outreach organizations. Technical assistance efforts across the portfolio were led by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL).

In FY 2009, Market Transformation comprised the following areas:

- Codes & Standards
- Workforce Development
- Technical Assistance
- Technical Outreach
- Operations and Planning

FY09 Budget	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Market Transformation	**3627**	**1506**	**7616**	**12716**
Codes & Standards	**200**	**100**	**905**	**1205**
Workforce Development	**0**	**0**	**565**	**565**
Technical Assistance	**2050**	**1140**	**2126**	**5316**
Technical Outreach	**175**	**0**	**1250**	**1425**
Operations & Planning	**1202**	**266**	**2098**	**3533**

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Codes & Standards Summary

The purpose of the Codes & Standards project is to improve the responsiveness, effectiveness, and accessibility of solar codes and standards to U.S. stakeholders at all levels. Current codes and standards that affect the domestic deployment of solar photovoltaic (PV) technologies include the National Electrical Code, Underwriters Laboratories (UL) product safety standards, the Institute of Electrical and Electronics Engineers (IEEE) standards for grid interconnection, and many others. The U.S. Department of Energy (DOE) supports solar codes and standards efforts to ensure the continued safe and rapid growth of the domestic solar market.

FY09 Budget	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Codes & Standards	**200**	**100**	**905**	**1205**
Solar America Board for Codes & Standards	**0**	**0**	**905**	**905**
Codes Laboratory Support	**200**	**100**	**0**	**300**

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Solar America Board for Codes & Standards

Performing Organizations:	New Mexico State University (NMSU) Research Foundation of the State University of New York at Albany (SUNY) Tucson Electric Power (TEP)
Key Technical Contact:	Holly Thomas (DOE/GO), 303-275-4818, holly.thomas@go.doe.gov
DOE HQ Technology Manager:	Charlie Hemmeline, 202-586-6646, charlie.hemmeline@hq.doe.gov
FY 2009 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 collecting and disseminating documents, regulations, and technical materials related to solar codes and standards (NMSU)
- Describe and experimentally compare methods quantifying the effective capacity credit of nondispatchable resources such as PV and build consensus for proposed methods (SUNY)
- Develop, test, and verify methods 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 two codes and standards study reports; conducted outreach to targeted audiences on these and previous study reports (NMSU)
- Convened three stakeholder meetings to provide input on codes and standard issues; distributed four newsletters on Solar America Board for Codes & Standards (ABCs) activities and other related codes and standards activities (NMSU)
- Began work on new tasks identified during previous year's gap analysis (NMSU)
- Adopted Solar ABCs policy on module nameplate tolerances (NMSU)
- Conducted fire safety research on rating of PV modules mounted on different roofing materials (NMSU)
- Participated in developing international and national standards through International Electrotechnical Commission (IEC) Technical Committee 82 and other standard-making organizations (NMSU)
- Modeled two methods to quantify the capacity credit of dispersed PV: (1) the effective load carrying capability (ELCC), based on 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 or storage to firm PV capacity (SUNY)
- Published a report, *Utility Solar Generation Valuation Methods* (TEP).

Future Directions

- Publish six additional codes and standards study reports and two white papers. Continue 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 ABCs Web site (NMSU)

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- Participate in developing international and national standards through IEC Technical Committee 82 and other standard-making organizations (NMSU)
- Adopt Solar ABCs policy on recommended standards for PV modules and systems (NMSU)
- Identify major gaps in the current work on codes and standards and prioritize them for a strategic plan for future work (NMSU).

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Workforce Development Summary

The purpose of the Workforce Development project is to ensure the rapid scale-up of a well-trained domestic solar workforce that can deliver safe, high-quality solar installations nationwide. The downstream workforce includes solar installers and sales professionals, local code officials, and inspectors who oversee installations. Increasing the availability of well-qualified installers and local training opportunities will support continued installation cost reduction as well as prevent worker shortages from inhibiting the growth of the domestic solar market. Funding in Fiscal Year 2009 supported the North American Board of Certified Energy Practitioners (NABCEP) for the certification of solar personnel and the Interstate Renewable Energy Council (IREC) for solar training and accreditation of instructors.

FY09 Budget	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Workforce Development	**0**	**0**	**565**	**565**
PV Certification	**0**	**0**	**265**	**265**
Training and Accreditation	**0**	**0**	**300**	**300**

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Photovoltaic Installer Certification

Performing Organization: North American Board of Certified Energy Practitioners (NABCEP)

Key Technical Contacts: Yana Rasulova (DOE/GO, Primary Contact), 303-275-4890, yana.rasulova@go.doe.gov
Carolyn Elam (DOE/GO), 303-275-4953, carolyn.elam@go.doe.gov
Kathleen Bolcar (DOE HQ), 202-586-6646, kathleen.bolcar@ee.doe.gov

DOE HQ Technology Manager: Charlie Hemmeline, 202-586-6646, Charlie.hemmeline@hq.doe.gov

FY 2009 Budget: $875K (NABCEP)

Accomplishments

- Increased the number of individuals who achieve the NABCEP Certifications and pass the photovoltaics (PV) entry level exam:
  - 325 individuals received NABCEP's Solar PV Installer Certification in 2009, a 98% increase from 2008; 14 administrators of the exam and 912 candidates have received the NABCEP Solar PV Installer certification
  - 3,510 individuals obtained NABCEP's PV Entry Level Certificate of Knowledge of Solar PV Systems in 2009. NABCEP has issued 4,812 Entry Level Certificates of Knowledge since the certificate's inception in 2005
  - 26 individuals received the Solar Thermal Installer Certification in 2009; 111 individuals have obtained NABCEP's Solar Thermal Installer Certification.
- NABCEP submitted its second *Annual Surveillance Report* to the American National Standards Institute (ANSI) to demonstrate NABCEP's ongoing compliance with its ISO/IEC 17024 accreditation.

Future Directions

- Conduct an aggressive marketing and outreach campaign to ensure significant increases in the number of individuals 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. Introduction

Since 2003, NABCEP has been awarding professional credentials and certificates to renewable energy practitioners. NABCEP's rigorous competency standards send a clear message to consumers, business leaders, and public officials that the industry stresses high-quality, safe, and ethical business practices and workmanship standards. NABCEP has the following Certification and Certificate Programs:

- Solar PV Installers
- Solar Thermal Installers
- Recertification programs for its certified Solar PV and Solar Thermal Installers
- Entry Level Certificate of Knowledge for Solar PV Systems

2. Technical Approach

NABCEP's primary objectives are to develop and implement quality credentialing and certification programs for renewable energy practitioners. Competency standards, such as those established by NABCEP, play a critical role in developing the renewable energy workforce and will help prevent disruptions in the rapid growth trajectory of the renewable energy market. NABCEP recognizes that renewable energy professionals receive their training and work experiences in a variety of ways

and has developed a series of eligibility categories to reflect these varied backgrounds. Both the PV and solar thermal credentialing programs are based on strict credentialing guidelines.

3. Results and Accomplishments

- 325 individuals received NABCEP's Solar PV Certification in 2009
- 3,510 individuals obtained NABCEP's PV Entry Level Certificate of Knowledge of Solar PV Systems in 2009
- 26 candidates were awarded the Solar Thermal Installer Certification in 2009
- 111 individuals have obtained NABCEP's Solar Thermal Installer Certification
- NABCEP submitted its second *Annual Surveillance Report* to ANSI to demonstrate NABCEP's ongoing compliance with its ISO/IEC 17024 accreditation
- NABCEP's new Web site was launched (03/09)
- During fiscal year (FY) 2009, NABCEP exhibited or presented, or both, at numerous conferences, including the following:
  - NESEA 2009
  - ASES 2009
  - PV America 2009
  - Solar Power International 2009
  - The Renewable Energy and Energy Efficiency Workforce Education Conference
  - The Midwest Renewable Energy Fair
  - The IEC National Convention & Electric Expo
  - The MREA Solar Thermal Conference.

4. Planned FY 2010 Activities

The first exam of NABCEP's Small Wind Installer Certification is scheduled for September 11, 2010 and a new PV Technical Sales Certification will also be available in the fall of 2010. NABCEP will continue to conduct marketing and outreach to ensure significant increases in the number of individuals pursuing NABCEP certification; work to increase awareness within the business community, state and federal agencies, and consumers about the benefits of NABCEP certification; and develop a new family of certification programs for the rapidly changing needs and roles in the renewable energy market.

5. FY 2009 Special Recognitions

- ANSI/ISO/IEC 17024 Accreditation

6. Major FY 2009 Publications

- Bi-monthly NABCEP Newsletters

7. University and Industry Partners

NABCEP works closely with representatives from numerous companies and organizations, including but not limited to the following:

- The National Renewable Energy Laboratory
- The National Electrical Contractors Association
- The International Brotherhood of Electrical Workers
- The Independent Electrical Contractors
- BP Solar
- Sandia National Laboratories
- The National Joint Apprenticeship & Training Committee
- The Small Wind Certification Council
- SunPower Corporation
- The North Carolina Solar Center
- The Florida Solar Energy Center
- The Solar Energy Industries Association
- The Solar Electric Power Association
- The American Wind Energy Association
- The Midwest Renewable Energy Association
- Lane Community College
- Austin Community College
- Hudson Valley Community College
- SUNY Ulster
- Solar Energy International
- *Home Power* magazine
- The New York State Energy Research and Development Authority.

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Solar Outreach & Communications

Performing Organization: Interstate Renewable Energy Council (IREC)

Key Technical Contacts: Yana Rasulova, (DOE/GO, Primary Contact), 303-275-4890, yana.rasulova@go.doe.gov
Kathleen Bolcar (DOE HQ), 202-586-2820, kathleen.bolcar@ee.doe.gov

DOE HQ Technology Manager: Charles Hemmeline, 202-586-6646, charlie.hemmeline@hq.doe.gov

Total FY 2009 Funding: $975K

Objectives

- Offer models and assistance on net metering/interconnection to lower both barriers and cost for installing solar electricity through the Connecting to the Grid Project
- Monitor and participate as appropriate in public hearings/meetings and supply input that could affect solar barriers or commercialization through public hearings on solar codes and standards
- Encourage and coordinate quality training workshops and other learning opportunities, as well as assist educational providers through the Workforce Training and Quality Assessment Project
- Connect experts with market transformation stakeholders on key issues in a cost-effective and convenient format
- Manage and maintain 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

- Continued educating and supporting information about net metering - in 16 states
- Continued educating and supporting information about interconnection in 13 states
- Launched University On-Line Directory of 4-year universities that are offering undergraduate and graduate courses in renewable energy and energy efficiency
- Held 10 workshops for code officials (both photovoltaic [PV] and solar thermal)
- Held five phone/webinar seminars on key topics such as the NEC, tax credits, and market trends
- Published and posted on the IREC website 26 issues of the IREC/SETP e-newsletter for more than 4,100 subscribers and 12 issues of the Interconnection/Net Metering e-newsletter for more than 4,200 subscribers
- Published *Annual Solar Market Trends Report* and 6th edition of *Connecting to the Grid* Guide.

Future Directions

- Coordinate workforce training and quality assessment workshops with states, cities, and stakeholders
- Continue to publish newsletters and hold telephone seminars
- Develop Solar Codes and Standards Hearing Project to address infrastructure barriers with states
- Maintain the IREC website.

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1. Introduction

IREC promotes increased stakeholder communications and education under the Solar Market Transformation activities; addresses infrastructure barriers to solar energy; and coordinates with industry, DOE, national laboratories, states, cities, and counties.

2. Technical Approach

IREC continues to promote better communications among stakeholders, address

infrastructure barriers by promoting easy and fair hook-up rules to the utility grid, promote quality training based on industry competency standards, and coordinate with multiple federal, state, and local stakeholders.

Workforce development and quality training are critical components, and IREC works with community colleges, the North American Board of Certified Energy Practitioners, the Institute for Sustainable Power, and subject matter experts.

3. Results and Accomplishments

- Participated in net metering and interconnection regulatory proceedings, rulemakings, and workshops in 20 states
- Organized five informative, interactive phone seminars
- Convened 10 workshops for code officials
- Convened four Introductory Workshops on Training and four Faculty Development Workshops
- Continued educating and supporting information about net metering in 16 states
- Continued educating and supporting information about interconnection in 13 states
- Launched University On-Line Directory of 4-year universities offering undergraduate and graduate courses in renewable energy and energy efficiency
- Expanded On-Line Directory of Renewable Energy Training Providers
- Held four 2-day faculty development workshops
- Held four introductory workshops on developing quality training programs set to industry standards
- Held 10 workshops for code officials (both PV and solar thermal)
- Held five phone/webinar seminars on key topics such as the NEC, tax credits, market trends
- Published 26 issues of the IREC/SAI e-newsletter for more than 4,100 subscribers and posted on the IREC website
- Published 12 issues of the Interconnection/Net Metering e-newsletter for more than 4,200 subscribers
- Updated *Job Trends Report*
- Published *Annual Solar Market Trends Report*
- Published the 6th edition of the *Connecting to the Grid* Guide
- Published updated *Net Metering and Interconnection Model Rules and Procedures*
- Published *2009 Update & Trends Report*.

4. Planned FY 2010 Activities

- 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
- Hold one or two Faculty Development Workshops
- Publish 12 Interconnection/Net Metering newsletters and 26 State/Stakeholder newsletters
- Monitor and engage in emerging trends in net metering, interconnection, and related issues such as SSAs, Community Solar, and Smart Grid
- Update *Best Practices in Training*.

5. Major FY 2009 Publications

- Annual *Updates & Trends Report*
- 6th edition of *Connecting to the Grid*
- Updated *Net Metering and Interconnection Model Rules and Procedures*.
- *Annual Solar Market Trends Report*

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
- Institute for Sustainable Power
- Hudson Valley Community College, Lane Community College, and other community colleges
- Industry and stakeholder groups.

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Technical Assistance Summary

The purpose of the Technical Assistance project is to provide high quality technical support to key stakeholders in their efforts to procure and install solar technologies, and design programs to promote accelerated market development. The U.S. Department of Energy's (DOE's)funded technical assistance can often be a critical driver of action and is an important tool to meet Market Transformation objectives. In Fiscal Year 2009, DOE provided technical support to our 25 Solar America City partnerships, several Solar America Showcase installation projects, and federal sector stakeholders through the Government Solar Installation Program. Organizations funded to deliver this technical assistance included the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), the Florida Solar Energy Center (FSEC), New Mexico State University, and CH2MHill.

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
Technical Assistance	**2050**	**1140**	**2126**	**5316**
Integrator	**0**	**0**	**1250**	**1250**
Regional Experiment Station Support	**0**	**0**	**400**	**400**
Laboratory Support	**1500**	**1140**	**276**	**2916**
Solar America Cities	**0**	**0**	**0**	**0**
Solar America Showcases	**0**	**0**	**0**	**0**
Government Solar Installer Program	**0**	**0**	**0**	**0**

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Technical Assistance Provider & Tiger Team Integrator

Performing Organization: CH2M HILL, Inc.

Key Technical Contact: Joe Lucas (DOE/GO), 303-275-4849, joe.lucas@go.doe.gov

DOE HQ Technology Manager: Hannah Muller, 202-586-4883, hannah.muller@ee.doe.gov

FY 2009 Budget: $1,550K

Objectives

- Supply supplemental technical assistance to the U.S. Department of Energy (DOE) Solar Energy Technologies Program's Market Transformation projects
- Coordinate and communicate to ensure collaboration of Tiger Team members across geographic areas, to maximize limited resources, to avoid duplication of efforts, and to achieve the highest quality product and delivery of services to the recipients.

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Accomplishments

- Collected metrics data from all 25 Solar America Cities (SAC) to measure program success and effect
- Completed solar mapping portals for Berkeley, Portland, San Francisco, and San Diego
- Completed solar for emergency management studies for New York City and Boston
- Completed solar site assessments for San Jose, Forest City, HI, and Minneapolis/St. Paul
- Completed solar economic development analysis for Milwaukee.

Future Directions

- Support all 25 SAC as they move from technical assistance to special projects
- Prepare a guidebook for best practices in solar permitting for the City of Philadelphia
- Develop a marketing and outreach plan for the City of New Orleans
- Develop solar mapping portals for Orlando, Madison, and New Orleans
- Develop a solar hot water strategy for the City of Knoxville
- Prepare a report outlining strategies for employing solar technologies for emergency management infrastructure
- Prepare a report outlining strategies for economic development that can be used by all 25 SAC, including a cost convergence model.

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1. Introduction

CH2M HILL was competitively awarded a 5-year contract to provide technical assistance to the DOE Solar Program's Market Transformation projects, including, but not limited to, Solar America Cities, Solar America Showcases, and Government Solar Installation Program projects. Technical assistance includes solar technology assistance, city/municipal planning, market/financial analysis support, architectural/structural analysis support, technical project implementation, regional facilitation, solar metrics data collection, communication, outreach and education, and project management.

2. Technical Approach

CH2M HILL is a member of the Tiger Teams offering technical expertise to the various participants in DOE programs. In addition, the company serves ensures collaboration of Tiger Team members, maximizes limited resources, and avoids duplication of effort through coordination and communication.

3. Results and Accomplishments

Solar for Emergency Management: Completed two studies investigating the use of solar technology to support emergency management infrastructure. New York City and Boston were evaluated to

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establish best solar technology alternatives for maintaining reliable power supplies during crisis events for public safety and business and economic continuity.

Solar Mapping Portal: Completed solar mapping portals for Berkeley, Portland, San Francisco, and San Diego. The portal tool allows residents and businesses to locate and obtain information on solar installations in their city and, in some cases, calculate the solar potential of their property. The application uses the Clean Power Estimator to estimate the resident's energy savings and payback time over the life of the project. Links to local solar installers are given if the resident wants to take the next step.

Solar Metrics Data Collection: Continued to study 31 metrics of solar development in all 25 SAC. These measure everything from installed cost per watt to the average permitting time required for solar implementations. When this study is complete, the SAC will have an accurate picture of their solar maturity and the DOE will have a baseline from which to measure success of the program.

Solar Site Assessments: Assisted SAC and Showcase Projects by conducting initial solar site assessments to determine the suitability of local buildings for solar projects. Assessments include roof inspections for suitable solar systems, modeling the energy output of proposed systems as well as cost, and other information a city would need to issue a Request for Proposal.

Solar Economic Development: Assisted the City of Milwaukee in developing a report investigating solar products manufacturing and the critical elements of the supply chain; made suggestions on how the city could position itself to be successful in attracting or growing solar products manufacturing industries.

Media Relations and Outreach: Worked with partner GroundFloor Media to develop a comprehensive media relations and outreach plan for the SAC program. This included media training, support of multiple events from a media perspective, and messaging and branding campaigns to maintain a clear and consistent message for the SAC program.

CREBs Application Assistance: Assisted the City of Santa Rosa and five other Sonoma County cities in completing the engineering sections of their Clean Renewable Energy Bonds (CREBs) applications to the Internal Revenue Service, with 8 of 10 applications approved; the projects are now eligible for funding through tax-free bonds.

System Commissioning: Assisted in commissioning a 1-MW PV system on the Orange County Convention Center in Orlando, FL. Efforts included planning the commissioning, performing the tests required to ensure operation of the system is consistent with design, and publishing a report on findings.

4. Planned FY 2010 Activities

Regional Facilitation: Provide regional facilitation for the SAC. Seven regional facilitators will work with specific cities and assist Tiger Team leads in coordinating efforts related to the SAC program. Responsibilities will include recording city accomplishments, offering limited technical assistance and connecting cities with technical resources, communicating DOE information, and maintaining a consistent and steady channel of communications.

Marketing Plans: Work with partner Imagine Solar to develop a comprehensive solar outreach and marketing plan for the City of New Orleans.
Solar Mapping Portals: Continue developing solar mapping portals for several cities, including Orlando, New Orleans, and Madison.

Solar Hot Water Strategy: Perform a qualitative analysis of solar hot water markets in Knoxville/Knox County.

Cross-Cutting Projects: Assist with two cross-cutting projects intended to be applicable to all 25 SAC. The first continues the work performed for New York City and Boston to focus on using solar technology to support and bolster emergency management infrastructure.

The second project will focus on economic development and will include a background and overview of the physical and business requirements of the major job-generating segments of the solar photovoltaics industry.

*Guidebook for Solar Permitting: A*ssist the City of Philadelphia in developing a guidebook for permitting for solar.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
Clean Energy Associates Steve Wiese	Austin, TX steve.wiese@cleanenergyassociates.com	Assisted in the development of parameters and a weighting system to determine solar install targets for all 25 Solar America Cities	20
Imagine Solar Michael Kuhn	Austin, TX michael.kuhn@imaginesolar.com	Assisted CH2M HILL in performing training and site assessments for Minneapolis/St. Paul	20
GroundFloor Media Ramonna Tooley	Denver, CO rtooley@groundfloormedia.com	Assisted CH2M HILL in providing media outreach, solar event media support, media training, messaging, and branding in support of the Solar America Cities program	300

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Laboratory Support

Performing Organizations:	Florida Solar Energy Center (FSEC) National Renewable Energy Laboratory (NREL) New Mexico State University (NMSU) Oak Ridge National Laboratory (ORNL) Sandia National Laboratories (SNL)
Key Technical Contacts:	Jason Coughlin (NREL), 303-384-7434, Jason.Coughlin@nrel.gov Norm Durfee (ORNL), 865-574-1830, durfeenw1@ornl.gov Vipin Gupta (SNL), 915-491-1158, vpgupta@sandia.gov Beth Richards (SNL), 505-844-6951, ehricha@sandia.gov
DOE HQ Activity Managers:	Charlie Hemmeline, 202-586-6646, charles.hemmeline@ee.doe.gov Hannah Muller, 202-586-4883, hannah.muller@ee.doe.gov
FY 2009 Budgets:	$2,996K (DOE), $2,996K (technical assistance from national laboratories)

Objectives

- Provide financial assistance awards, also called cooperative agreements, of 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. These awards will be used to propose activities that support DOE objectives and Solar Energy Technologies Program Market Transformation (MT) activities. The 25 cities all have populations of 100,000 or more
- Provide up to $250,000 in tailored technical assistance from DOE national laboratories and contractors to each of the Solar America Cities to accomplish project goals.

Accomplishments

- Held the Solar America Cities 2nd Annual Meeting in San Antonio, which brought together the 2007 and 2008 awardees to share best practices, share lessons learned, present new ideas, and engage in networking
- Launched Solar America Cities Information Network (SAmCIN)
- Provided technical assistance for each of the 2007 and 2008 cities. The following entities provided this assistance: the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), Oak Ridge National Laboratory (ORNL), the Southwest Regional Experiment Station (SWRES) at New Mexico State University (NMSU), and the Southeast Regional Experiment Station (SERES) at the Florida Solar Energy Center (FSEC).

Future Directions

- Integrate solar energy technologies into city energy planning and remove market barriers to solar energy development that exist in urban planning charters, zoning regulations, building codes, and permitting and inspections procedures
- Promote solar energy technologies through outreach, curriculum development, incentive programs, and other innovative approaches targeted at residents and local businesses Develop a comprehensive city government approach to solar implementation involving key stakeholders, utilities, and private partners
- Target specific barriers through the special projects
- Institutionalize the Solar America Cities approach, experiences, lessons learned, and types of activities with long lives in other cities
- Establish target barriers to solar employment through the use of cross-cutting projects (e.g., solar hot water).

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1. Introduction

Through the U.S. Department of Energy's Solar America Cities partnership, 25 major U.S. cities are working to accelerate the adoption of solar energy technologies for a cleaner, more secure energy future. Each of the 25 cities has a team of technical and communications experts who are dedicated to helping them develop a sustainable solar infrastructure that removes market barriers and encourages the adoption of solar energy by residents and businesses.

The teams are led by experts from FSEC, NREL, NMSU, ORNL, and SNL.

2. Technical Approach

The objectives of the Solar America Cities 2009 Special Projects funding opportunity announcement (FOA) were to facilitate mainstream adoptions of solar technologies and to create models for other cities that include experience and expertise in financing, permitting, and technical integration. DOE selected 25 cities to help set the foundation for a solar energy market that can serve as a model for cities around the nation.

Each Solar America City was eligible for the Special Projects FOA. The cities submitted proposals outlining their plans to scale up their most promising projects and concepts. The goal was to overcome key barriers to urban solar energy use in their communities, allowing innovative programs and policies to be replicated across the nation.

On-Site Technical Assistance

In their proposals, the cities identified the technical assistance their projects might require in areas such as city planning, technology selection, project financing, building codes, architecture, and community outreach. DOE appointed a technical assistance leader, called a Tiger Team Lead, to each city. Members of the Tiger Team were drawn from NREL, SNL, ORNL, the SWRES at NMSU, and SERES at FSEC.

3. Results and Accomplishments

In April 2009, DOE held the Solar America Cities 2nd Annual Meeting to share experiences, lessons learned and give the 2007 and 2008 cities opportunities to network. DOE launched a Solar America Cities SAmCIN to promote the goals and accomplishments.

Details of accomplishments in each city follow.

Ann Arbor took its real-time monitoring system for the photovoltaic (PV) systems at the Leslie Science Center on Earth Day (April 22, 2009). The city is having CH2M HILL perform system commissioning of three PV systems and two solar thermal systems located at three separate sites within the city.

Austin issued a final report on benchmarking of solar energy programs.[1] Austin also assessed potential for distributed renewable power within the city and the potential for energy generation from renewable energy sources in west Texas that would serve Austin electricity customers.

Berkeley partnered with Community Energy Services Corporation (CESC) to create the SmartSolar Program to promote cost-effective investment in solar water heating (SWH) and solar electric technologies in the residential and small-to-medium commercial/public building sectors.

Boston explored innovative financing strategies to facilitate the bulk purchase, financing, and installation of solar energy technologies.

Madison developed a Madison Solar Map to integrate with NREL's IMBY tool. The integrated map and tool will give citizens interested in rooftop solar information on various PV systems that would fit their roofs.

New Orleans conducted Solar Thermal Training. The city also completed the installation of an advanced hurricane-resistant 28-kilowatt (kW) solar roof on Warren Eaton Senior High School through a partnership among Energy Corporation, Nike Corp, Winrock International, USGB LA chapter, and the City of New Orleans.

New York reduced or even eliminated many of the barriers to PV deployment that were identified in the New York City Million Solar

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[1] City of Austin. *U.S. Department of Energy 2007 Solar America City, City of Austin, Texas Benchmarking of Solar Energy Programs.* December 2008. Available for download at http://www.solaramericacities.energy.gov/cities/austin/City-of-Austin-Texas-Benchmarking-of-Solar-Energy-Programs.pdf

Roofs Initiative. The New York Solar America Cities team proposed the Smart Solar City Project and made significant progress toward understanding the technical barriers to interconnecting distributed PV to a network grid. A citywide data acquisition system (Smart Solar City DAS) that can communicate with a smart grid is being developed.

Pittsburgh hired a consultant to perform a site assessment of the General Services Repair Shop in Pittsburgh. The city also launched a fellowship program to carry the solar torch once the Tiger Team and City Team have been disbanded.

Portland initiated a complementary suite of neighborhood-focused activities and programs designed to lower the barriers to solar installations for residents. The city also installed a solar roof membrane at the Scott K-8 School.

Salt Lake City helped develop and improve solar-panel installation courses and instruction modules through a grant awarded to Salt Lake Community College. These courses and modules will be used by several community colleges and schools in 11 surrounding states.

San Diego kicked off plans to initiate large-scale solar financing options through property taxes starting in 2010. The city submitted a proposal to equip city-owned recreation centers with renewable generation and storage for full-service wildfire emergency response islands.

San Francisco provided PV safety training for local firefighters in December 2009.

Tucson continued to explore the installation of solar-powered streetlights in portions of the city and to investigate widening the application of commercial SWH to, for example, launderettes and car washes. Tucson Electric Power received regulatory approval for a 25-megawatt (MW) solar farm on city land. The city also held its 4th Annual Solar Rock Event.

Denver brought a 1.6-MW Sharp solar array online to power Denver International Airport's fuel-storage and distribution facility. The city also created a Web site to support local governments in the metro area interested in launching municipal solar programs.

Houston continued to develop an idea for deploying solar at the Port of Houston to supply backup power for crane operations in the event of a grid power outage. The city also developed a survey to be used for consumer marketing in Houston, held a class on innovative solar financing for Houston stakeholders, installed a large PV demonstration on the George Brown Convention Center, and discussed financing options with a variety of stakeholders.

Knoxville designed and issued a bid package for solar installation on the new Knoxville Transit Center and on Knox Heritage House. The city also installed solar on Ijams Nature Center and on Knoxville Convention Center with block grant funds. Finally, the city brought in experts for SWH and inspector training.

Milwaukee displayed a Solar in the City exhibit at the Betty Brinn Children's Museum. In addition, the city held five PV introductory classes for installers, two site assessment classes, four intermediate PV installation classes, SWH classes, and ten homeowner classes. Finally, the city completed 25 site assessments to examine the feasibility of PV and solar thermal technologies.

Orlando continued the rebate program it launched in 2008, which offers $200 per customer for installing a solar thermal system and receiving an energy audit.

Philadelphia conducted an initial round of meetings to solicit feedback from critical stakeholders for Philadelphia's solar future.

Sacramento identified 16 potential sites for solar PV. Ten of these sites exist and six would be new construction sites.

San Antonio conducted a press conference on the groundbreaking of a "Peak Performance House," an experimental solar laboratory.

San Jose conducted site evaluations of nine city facilities for installation of both novel and mature solar technologies. The city's finance department used detailed solar financial analysis to develop a finance model to help the city decide among options, which include direct purchase, PPA, or doing nothing.

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 to educate Seattle City Light (the local utility) customers.

Minneapolis–Saint Paul launched a new solar PV rebate program, which the State Energy Office will put in place throughout the state. A consultant provided PV code training to building officials from the Twin Cities, and CH2M HILL conducted site assessments and site assessment training courses.

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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; Minneapolis–Saint Paul, MN

Key Technical Contacts: Stephanie Sung, (DOE/GO), 303-275-4899, Stephanie.sung@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: Charles Hemmeline, 202-586-6646, Charlie.hemmeline@ee.doe.gov

FY 2009 Budgets: $2.4 million (DOE), $2.4 million (technical assistance from national laboratories)*
*These funds were awarded in fiscal year (FY) 2008; however, the awardees actively pursued project goals through FY 2009.

Objectives

- Manage and support the financial assistance awards (cooperative agreements) for the 25 Solar America Cities that support the objectives of DOE and activities under the Solar Market Transformation Program

- 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 Funding Opportunity Announcement (FOA) for Solar America Cities Special Projects that resulted in the award of 40 projects to 16 current Solar America Cities with a total value of more than $9 million in federal funds
- Held the Solar America Cities 2nd Annual Meeting in San Antonio, bringing together the 2007 and 2008 awardees to share best practices and lessons learned, present new ideas, and engage in networking
- Provided technical assistance for each of the 2007 and 2008 cities. The following entities provided this assistance: the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), Oak Ridge National Laboratory (ORNL), the Florida Solar Energy Center (FSEC), and the Southwest and Southeast Regional Experiment Stations (RESs) at New Mexico State University (NMSU).

Future Directions

- Integrate solar energy technologies into city energy planning and remove market barriers to solar energy development that exist in urban planning charters, zoning regulations, building codes, and permitting and inspections procedures
- Promote solar energy technologies through outreach, curriculum development, incentive programs, and other innovative approaches targeted at residents and local businesses
- Develop a comprehensive city government approach to solar implementation involving key stakeholders, utilities, and private partners

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- Bring about a widespread increase in the adoption of solar energy technologies across the cities in the residential, commercial, and public building sectors, as well as at utilities.

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1. Introduction

Launched in 2006, Solar America Cities is a key component of DOE's Solar Energy Technology Program (SETP) Market Transformation efforts to accelerate the development of advanced solar technologies with the goal of making them cost-competitive with conventional forms of electricity from the utility grid by 2015.

2. Technical Approach

The Solar America Cities objective is to support cities ready to take a comprehensive, systemic, citywide approach to solar technology. The program is designed to facilitate mainstream adoption and provide a model for other cities to replicate. DOE selected 13 Solar America Cities in June 2007 and 12 more 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 25 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.

The winning cities for 2008 and 2007 follow:

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
Minneapolis–Saint Paul, MN	200

Solar America Cities 2007	FY 2007 Budget ($K)
Ann Arbor, MI	200
Austin, TX	187
Berkeley, CA	200
Boston, MA	150
Madison, WI	200
New Orleans, LA	200
New York , NY	190
Pittsburgh, PA	200
Portland, OR	200
Salt Lake City, UT	197
San Diego, CA	200
San Francisco, CA	200
Tucson, AZ	200

On-Site Technical Assistance
In their proposals, each of the 25 Solar America Cities identified the technical assistance their projects might require in areas such as city planning, technology selection, project financing, building codes, architecture and community outreach. DOE appointed a technical assistance lead, called a Tiger Team leader, to each city. Members of the Tiger Teams were drawn from NREL, SNL, ORNL, the Southwest and Southeast RESs at NMSU, and FSEC.

3. Results and Accomplishments

DOE held the Solar America Cities 2nd Annual Meeting in San Antonio (March 30–April 2, 2009) to share experiences and lessons learned and give the cities an opportunity to network.

DOE continued to refine and add enhancements to the Solar America Cities Web site at http://solaramericacities.energy.gov/Home.aspx. These improvements have allowed the Solar America Cities to add content and access the best practice documents and other valuable materials created during the first two years of the Solar America Cities combined effort.

Details of accomplishments in each city follow.

Ann Arbor trained code officials on solar technology, trained local teachers on solar energy curriculum, and drafted the Ann Arbor Solar Plan.

Austin installed two solar installations at two community college campuses. Solar Curriculum for K-12 has been completed and is being used by the school district this year.

Berkeley developed and launched a program to offer clients independent advice and guidance integrating solar and energy efficiency.

Boston initiated 500 kilowatts (kW) of municipally owned photovoltaic (PV) projects including a 240-kW system at the headquarters of the Boston Water and Sewer Commission and more than 100 kW at five public schools. Solar Boston also coordinated the installation of the first city-owned solar water heating (SWH) system at the Boston Public Health Commission's treatment facility on Long Island in Boston Harbor.

Madison installed 12 SWH and 8 PV systems on city buildings to demonstrate the technology to the public. A solar agent evaluated 500 private properties of solar-interested owners and advised owners about solar options.

New Orleans commissioned a 28-kW PV system on Warren Easton High School. Full-day symposiums on both solar thermal and PV inspections were presented to Orleans Parish Code Officials. The city also established a NABCEP solar installer training program in the New Orleans Community College System.

New York worked with NREL on a study of barriers and solutions to interconnecting PV on the local utility's network grid system. The city also completed studies on solar in emergency management and on the impacts of real-time pricing on solar economics.

Pittsburgh hosted the Northeast Region Solar Conference to share best practices and regulatory models with cities in the Northeast. The city also conducted training for municipal officials to promote solar across the different city departments.

Portland launched the Oregon Clean Energy map (available at http://oregon.cleanenergymap.com/) encouraging residents and businesses in the Portland metro area to choose renewable energy. In addition, the Solar Now Partners developed and launched a new commercial solar workshop series titled Basics of Commercial Solar.

Salt Lake City worked to resolve the existing financial and regulatory barriers in an effort to dramatically propel Salt Lake City and County toward the shared long-term solar goal of increasing solar installations to 10 megawatts (MW) by 2015. With these barriers removed, Phase II of the Solar Salt Lake Project expects to create roughly $60 million in new solar investment opportunities and more than 220 new solar manufacturing, installation, and maintenance jobs in Utah.

San Diego focused on developing a Barriers and Solutions report, based on survey data and focus group meetings, which documents the perspectives from resident, realtor, and permit reviewers. The city also expanded its Solar Map, found at http://sd.solarmap.org/solar/index.php, and populated it with all of the solar installations in the city, Associated with the map are a searchable database, an electric rate analyzer, and an informative solar blog.

San Francisco worked through the Mayor's Solar Founders' Circle to allow the San Francisco Department of the Environment to conduct 92 rooftop solar assessments for commercial and nonprofit buildings in the city. In addition, the city held three Solar Champions courses in cooperation with PG&E's Pacific Energy Center training facility. San Francisco also convened a new SWH working group to identify and address ways to facilitate and increase SWH adoption in the city.

Tucson completed the *Greater Tucson Solar Development Plan* (available at http://www.pagnet.org/documents/solar/SolarDevPlan 2009-01.pdf), issued $7.6 million in CREBs, and began constructing 1 MW of PV on various city sites. In addition, the city implemented a Solar Ready Homes ordinance; conducted a two-day SWH training session for 60 installers, inspectors, and others; and assisted in developing a Green Map of Tucson showing PV and SWH installations.

Denver, working with partner county Boulder, launched the ClimateSmart Loan Program, developed a Web site to promote solar development within local government, installed 1.6 MW of new PV at Denver International Airport, and issued a joint RFP with Denver Public Schools that will result in almost 3 MW of new solar in 2010.

Houston installed 50-kW polycrystalline solar and 50-kW thin film solar arrays at the George R. Brown Convention Center, along with an educational kiosk.. Houston Mayor Bill White gave the keynote address at the press event marking the completion of the project. The city also expanded and improved on its Solar Houston Initiative Web site at www.solarhoustontx.org.

Knoxville facilitated the creation of a 96-hour solar PV installation curriculum program at Pellissippi State Community College. In conjunction with IREC, the Solar Knoxville Program hosted a full-day training seminar on PV systems and the National Electrical

Code (NEC) for regional code officials and building inspectors.

Milwaukee launched a marketing campaign (e.g., radio ads, a Web site, a large graphic display, and a revolving children's exhibit). The city also contracted a solar coach to conduct outreach and lead local solar classes and workshops, and contracted for a feasibility study for solar manufacturing. Finally, the city presented solar financing options to its Common Council.

Orlando developed and advanced the GIS Solar Mapping Project as well as planning for Stakeholder Charette and Solar Training Workshops. The city also worked on the SOQ applications for a 10-MW PV project.

Philadelphia conducted over 10 site investigations to determine feasibility for solar PV on both public and private facilities. The city began installing a solar PV project at the Philadelphia Water Department's Wastewater Treatment facility. In addition, for smaller scale projects, the city's Licenses and Inspections team is working with the local utility and DOE to develop a guidebook for the permitting process and to expedite projects under 10 kW.

Sacramento identified 11 potential sites for solar PV with completed preliminary sizing of systems. The city edited Solar License Agreement and Solar Power Purchase Agreements provided by DOE, which are now ready for the city's use. The city also developed a revised standardized application and established a flat fee for residential permits. Both supersede the existing fee waiver that expired on December 31, 2009.

San Antonio released the *City of San Antonio: Mission Verde Sustainability Plan.* (available at http://www.sanantonio.gov/oep/sustainabilityplan.asp?res=1024&ver=true). Working with the Metropolitan Partnership for Energy, Solar San Antonio, and CPS Energy, the city also developed a San Antonio Green Awards event that includes a Solar Technology award. CPS Energy unveiled two 10-MW solar installations located in San Antonio and West Texas.

San Jose installed 6 PV arrays on municipal facilities and negotiated PPAs with a vendor for a 1.3-MW PV array at the city's Central Service Yard. The city also began coordinating and developing a Property Assessment for Clean Energy (PACE) program, sponsored the 2nd Annual Regional Renewable Energy Summit, and developed a city employee solar financing pilot program.

Santa Rosa held training classes on safety and installation procedures for solar PV and solar thermal installers, provided support and facilitated stakeholder input during the development of a PACE financing program known as, the Sonoma County Energy Independence Program (SCEIP). This program was the first countywide PACE program in the United State. In addition, the city implemented a standardized residential solar permit form and process for Sonoma County.

Seattle engaged more than 700 residents through Solar Works! workshops and provided NEC 690 code training to more than 100 utility staffers and electrical inspectors. In addition, the city drafted an interconnection standard for systems up to 20 MW, tapped into NREL's technical assistance for help on production metering and secondary network issues, and conducted thorough research on community solar models.

Minneapolis–Saint Paul began a revitalization of the state's solar rebate program; initiated a $3-million distributed solar, energy efficiency, and energy storage pilot program in the Minneapolis–Saint Paul Energy Innovation Corridor; and launched several new solar energy programs directed to cities, counties, and school districts. The cities also created several training opportunities for local government staff, covering best practices in solar system permitting, solar site assessments on public buildings, and regulatory barriers to solar energy systems development.

4. Planned FY 2010 Activities

- Replicating the PACE Program model for local governments to give residential and commercial sectors financial incentives to integrate solar into homes and businesses
- Targeting outreach to local governments across the United States, which will present best practices and models developed from the 25 current Solar America Cities
- Developing outreach and education programs designed to inform the public about the steps necessary to implement solar, as well as the resources and incentives available
- Facilitating demonstration installations with accompanying educational components
- Developing solar training programs and roadmaps for integrating solar energy into each city's emergency planning

- Expanding solar installer training programs that steps city planners through all phases of solar implementation on city properties
- Creating Web sites featuring comprehensive one-stop-shopping for solar information with solar mapping capabilities
- Continuing to implement energy audits and solar assessments across the Solar America Cities
- Publishing information on solar financing options and developing city-specific fact sheets and project case studies
- Identifying and implementing cost-effective tools to overcome market barriers to the adoption of commercial and residential-scale solar technologies.

5. Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/Principal Investigator	Location/E-mail	Description/Title of Research Activity
FSEC Dave Click	Cocoa, FL DaveClick@fsec.ucf.edu	Tiger Team Lead
NMSU Andy Rosenthal	Las Cruces, NM arosenth@nmsu.edu	Tiger Team Lead
NREL Alicen Kandt Andy Walker Jason Coughlin Jesse Dean Liz Brown Nancy Carlisle Otto VanGeet Sheila Hayter	Golden, CO alicen.kandt@nrel.gov andy.walker@nrel.gov jason.coughlin@nrel.gov jesse.dean@nrel.gov elizabeth.brown@nrel.gov nancy.carlisle@nrel.gov otto.vangeet@nrel.gov sheila.hayter@nrel.gov	Tiger Team Lead Tiger Team Lead Tiger Team Lead Tiger Team Lead Tiger Team Lead Tiger Team Lead Tiger Team Lead Tiger Team Lead
ORNL Curt Maxey	Oak Ridge, TN maxeylc@ornl.gov	Tiger Team Lead
SNL Dick Fate Elizabeth Richards Greg Kolb Vipin Gupta Warren Cox Howard Passell	Albuquerque, NM refate@sandia.gov ehricha@sandia.gov gjkolb@sandia.gov vpgupta@sandia.gov wbcox@sandia.gov hdpasse@sandia.gov	Tiger Team Lead Tiger Team Lead Tiger Team Lead Tiger Team Lead Tiger Team Lead Tiger Team Lead

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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 2009 Budgets: $650K

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 #2 Military Communities

- Conducted a site assessment that defined the design features of a photovoltaics (PV) Smart Grid at the Kaneohe Bay Marine Corp Base, Hawaii.
- Defined the technical options for siting a PV array and solar water heating (SHW) collector on a historic Marine Corps officer housing unit slated to become a net zero energy home.
- Conducted a site survey to define options to explore in greater depth on the technology selection, operation with energy storage, and grid integration of a 2-3 MW solar farm on the Big Island.

City of San Jose

- Provided follow-up technical assistance, based on the site evaluations the team did the year before at eight city facilities.

Future Directions

- Continue to seek solar projects to support in fiscal year (FY) 2010 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 SWH applications.

The types of installations DOE SAS supports are described in the following paragraphs:

Regarding the *scale* of the project, SAS awards until April of 2009 were required to include projects with solar systems greater than 100 kilowatts. This requirement was increased to a minimum of 250

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kilowatts for the most recent winners. Projects may include multiple sites and do not have to be co-located. In addition to the initial installation, the kW total also may 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.

Regarding the *visibility* of the project, DOE seeks projects that are centrally located in towns, are sited near highly trafficked vehicle or pedestrian areas, house hundreds of residents or workers, are a part of an area frequented by tourists, are part of a popular public destination (e.g. shopping centers, courthouses, etc.), or have some other high visibility component. The project also would have an outreach component that provides information about the installation.

Regarding the *novel solar technology*, DOE tries to support projects that introduce new solar technologies that hold the promise of reducing initial costs, simplifying installation, and boosting consumer confidence, but which have little testing to date that demonstrates such improvements. Examples include new cell or module technology, new materials, or innovative installation and mounting techniques. By offering technical assistance, DOE can help these new solar technologies develop a performance record in the marketplace, identify technical problems early in mass product releases, and devise solutions and alternatives that move specific solar technologies to cost-competitiveness by 2015.

Regarding the *novel solar application*, DOE tries to support projects that utilize solar technology in new ways. One example would be to include new methods of building integration beyond traditional roof-mounted modules. DOE also supports innovative designs and methods that open up previously untapped markets or end uses to solar technology adoption. Acceptable solar applications also could include those that are used in other geographic areas but not in the vicinity (state or region) of the proposed site.

Regarding *replicability*, DOE looks to support projects that can either be replicated by the entity requesting the technical assistance or by others. The entire project should be replicable, or have replicable components, unless installations are of an extremely large size that justifies DOE support without replicability. Replication of projects is a critical component to advance solar commercialization.

2. Technical Approach

SAS awarded technical assistance to organizations that represented a broad spectrum of applications with cross-cutting issues that allowed the SETP Market Transformation activity to work on several barriers. These barriers included:

- Addressing financing barriers for solar applications in a municipality.
- Creating a Request for Proposals (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

<u>Forest City #2 Military Communities SAS Project</u>

- Conducted a site assessment that defined the design features of a PV Smart Grid at the Kaneohe Bay Marine Corp Base.
- Defined the technical options for siting a PV array and SHW collector on a historic Marine Corps officer housing unit slated to become a net zero energy home.
- Conducted a site survey to define options to explore in greater depth on the technology selection, operation with energy storage, and grid integration of a 2-3 MW solar farm on the Big Island.

The Big Island project is a window to the future for the U.S. mainland. The Big Island grid already has approx. 30% of intermittent renewable energy sources linked to it. What the utility (HELCO) needs now is a predictable and dispatchable supply of electricity from renewable sources such as solar. This requires the integration of storage which is what the Technical Assistance Team will explore in greater depth and detail.

<u>City of San Jose SAS Project</u>

The Technical Assistance Team answered follow-on technical questions from the City of San Jose, based on the site evaluations the team did the year before at eight city facilities. These technical

questions covered a range of issues from the location of solar near burrowing owl habitats to the effect of solar PV on the warranty lifetime of the roof to the aesthetically blending the PV array into the barrel roof of the convention center. The follow-on assistance also included a survey of power purchase agreement terms and conditions to address city requirements to abide by non-appropriation clause provisions stipulated by the state and non-substitution clause provisions to reassure PPA provider interests.

SW Solar SAS Project

The technical support team for SW Solar Tech will provide technical support as SW Solar Tech develops and fields an innovative energy system that includes solar energy dishes (up to 5 MW), compressed air energy storage and natural gas backup. To date, the following have been completed:

- Traveled to Phoenix to coordinate work.
- Work on cyber analysis and power systems analysis has begun.
- Work on compressed air storage and solar engineering support will start later in FY2010.

4. Planned FY 2010 Activities

- Complete San Jose SAS
- Complete main part of technical assistance for Forest City #2 SAS
- Complete Mystic Seaport Showcase (FSEC)
- Initiate and lead new State of New Mexico Zero Energy Home Showcase (NMSU)
- Initiate and lead University of Central Florida Showcase (FSEC)
- Bring SW Solar Showcase to a technically and organizationally sensible conclusion
- Plan people and budget to initiate one new SAS project (e.g., Kennecott Land or new showcase from Mar 2010 FOA).

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Government Solar Installation Program

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)
CH2M Hill

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
Steven Peck (CH2M Hill), 720-286-2552, steve.peck@CH2M.com

DOE HQ Technology Manager: Charles Hemmeline, 202-586-6646, charles.hemmeline@ee.doe.gov

FY 2009 Budgets: $630K

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.
- Reviewed four PV feasibility studies for the GSA.
- Assessment of Alcatraz site in California.
- Initiated work on the Federal Solar Guidebook.

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.
- Identify and partner with other federal agencies to help identify locations where solar can be installed in a cost-effective manner on their buildings.
- Accelerate Federal adoption of solar with strategic technical assistance.
- Assist GSA with American Recovery and Reinvestment Act of 2009 (ARRA) installations.

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1. Introduction

The Government Solar Installation Program (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 (TEAM) Initiative, a department-wide effort aimed at reducing energy intensity across the nationwide DOE complex by 30%. GSIP is a single program with a three-phased structure. In Phase 1, DOE will evaluate DOE facilities for pilot sites for solar installations. In Phase 2, DOE will complete installations on the appropriate sites identified in Phase 1. In Phase 3, DOE will work with other federal agencies to apply the lessons learned and assist with solar installations on their individual facilities.

The major partners in the GSIP are the DOE Solar Energy Technologies Program (SETP), DOE Federal Energy Management Program (FEMP), and General Services Administration (GSA). The organization's roles include:

SETP
- Phase 1: Primary responsibility for the pilot installations.
- Phase 2: Participate in decision-making on solar TEAM projects.
- Phase 3: Provide technical assistance.

FEMP
- Phase 1: Provide government energy procurement assistance to SETP.
- Phase 2: Take primary responsibility for installations to complete the TEAM effort.
- Phase 3: Assist with energy purchases.

GSA
- Phase 1: Provide procurement vehicles for power purchase agreements (PPAs) as well as direct system and service purchases.
- Phase 2: Develop a Web portal.
- Phase 3: Take primary responsibility for procurements with DOE support.

Technical assistance teams, also known as Tiger Teams, provide any needed assistance and are comprised of representatives from the national laboratories (NREL, ORNL, and SNL) as well as CH2M Hill, New Mexico State University and the University of Central Florida.

2. Technical Approach

The GSIP initiative meets or exceeds energy efficiency goals mandated by EPAct 2005, as well as Executive Order 13423, directing federal agencies to:
- Reduce energy intensity and greenhouse gas emissions.
- Increase energy efficiency and use of renewable energy technologies.
- Adopt sustainable design practices.
- Reduce petroleum use in federal fleets.

This initiative adopts a more ambitious timeline and targets changes that will have an impact on DOE's energy use as early as next year.

GSIP is a single program with a three-phased structure: Phase 1 includes DOE facilities and will collaborate with DOE's TEAM Initiative. The TEAM Initiative is a nationwide effort to reduce energy intensity by 30% in DOE buildings. This energy reduction will save approximately $90 million in taxpayer dollars per year, after projects are paid for. The TEAM Initiative aims to meet or exceed the aggressive goals for increasing energy efficiency throughout the federal government as stated in the executive order.

Phase 2 will focus on the most appropriate sites for solar applications identified during Phase 1. The GSIP program approach is to use power purchase agreements, except where straight purchases are more cost effective. The program will initially emphasize solar installations in regions of the country with regulations or incentives in place, conducive to solar energy projects, such as in California and New Jersey. The program then will transition to other regions as the cost of PV falls and other state or local incentives for renewable energy develop.

Phase 3 of the GSIP broadens the effort to include other federal agencies beyond DOE, as well as state and local governments. Lessons learned during the first two phases of the program will be useful for helping other agencies to overcome barriers to solar installations.

The strategic approach of the GSIP is to:
- Leverage federal purchase power to create significant demand pull.
- Promote U.S.-manufactured products.
- Promote an installation development model using a power purchase agreement model.
- Increase demand for installers and thereby boost U.S. jobs.

- Facilitate achievement of EPAct 2005 and other federal goals by using a market-based approach rather than regulation.
- Use growing capital markets to finance installations.
- Support domestic power purchase agreement providers.
- Facilitate the process by minimizing government involvement.

3. Results and Accomplishments

The following projects were either installed or assessed as part of this program:

Fallon 3MW PV Analysis:
Provided technical information to the Navy to support their "Right of Way" application for a 3 MW solar plant at Fallon AFB. Conducted an analysis to determine the mounting options for single axis PV collectors.

San Juan, Puerto Rico – GSA Courthouse:
Conducted a feasibility assessment to optimize the placement of solar energy systems for both photovoltaic (PV) and solar thermal on the Federico Degetau Federal Building (Federal Building) and the Clemente Ruiz Nazario U.S. Courthouse (Courthouse). This was a follow-on report to one submitted on March 25, 2009 titled "Feasibility of Solar Energy Systems on Two Government Buildings in San Juan, Puerto Rico," which was a scoping study; this is a 90% feasibility study for the PV and solar thermal systems.

Alcatraz Island, and Calexico, California
Assist in the preparation of the request for proposals (RFP) and bid evaluations including technical and financial consideration (cost, incentives, operation and maintenance (O&M cost), and determined life cycle cost, which the selection is based on).

4. Planned FY 2010 Activities

- Finalize the Federal Solar Guidebook and conduct outreach activities to distribute.
- Provide technical assistance in awarding contract for an off-grid PV hybrid system on Alcatraz Island in California.
- Continue to review PV feasibility studies and project proposal for the GSA on an as needed basis.

5. University Partners

The following organizations partnered in GSIP research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity
New Mexico State University Andy Rosenthal	Las Cruces, NM arosenthal@nmsu.edu	Technical assistance teams, also known as Tiger Teams, are comprised of representatives from the national laboratories (NREL and SNL) as well as universities.
Florida Solar Energy Center Robert Reedy	University of Central Florida reedy@fsec.ucf.edu	

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Technical Outreach Summary

The purpose of the Technical Outreach project is to provide high-quality solar technology and policy information to key stakeholders to accelerate solar adoption and domestic market growth. Technical outreach efforts aim to support policy and program innovation, as well as speed the dissemination of current best practices. Specifically, the U.S. Department of Energy (DOE) has identified state decision-makers (including State Energy Offices, Public Utility Commissions, and state Legislatures) and utilities as being critical to the establishment of robust domestic solar markets. State governments have led the way on solar market development through renewable portfolio standards and other policies. Additionally, utilities play a key role in the growth of solar through their interconnection and net-metering practices, and by increasing the share of solar in their own generation mix. To reach these important audiences, DOE Fiscal Year 2009 funding supported the Solar Electric Power Association (SEPA), the Interstate Renewable Energy Council (IREC), the National Conference of State Legislatures (NCSL), the National Association of Regulatory Utility Commissioners (NARUC), and the Clean Energy Group (CEG).

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
Technical Outreach	**175**	**0**	**1250**	**1425**
Utility Outreach	**0**	**0**	**175**	**175**
State Outreach	**175**	**0**	**975**	**1150**
Market Transformation Analysis – PV Cost Trends	**0**	**0**	**100**	**100**

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State & Utility Outreach

Performing Organizations: National Conference of State Legislatures (NCSL)
Clean Energy Group (CEG)
National Association of Regulatory Utility Commissioners (NARUC)
Solar Electric Power Association (SEPA)

Key Technical Contact: Steve Palmeri, 303-275-4832, steve.palmeri@go.doe.gov

DOE HQ Technology Manager: Charlie Hemmeline, 202-586-6646, charlie.hemmeline@hq.doe.gov

FY 2009 Budgets: NCLS (*$247.5K)
CEG (*$247.5K)
NARUC (*$203.4K)
SEPA ($175K)
**(These awards were fully funded in FY 2007; however, the awards actively pursued project goals through FY 2009.)*

Objectives

- Foster dialogue among, and educate, state officials (state public utility commissioners and state energy office officials) and furnish them with the resources and technical basis needed to effect changes to state policy and regulation
- Increase the implementation of policies that foster solar technology deployment
- Enlist the assistance of a utility membership organization to deliver key technical and informational assistance to utilities to promote their acceptance and use of solar.

Accomplishments

- Released the legisbrief "Financing Renewable Energy and Energy Efficiency," which introduces legislators to property tax financing approaches for solar and energy efficiency and improved its database for a comprehensive legislation list (NCSL)
- Updated website and listserve resources tools for state policy makers and decision makers interested in developing solar programs and policies and released a new Renewable Energy Finance Toolkit for states and municipalities (CEG)
- Released the Solar Energy Technology and Policy Reference Guide with information on solar regulatory policies, technologies, and state and industry perspectives (NARUC)
- Launched a utility solar toolkit, an innovative new online tool with "smart filters" for accessing research reports, webinar recording, RFPs, online tools, upcoming events, and news, and held first annual Utility Solar Conference.

Future Directions

- Hold a Solar Policy Institute for southeastern legislators October 8–9, 2009, and a web audio conference on property-assessed clean energy financing options in February 2010 (NCSL)
- Hold two webinars on solar program best practices, publish a state solar program database results through 2008 (CEGI)
- Hold a regional dialogue for the Northeast and Mid-Atlantic to examine the regional solar initiative (NARUC).
- Create a Solar Program Options Tool (SPOT) and an Online Resource Library (SEPA).

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1. Introduction

The DOE Solar Energy Technologies Program is partnering with key stakeholders to accelerate commercialization of photovoltaic (PV) systems R&D to meet aggressive cost and installed capacity goals. To complement the R&D and testing/evaluation DOE is conducting market transformation (MT) efforts to reduce market barriers and promote market expansion of solar

energy technologies. This falls into two areas: (1) provide technical, regulatory, institutional, financial, and educational solutions to market transformation barriers; and (2) accelerate demand for new solar technologies, primarily through technical assistance in reaching levelized cost of energy and cost-competitiveness goals by 2015.

2. Technical Approach

Cooperative agreements are ongoing with several organizations. Their work and plans are as follows.

CEG: $345,000 (FY 2007–FY 2009):
CEG uses education, research, and information services to (1) supply information and technical assistance to state leaders and state renewable energy programs in developing effective solar programs; (2) identify and foster solar program best practices; and (3) identify and promote strategic opportunities for states and DOE to advance solar technology deployment through partnerships, collaboration, and targeted activities.

NCSL: $263,672 (FY 2007–FY 2009)
NCSL's Solar Energy Project offers outreach to state policymakers on solar technology and policy options that can assist in integrating solar energy into the fuel mix while breaking down market barriers to the adoption of solar energy technology.

NARUC: $303,004 (FY 2007–FY 2009)
NARUC continues to (1) furnish key state agencies with resources to help solar technologies overcome regulatory and market barriers; and (2) take advantage of emerging opportunities to encourage greater deployment and penetration of solar technologies into society. Their work continues to include outreach and education, regulatory and technical best practices, and renewable portfolio standards (RPS) and market structures.

SEPA: $1,597,092 (FY 2007–FY 2009)
(
SEPA works with utilities through utility-owned systems and utility programs to facilitate customers' use and ownership of solar electric power.

3. Results and Accomplishments

The DOE and NARUC State Solar Energy Analysis Partnerships created work plans and are working closely together to reach the outlined goals. Twelve state commissions are involved in direct NREL assistance for solar-related technical and policy issues. Through these partnerships, best practices and policy standards are being created for state use in future decision-making. NARUC released the Solar Energy Technology and Policy Reference Guide, available from; www.naruc.org/programs.cfm?c=Domestic.

Solar Energy Institute for Southeastern Legislators: NCSL Held the Solar Energy Institute in Washington, DC for on October 8-9, 2009. , The meeting was tailored to the Southeast and included a tour of the solar decathlon NCSL).

Solar Legisbriefs: NCSL published a legisbrief on financing renewable energy through property tax assessments and utility on-bill programs.

Solar Legislation Database: NCSL expanded the reach of its solar legislation database (www.ncsl.org/?tabid=13011), which now contains nearly 800 solar-related bills.

Solar Information and Analysis for Legislators: NCSL responded to more than 50 solar-specific information requests in 2009 by state legislators and their staff. NCSL testified before legislators in Nebraska on renewable energy and solar policy.

Solar Regional Utility Outreach Coordinators: SEPA's three regional directors continued and expanded their direct utility outreach efforts.

Utility Solar Toolkit & Tools: SEPA launched the Utility Solar Toolkit on their website, with numerous solar resources.

Utility Focus at Events: SEPA held two solar industry conferences: the Utility Solar Conference was geared toward utilities exclusively with approximately 300 attendees, and the Solar Power International Conference had utility-only events such as networking and conference sessions geared toward utility interests.

Utility Focused Research Reports: SEPA released six research reports pertaining to topics that relate to utilities' interest in solar.

PV Peer Network: CEG added new members to the PV Peer Network, a listserve comprising more than 100 state clean energy fund managers, policy leaders, and stakeholders from 30 states, Puerto Rico, and Guam. Four Network webinars were

held on PV cost trends, state solar program initiatives, and solar marketing strategies.
State-Federal RPS Implementation Collaborative: CEG managed the collaborative, released Recommended Principles and Best Practices for State RPS Programs, and organized the second annual National RPS Summit.

Smart Solar Marketing Strategies Report: CEG and SmartPower published *Smart Solar Marketing Strategies: A Clean Energy State Program Guide*.

Solar Workshops: CEG held a "State Best Practices for Solar Marketing workshop at the Clean Energy States Alliance (CESA) national meeting; conducted session on state solar program innovations at the ASES Solar Conference; held a session for CESA on the implications for state solar programs of increasing utility interest in supporting/owning solar PV; presented at a Midwest State Recovery Roundtable; and presented at the Council of State Governments annual meeting on approaches to clean energy and solar project financing.

Primer on RE Finance Tools for States: CEG and CESA published *Distributed Renewable Energy Finance and Policy Toolkit,* a guidebook to assist states in using effective financing tools to support clean energy project development.

Direct State Support: CEG furnished direct technical assistance to more than 15 state solar programs and more than 50 state officials on solar policy and program development.

Renewable Energy Database: CEG and CESA developed a national database to summarize the project results and trends of state efforts (www.statesadvancingsolar.org) and listserve (pvpeernetwork@cleanenergystates.org).

4. Planned FY 2010 Activities

CEG

- Hold a webinar on a new CESA report, *Distributed Renewable Energy Finance and Policy Toolkit* (03/10), and on RPS support policies for PV technology (06/10)
- Hold solar workshops, including PACE financing for CESA national meeting (02/10)
- Present *State Solar Marketing Recommendations Report* at the 2010 ASES Meeting (05/10)
- Release annual revision to state clean energy funding results database (05/10).

NARUC
Activities for FY 2010 will consist of a mixture of written reports and trainings for NARUC and NASEO members, including:

- Complete FAQ on feed-in tariffs for state government officials
- Go on solar fact-finding mission to Europe with Solar States Working Group (08/10)
- Write paper on solar policy design and its effect on the advancement of solar energy (08/10).

NCSL

- Another Solar Policy Institute for southeastern state legislators
- Expand current technical outreach with several states that are developing solar and renewable energy incentives
- Contact newly elected legislators to supply information and technical assistance on solar energy other renewable energy issues
- Hold a web-audio conference for state policymakers on property-assessed clean energy financing, case studies, and options
- Continue to refine and expand solar bill tracking abilities, adding summaries of solar policy activity to NCSL's web site.

SEPA

- Contact target utilities and facilitate regional working group meetings and regional workshops
- Conduct 2nd Utility Solar Conference, May 2010, in Colorado
- Hold utility networking receptions at various industry functions, continue adding to peer networking tool and publicizing it
- Develop research tools, including research reports, solar toolkit, newsletters, and webinars.

5. Major FY 2009 Publications

G. Andersen, "Financing Renewable Energy and Energy Efficiency," *Legisbrief* **17**(31) **(**August-September 2009).

SEPA, *Special Report: Electric Utilities and Solar: A Market Review*, Washington, DC: Solar Electric Power Association, October 2008.

W. Shirley and M. Taylor, *Decoupling Utility Profits for Sales*," Washington, DC: Solar Electric Power Association, February 2009.

C. Kubert and M. Sinclair, *Distributed Renewable Energy Finance and Policy Toolkit*, Montpelier, VT: Clean Energy States Alliance, December

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2009. Available from: http://www.cleanenergystates.org/Publications/cesa-financial_Toolkit_Dec2009.pdf.

6. Industry Partners

The following organizations partnered in the project's research activities during FY 2009.
(These awards were fully funded in FY 2007; however, the awards actively pursued project goals through FY 2009.)

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity
John Nimmons & Associates, Morse and Associates	1220 19th St., NW, Suite 401, Washington, DC	Facilitating Utility Use and Integration of Solar Electric Power

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Photovoltaic Cost Trends

Performing Organization: Lawrence Berkeley National Laboratory (LBNL)

Key Technical Contact: Ryan Wiser (LBNL), 510-486-5474, rhwiser@lbl.gov

DOE HQ Technology Manager: Charlie Hemmeline, 202-586-6646, charles.hemmeline@ee.doe.gov

FY 2009 Budget: $50K

Objectives

- Summarize and analyze trends in the installed cost of grid-connected photovoltaic (PV) systems in the United States based on project-level cost data.

Accomplishments

- Completed inaugural edition in *Tracking the Sun* report series (February 2009)
- Completed all analysis and a review draft of the second report in the series, *Tracking the Sun II* (final report published in early FY 2010)
- Presented the work in numerous forums, including CPUC workshop, PG&E briefing, SPI 2008, webinars sponsored by SEPA, and the PV Peer Review Network
- Contributed to DOE's *Solar Market Data Report* and NREL's Open PV Project.

Future Directions

- Compete third edition of the *Tracking the Sun* report series (publication expected July 2010)which will summarize cost trends for projects installed through 2009
- Compete statistical analysis of cost data and associated journal article
- Continue contributions to DOE's annual *Solar Market Data Report*.

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1. Introduction

The project analyzes trends related to the installed cost of grid-connected PV systems in the United States.

2. Technical Approach

The analysis uses project-level data collected from PV incentive programs throughout the country. The most recent edition, *Tracking the Sun II*, was based on data from approximately 71% of all grid-connected PV systems installed nationwide from 1998 to 2008.

3. Results and Accomplishments

LBNL completed its second annual *Tracking the Sun* report (October 2009). The report series has proven to be highly valuable to the solar industry and policy makers: it represents the only detailed summary of U.S. installed cost trends, based on a reasonably comprehensive dataset. These data and the associated analyses also formed a key input into DOE's annual *Solar Market Data Report*.

4. Planned FY 2010 Activities

LBNL will again produce an updated report on installed cost trends for PV systems installed through 2009. The data will be collected from the same PV incentive programs as before, potentially adding several more programs. Publication is expected in July 2010. The data and updated analysis will again be a key input into the third annual DOE solar data report. FY 2010 funding will also allow LBNL to contribute to database coordination among parties (including SEIA, NREL, and IREC) developing datasets of installation-level PV data. Funding will also be used to conduct more-detailed statistical analysis.

5. Major FY 2009 Publication

R. Wiser, G. Barbose, and C. Peterman, *Tracking the Sun*, LBNL-1516E, Berkeley, CA: Lawrence Berkeley National Laboratory (2009).

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Concentrating Solar Power Highlights

The revitalization of Concentrating Solar Power (CSP) that began in fiscal year 2007, continued in FY 2009 but at an accelerated pace. Although the normal appropriation maintained the budget at $30 million, the *American Recovery and Reinvestment Act of 2009 (ARRA)* doubled that amount. The combination enabled the addition of 15 new storage contracts with the industry and universities as well as the addition of new and upgraded facilities at both Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL). These new activities complemented research and development (R&D) carried out by the labs and the dozen existing R&D contracts with industry that addressed many aspects of trough, tower, dish, and Fresnel systems. Optimism for continued growth led to the development of a baseload funding opportunity announcement to address the long-term potential of CSP. Awards for this solicitation will be made in FY 2010. In addition to R&D, the CSP subprogram worked closely with the Bureau of Land Management (BLM) on the Solar Programmatic Impact Statement (PEIS).

The addition of storage contracts in FY 2009 is indicative of the high value the U.S. Department of Energy (DOE) places on CSP systems capable of storing energy. These new contracts are exploring salt mixtures with lower melting points and higher heat capacities, a number of phase change materials, storage in solids, and storage through chemical reactions. Another set of storage activities resulted from a solicitation specifically for national laboratories that was enabled by the ARRA funding. This solicitation led to awards from six laboratories: three for storage and three for advanced heat transfer fluids.

Most of the ARRA funding, however, went toward facilities, with both SNL and NREL establishing laboratories to do materials research and to help industry test component concepts. Both labs also improved those facilities which help the industry to determine the performance of solar collectors. ARRA funds enabled SNL to replace the 35-year-old glass reflectors on the heliostats at the National Solar Thermal Test Facility. In cooperation with Southern California Edison, ARRA funds were also used to decommission Solar II, which had fallen into disrepair.

Work on the PEIS accelerated during FY 2009. BLM, which was not able to provide funding for the PEIS during FY 2008, added nearly $10 million to the effort in FY 2009, significantly increasing the work being done by Argonne National Laboratory (ANL) to gather environmental data and identify areas of the southwest best suited for large utility-scale solar projects. BLM announced 24 solar study areas comprising 676,000 acres (over 1,000 square miles) which may be appropriate for solar. ANL looked at each area in more detail than previously planned, pushing back the completion of the draft to December 2010 and the final PEIS to December 2011.

	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Concentrating Solar Power	**6726**	**6035**	**17239**	**30000**
Parabolic Trough R&D	**1949**	**580**	**4669**	**7198**
Dish/Stirling R&D	**0**	**1500**	**1765**	**3265**
Thermal Storage R&D	**965**	**1250**	**3743**	**5958**
Advanced CSP Concepts	**725**	**900**	**2910**	**4535**
CSP Market Transformation	**2435**	**250**	**2240**	**4925**
Operations & Planning	**652**	**1555**	**1912**	**4120**
ARRA funds	**4400**	**18400**	**8100**	**30900**
SNL facilities	**0**	**18400**	**0**	**18400**
Solar 2 decommission	**0**	**0**	**2500**	**2500**
NREL facilities	**4400**	**0**	**0**	**4400**
Laboratory solicitation	**1000**	**0**	**4600**	**5600**

Parabolic Trough R&D

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

Key Technical Contacts: Chuck Kutscher (NREL), 303-384-7521, chuck.kutscher@nrel.gov
Tim Moss (SNL), tamoss@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2009 Budgets: $2,277K (NREL), $780K (SNL)

Objectives

NREL

- Support development of 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 long-term goals of the DOE Solar Program Multi-Year Technical Plan (MYTP)
- Support the expansion of U.S. industry to supply parabolic trough technology
- Support continued SunLab collaboration on parabolic trough technology development and testing.

SNL

- Improve TOP mirror alignment of existing trough plants that increases the intercept factor, which increases the efficiency of the plant, which decreases the LCOE:
  - Improve algorithm calculating amount of mirror misalignment
  - Improve data acquisition program to obtain photographs with optimum contrast and hue to optimize edge finding in the data analysis program
  - Improve analysis program for less human interaction finding mirror and receiver edges
  - Align a second loop at Kramer Junction and Sunray– yet to be determined
- Use salt in troughs to allow higher operating temperatures and increase the efficiency of the turbine generator as well as thermal storage, which will lower the LCOE; salt, however, has a higher freezing temperature than the current fluid being used (approximately 100°C vs. 15°C); explore ways to recover from a freeze and its effects on the receiver
- Test trough module and receiver on the AZTRAK rotating platform
- Test Sky Fuel trough module in early 2010.

Accomplishments

NREL

Trough Solar Field

Reflector Optical Measurement

- Used the Video Scanning Hartmann Optical Test (VSHOT) instrument to evaluate the new SkyTrough parabolic trough collector; made significant improvements; tested individual mirrors from Rioglass and a SolarCat dish
- Developed a larger target for VSHOT to allow testing of larger mirrors.

Receiver Heat Loss

- Tested the newest model Schott and Solel receiver tubes and performed preliminary experiments on the impact of xenon/hydrogen mixtures in the receiver vacuum space
- Performed preliminary tests on a system to inject inert gas into contaminated receivers in the field.

Hydrogen Mitigation

- Expanded computer model of hydrogen generation and transport to include an estimate of the time required to remove hydrogen from an operating trough field; also signed a nondisclosure agreement with FPL Energy and began discussions of collaborative work in FY 2010.

Optical Efficiency Test Loop

- Completed normal incidence and incident angle modifier testing of the SkyFuel parabolic trough collector and helped SkyFuel make design improvements.

Advanced Trough Materials

- Signed a license agreement with a U.S. industry partner who will license the improved solar selective coating.

Distant Observer Technique

- Significantly improved analysis software needed to determine receiver position and mirror slope errors from photographic images taken from an aerial platform; performed numerous tests of a small test collector using a camera mounted in both a balloon and a radio-controlled plane; took images of the SkyTrough from elevated land-based positions.

Power Cycle and Balance of Plant

Heat Rejection

- Produced a report giving the water savings and cost penalties associated with air and hybrid cooling (WorleyParsons).

O&M Cost Analysis

- Prepared a report summarizing O&M data.

Plant Optimization and Costing

- Compared various modeling programs and chose IPSEpro because it provides the most flexibility for user-generated subroutines

Industry Support

- Served as technical advisors for four trough FOA contracts: Abengoa, Solar Millennium, Alcoa, and SkyFuel
- Provided technical support to a wide range of CSP companies, including SkyFuel, Abengoa, Schott, Solel, and Rioglass.

SNL

TOP Alignment

- Modified TOPCAT software to account for module-to-module alignment issues within a solar collector array (SCA), perspective, and mirror focal length deviations from the ideal
- Enabled TOPCAT software to manually control camera brightness and hue to account for the variability of daylight from morning to afternoon and from clear sky to cloudy skies
- Modified TOPCAT hardware and software to accommodate LS-3 modules
- Acquired TOP Alignment data for multiple loops at SEGS II, VI, VII, VIII, and IX
- Aligned one LS-3 loop at SEGSVIII that resulted in more than 5°F, or more than 3.5%, increase in the temperature of that loop.

Salt Freeze/Thaw

- Researched impedance heating as a means to recover from a freeze.
- Researched receivers filled with salt will plastically deform during a freeze/thaw if it is completely filled with salt but does not bend at all if it is only partially filled.

Testing

- Consolidated control room instrumentation racks to increase overall space to facilitate the SkyFuel testing; the software is being upgraded to allow all operations to run on one computer instead of two.

Future Directions

NREL

Trough Solar Field

Reflector Optical Measurement

- Continue to improve the VSHOT capability, with an emphasis on developing a platform for performing outdoor tests
- Continue to test collectors from manufacturers such as SkyFuel, Alcoa, Abengoa, and FPL Energy.

Receiver Heat Loss

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- Test various mixtures of hydrogen and inert gas in receiver tubes; continue to test the latest receiver designs.

Hydrogen Mitigation

- Perform tests of hydrogen purging in the receiver test laboratory.

Optical Efficiency Test Loop

- Conduct optical efficiency measurements of the new Alcoa and Abengoa collectors; this will include both normal incidence and incidence angle modifier tests.

Advanced Trough Materials

- Continue outdoor and weatherometer tests to determine long-term durability of reflector materials
- Develop an accelerated test for anti-soiling coatings.

Distant Observer Technique

- Perform distant observer testing at one or more operating parabolic trough plants.

Power Cycle and Balance-of-Plant

Plant Optimization and Costing

- Develop a detailed parabolic trough model.

Heat Rejection

- Use IPSEpro to conduct analyze parallel hybrid cooling systems for parabolic trough plants and publish a paper on this subject.

Industry Support

- Continue to provide support for industry FOA contracts as well as provide other industry support on an as-needed basis.

SNL

TOP Alignment

- Align another loop at SEGS II and SEGS VI (or VII depending on the plant operators), or more, and document its improvement.

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1. Introduction

Parabolic trough technology is now actively being reintroduced into the marketplace. The Acciona Solar 64 MW Nevada Solar One power plant outside of Las Vegas was dedicated in October 2008 (Fig. 1). The focus of the DOE parabolic trough R&D efforts has been to:

- Advance technologies that have an opportunity to be deployed in early projects
- Encourage the development of advanced technologies that will improve the competitiveness of future parabolic trough plants
- Encourage expanded U.S. supply in these early plants
- Develop improved tools, testing capabilities, and the knowledge base necessary to support the needs of a growing U.S. parabolic trough industry.

2. Technical Approach

At NREL, the parabolic trough R&D effort is divided into three areas: (1) trough solar field, (2) power cycle and balance of plant, and (3) industry support.

Fig. 1. New 64-MW Solar One power plant using Acciona parabolic trough concentrator and Schott receivers.

2.1 Trough Solar Field

The solar field technology agreement focuses on SunLab development of new parabolic trough solar technology and tools for evaluating trough technology. In FY 2009, NREL activities focused on the following:

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Reflector Optical Measurement: The Video Scanning Hartmann Optical Test (VSHOT) instrument (see Fig. 2) allows NREL to quickly assess the accuracy of the reflector shape. NREL is constantly improving this technology and using it to help industry maximize the accuracy of new mirrors and collectors.

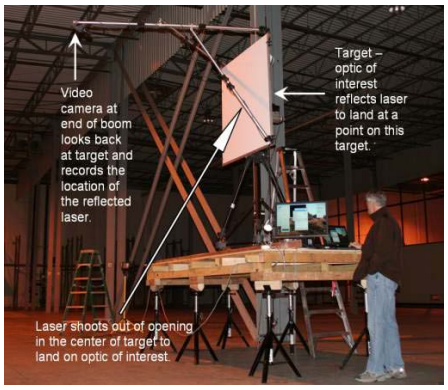

Fig. 2. Optical testing of new SkyTrough collector.

Receiver Heat Loss: NREL measures the heat loss of the latest commercial receiver tubes in its receiver test laboratory. This laboratory is also used to study means for mitigating hydrogen gas infiltration into receiver tubes. The apparatus is shown in Figure 3.

Hydrogen Mitigation: NREL uses a computer model of hydrogen generation and transport to examine ways to mitigate this problem, which increases receiver heat loss. NREL also invented a concept for removing hydrogen centrally in a plant and is working with an industry partner to test this concept in an actual plant.

Fig. 3. Parabolic trough receiver thermal loss test bed.

Optical Efficiency Test Loop: NREL's loop consists of a two-axis tracker and fluid flow system that allows the direct outdoor measurement of the overall optical efficiency of parabolic trough collectors at normal and off-normal incidence angles.

Advanced Trough Materials: NREL uses extensive materials testing capability to measure the performance of reflector and absorber materials. State-of-the art deposition chambers are used to create new thin-film coatings. Outdoor test racks and weatherometers are used to determine the long-term durability of materials, and the results are compiled into an extensive materials data base.

Distant Observer Technique: NREL is developing an aerial-mounted photographic technique for rapidly assessing the performance of an individual collector or an entire field of collectors. By analyzing photographs of the images of receiver tubes in the collector mirrors taken at a distance and from different angles, errors associated with mirror slope errors and receiver positioning can be determined.

2.2 Power Cycle and Balance of Plant

The power cycle and balance of plant agreement focuses on improving overall parabolic plant performance.

Plant Optimization and Costing:_NREL has used subcontractors and consultants to perform overall plant modeling, but determined it is more cost-effective and provides greater flexibility in analysis to bring this capability in-house. NREL compared different commercial modeling packages and chose one that was best suited to our needs. This model is being used to optimize CSP plants and subsystems, and it can generate results for inclusion in the Solar Advisor Model.

Heat Rejection: Water consumption is a key concern with CSP plants in desert regions of the Southwest. This activity uses computer models to study alternative means for reducing water consumption.

2.3 Industry Support

This activity focuses on technical support to the CSP industry. NREL provides technical support to a wide range of CSP industry members, including FOA awardees.

2.4 TOP Alignment

The development of the TOP Alignment system has been a stepped approach. The average time to acquire data started at 70 s/module and has been reduced to less than 20 s/module thanks to hardware and software improvements. TOPCAT has been used to acquire data from at least one loop at every LS-2 and LS-3 trough plant in California. The first loops aligned were LS-2 loops at SEGSVI, which saw less than 10°F improvement, and SEGSII, which saw no improvement. The null improvement at SEGS II led to improving the mirror alignment algorithm to include module-to-module misalignments within an SCA, perspective, and different mirror focal lengths. After these improvements, a LS-3 loop at SEGS VIII was aligned with a documented improvement of 5°F, or 3.5%. Improvements in the analysis software will be aimed to increase its ability to find the mirror and receiver edges to decrease the analysis time from the current 5 min/module.

2.5 Rotating Platform

The system has not operated since early 2004. To facilitate startup, all legacy systems were removed and the remaining systems consolidated. The software was also upgraded. The data acquisition system will be upgraded later in FY 2010.

2.6 Salt Freeze/Thaw

This was designed to be a quick test to understand the effects of salt freezing and thawing in trough receivers. The receivers are mounted above ground horizontally and filled with HiTec HT salt with a freezing point around 120°C.

3. Results and Accomplishments

3.1 Trough Solar Field

Reflector Optical Measurement: In FY 2009 NREL made additional improvements to this technology, such as constructing an outdoor test platform. NREL used the capability to measure the performance of several industry collectors and mirrors. Extensive testing resulted in significant improvements to the SkyFuel parabolic trough collector, and this won a 2009 R&D 100 Award.

Receiver Heat Loss: NREL continued to obtain performance data on the latest receiver designs and also conducted tests on receiver tubes containing xenon gas. The latest test results on the effect of xenon on the Schott PTR 70 receiver tube are shown in Figure 4.

Advanced Absorber Materials: NREL finalized a licensing agreement with a major receiver manufacturer to develop NREL's low-emittance absorber coating (Fig. 5).

Hydrogen Mitigation: NREL expanded its computer model of hydrogen generation and transport to include an estimate of the time required to remove hydrogen from an operating trough field. NREL also signed a nondisclosure agreement with FPL Energy and began discussions of collaborative work in FY 2010.

Optical Efficiency Test Loop: NREL completed normal incidence and incident angle modifier testing of the SkyFuel parabolic trough collector and helped SkyFuel make design improvements. Control modifications were made to the two-axis tracker to allow for incident angle modifier tests.

Distant Observer Technique: NREL obtained several large balloons, including a radio-controlled gimbal for carrying a camera. NREL also obtained a telescope for taking distant images from ground locations. Extensive imaging was taken of the SkyTrough collector and a smaller test collector. Significant improvements were made in the software used to analyze the images. Photogrammetry methods were also used to accurately determine the position of the camera.

In FY 2009, NREL reached an agreement with Schott to license our low-emissivity absorber coating.

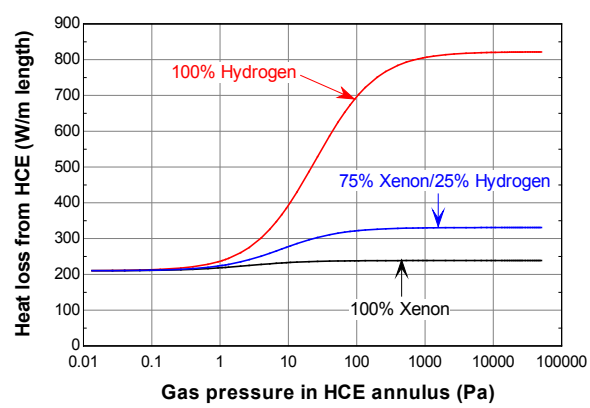

Fig. 4. Parabolic trough receiver thermal loss test bed results for mixed gases.

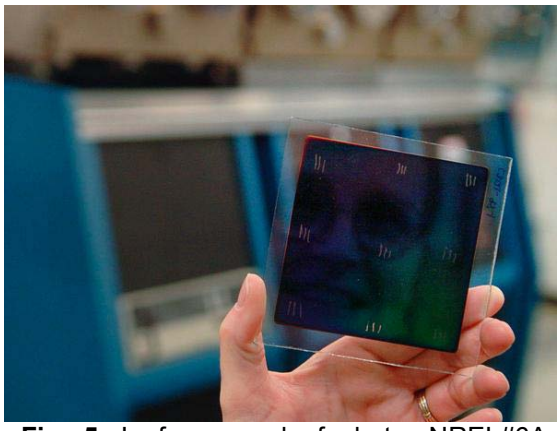

Fig. 5. In foreground of photo, NREL#6A solar selective coating deposited by directly and reactively evaporating the layers by elemental co-deposition. Shown in the background is the deposition system.

FY 2009 milestones:
- Completed VSHOT measurements of slope error of new SkyTrough solar collector
- Completed optical efficiency measurements of SkyTrough Collector and issued a report
- Deployed a prototype distant observer tool (09/09)
- Completed heat loss testing of latest Schott PTR70 and PTR80 receivers.

3.2 Power Cycle and Balance of Plant

Plant Optimization and Costing: In FY 2009 NREL compared various computer models that can be applied to CSP power plants: Aspen, GateCycle, TRNSYS, and IPSEpro. IPSEpro was deemed the most powerful and adaptable. It is also used by EPRI and by European CSP researchers, making it possible to compare and share modules. We began to develop a detailed parabolic trough model.

Heat Rejection: NREL made final improvements to a report to Congress, NREL also began to develop cooling system models in IPSEpro.

FY 2009 milestones:
- Completed report to DOE, "Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation"
- Identified and obtained IPSEpro, process simulation software (06/09)
- Completed a detailed power plant model (09/09).

3.3 Industry Support

NREL provided technical support to a wide range of CSP industry members, including FOA awardees.

FY 2009 milestones:
- Participated in regular review meetings and for SkyFuel, Abengoa, Alcoa, and Solar Millennium FOA line focus collector projects
- Provided VSHOT measurement support to Alcoa and SkyFuel.

3.4 TOP Alignment

SNL's data acquisition improvements in the hardware included using GigE cameras with an auto-brightness ability greatly increased the download times and the time to obtain a photograph within a certain manually determined exposure, mounting a new and improved TOPCAT system on the back of a truck instead of a trailer greatly improved mobility in the field, added ability to use system on LS-3 modules, and a ultrasonic meter to measure the actual distance from the camera to the trough module. With the improvements in the acquisition hardware and software the time to acquire data was reduced from 70 seconds/module to less than 20 seconds/module. With close to 5,000 modules for each 30 MW trough plant reducing this time is very important. The data analysis software was improved to account for module-to-module alignments within an SCA, the perspective from the cameras not being perfectly aligned to the trough module, and changes in the mirror focal lengths being different from the ideal focal length. With these improvements a LS-3 loop at SEGS VIII was aligned. Very good temperature data was obtained before and after the alignment that showed a 5°F, or 3.5%, improvement in temperature.

FY 2009 task/milestones:
- Align an LS-3 loop (05/09).

3.5 Rotating Platform Testing

In general, SNL prepared the rotating platform system for testing the SkyFuel trough module. The software was updated to the latest version. The oil loop interlock box made up of relays, which many were sticky and not operating properly, was replaced with a FPGA-based system.

FY 2009 task/milestones:
- Complete testing of SkyFuel trough module (not completed).

This was not completed because SkyFuel did not deliver a trough module to test. It was installed on

the rotating platform the last week of September. The testing is scheduled to be completed 07/10.

3.6 Salt Freeze/Thaw

SNL completely set up a new system with data acquisition, controller, impedance heating system, and set up two trough modules for the freeze/thaw test. Because of equipment problems, the computer and controller both died on the same day, and testing is still ongoing.

4. Planned FY 2010 Activities

The NREL task/milestones are as follows:

- Extend VSHOT capability to examine the impact of structural loads on reflector shape
- Test the Distant Observer system at an operating parabolic trough installation
- Test the Alcoa and Abengoa parabolic trough collectors at the Optical Efficiency Test Loop
- Improve the speed of the SolTrace optical computer model
- Conduct receiver heat loss measurements on the latest commercial receiver tubes, including a tube that uses NREL's low-emissivity coating
- Test a hydrogen mitigation method at an operating parabolic trough plant
- Utilize in-house modeling capability to evaluate the performance of hybrid cooling systems
- Provide continued technical assistance to the CSP industry, especially for those companies that won contracts under the parabolic trough Federal Opportunity Announcement (FOA).

The SNL task/milestones are as follows:

- Continue upgrades on the TOPCAT system (09/08)
- Modify TOPCAT for the Solar Millennium trough (03/10)
- Complete testing of the SkyFuel trough module on the rotating platform (7/10)
- Begin work on a trough sensor for closed loop tracking (9/10).

5. Major FY 2009 Publications

K. Stynes, C. Gawlik, C. Kennedy, and C. Kutscher, "Optical Efficiency Measurements of the SkyTrough Solar Collector," April 10, 2009.

F. Burkholder and C. Kutscher, "Heat Loss Testing of Schott's 2008 PTR70 Parabolic Trough Receiver."

J. Crawford and F. Burkholder, "Heat Loss Testing of Schott's Prototype PTR 80-4.7 (2008) Parabolic Trough Receiver," August 2009.

K. Stynes, F. Burkholder, G. Jorgensen, A. Gray, T. Wendelin, K. Gawlik, and J. Crawford, "Feasibility Study of the Distant Observer Method for Rapid Optical Characterization of Parabolic Trough Solar Fields," September 2009.

6. University and Industry Partners

The following organizations received subcontract funds to support activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
WorleyParsons		Dry and hybrid cooling systems analysis	$100
Kearney and Associates	Seattle, WA dwk@jkearney.com	Development of a solar field acceptance test standard	$25

Parabolic Trough 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
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 2009 Budgets: $1,222K

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 southwestern United States, 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

- Announced competitive selections in late 2007 and made awards before mid-2008
- Defined roles and responsibilities of program management team, including technical advisors at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories
- Finished Phase 1 (two projects; now in Phase 2); the third project is near the end of Phase 1.

Future Directions

- Evaluate progress toward critical milestones and make decisions 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 are expected to produce commercial parabolic trough components or subsystems within the next 5 years, enabling CSP to meet a nominal 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 currently can be obtained only from a few foreign companies.

The selected projects are:

Organization, Principal Investigator, and Agreement Title	**FY 2009 Budget ($K)**
Alcoa, Inc.—Adam Schaut "Reflector Technology Development and System Design for CSP Technologies"	402
Abengoa Solar, Inc.—Keith Boyle "Development of Advanced Polymeric Reflector for Concentrating Solar Power"	609
Abengoa Solar, Inc.—Patrick Marcotte "Development of Next-Generation Parabolic Trough Collectors and Components for CSP Applications"	211

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Alcoa, Inc.

Reflector Technology Development and System Design for CSP Technologies

Total Award: $3,658K DOE/Recipient: $2,128K/$1,530K

Objectives

- Develop aluminum-intensive collector with superior total life-cycle cost
- Achieve 25%–50% cost savings for the solar field, lowering LCOE at least 20%
- Achieve high optical performance and superior outdoor durability (10 years)
- Positively affect U.S. manufacturing base.

Accomplishments

- Showed two independent approaches to reflective surface development had performance or cost parity with commercially available technology, so this portion of the program was discontinued
- Performed detailed design, performance analysis, and cost modeling on an advanced, aluminum-intensive trough concept
- Found through cost modeling that 20%–25% solar field cost saving is achievable
- Fabricated and tested full-scale trough prototype at Alcoa Technology Center to validate performance of advanced trough concept.

Future Directions

- Continue validation testing of trough prototype at NREL
- Complete Phase 2 report, including revising Phase 3 plans based on Phase 2 results
- Initiate Phase 3.

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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-metalized glass mirrors, which have disadvantages such as fragility, weight, and cost. Alcoa is using an optimized system design approach to develop an advanced, aluminum-intensive collector.

2. Technical Approach

Alcoa's efforts on this program during FY 2009 focused on Phase 2 of a three-phase project. The technical approach followed the tasks outlined in Alcoa's Statement of Project Objectives. These high level tasks are as follows:

2.1 Reflective Surface Optimization
2.2 Detail System Design
2.3 Internal Critical Design Review
2.4 Prototype Build
2.5 System Validation
2.6 Update Phase 3 Plan
2.7 Phase 2 Review with DOE.

3. Results and Accomplishments

Alcoa researchers investigated two aluminum-based reflective surface development approaches throughout Phases 1 and 2 of the program: thin film and silver film. For thin film, they used deposition testing on coated and leveled aluminum sheets via accelerated procedures, finding that the required reflectivity could not be obtained at a lower cost compared to commercially available thin film products. For silver film, they produced and evaluated various silver-metalized films. Although reflective performance targets could be obtained, the estimated cost would be at parity to commercially available silver film products. Based on these results, Alcoa discontinued developing an aluminum reflective product for CSP applications.

Alcoa completed the detailed design, analysis, and cost modeling for the down-selected trough concept from Phase 1. Because the design still achieved desired production cost targets, they built a full-scale trough prototype to validate the performance of the design. In 2009, the trough prototype was structurally and optically (V-Shot) tested at Alcoa. Final validation of the prototype trough will be done at NREL in 2010, which will conclude Phase 2 of the program.

4. Planned FY 2010 Activities

In 2010, the full-scale trough prototype will be shipped to Golden for further performance

validation testing on NREL's large payload tracker. Prototype validation testing will include VSHOT, wind loading, and thermal efficiency.

Initial results will be available by mid-2010, and although additional thermal efficiency work will continue throughout 2010, Phase 2 completion will be based on the initial results. Phase 2 reporting, a rescoping of Phase 3, and the decision about proceeding to Phase 3 will be completed.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity
Alcoa, Inc./Adam Schaut	Alcoa Technical Center, PA Adam.schaut@alcoa.com	Recipient/Awardee, Reflector Technology Development and System Design for Concentrating Solar Power (CSP) Technologies
CSP Services (DLR)/ Eckhard Luepfert	Cologne, Germany e.luepfert@cspservices.de	Subcontractor to Alcoa, Inc., CSP technology and performance expertise

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Abengoa Solar, Inc.
Development of Advanced Polymeric Reflector for Concentrating Solar Power
Total Award: $2,076K DOE/Recipient: $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 planned for initial operation in 2010–2013 timeframe
- Source as much collector technology (e.g., reflector components) from U.S. sources as possible.

Accomplishments

- Successfully transferred and validated deposition process from lab to commercial environment
- Produced high-quality, hard coat protected samples with reflectance, well beyond glass mirrors
- Completed Phase 1 objectives with cost model results showing a clear path to reduced LCOE.

Future Directions

- Transfer, refine, and validate process for pilot-scale production
- Create full-scale solar reflector using ASRM
- Complete Phase 2 objectives; use Phase 2 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, which could lead to entirely new approaches to low-cost concentrator design.

2. Technical Approach

The team will scale up the ASRM (produced in 2003 under sponsorship by NREL) from laboratory scale to limited production runs on a commercial-scale 48-inch wide roll coater. Phase 1 work will test validate the scale-up to commercial roll-to-roll coating, and production costs will be modeled. During Phase 2, the process will be scaled up to a ½-width pilot production system. Results will be used to create a full-scale solar 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. Products from this test run will be used in a full-scale solar reflector to field test the product.

3. Results and Accomplishments

Phase 1 task highlights:

- Initial ASRM samples produced in commercial environment
- Prototype samples produced and sent to NREL
- NREL data show 96%–97% solar weighted value reflectance across samples
- ASRM passes initial scrub-washing abrasion tests with negligible degradation.

The ASRM process was transferred to a commercial roll-to-roll environment at Marian facilities. The resulting ASRM samples were produced at 12-inch widths, and showed good consistency and specularity across the width (Fig. 1).

Fig. 1. Sample produced in 09/09, showing both high reflectance and specularity.

NREL measured samples with reflectance in the range of 96%–97% and negligible degradation in initial tests for durability and scrub-resistance. Using ASRM deposition data, Swisher's cost modeling shows a reasonable path to reduced LCOE, based on existing commercially available

reflective film products and on large-scale CSP systems.

3. Planned FY 2010 Activities

Phase 1 will be evaluated in early 2010 for progression to Phase 2, and go/no-go and budget decisions will affect what is feasible. The focus of Phase 2 would be:

- Transfer process to pilot production chamber
- Produce and test pilot production samples, demonstrating multiple E-beam sources, expanded sample width, and higher overall throughput rates
- Collector test samples, designing and building a test module and solar reflector to begin small scale, initial tests of pilot production samples in the field.

4. University and Industry Partners

Organization/ Principal Investigator	Location	Description/Title of Research Activity
SAIC/ Dr. Russell Smilgys	McLean, VA	Transition of ASRM work into commercial environment
CSI/Marian/ Tom Judish	San Diego, CA	Integration of ASRM into commercial equipment and scale-up of production
Swisher & Assoc./ Dr. Richard Swisher	Northfield, MN	Transition, adaption, and cost model revision for ASRM

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Abengoa Solar, Inc.
Development of Next-Generation Parabolic Trough Collectors and Components for CSP Applications
Total Award: $606K (Phase I) DOE/Recipient: $485K/$121K

Objectives

- Reduce cost of collector technologies that could be deployed in first U.S. CSP plants in 2010–2013 time frame
- 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

- Compared in depth three state-of-the-art CSP trough collector candidates and identified best design elements, construction techniques, and final LCOE performance of each
- Performed advanced design and evaluation of a near-term advanced collector, culminating in prototype testing
- Identified and commenced analysis of promising pathways for midterm trough development.

Future Directions

- Test and iterate near-term collector to advance the state of the art in cost and performance
- Continue to build analysis, evaluation, and testing capabilities, complete module-scale (ASI Lakewood) and loop-scale (SolarTAC) collector test sites
- Complete specification for midterm collector system and evaluate multiple design concepts
- Prototype one or more midterm trough candidates, test and evaluate LCOE impacts.

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1. Introduction

The goal is to develop the technology 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

In Phase 1 the team evaluated and compared three state-of-the-art collector systems aimed at LCOE reduction beyond established designs (LS-2 /EuroTrough/Astro). This system-level evaluation established uniform metrics and test protocols to enable accurate LCOE-based design comparison. This process involved growth in knowledge and capability within Abengoa that is informing current efforts to develop and validate next- generation collectors and subcomponents.

Going forward, the most promising designs from Phase I will be further improved and tested extensively to maximize near-term project performance. In parallel, several more radical design approaches that move away from current subframe and reflector configurations are being developed and will ultimately result in testing of a true “next-generation” collector system.

3. Results and Accomplishments

The Phase 1 contracted work was completed in 06/09 and continuation to Phase 2 was approved 11/2009. Results of the Phase 1 effort were:

- Identified a 5¢/kWh LCOE spread among near-term trough collector candidates
- Identified near-term SCA cost reduction opportunities of at least 10% additional
- Explored midterm collector designs to realize SCA savings 25%–35%
- Tested first and second generation prototypes of a near-term improved collector system (Abengoa design team)
- Erected Lakewood, CO test site for structural, optical, and small-scale operating tests; preparing for loop-scale deployment and operational testing at SolarTAC (Aurora, CO)

- Internalized several new capabilities, including VSHOT, laser radar metrology, NASTRAN FEA, and ray-tracing, in Phase 1; these are being leveraged to support the development process.

4. Planned FY 2010 Activities

- Complete small-scale (Lakewood) and loop-scale (SolarTAC) test sites, and perform extensive testing to validate Phase 1 assumptions
- Test second generation (ongoing) and third generation Phoenix (Q3 2010)
- Analyze costs and performance to inform development of advanced Phoenix troughs (Gen 3+)
- Complete structural, optical, and solar field modeling tools from Phase 1
- Perform parametric optimization to refine midterm trough specification (aperture width and concentration, collector length)
- Perform first-order analysis of midterm structure concepts, down-select
- Design and fabricate advanced trough prototype.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
Arizona State University School of Construction Management / Dr. Kenn Sullivan	Phoenix, AZ / Kenneth.Sullivan@asu.edu	Construction Labor Review and Survey of Related Industry Experience	
Martin / Martin Consulting Engineers / Stan Welton,	Denver, CO / Welton@martinmartin.com	Analysis & Design of Solar Collector Foundations	

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Dish/Stirling R&D Summary

The Dish-Engine R&D program is focused on support leading to commercial deployment of dish engine systems. Sandia National Laboratories (SNL) has worked closely with Stirling Energy Systems (SES) on their pre-production SunCatcher™ dish Stirling system in support of several announced projects totaling well over 1 gigawatt installed over the next few years. SNL's primary area of support this year included optical design and characterization, including tools that were deployed to the factory and development floors. Four new prototype systems were installed at SNL for developmental testing, and a 60-unit installation near Phoenix was started. SNL optical tools and analysis played a key role in these new systems. In addition, SNL supported controls development systems engineering tasks, and reliability improvement.

SNL supported Infinia Corp. in the installation and testing of (4) 3-kilowatt units at SNL, which are being used for product development and certification testing. SNL also supported the U.S. Department of Energy (DOE) funding opportunity announcement (FOA) with several dish engine companies. SNL assisted Infinia in filling capsules for thermal storage testing, and monitored design work on a 30-kW free piston Stirling engine. Finally, SNL supported Brayton Energy in their FOA, particularly with optical analysis and characterization tool support.

The future appears bright for dish engine companies. The technology is maturing to commercial readiness through large infusions of private capital in rigorous design for manufacture and deployment processes. This approach to deployment is leading the way to highly producible designs ready to supply utility scale power.

	NREL	SNL	Other	Solar
	Total $K	Total $K	Total $K	Total $K
Dish/Stirling R&D	**0**	**1500**	**1765**	**3265**
Dish Solar Field	**0**	**1400**	**0**	**1400**
CSP Funding Opportunity Announcement – Dish	**0**	**100**	**1765**	**1865**

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Dish Engine R&D

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

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 2009 Budget: $1,850K (SNL, carryover from FY 2008)

Objectives

- Improve reliability and reduce cost of dish engine components and systems
- Support industry in commercialization of the technology
- Develop tools for industry to characterize and deploy their systems and components
- Perform research and development on dish engine system components and systems
- Test, evaluate, and improve performance of dish engine components and systems.

Accomplishments

- Participated in optical design and analysis of Stirling Energy Systems (SES) production SunCatcher™ system, resulting in substantial weight and cost reduction
- Assisted with the installation and operation of four prototype production SES SunCatcher™ systems at SNL
- Developed and deployed rapid facet characterization system (Sandia Optical Fringe Analysis Slope Tool, SOFAST) on SES factory floor, instrumental in rapid improvement of manufactured facets
- Participated in controls development and refinement for SES production SunCatcher™ systems
- Mentored new solar engineers through SNL programs and at industry partners
- Deployed and tested two Infinia 3-kW systems at SNL, and prepared for installation of four production units
- Enhanced CIRCE2 model to support direct facet measurements (SOFAST or VSHOT)
- Participated in Funding Opportunity Announcement projects (FOAs) team for dish Brayton system, particularly in dish optics consultation
- Completed a draft report of the CSP cost study, which is being reviewed by the CSP industry.

Future Directions

Primary activities in fiscal year (FY) 2010 will support industry's efforts toward commercialization:

- Support SES system refinement to address any outstanding performance and cost issues
- Develop rapid optical tools for alignment in a production setting, applicable to SES, Brayton, and others
- Continue to participate in reliability improvement and characterization of SES SunCatcher™ systems
- Support SES data reduction and analysis of Maricopa and Model Power Plant (MPP)systems leading to improved performance and reliability
- Install and operate four new Infinia systems at SNL
- Support Brayton in first system deployment in Phoenix, including optical characterization (VSHOT, Fluxmapping, alignment, tracking)
- Support Infinia operations, commercialization, and FOAs on dish engine storage and 30-kW free piston engine development
- Evaluate possible additional dish engine products, as needed
- Complete final CSP cost study

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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. The primary focus of SES this year was developing and deploying 60 production systems at Maricopa Solar in Peoria, AZ, which encompassed a significant and successful design for manufacture and cost phase. The MPP at SNL was expanded with four production systems, and SNL and SES continued to gain operational experience with the MPP.

SES is pursuing the aggressive deployment of 25 kW dish Stirling systems for bulk power generation. The success of the MPP has led to agreements with Tessera Solar, SES's sister company responsible for project development, and Southern California Edison for up to 850 MW of power and with San Diego Gas and Electric for up to 750 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 entered into a memorandum of understanding with Infinia to support several Infinia staff on SNL premises. Two prototype dishes were set up and operated at SNL, and four additional preproduction systems are being installed.

2. Technical Approach

The dish engine systems program is industry led as each company involved drives toward commercial deployments. The laboratories provide technical assistance, expertise, measurement, and support where significant experience can be leveraged to enhance the success of these companies. The laboratories have particular expertise in systems engineering, optical design, optical characterization, and controls. Often, the laboratories are able to identify needs and help with solutions before they become critical path needs, thanks to the experience of laboratory personnel.

A contract is in place for a CSP cost and market study. The purpose of this project is to develop engineering estimates of the current and projected cost of electricity from CSP power systems, troughs, molten-salt towers, and dish Stirling systems, as characterized by their installed costs and the cost of electricity (referred to as the levelized cost of energy, LCOE). In addition, this program supports FOAs, funded through the DOE Golden Field Office, for several dish-related projects. The laboratories monitor progress and provide consultation or test support as appropriate.

3. Results and Accomplishments

In 2009, SES designed, developed, and deployed a production version of the SunCatcher™ 25-kW dish system. This production version incorporates significant cost reduction features, and is simpler to install and commission. It features a steel-efficient gore facet layout, a production engine with a substantial parts count reduction, and all new modernized controls for the dish and engine. The prototype systems are more than 4,000 pounds (out of 17,500) lighter than the MPP systems. Four prototypes were erected and tested at SNL in the spring of 2009, and 60 production units (1.5 MWe total) were installed near Phoenix in the fall of 2009.

The SES engine was designed for manufacture with the assistance of their engine partner, Linamar/McLaren Performance Technologies, a Detroit, Michigan-area company. The significant parts count reduction speeds assembly and improves reliability. Many issues cataloged on the old engine during MPP operation were addressed in the design for manufacture. Several engines accrued more than 2,000 hours each in test cells at Linamar, and the durability of these engines is dramatically improved over the prior model.

SES and SNL continued to operate the enhanced model power plant, accruing a total of 29,300 dish-hours on sun by the end of the FY 2009, including 750 dish-hours on the new production prototype systems. The operational emphasis has shifted to the new systems, and operation of the six older systems has been largely phased out.

SNL completed development of and deployed the SOFAST at SES's facet manufacturer. This rapid characterization system was instrumental in the rapid development of facet manufacturing techniques at Tower Automotive. The quality of the facets improved by about a factor of 3, and met specifications, in less than a year of development.

SNL continued to develop a facet alignment system based on SOFAST. This alignment system will automatically collect facet surface data, determine a representative pointing vector for each facet, and give automated tooling with updates to correctly orient the representative vector. This is a key to rapid deployments, and is seen as a possible solution to heliostat assembly and canting as well.

Fig. 1. A production prototype SunCatcher™ dish system deployed at SNL.

SNL supported the installation and testing of two prototype 3-kW dish-engine systems at SNL. The Infinia system is a 3-kWe free-piston Stirling system. Infinia plans large and small installations throughout the world, and several demonstration plants are already operational. They are installing four production units at SNL for further operational and qualification testing. Infinia attained UL certifications of their electrical subsystems.

The Infinia 30-kW engine development FOA passed phase 1 completion and began phase 2. SNL continues to support this effort with monthly consultation and review.

SNL and NREL have supported the Brayton Energy FOA for developing a large Brayton cycle system. A prototype is slated for deployment in Phoenix in FY 2010. SNL gave a detailed tutorial workshop for alignment of dish system facets. In FY 2010, SNL will perform flux characterization support, and NREL will produce a VSHOT characterization of the dish reflector.

The CSP industry is reviewing the draft of the CSP cost study project report. After Sargent & Lundy evaluate the comments and recommended changes, the final report will be prepared and published by April 2010.

Fig. 2. Six Infinia 3-kW preproduction prototype dish systems at SNL.

4. Planned FY 2010 Activities

SES Field Operations:

- Operate the MPP at SNL for reliability improvement, O&M operations definition, controls development, and system characterization
- Controls: Provide background knowledge, simulations, consultation, and expertise to facilitate the continued development and testing of next-generation dish and engine controls
- Production systems: Develop effective test plans, processes, and equipment to qualify production prototypes
- Production systems: Perform critical optical design, analysis, and testing of prototype commercial systems
- Support completion and operation of 1.5-MW SES/Tessera Demonstration Plant near Phoenix
- Engine testing. Complete Engine Test Facility upgrades to support continuous steady and cyclic operation of engines at full power
- Development. Deploy and test field SCADA systems, engine parts alternatives, mirror modules, alignment tools, and field O&M systems such as wash vehicles. The labs and SES will do the developing, and SES will prioritize elements of the work.

SES Next-Generation Tools and Manufacturing Support:

- Alignment systems: Complete hardware and software development and demonstrate operational system

- Optical design: Continue to support SES in optical and thermal design of dish, cavity, receiver, and engine
- Assist SES in developing predictive algorithms for engine and dish operation.

Infinia Site Support:

- Furnish test support and logistics to test six systems at SNL
- Give assistance in problem solving as requested.

Dish FOA Support:

- Support Brayton Energy in deploying and characterizing their first prototype dish engine system in Phoenix
- Support Infinia in the phase 2 design efforts and testing of the 30-kW free piston multicylinder engine.

CSP Cost Study:

- Complete the CSP cost study report and publish in April 2010.

5. FY 2009 Special Recognitions and Patents

- Technical Advance filed for SNL's SOFAST facet characterization system.

6. Major FY 2009 Publications

C.E. Andraka, S. Sadlon, B. Myer, K. Trapeznikov, and C. Liebner, "Rapid Reflective Facet Characterization Using Fringe Reflection Techniques," *Proc. Energy Sustainability 2009, San Francisco CA, July 2009.*

C.E. Andraka, S. Sadlon, B. Myer, K. Trapeznikov, and C. Liebner, "SOFAST: Sandia Optical Fringe Analysis Slope Tool For Mirror Characterization," *Proc. Solar Paces 2009, Berlin, Germany, September 2009.*

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
Sergeant & Lundy Engineering/ Robert Charles	robert.p.charles@sargentlundy.com	CSP Cost Study. The project involves three primary tasks. Task I is the fact-finding part of the project where the contractor will review existing information and interview industry representatives to obtain available cost information and to identify any limitations on deployment caused by the availability of equipment and/or near-term supplier constraints. The contractor will also establish the parameters for the cost estimates, financial assumptions, and federal and state incentives, and develop the methodology for the installed and LCOE cost estimates. The three deployment scenarios for each of the technologies will be developed in Task I. Task I will culminate in a report, which must be approved by the SCR prior to starting Task II of the project, in which the initial costing parameters, financial assumptions, incentives, deployment scenarios, study methodology, and deployment scenarios are defined.	250

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Dish 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
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 2009 Budget: $1,916K (DOE/GO)

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.
- Perform preliminary exploration/feasibility analysis of new concentrating solar power (CSP) approaches for electrical power production.

Accomplishments

- Continued two CSP Advanced Systems and/or Component (Dish) awards
- Completed two phase I go/no-go reviews (both awardees received a "go" decision)
- Continued to assess CSP Advanced Systems and/or Component (Dish) awards against the Solar Energy Technologies Program (SETP) CSP subprogram goals and objectives.

Future Directions

- Evaluate the CSP Advanced Systems and/or Component (Dish) awards to ensure they are progressing to meet the SETP CSP subprogram objectives to identify concepts that can generate low-cost power (under 7¢/kWh) with storage (12–17 hours) by 2020.

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1. Technical Approach

CSP is one of the most attractive renewable energy options in the southwestern United States, with a nominal levelized cost of energy (LCOE) target of 7¢–10¢/kWh by 2015 and 5¢–7¢/kWh by 2020. In-depth systems analysis specifies characteristics of a 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 (O&M) costs. The funding opportunity announcement (FOA) investigated three areas to resolve market barriers for utility-scale generation of CSP technologies: thermal storage, trough component manufacturing and advanced CSP systems or components (dish Stirling R&D).

The selected projects are as follows:

Organization, Principal Investigator, and Agreement Title	FY 2009 Budget ($K)
Brayton Energy—James Kesseli, Brayton Solar Power Conversion System	1,000
Infinia Corporation—Qiu Songgang, 30-kW Maintenance Free Stirling Engine for High Performance Dish Concentrating Solar Power	916

Brayton Energy
Brayton Solar Power Conversion System
Total Award: $4,269K DOE/Recipient: $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 principles 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:
  - Turboalternator: 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-m^2 dish, characterizing cavity and overall heat losses.

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1. Introduction

Brayton Energy performed extensive design and analysis of a novel CSP conversion system. It uses a specialized recuperated gas turbine generator with a solar receiver. Prototype units will be fabricated at an assembly plant for volume manufacturing near Phoenix, AZ. The focus is on the engine/receiver module design and component tests.

2. Technical Approach

The power module is designed to produce 84 kWe of net power on 850-W/m^2 insolation, which equates to a dish of nominally 320 m^2. DOE work is focused exclusively on the power conversion system, and the affiliate SolarCAT Inc. is developing and deploying a large dish that will be made available for receiver tests in this project. Several tasks were planned for this fiscal year.

The turbine and hot section will be fabricated and tested on the turboalternator test rig. The goal is to achieve an adiabatic turbine efficiency > 84%. The lab test rig at Brayton will be fired by custom-designed SolarCAT hybrid burners. For the second phase of fundingdecision, the early turbine efficiency target for the initial test trials in this phase has been set at 80%.

The high-speed alternator will be fabricated and tested on the turboalternator test rig. The goal is to achieve an efficiency of > 96%.

Brayton will also validate efficiency prediction models to show that cycle efficiency varies less than +/-2 percentage points over the control range (200 to 1,000 W/m^2). The lab test rig will be built to measure overall turbine-alternator efficiency.

The overall integrity of the turbine and hot section will be demonstrated. After testing for nominally 50 hours, researchers will check for material distress. Also, avoiding VAN galling caused by thermal distortion will be a key objective.

Researchers will conduct to correlate heat transfer and friction characteristics from testing, for a final receiver design. A receiver will be fabricated and delivered to a concentrator test facility at the SolarCAT Inc. facility near Phoenix.

Manufacturing trials will be conducted to qualify tube bending and joining procedures and to gain experience to establish greater confidence in the cost estimate for the solar receiver.

The DOE review board on December 18, 2008, recommended adding the following items:

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1. Develop a test plan for the experimental solar receiver and dish module
2. Integrate the prototype component/system (dish integration with the solar receiver)
3. Test dish receiver on sun test and validation results, in accordance with the test plan.

SNL, NREL, Brayton, and SolarCAT Inc. will collaborate on developing a dish and receiver test plan. Brayton will produce design information and documents at various stages of the design process for SNL and NREL for review and comment on both the preliminary and the final component and system designs.

3. Results and Accomplishments

Researchers completed designing the turboalternator and recuperator and continue to analyze the durability of critical design elements. The LCOE analysis is complete and has met objectives, based on performance analyses, capital cost, and life/maintenance expectations. The findings support the achievability of near-term DOE cost targets of $0.075 to $0.10/kWh. The final design employs intercooling and high levels of recuperation and reheat, enabling engine thermal-electric efficiency to exceed 37% at moderate turbine inlet temperatures. A detailed bill of materials has been prepared for the engine and receiver.

4. Planned FY 2010 Activities

- Fabricate and test purpose-built gas turbine engine with hydrocarbon fuels
- Integrate receiver and engine with purpose-built solar concentrator
- Test and characterize the turboalternator: complete power conversion system in a laboratory setting with hybrid fuel systems but no solar receiver, measuring efficiencies and emission levels; test and characterize the solar receiver in lab environment and 320-m^2 dish, characterizing cavity and overall heat losses.

5. FY 2009 Special Recognitions and Patents

Brayton Energy received two patents, on power conversion systems and a variable position turbine nozzle. They submitted six other filings related to recuperators, turbomachinery, and solar receivers.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Oak Ridge National Labs/Dr. Bruce Pint	Oak Ridge, TN	High-temperature materials evaluation	26	0
University of New Hampshire/Chad Everbeck, Martin Wosnik	Durham, NH	Advanced heat exchanger design and integration for Brayton solar power conversion	0	0
SolarCAT Inc./ Herb Hayden	Glendale, AZ	Dish design, fabrication, testing. Assembly factory deployment. 100-MWe site development	0	73

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Infinia Corporation
30-KW Maintenance Free Stirling Engine for
High Performance Dish Concentrating Solar Power System
Total Award: $3,196K DOE/Recipient: $2,062K/$1,134K

Objectives

- Provide prototype engine preliminary design and preliminary LCOE estimate by the end of phase 1 (FY 2008–FY 2009)
- Build and demonstrate a 30-kW engine laboratory prototype by the end of phase 2 (FY 2009– FY 2010)
- Deliver and field test a prototype 30-kW Stirling engine by the end of phase 3 (FY 2010–FY 2012).

Accomplishments

- Completed detailed design, with projected performance expected to meet SETP and LCOE goals
- Initiated prototype fabrication
- Completed Preliminary LCOE, initiated detailed LCOE analysis.

Future Directions

- Complete fabrication and assembly of engine
- Complete test station design and instrumentation
- Test and evaluate engine
- Complete detailed LCOE analysis
- Address any residual technical or cost barriers.

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1. Introduction

For dish Stirling CSP, two critical issues are engine life/reliability and O&M costs. The primary objective of this program is to apply Infinia's proven engine life and reliability to a maintenance-free 30-kW multicylinder free-piston Stirling engine (MCFPSE), greatly improving reliability and reducing overall levelized cost of energy.

2. Technical Approach

Phase 1 was conducted during FY 2008 and FY 2009. FY 2009 activities focused on completing the preliminary design and cost analysis. Phase 2 was initiated in FY 2009 and continues into FY 2010. During FY 2009, phase 2 activities focused on completing the detailed design of the engine and refining the preliminary cost analysis developed during phase 1. The general approach in phase 1 was to adapt proven free piston Stirling engine (FPSE) technology into an innovative, double-acting, multicylinder 30-kW design. To facilitate this process, SAGE (a Stirling engine simulation code) was used to simulate and support design of a six-cylinder engine.

This detailed SAGE analysis provided a basis to launch the detailed design of the test engine. A design for manufacturability and assembly (DFMA) analysis was conducted during the detailed design process to ensure that the engine would meet commercial manufacturing requirements. Changes for manufacturability were then added to the SAGE model, to assess any performance impact.

Engine design was completed and all fabrication drawings were finalized. Initial fabrication of the 30 kW engine began in late 2009.

Using commercial component data from Infinia's 3-kW engine, and analysis by leading automotive industry experts, Infinia performed a preliminary cost analysis of a 30-kW dish Stirling system based on the engine designed here. This analysis indicated a, LCOE in the range of 6.5¢ to 14.8¢/kWh, depending on subsidies and financing alternatives. The phase 2 cost analysis, based on the detailed engine design, was initiated in late 2009.

3. Results and Accomplishments

Infinia achieved substantial progress in the design and costing of its 30-kW prototype during FY 2009. Figure 1 shows the prototype engine configuration. The prototype design consists of six individual engine cylinders with interconnecting

ducts that form two 15-kW engine modules. Each 15-kW engine module cancels its own vibration but not its own nutating motion. The two integrated 15-kW engine modules cancel all vibration and nutating motion. This results in a design with no theoretical vibration transmitted to the supporting structure.

The 30-kW engine is designed such that each cylinder is rigidly connected to the others, which results in an exceptionally stiff and strong engine.

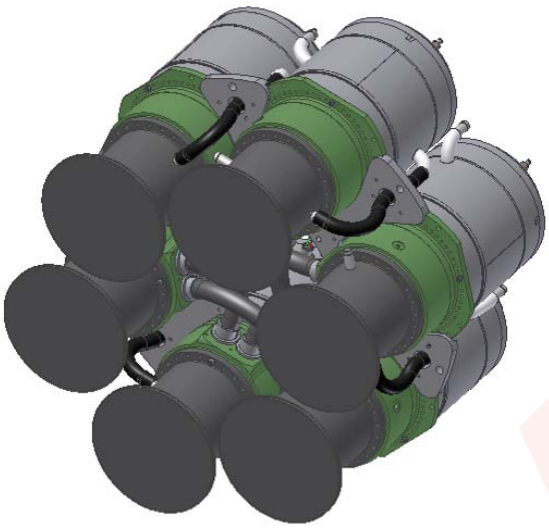

Fig. 1. 30-kW MCFPSE engine

A refined cost analysis for the engine and dish is ongoing with completion scheduled in FY 2010. Infinia will develop a preliminary assessment of the high-volume production cost of the system and O&M costs as they relate to the engine's effect on overall LCOE. Vendor information is being used and manufacturability examined in relation to cost/performance trade-offs. Engine costing began with preliminary part drawings. Infinia enlisted automotive and manufacturing expert, Ricardo, LLC, to assist. Ricardo has experience with Infinia's and other developers' Stirling engines and routinely develops high-volume cost models for the automotive industry.

4. Planned FY 2010 Activities

During FY 2010, phase 2 will be completed and phase 3 will be started. Phase 2 activities to be completed early in FY 2010 include:

- Finish fabricating the prototype engine
- Test and evaluate prototype engine
- Perform manufacturing cost analysis for the engine and dish
- Determine and resolve any residual technical or cost barriers.

Phase 3 objectives will be to fabricate and assemble an engine and balance of plant while incorporating any required improvements from phase 2. This will then be attached to an existing dish for performance testing.

Specific phase 3 deliverables include:

- Complete engine and balance of plant design suitable for dish mounting
- Assemble dish-mounted 30-kW engine prototype
- Conduct performance and characterization testing on sun.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity
Butler Sun Solutions/ Barry Butler	Solana Beach CA barry@butlersunsolutions.com	Sourcing of dish and dish costing analysis
Consultant/ Barry Penswick	Stevenson WA lbpeng@saw.net	Stirling engine design
Ricardo, LLC/ Alan Munday	Detroit, MI Alan.Munday@ricardo.com	Cost analysis

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Thermal Energy Storage Summary

The concentrating solar power (CSP) storage project comprises two important areas of research and development - advanced heat transfer fluids and thermal energy storage systems. Both topic areas include specific research activities that are directed towards increasing the performance and lowering the cost of CSP technologies. Specifically, this project's goals are to reduce the cost of thermal storage systems and increase CSP plant performance to meet the near-term CSP program goals of being cost-competitive with intermediate load markets by 2017 and carbon-constrained baseload markets by 2020.

Work within advanced heat transfer fluids seeks to improve the properties of heat transfer and storage fluids. Heat transfer fluids limit the maximum operating temperature of parabolic trough and power tower plants.

Work within thermal energy storage systems seeks to increase the stored energy density of the systems, which reduces the required inventory and cost of the systems. In addition, identifying systems that use less expensive storage media is also a priority. Both of these efforts require the identification and development of new storage materials.

Work within this project is performed at the U.S. Department of Energy's (DOE's) national laboratories – National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) – and at various universities and companies. The work is a blend of near-term analysis and materials development that is intended to quickly advance the technology and long-term research that will produce more dramatic technical advances as the technology matures.

Thermal storage projects comprise the following areas:

- Storage Systems
- Advanced Heat Transfer Fluid Development
- Storage Industry Projects
- Storage/Heat Transfer Fluids Industry Projects.

	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Thermal Storage R&D	**965**	**1250**	**4128**	**6343**
Storage Systems & Components	**510**	**700**	**0**	**1210**
Advanced Heat Transfer Fluid (HTF) Development	**405**	**500**	**0**	**905**
CSP Funding Opportunity Announcement #1 – Storage	**50**	**50**	**2930**	**3030**
CSP Funding Opportunity Announcement #2 – Storage/HTF	**0**	**0**	**1198**	**1198**

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Storage Systems

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

Key Technical Contacts: Greg Glatzmaier (NREL), 303-384-0000, greg.glatzmaier@nrel.gov
Nathan Siegel (SNL), 505-284-2033, npsiege@sandia.gov

DOE HQ Technology Manager: Tex Wilkins, 202-586-1684, frank.wilkins@hq.doe.gov

FY 2009 Budgets: $750K (SNL) and $510K (NREL)

Objectives

- Upgrade molten salt component test capability including central receivers. (SNL)
- Develop materials, methods, and hardware for deploying low melting point salt in parabolic troughs. (SNL)
- Provide computational fluids dynamics (CFD) modeling to assess and improve performance of thermal storage systems and their integration into Concentrating Solar Power (CSP) power plants. (NREL)
- Provide cost analysis to determine capital costs and levelized costs of energy (LCOE) impacts of thermal storage systems. (NREL)
- Design and establish a new thermal storage process and components integration laboratory to determine performance and operation of new storage concepts at laboratory scales. (NREL)
- Improve thermal energy storage (TES) systems to reduce the LCOE by $0.018/kW-h. (NREL)

Accomplishments

- Completed the conceptual design for upgraded molten salt component test facilities following a survey of industrial needs. (SNL)
- Experimentally identified a receiver failure mode for parabolic troughs using a molten salt heat transfer fluid (HTF). (SNL)
- Developed computational models of the freeze/thaw behavior of molten salt in a parabolic trough heat collection element (HCE). (SNL)
- Began construction of 650°C molten salt corrosion system and the second generation freeze/thaw experiment. (SNL)
- Provided support to thermal energy storage contract awardees. (SNL/NREL)
- Conducted performance modeling of thermocline storage system with packed filler material. (NREL)
- Performed survey of tank manufacturers to determine largest practical size for storage vessels. (NREL)
- Performed cost analysis to determine the current LCOE for electricity from a 100 megawatt (MW) parabolic trough power plant with 6 hours of thermal energy storage using 2-tank molten salt storage system. (NREL)

Future Directions

- Develop molten salt mixtures stable to 650°C. (SNL)
- Complete the design and construction of molten salt facility upgrades. (SNL)
- Identify additional failure modes related to salt freeze/thaw in parabolic troughs. (SNL)
- Complete CFD modeling of thermocline storage systems. (NREL)
- Complete cost analysis of thermocline storage systems. (NREL)
- Construct full-plant performance models in TRaNsient SYstem Simulation Program TRNSYS for integrating thermal storage into power plants. (NREL)

DRAFT

- Specify and fabricate thermal storage test loops and supporting instrumentation for thermal storage process and components integration laboratory. (NREL)

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1. Introduction

SNL

CSP plants, both parabolic trough and power towers, are being built or planned that will generate significant electrical power output in the near-term. TES incorporated into such plants would reduce the LCOE and provide dispatchability at the most valuable time of day. Commercially available nitrate salts can provide high capacity storage and have properties that are readily adaptable to the operating characteristics of both trough plants and power towers. However, realizing the lowest-cost energy production with CSP involves moving beyond the limits of current TES technology. The purpose of this project is to develop improved thermal storage media, hardware, and operational methodologies that can help reduce the cost of solar-generated electricity.

NREL

This agreement focuses on systems analysis issues relating to evaluating and improving the performance and cost of thermal storage systems for parabolic trough power plants.

Systems modeling and cost analysis dictate that thermal storage be integrated into the parabolic trough solar plant in order to operate efficiently and, most importantly, in a cost-effective fashion. This necessitates integrating thermal storage into cost and performance models to evaluate the sensitivities that result from changes in the storage system design, i.e., working fluid, fluid flow rates, heat exchanger designs, storage volume, etc.

2. Technical Approach

SNL

Technical work at SNL in FY09 was focused on the following tasks outlined below:

- *Molten Salt Components and Receiver Test Facility* – SNL is currently upgrading its capability to test salt-service components at the conditions necessary for operation in advanced parabolic trough plants and in central receivers. This work involves the design and construction of two facilities. The first will be used to test trough components, up to a complete module, at realistic flow rates and temperatures up to 500°C. This same facility also will be capable of testing valves and other components for central receiver service up to a temperature of 580°C. The second facility will support central receiver panel testing at SNL's power tower facility as well as component development. This facility will be capable of 650°C operation, consistent with the performance requirements of future advanced power towers operating with more efficient power cycles. Input was solicited from potential industrial users during the initial design stages for both facilities.
- *Corrosion Testing* – In order to achieve the lowest cost electricity from CSP the temperature at which the power cycles operate must increase, possibly beyond 650°C. Currently there is little information available related to the corrosion of engineering materials in nitrate salts at this temperature. We have designed a corrosion test facility to evaluate both the stability of nitrate salts at 650°C and the corrosion of engineering materials. The facility will be built in FY10.
- *Freeze/Thaw Experiments and Analysis* – Using nitrate salts as the heat transfer fluid in parabolic troughs offers some benefits with respect to performance and cost. However, the possibility of the salt freezing in heat collection elements (HCE) poses a significant technical challenge. In FY09 we conducted experiments to evaluate the behavior of molten-salt filled HCEs during phase change processes. We also developed computational thermo-mechanical models of the system in parallel with the experimental efforts.
- *Support of funding opportunity announcement (FOA) Awardees* – Several researchers at SNL continue to serve as technical monitors and advisors for thermal energy storage FOAs.

NREL

- This agreement is divided into two primary activities: performance modeling and cost analysis.
- Performance modeling is an internal NREL activity. It uses computational fluid dynamics (CFD) modeling techniques to estimate and predict heat transfer and fluid flow within complex flow geometries. This capability is used to characterize the performance of thermocline thermal energy storage systems. Modeling of thermocline performance is necessary because large temperature gradients exist within this storage system.

These gradients generally occur axially along the direction of fluid flow but also exist between the fluid and solid storage medium and within the solid medium itself. Thermocline operation is highly transient in nature. For these reasons, CFD modeling is necessary to characterize and understand the performance of thermocline storage systems for CSP applications.

- In contrast, performance characterization of the 2-tank molten salt storage system does not require CFD modeling because each tank is isothermal and operation is relatively simple compared with the thermocline.
- Performance modeling of either storage system considers the total storage requirements, charging and discharging power requirements, storage vessel size limitations, vessel orientation, and aspect ratio. The goal is to determine the optimum storage configurations for likely solar field sizes (or solar multiples) that minimize the levelized cost of electricity.
- Cost analysis was performed as part of a larger task that updated the costs for a parabolic trough power plant with 6 hours of thermal energy storage. This work was subcontracted to Worley Parsons, a large design & engineering firm with EPC management experience in parabolic trough power plants. Worley Parsons was able to contact component vendors and acquire cost information that was needed to perform the cost analysis.

3. Results and Accomplishments

SNL

The results of the technical work performed at SNL in FY09 are summarized below:

- *Molten Salt Components and Receiver Test Facility* – A decision was made to eliminate the support for testing long-shafted pumps from the original facility plan. A new facility configuration was developed after interviewing several potential industrial partners/users (9/09). Valves, instrumentation, and other components for salt service must be developed and demonstrated in realistic operating conditions in order to justify their use in CSP facilities. Our upgraded test facility will have two independent loops for providing flowing molten salt at a controlled temperature to three test segments. Two of the test segments accommodate parabolic trough components; the other accommodates central receiver components. An illustration of the facility is shown in Figure 1.

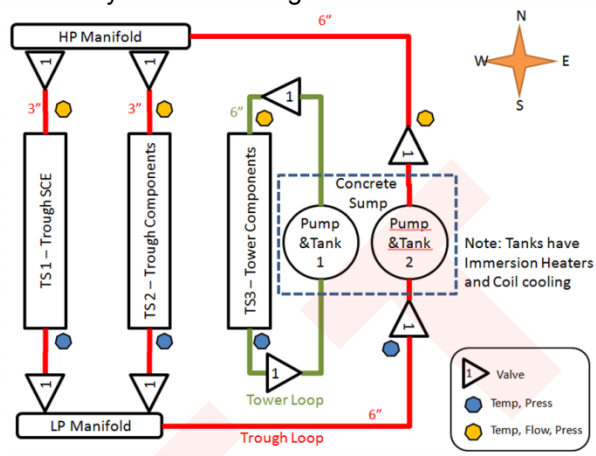

Figure 1. The molten salt component test facility at SNL

- *Corrosion Testing* – The design and heat transfer analysis of the 650°C corrosion test facility was completed and the required hardware purchased (8/09).

Figure 2. Simulated HCE deformation during a freeze/thaw cycle for a fully filled tube.

- *Freeze/Thaw Experiments and Analysis* – Testing continued through FY09. During several tests we identified conditions under which salt-filled HCEs would plastically deform during impedance heating. Using molten salt as opposed to synthetic oil as the heat transfer fluid in a parabolic trough power plant offers performance and cost benefits. In FY09 we performed experiments and developed models to investigate strategies that may be used to recover a trough field should the molten salt heat transfer fluid freeze in the HCEs. We found that, using an impedance heating strategy, it is possible to cause permanent damage (plastic deformation) to receiver tubes during the thawing process if the conditions are such that the HCEs completely fill with salt during solidification. If liquid salt is not allowed to fill in the gaps upon freezing, the stress on

the tube is reduced and plastic deformation can be avoided. Figure 2 shows magnified tube deformation during thaw for a completely filled HCE when heated from 80-140°C.

- *Molten Salt Steam Generator Analysis* – In FY09 SNL placed a contract with Texas Tech University to perform a CFD analysis of a molten salt steam generator proposed for central receiver applications by TEi-Struthers Wells. The purpose of the work is to evaluate the extent of salt cross-over between the hot and cold sides of the heat exchanger and seek ways to reduce its impact on performance. This work is still in progress.
- *Support of FOA Awardees* – SNL staff members support all of the DOE thermal energy storage FOAs.

NREL

During FY2009, we completed the following activities:

- Conducted performance modeling of thermocline storage system with packed filler material (results presented in publication list in section 6).
- Performed survey of tank manufacturers to determine largest practical size for storage vessels.
- Performed cost analysis to determine the current LCOE of electricity from a 100 MW parabolic trough power plant with 6 hours of thermal energy storage using 2-tank molten salt storage system.

4. Planned FY 2010 Activities

SNL

- Finalize the design (9/2010) and begin construction of both the molten salt component test facility and the central receiver test loop.
- Upgrade the HCE freeze/thaw test to include receiver tube mounted instrumentation. Complete the first round of testing (7/2010). Update computational models and identify the processes governing tube failure (8/2010).

NREL

- Complete a design basis for thermocline storage systems for parabolic trough and central receiver power plants.
- Complete a CFD thermocline modeling effort that models heat transfer and fluid flow through structured packing.
- Complete a cost estimation for thermocline storage systems for parabolic troughs and central receiver power plants.
- Complete a design specification for the new thermal storage process and components integration laboratory.

5. Major FY 2009 Publications

SNL

Kolb, G.J., Ho, C.K., Iverson, B.D., Moss, T.A., Siegel, N.P., "Freeze-Thaw Tests of Trough Receivers Employing a Molten Salt Working Fluid." Submitted to Energy Sustainability 2010, ASME, 2010.

NREL

D. Bharathan, G. C. Glatzmaier, Progress in Thermal Energy Storage Modeling, Proceedings of ES2009, ASME Energy Sustainability, San Francisco, California, July 19-23, 2009.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

SNL

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
Texas Tech University Dr. Darryl James	Lubbock, TX Darryl.james@ttu.edu	Analysis of molten salt steam generator design.	60

NREL

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
Worley Parsons	Golden, CO/Rodney Gartner; Rodney.Gartner@WorleyParsons.com	Cost analysis of 2-tank TES	75

Advanced Heat Transfer Fluids Development

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

Key Technical Contacts: Robert Bradshaw (SNL), 925-294-3229, rwbrads@sandia.gov
Nathan Siegel (SNL), 505-284-2033, npsiege@sandia.gov
Greg Glatzmaier (NREL), 303-384-7470, greg.glatzmaier@nrel.gov

DOE HQ Technology Manager: Tex Wilkins, 202-586-1684, frank.wilkins@hq.doe.gov

FY 2009 Budgets: $500K (SNL), $405K (NREL)

Objectives

- Develop cost-effective thermal energy storage (TES) for parabolic trough plants (TES cost objective: $20/kWh) (SNL)
- Formulate heat transfer fluid (HTF) for advanced parabolic troughs enabling higher operating temperatures than current fluids and thus higher efficiency (levelized cost of energy [LCOE] objective ~7¢/kWh, temperature objective 500°C) (SNL)
- Discover and characterize new HTFs with low freezing points, high temperature thermal stability, and increased thermal conductivity; new storage materials with improved heat capacity (NREL)
- Improve heat transfer fluids and storage materials to each reduce LCOE by $0.008–0.018/kWh (NREL).

Accomplishments

- Developed multicomponent molten nitrate salt mixtures that solidify below 90°C (SNL)
- Discovered molten nitrate/nitrite salt mixtures that solidify below 80°C (SNL)
- Demonstrated chemical stability of nitrate-only molten salts to 500°C (SNL)
- Determined physical properties and corrosion activity of molten salt HTF (SNL)
- Began computational chemistry studies (molecular dynamics, thermodynamics) to search for salt compositions (SNL)
- Expanded nanofluids research to include experimental synthesis of nanoclusters for incorporation into fluids; increased heat capacity of nanofluids will reduce LCOE by $0.018/kWh (NREL)
- Initiated thermodynamics modeling of salt formulations using FactSage to identify useful salt formulations that have components other than nitrates and nitrites; improved properties will reduce LCOE by $0.008/kWh (NREL)
- Established thermal storage materials laboratory for characterizing new heat transfer fluids and storage materials; this laboratory supports other R&D activities (NREL).

Future Directions

- Complete property characterization studies of low-melting nitrate and nitrate-nitrite salt mixtures (SNL)
- Evaluate maximum operating temperature possible with binary solar salt for central concentrating solar power (CSP) (SNL)
- Extend computational chemistry methods to search for better compositions and predict properties (SNL)
- Assess properties of molten salt hydrates as low-melting HTFs (SNL)
- Evaluate concept for encapsulating a metallic phase-change material (SNL)
- Expand scope of nanofluids modeling and synthesis to include metal alloys and encapsulated nanoclusters (NREL)
- Develop laboratory protocols for new instrumentation; build thermal conductivity instrument (NREL)

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- Identify and refine storage material formulations using FactSage software (NREL).

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1. Introduction

At SNL, parabolic trough solar concentrating plants are being built or planned that will generate significant electrical power in the near term. TES incorporated into such plants would reduce the LCOE and ensure dispatchability at the most valuable time of day. SNL developed and evaluated novel inorganic molten salts that can be used at temperatures up to 500°C, increasing power cycle efficiency vs. oil-based HTFs, which are limited to 400°C. The molten salt HTF is amenable to use in large TES tanks because it is inexpensive relative to organic fluids and has negligible vapor pressure.

The purpose of this agreement with NREL is to discover and characterize new HTFs and storage materials for CSP applications. This work consists of complementary efforts in molecular dynamics, thermodynamics modeling, experimental synthesis, and property characterization. Development of new HTFs will increase the thermodynamic efficiency of CSP power plants. New storage materials will increase TES density. Both improvements will decrease the LCOE for CSP plants.

2. Technical Approach

The technical approach at SNL in FY 2009 was to expand the preliminary work performed in FY 2008 to conduct a wide-ranging laboratory evaluation of the newly developed molten salt HTF. The strategy for developing improved molten nitrate salt HTF involved using a limited experimental matrix to observe low-melting mixtures and to estimate the direction of optimal composition for the next group of experiments. The candidate low-melting salt mixtures were then subject to determinations of chemical stability, physical properties, and corrosion activity. Physical property measurements and corrosion tests were also performed on candidate mixtures.

In FY 2009, NREL focused on developing and establishing new research capabilities. Past work within this agreement was limited to molecular dynamics modeling of nanoscale particles for nanofluids applications. NREL initiated experimental work to synthesize and characterize nanoscale particles. These materials will be incorporated into fluids to determine improvements in the fluid properties. NREL also initiated a new thermodynamics modeling capability to explore salt formulations beyond the conventional nitrate/nitrite compositions to identify alternative formulations with improved properties. Finally, NREL established a thermal storage materials laboratory that includes instrumentation to fully measure and characterize the thermophysical properties of new heat transfer fluids and storage materials.

3. Results and Accomplishments

<u>SNL</u>

- Developed multicomponent molten nitrate salt mixtures that solidify below 100°C by limited combinatorial experiments
- Demonstrated chemical stability of these molten salts to 500°C
- Determined viscosity and density of molten salt HTF
- Completed analysis of corrosion test alloys
- Demonstrated multicomponent nitrate-nitrite salt mixtures that solidify near 80°C.

This project developed a novel molten salt HTF capable of both low and high temperature operation. Nitrate-only and nitrate-nitrite mixtures were studied. The chemical stability limits of low-melting nitrate mixtures were determined by chemical analysis of molten salts maintained at high temperatures. Further, SNL conducted corrosion tests for 3000 hours at 500°C without degradation of the salt. Viscosity measurements showed that adding calcium nitrate to the multicomponent molten salts significantly increased the viscosity but was still acceptable for trough operations. Density was determined against composition and temperature to 500°C. Corrosion tests were conducted for stainless steels, carbon steel, and alloy steels. Specimens were evaluated gravimetrically and metallographically to determine their performance.

SNL conducted laboratory work to investigate the properties of mixtures of nitrate (NO_3^-) and nitrite (NO_2^{-1}) salts using sodium, potassium, and lithium in varying proportions. Melting points near 80°C were observed with mixed anion compositions. Work is continuing to obtain a complete phase-diagram and evaluate properties.

Molecular dynamics simulations and continuum (free-energy based) thermodynamics calculations were used to study solid-liquid phase equilibria for alkali nitrate salt mixtures.

NREL

- Modeled nanoparticles with encapsulating shells that stabilize the particle during phase transitions (06/2009)
- Initiated synthesis of nanoparticles (07/2009)
- Surveyed the open literature to establish a database of 900 references for relevant nanomaterials work (07/2009)
- Purchased and installed instrumentation for the thermal storage materials laboratory (02/2009)
- Initiated thermodynamics modeling using FactSage software (03/2009).

4. Planned FY 2010 Activities

SNL

- Extend physical property determinations of molten salt HTF to include heat capacity and thermal conductivity
- Complete study of nitrate-nitrite molten salt system for low-melting HTF compositions
- Explore molecular dynamics and continuum thermodynamic computational methods to discover better low-melting salt compositions
- Establish lab capabilities with new instruments for TGA/MS and DSC
- Evaluate stability limits of binary solar salt for 700°C use in central receivers
- Assess novel method for encapsulating metallic PCM.

NREL

- Complete first round of nanoparticle synthesis
- Complete laboratory protocols for materials laboratory
- Design and build thermal conductivity instrument
- Use FactSage modeling to identify promising new storage materials.

5. FY 2009 Special Recognitions and Patents

Patent awarded, USP #7,588,694, Low-Melting Point Inorganic Nitrate Salt Heat Transfer Fluid, R.W. Bradshaw and D.A. Brosseau, Sept. 15, 2009.

Patent application #12/336,657, Low-Melting Point Inorganic Nitrate-Nitrite Salts, J.G. Cordaro and R.W. Bradshaw, filed Dec. 17, 2008.

6. Major FY 2009 Publications

D.M. Blake, *Nanomaterials for Heat Transfer Fluid and Thermal Storage Applications in Concentrating Solar Plants*, NREL/SR-550-46591, Golden, CO: NREL (September 2009). A Review of 206 References.

R.W. Bradshaw and N.P. Siegel, "Development of Molten Salt Nitrate Mixtures For Concentrating Solar Power Systems," *SolarPACES 2009, Paper 11583, Berlin, DE, Sept. 15–18, 2009.*

R.W. Bradshaw, J.G. Cordaro, and N.P. Siegel, "Development of Inorganic Molten Salt Mixtures for Solar Thermal Energy Systems," *ASME Energy Sustainability 2009, Paper ES2009-90140, San Francisco, CA, July 19–23, 2009.*

G.C. Glatzmaier, J. Kang, Y.-H. Kim, D.M. Blake, and C. Curtis, "Nanoscale Materials Modeling for Improved Heat Transfer and Storage Fluids," *Solar PACES 2009, Berlin, Germany, September 15–18, 2009.*

J. Kang and Y.-H. Kim, "Half-Solidity of Tetrahedral-Like Al55 Clusters," *ACS Nano*, in press.

H. Xiang, J. Kang, S.-H. Wei, Y.-H. Kim, C. Curtis, and D. Blake, "Shape Control of Al Nanoclusters by Ligand Size," *J. Am. Chem. Soc.* **131**, 8522 (2009).

7. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
Daniel M. Blake	daniel.blake@nrel.gov	Support nanofluids and thermal storage R&D for the CSP Program	60

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Storage 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 2009 Budgets: $0 (DOE/GO); funded in FY 2008, no additional funding to date

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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.
- Develop low-cost, high-temperature storage that enables concentrating solar power (CSP) trough systems to reach nominal levelized cost of energy (LCOE) target of 5-7¢/kWh with storage (12–17 hours) by 2020.

Accomplishments

- Continued two CSP Advanced Systems and/or Component awards
- Completed one Phase I go/no-go reviews (awardee received "go" decision)
- Continued to assess CSP Thermal Storage awards against the Solar Energy Technologies (SETP) CSP subprogram goals and objectives.

Future Directions

- Evaluate each CSP Thermal Storage award to ensure they are progressing to meet the SETP/CSP goals and objectives.

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1. Introduction

CSP is one of the most attractive renewable energy options in the southwestern United States, with a nominal LCOE target of 7-10¢/kWh by 2015 and 5-7¢/kWh by 2020. The CSP thermal storage R&D activities are expected to develop low-cost, high-temperature storage that enables trough technologies to reach the nominal LCOE target. To achieve this goal, a storage cost of less than $15/kWh thermal is desired with round-trip efficiencies at or greater than 93%. .

Organization, Principal Investigator, and Agreement Title	FY 2009 Budget ($K)
Abengoa Solar Inc., Bruce Kelly, Development of Molten Salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants	0
Hamilton Sundstrand Corporation, Michael McDowell, Concentrating Solar Power Molten Salt Pump	0

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Development of Molten-Salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants
(Abengoa Solar, Inc.)
Phase 1 Award: $625K DOE/Recipient: $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

- Investigated using current receiver tube technology with molten salt up to 500°C
- Identified potential collector joint concepts and joint materials compatible with molten salt heat transfer fluid (HTF) to be tested in Phase II
- Determined an optimum collector geometry and associated field piping layout for use with molten salt HTF
- Identified compatible instrumentation for use with molten salt HTF
- Developed specifications for freeze prevention/recovery systems for the entire field piping system
- Developed loop operations and maintenance procedures specific to molten salt HTF
- Developed transient performance models in TRNSYS of entire molten salt plant, including two options for direct thermal energy storage (2-Tank and Self-Supporting Bed Thermocline)
- Analyzed plant performance with TRNSYS models
- Received detailed preliminary engineering, procurement, and construction costs for molten salt plant with two thermal energy systems (TES) options.

Future Directions

- Test prototype components for molten salt use (ball joints, high-temperature receivers)
- 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 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 reduce LCOE enough to pursue further development and to develop the components required for molten salt use.

2. Technical Approach

Abengoa is developing sizing models in Engineering Equation Solver (EES) and transient performance models in TRNSYS to both assess plant performance and create a bill of materials necessary for engineering, procurement, and construction cost estimate.

3. 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 focuses on economic concerns, performing a design tradeoff between the higher cost of these salts and the lower equipment cost. Heat balances were also developed for the reference Therminol, and the baseline molten salt plants. An engineering assessment, using capital cost data, was developed for the reference Therminol and the baseline molten salt plants, based on half of the 250-MWe Solana project for Arizona Public Service.

4. Planned FY 2010 Activities

- Produce Phase 1 final report
- Receivego/no go decision on Phase II
- Develop prototype and scale up if Phase II approved.

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5. Major FY 2009 Publications

D.A. Arias, A. Gavilan, and R. Muren, "Pumping Power Parasitics in Parabolic Trough Solar Fields," *SolarPACES 2009, Berlin, Germany, September 15–18, 2009.*

D.J. Chapman and D.A. Arias, "Effect of Solar Brightness Profiles on the Performance of Parabolic Concentrating Collectors," *Proc. ASME 2009 3rd International Conference on Energy Sustainability ES2009, San Francisco, CA, July 19–23, 2009*.

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Concentrating Solar Power Molten Salt Pump
(Hamilton Sundstrand Corporation)
Total Award: $4,374K DOE/Recipient: $3,219K/$1,155K

Objectives

- Develop molten salt pump requirements
- Evaluate existing hardware designs for necessary modifications
- Create a preliminary design of the pump concept
- Develop and refine cost estimates for Phase II and Phase III.

Accomplishments

- Achieved all Phase I objectives
- Held Conceptual Design Review (CoDR) on November 4, 2009
- Submitted Phase I continuation report on December 22, 2009.

Future Directions

- Begin Phase II (design, fabricate, build), DOE continuation evaluation under way
- Phase III testing at Sandia National Laboratory.

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1. Introduction

This project addresses the integration of advanced low-cost thermal storage with parabolic trough systems. The intent of this project is to design, build, and test a long-shafted (~50 feet) molten salt pump, capable of operation at 1,050°F. The design will be evaluated using parameters expected with the thermal storage system of a commercial-scale solar trough plant.

2. Technical Approach

The intention is to improve the technology of long-shafted pumps to replace the sump-type of pump, and eliminate the associated valving, piping, and heat trace. The technical innovation necessary for this project reflects the need to expand the performance envelope of long-shafted molten salt pumps. The system for the pump application has been defined, and pump operations necessary for successful plant operation has been developed. As part of Phase I, cost estimates for the design, build, and testing in Phase II and Phase III will be developed.

Rocketdyne has partnered with Friatec N.A., LLC to jointly develop a molten salt pump, creating top level specifications, a conceptual design, and detailed cost estimates. Friatec N.A., LLC will also support activities in Phase II and Phase III.

3. Results and Accomplishments

Phase I major accomplishments:

- Defined molten salt pump system requirements (07/09)
- Evaluated existing hardware for necessary modifications (10/09)
- Generated conceptual design, hold design review (11/09)
- Evaluated cost estimates of Phase II and Phase III (12/09)
- Submitted continuation report (12/09).

The pump design should support a 100-MWe power plant with 4 hours of thermal storage capacity. Although double the size of existing trough plants, this was considered to be a reasonable increase in capacity. Friatec examined its existing designs. Having significant involvement with molten salt applications in both the United States and Europe, the review covered 300 molten salt pump applications, including single- and multistage wet ends, 20 impeller sizes, 5 bearing pedestal sizes, and 7 different materials used for the columns, wet end, and pump discharge. All pumps were designed to operate in the same temperature range (~550°F to 1050°F) as required for this project, using motors up to 800 HP. Shaft lengths, however, were shorter (20 feet versus 50 feet).

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The pump will be designed for a two-tank plant (hot and cold). Focus will be on the hot tank design, with a vertical pump orientation and top entry specified. The result of this configuration will be a reduction in the necessary valving, piping, fitting and heat trace. The pump will operate at 1,800 RPM, but will have variable speed capability.

The vendor evaluated its existing line of pumps, based on the current RFP requirements for solar trough plants with thermal energy systems (TES) using molten salt pumps. For reference, 68% of the time a pump with a 10-inch discharge, a 16.5-inch impeller diameter, and an operating speed of less than 1,800 RPM met customer requirements. The size of the pump selected for this application would be used in parallel with two pumps of the same size to provide redundancy within the TES system, to control equipment costs, and to reduce the risk of a complete system shut down because of a pump failure

It was determined that the pump required for the program is similar to the production pump model GVSO 250/355 (10-inch discharge, 16.6-inch diameter impeller, 1,800 RPM, 250 HP, single stage wet end). Finite element analysis (FEA) and computation fluid dynamic (CFD) analysis on a similarly sized 200/400 pump (8-inch discharge, 18.3-inch diameter impeller, 1800 RPM, 2300 HP, 4 stage wet end) have already been performed. For this project, the only major change required to the existing design would be to increase the shaft length. This change would be significant, because the planned application requires a shaft of greater than two times the existing design.

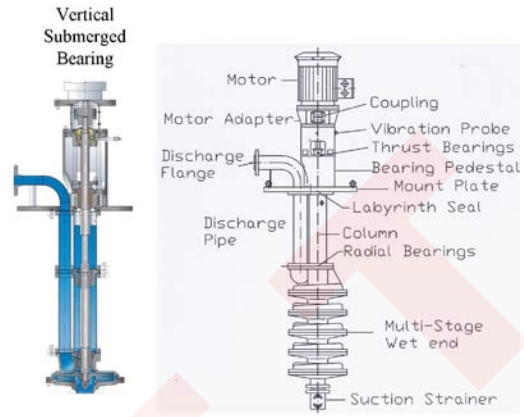

Fig. 1. Pump cross section and major components.

4. Planned FY 2010 Activities

Phase II of the project is scheduled for a period of 18 months. During this period, the detailed design will be finalized. To minimize the chance of technical issues, FEA and CFD models will be generated to assist in understanding the effects of the necessary design changes. In the next period, the preliminary and critical design reviews will be held. This will be followed by the fabrication of the pump components, pump assembly, and shipment of the pump to the test facility. Testing of the prototype pump will be conducted in Phase III at the facilities of Sandia National Laboratories.

5. University and Industry Partners

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Friatec N.A., LLC / Jeff Kelly	Odessa, FL	Long Shafted Molten Salt Pump Development	236	47

Advanced Heat Transfer Fluids and Novel Thermal Storage Concepts for Concentrating Solar Power Generation

Performing Organizations: Abengoa Solar, Inc. (2)
ACCIONA Solar Power, Inc. (2)
City College of New York (CUNY)
General Atomics
Infinia Corporation
Lehigh University
Symyx Technologies
Terrafore, Inc.
Texas A&M University (Texas Engineering Experiment Station)
University of Connecticut
The University of Alabama (UA), Tuscaloosa
University of Arkansas
US Solar Holdings, LLC

Key Technical Contacts: Carolyn Elam, DOE Golden Field Office (DOE/GO), 303-275-4953, carolyn.elam@go.doe.gov
Brad Ring, DOE/GO, 303-275-4930, brad.ring@go.doe.gov
Jim Payne, DOE/GO, 303-275-4756, jim.payne@go.doe.gov
Brian Hunter, DOE/GO, 303-275-4934, brian.hunter@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 2009 Funding: $1,499K (DOE/GO)

Objectives

- Support long-term R&D and near-term demonstration in two areas that could increase the efficiency and reduce the cost of concentrating solar power (CSP) systems to make them cost competitive:
  - Improved heat transfer fluids (advanced HTF): Identify and characterize novel fluids or fluid types that possess the physical and chemical properties required for an improved HTF and thermal storage fluid for CSP technologies.
  - Novel thermal energy storage (TES) concepts (novel TES systems): Generate and evaluate novel concepts for TES that have the potential to reduce the cost of TES to less than $15/kW thermal and achieve round-trip efficiencies greater than 93%.

Accomplishments

- Negotiated 15 CSP HTF/TES awards; held kick-off meetings with award recipients
- Defined roles and responsibilities of program management team, including technical advisors at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL)
- Continued to assess CSP HTF/TES awards against the Solar Energy Technologies Program (SETP)/CSP subprogram goals and objectives.

Future Directions

- Evaluate progress toward critical milestones; make go/no-go decisions at the end of the each project's first phase, starting in FY 2009 and extending into FY 2010
- Evaluate each of the CSP Advanced HTF/TES awards to ensure they are progressing to meet the SETP/CSP subprogram objectives to identify concepts that can reduce the cost of TES to less than $15/kW thermal and achieve round-trip efficiencies greater than 93%.

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1. Introduction

Funding Opportunity Announcement (FOA) DE-PS36-08GO98032, titled "Advanced Heat Transfer Fluids and Novel Thermal Storage Concepts for Concentrating Solar Power Generation," resulted in 15 FY 2008 awards in three topic areas: Advanced Heat Transfer Fluid Research and Development (1 award), Thermal Energy Storage Research and Development (10 awards), and Thermal Energy Storage Near-Term Demonstration (4 awards). The financial assistance agreements are listed in the following table.

Recipient/Principal Investigator Agreement Title	FY 2008 Funding ($K)	FY 2009 Funding ($K)
Advanced HTF Research and Development		
Symyx Technologies/J. Raade Deep Eutectic Salt Formulations Suitable as Advanced Heat Transfer Fluids	500	0
TES Research and Development		
Abengoa Solar, Inc./B. Kelly Advanced Thermal Energy Storage for Central Receivers with Supercritical Coolants	303	0
ACCIONA Solar Power, Inc./Newmarker Sensible Heat, Direct, Dual-Media Thermal Energy Storage Module	100	0
City College of New York/R. Shinnar A Novel Storage Method for Concentrating Solar Power Plants Allowing Operation at High Temperature	445	0
General Atomics/B. Wong Thermochemical Heat Storage for Concentrated Solar Power	500	0
Lehigh University/S. Neti Novel Thermal Storage Technologies for Concentrating Solar Power Generation	350	20
Terrafore, Inc./A. Mathur Heat Transfer and Latent Heat Storage in Inorganic Molten Salts for Concentrating Solar Power Plants	469	0
Texas A&M University (Texas Engineering Experiment Station)/M. Schuller Molten Salt-Carbon Nanotube Thermal Energy Storage for Concentrating Solar Power Systems	543	0
University of Connecticut/A. Faghri Research and Development for Novel TES Systems for CSP	449	0
The University of Alabama/R Reddy Novel Molten Salts Thermal Energy Storage for Concentrating Solar Power Generation	500	0
University of Arkansas/P. Selvam Development and Performance Evaluation of High Temperature Concrete for Thermal Energy Storage for Solar Power Generation	224	0
TES Near-Term Demonstration		
Abengoa Solar, Inc./B. Luptowski Reducing the Cost of Thermal Energy Storage for Parabolic Trough Solar Power Plants	500	0
ACCIONA Solar Power, Inc./M. Newmarker Indirect, Dual-Media, Phase Changing Material Modular Thermal Energy Storage System	500	0
Infinia Corporation/S. Qiu Innovative Application of Maintenance-Free Phase-Change Thermal Energy Storage for Dish Engine Solar Power Generation	500	1479
US Solar Holdings, LLC/J. Stephens CSP Energy Storage - Multiple Technologies Compared	236	0

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Deep Eutectic Salt Formulations Suitable as Advanced Heat Transfer Fluids
Symyx Technologies
Total Award:$2,635K ($1,500K DOE / $1,135K nonfederal)

Objectives

- Develop an advanced HTF with a melting point below 80°C and thermal stability up to 500°C. A material with these properties could reduce the levelized cost of energy (LCOE) from CSP by $0.02/kWh. This project will focus on complex mixtures of inorganic salts that exhibit a high thermal stability, a low melting point, and other favorable characteristics. Symyx will conduct a high-throughput combinatorial research and development program in order to achieve the project objective.

Accomplishments

- Screened more than 2,500 unique salt blends for melting point so far
- Discovered two distinct families of salt blends with melting points below the 80°C target
- Completed method development for the thermal stability measurement of salt blends; began to screen blends that passed the melting point target
- Assessed the utility of thermodynamic modeling software tools.

Future Directions

- Complete the screening program of 5,000 unique blends by December 31, 2009
- Perform secondary screening and then field testing of candidate blends to arrive at a commercial candidate heat transfer fluid.

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1. Introduction

Current CSP plants use a synthetic oil-based heat transfer fluid that limits their operating temperature to 400°C. Next-generation plants are targeting an operating temperature of 500°C to increase efficiency and reduce the LCOE. Molten salts exhibit many desirable heat transfer qualities within the range of the project objectives but typically have high melting points, preventing their application in commercial CSP plants.

2. Technical Approach

Symyx will investigate complex mixtures of inorganic salts to discover deep eutectic or low melting point formulations suitable as advanced HTFs. Eutectic mixtures of salts exhibit dramatic melting point reductions, but little experimental data exist for quaternary or higher order systems.

3. Results and Accomplishments

Symyx developed a high throughput workflow capable of dispensing, melting/mixing, and characterizing up to 400 unique salt blends per week. The workflow consists of automated Symyx equipment such as the Powdernium powder dispensing robot and Parallel Melting Point Workstation. A thermogravimetric analysis (TGA) device measures the thermal stability of the salt blends.

4. Planned FY 2010 Activities

- Viscosity screening (lower viscosity of heat transfer fluid means lower parasitic pumping losses)
- Thermodynamic modeling with the FactSage software and databases; model eutectic behavior and high-temperature reactions
- Thermal stability enhancement.

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Advanced Thermal Energy Storage for Central Receivers with Supercritical Coolants
Abengoa Solar, Inc.
Total Award: Phase 1 $379K ($303K DOE / $76K nonfederal)
Phase 2 $379K ($303K DOE / $76K nonfederal)
Phase 3 To Be Determined (TBD)

Objectives

- Determine if supercritical heat transport fluids in a central receiver power plant, in combination with ceramic thermocline storage systems, reduce the LCOE over a baseline nitrate salt concept
- If so, demonstrate a prototype thermocline storage unit.

Accomplishments

- Examined the following six plant designs:
  - Two reference nitrate salt designs, each using a two-tank nitrate salt thermal storage system:
    - A subcritical design, using a Rankine cycle operating at 125 bar, with live and reheat steam temperatures of 540°C
    - A supercritical design using a Rankine cycle operating at 300 bar, with live and reheat steam temperatures of 590°C
  - Two supercritical steam receiver designs:
    - A low-temperature variation, using a two-tank nitrate salt thermal storage system
    - A high-temperature design, using a packed bed thermocline storage system
  - Two supercritical carbon dioxide receiver designs:
    - A low-temperature variation, using a two-tank nitrate salt thermal storage system
    - A high-temperature design, using a packed bed thermocline storage system
- Developed conceptual heliostat field layouts, together with optimum tower heights and receiver absorber dimensions, using the RCell computer program (Tietronix)
- Developed incident flux and temperature maps for each of the receiver concepts to estimate thermal efficiency and fatigue life
- Developed models of the temperature profiles in the high-temperature storage designs using a finite element approach for the solution of the Schumann simultaneous partial differential equations to model the heat transfer in a packed bed thermocline
- Developed annual plant performance calculations with the SOLERGY computer program
- Assembled plant capital cost estimates, and annual operation and maintenance cost estimates, from a range of earlier studies and an in-house estimating database
- Developed LCOE calculations using a 30-year cash flow analysis and financial parameters typical for an independent power producer.

Future Directions

- Further research packed bed thermocline using supercritical H_2O, found to be impractical due the wide range of fluid specific heats near the bottom (low temperature portion) of the vessels.
- Further research packed bed thermocline using supercritical CO_2,found to offer stable, and repeatable, temperature profiles. However, the high pressures characteristic of supercritical CO_2 (~150 bar) require expensive pressure vessels to contain the ceramic storage media.
- Recommend to DOE to conclude the study at the end of Phase 1 and not to proceed with the more detailed thermocline analyses planned for Phase 2, since neither of the thermocline storage designs offered a reduction in LCOE compared to the reference nitrate salt storage designs.

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Sensible Heat, Direct, Dual-Media Thermal Energy Storage Module
ACCIONA Solar Power, Inc.
Total Award: Phase 1 $125K ($100K DOE / $25K nonfederal)
Phase 2 TBD
Phase 3 TBD

Objectives

- Design and validate, at prototype level, a sensible heat TES module with round-trip efficiency greater than 93%;

the module will be part of a TES system that can facilitate a decrease in LCOE by 2020.

Accomplishments

- Derived several different configurations
- Began developing a heat transfer model that can be adapted to each design.

Future Directions

- Perform detailed heat transfer and fluid dynamic modeling
- Generate a basic design of the sensible-heat TES module.

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1. Introduction

An unsophisticated, modular, and scalable TES system could facilitate the attainment of an LCOE of $0.07/kWh by 2015.

The proposed sensible-heat TES module is a direct heat transfer TES system in which HTF circulating through the solar field charges the storage and serves as limited storage media in itself. The direct, dual-media TES module consists of HTF and pressure containment vessels filled with a solid storage media.

2. Technical Approach

During FY 2009 researchers examined the design concept using value engineering criteria, consolidating the best configurations for the TES module.

Also during FY 2009, ACCIONA created a heat transfer model with TRNSYS. This model will determine the heat storage capability and will be used as a key go/no go evaluation of the project.

2. Results and Accomplishments

The first achievement of this project was to consolidate all the design concepts examined for this project. Two different design concepts were derived.

Next, TRNSYS was used to begin modeling the problem using standard program components. The current iteration can charge the storage system based on step functions and temperature dependent flow control.

3. Planned FY 2010 Activities

- Continue heat transfer modeling with standard components and add the ability to simulate discharge (03/10)
- Begin building proprietary components (04/10)
- Begin fluid dynamic analysis of the two designs; this modeling will be used as a key go/no go evaluation (06/10)
- Complete a basic design of the sensible-heat TES module (11/10).

DRAFT

A Novel Storage Method for Concentrating Solar Power Plant Allowing Operation at High Temperature
City College of New York
Total Award: $1,904K ($1,328K DOE / $576K nonfederal)

Objectives

- Develop a storage method for CSP plants that can operate without any practical constraints at both the lower or upper temperature extremes (from ambient to 2500°F), and be added to a CSP plant without affecting the cost of daily kilowatt-hours generated.

Accomplishments

- Identified a filling material for the storage unit for both water/steam and CO_2 storage
- Developed reduced models for CO_2 and water/steam storage
- Designed a laboratory pilot plant to demonstrate heat storage using both CO_2 and water/steam; contracted construction of the plant.

Future Directions

- Focus on the pilot plant operation to demonstrate the concept of heat storage and produce data to improve the computer models
- Perform optimization studies of the filling material to reduce cost and storage volume.

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1. Introduction

The main objective of the work is to develop and test a storage method that is able to completely remove both upper and lower operating temperature constraints, which currently strongly limit the efficiency of CSP plants, and to significantly reduce the costs well below the cost goals fixed by this FOA.

2. Results and Accomplishments

An experimental setup to test the filler material was constructed. All testing will be conducted during FY 2010 and will be documented in the report for that year.

A model for CO_2 storage was developed. Results show that the heat front advances as a sharply defined gradient, thus giving a total available volume for storage of about 80%.

A laboratory-size plant was designed. A company willing to work within our budget to optimize the design and build it was identified: Chemtech Services Inc. of Joliet, IL. The plant is being built and it is expected to be completed in February 2010.

3. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Chemtech Services Inc./ John F. Hart	Joliet, IL Jhart@chemtechservicesinc.com	Fabrication of pilot plant	180	0

DRAFT

Thermochemical Heat Storage for Concentrated Solar Power
General Atomics
Total Award: $2,434K ($1,500K DOE / $934K nonfederal)

Objectives

- Identify and assess solid oxide thermochemical cycles (TC) that can be used for TES in an open-loop system in which air is used as both the heat carrier and the reactant
- Determine reaction thermodynamics of all solid oxide TC and evaluate their potential as TES candidates; carry out laboratory studies to verify the feasibility of using the potential TC candidates for TES and to establish a protocol for future experimental evaluation
- Establish a baseline process model for an electricity plant integrated with TES; apply all potential TES candidates to the model and estimate their process efficiency, chemical heat storage cost (target: $15/kWh), and LCOE (target: $0.08/kWh$_e$)
- Down-select the potential candidates based on computed economics and preliminary experimental data; selected systems will undergo more detailed experimental characterizations. Use the data to support process component designs and modeling to obtain a more accurate economic assessment. Carry out a conceptual design for "on sun" demonstration if the economic viability of the selected TC is demonstrated.

Accomplishments

- Surveyed pure and mixed oxides TC applicable to TES using thermodynamic calculations and literature data
- Completed the thermodynamic assessment of all single-component solid oxide systems using HSC Chemistry software; identified 15 pure oxide TC as potential TES candidates
- Developed a preliminary process flowsheet for an electricity plant incorporated with a solid oxide based TES system; estimated the chemical storage cost and LCOE with respect to each potential pure oxide TC
- Completed the construction of packed bed test systems for preliminary feasibility studies.

Future Directions

- Complete preliminary experimental evaluation of potential TES candidates
- Down-select potential solid oxide TES candidates
- Conduct a more detailed experimental characterization of the selected TES candidates
- Identify pathways and conduct experiments to modify the properties of the selected TES candidates
- Conduct thermochemical heat storage reactor and solar interface designs and establish a process model for a CSP power plant integrated with a solid oxide TES system.

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Novel Thermal Storage Technologies for Concentrating Solar Power Generation
Lehigh University
Total Award: $1,497K ($1,103K DOE / $394K nonfederal)

Objectives

- Establish technical feasibility of using specially made encapsulated phase-change materials (EPCM) at elevated temperatures and acquire engineering results that will lead to the demonstration of large-scale thermal storage systems.

Accomplishments

- Performed heat transfer analysis to transfer enthalpy into and out of storage material; heat transfer does not appear to be an impediment for solar thermal energy storage
- Considered various methods for the encapsulation of phase-change material (PCM, zinc) have been considered; completed stress analysis of the encapsulating material for three geometries
- Evaluated the actual enthalpy into or out of the PCM using calorimetry; built and now testing a precision calorimeter.

Future Directions

- Explore further analysis of heat transfer into the PCM and in a bed full of EPCM; manufacture sample EPCM and build a heat transfer bed to test the TES concept; this will include issues related to the repeated thermal cycling of the EPCM.

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1. Introduction

Solar power generation has proved to be an excellent source of renewable energy. CSP technology is recognized as an attractive option for solar power, for plants of 100 MW or greater capacity. Two key needs for this technology are improved HTF and improved methods for TES. This project addresses the second need, with the objective of developing a novel TES technology that uses phase-change latent heat to increase thermal capacity, and offers energy storage at high temperatures (~400°C) to improve thermodynamic efficiency.

Using latent heat thermal energy storage could have significant advantages. In the present work zinc is used as PCM for storing thermal energy. Because the melting point of zinc is 420°C, it is an ideal candidate for the storage of latent as well as sensible heat. It can enable the production of high-temperature steam from solar energy even during nondaylight hours.

The change material needs to be encapsulated to provide sufficient heat transfer surface during the energy storage and retrieval process. Nickel and stainless steel are being considered as encapsulation material to make up the zinc-nickel EPCM.

The TES will be accomplished in a large bed of EPCM through which the HTF from the solar field flows to charge and discharge the bed, thus storing and retrieving energy.

Heat transfer in the PCM modules is very important for the TES process. Transient one-dimensional analysis in the PCM indicates that heat transfer into and out of the PCM is not likely to be a major impediment to TES. Work to further appreciate these concepts continues.

The PCM material will expand as it is heated to the desired storage temperatures. The expansion could be as much as 10% to 11%, corresponding to as much as 3% strain in the encapsulating material. Researchers used the properties of nickel at 450°C and finite element analysis that includes plastic deformation. Abaqus was used for this plastic deformation and stress analysis. With appropriate choice of the encapsulating material thickness and geometry for encapsulation, it is possible to construct EPCM modules that will result in stress under permissible values despite the high-temperature conditions. Sample EPCM modules will be built soon.

The amount of thermal energy stored is being verified using calorimetry. Because of the special nature of the materials used and because commercially available calorimeters

were not adequate, researchers designed and built a precision calorimeter. Measurements with heated cylinders indicate that overall energy balances of about 2.5% are possible.

Plans for the immediate future include additional calorimetry work and the design and development of an EPCM bed with hot/cold air flow through it to make TES measurements. We anticipate building a 25-kW system that can handle approximately 25-mm-diameter, 40-mm-long EPCM cylinders. This system will be capable of demonstrating thermal energy storage in zinc-nickel EPCM.

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Heat Transfer and Latent Heat Storage in Inorganic Molten Salts for Concentrating Solar Power Plants
Terrafore, Inc.
Total Award: $1,834K ($1,439K DOE / $395K nonfederal)

Objectives

- Develop a salt mixture composition based on a dilute eutectic and develop a coating material for heat transfer tubes that inhibits sticking
- Identify economical salt mixtures for use with CSP plants (power tower and linear Fresnel reflectors or parabolic troughs).

Specific benefits of using PCM TES include:

- A 30% reduction in amount of salt and a 60% reduction in container size compared to equivalent sensible heat TES
- Improved overall CSP system efficiency by 2% to 3%
- Reduced TES costs by 30% over conventional sensible-heat TES, reducing LCOE costs by more than 6%.
-

Accomplishments

- Selected salt mixtures suitable for commonly used steam cycles (6 to 13 MPa steam pressures and 560°C) with various CSP plants
- Identified and characterized two candidate coating technologies for use with the heat exchanger
- Developed an experiment setup for qualifying coatings as "anti-stick" to selected salt mixture; in the experiment rig, the salt mixture is pumped through an external heat exchanger with partial frozen salt slurry returning to tank
- Developed a mathematical model of the PCM storage system.
-

Future Directions

- Continue tests with coatings and salt mixtures
- Develop mathematical models and empirical correlations and conduct simulation and economical analysis
- Demonstrate the concept with a scaled engineering model.

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1. Introduction

CSP plants are being designed to generate power between 50 and 100 MW using high-pressure steam Rankine system cycles. In a typical CSP system, the heat transfer fluid is heated to 400°C to 565°C to provide heat for vaporizing and superheating steam at steam pressures from 5.9 MPa (850 psia, saturated steam temperature of 274°C) to 12.4 Mpa (1,800 psia, saturated steam temperature of 327°C). The collected heat is stored in a TES system to ensure heat on cloudy days and at times when the sun is not shining. In conventional systems, this heat is stored as sensible heat in salts or oil. Storing heat as latent heat of fusion in inorganic salts (PCM storage), however, significantly reduces the amount of salt required and the tank size. For PCM storage, this system has many challenges. DOE and Terrafore are jointly researching approaches to address these challenges in this project.

2. Technical Approach

Our innovative approach to solve this is to use inorganic salt mixtures that have a simple phase diagram, and the mixture is a dilute eutectic composition. When a dilute eutectic freezes, an equilibrium liquid becomes associated with it. This solid with the associated liquid has the consistency of a slurry, which can be pumped to an external heat exchanger, thus forcing the molten salt over the heat exchanger tubes and causing the freezing solid particles to remain in the molten slurry. The forced convection heat transfer caused by flow velocity is significantly larger than conduction through solid. In addition to this, a "salt-phobic" coating on the heat exchanger surface can further prevent the salt from sticking to the tubes, and a nucleating agent and chemical added to the salt mixture can help with the flow and heat transfer properties.

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3. Results and Accomplishments

The project funded by DOE will affect the overall economics in three ways:

- Reduce total thermal storage cost in dollars per kilowatt-hour ($/kWh). We estimate a reduction of at least 6% over the conventional systems. The amount of salt used is reduced by more than 30%.
- Improve cycle efficiency because of the use of higher turbine cycle pressure such as 2,400 psia. A 2% to 3% improvement in system efficiency is indicated.
- Introduce flexibility to charge storage when collection temperatures are lower than the design such as during partial cloud cover and early morning. During these times, the energy is collected at lower temperatures to melt the PCM salt in the tank.

FY 2009 accomplishments include the following:

- Selected salt mixtures suitable for commonly used steam cycles (7 to 16 MPa steam pressures and 560°C)
- Identified and characterized two candidate coating technologies for use with a heat exchanger
- Developed an experiment setup for qualifying coatings as anti-stick to a selected salt mixture; in the experiment rig, the salt mixture is pumped through an external heat exchanger with partial frozen salt slurry returning to tank
- Produced solids different from that of single salt using a qualified Terrafore proprietary composition of salt mixture (dilute eutectic).

Solidification morphology

- Started measuring salt solidification morphology versus temperature using contact angle rig
- Started measuring viscosity of solid slurries
- Polished samples of frozen solids to view them in the scanning electron microscope to study the interface between solid and tube surface.

Mathematical model

- Developed a mathematical model for predicting heat transfer coefficient in external heat exchangers as molten salt freezes on heat transfer tubes
- Developed a mathematical model for storing heat using thermal stratification in a tank with freezing slurry returning to the tank.

4. Planned FY 2010 Activities

- Continue tests with coatings and salt mixtures
- Develop a heat exchanger and demonstrate on a laboratory-scale system.

5. FY 2009 Special Recognitions and Patents

- Submitted patent on latent heat storage for CSP systems.
- Presented at a CSP conference in San Francisco
- Interviewed on Radio Melbourne on challenges and benefits of PCM storage.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009:

- Terrafore, Inc., Riverside, CA
- University of California at Riverside, CA
- Jet Propulsion Labs, Pasadena, CA
- Pratt & Whitney Rocketdyne, Pasadena, CA
- H.V. Setty, University of Minnesota, MN.

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Molten Salt-Carbon Nanotube Thermal Energy Storage for Concentrating Solar Power Systems
Texas A&M University, Texas Engineering Experiment Station
Total Award: $1,875K ($1,500K DOE / $375K nonfederal)

Objectives

- Evaluate the ability of composite TES materials (nanoparticles in a molten salt) to:
  - Reduce $/kWh$_{th}$ for TES system
  - Increase specific heat of TES materials
  - Increase thermal conductivity of TES materials
  - Increase temperature range of TES materials
- Demonstrate that the composite material does not increase corrosion of stainless steel.

Accomplishments

- Demonstrated 20%–75% improvement in specific heat of carbonate eutectic TES material by adding 0.1%–1.5% by weight concentration of nanoparticles
- Demonstrated 10% improvement in specific heat of nitrate TES material (75% transient improvement)
- Discovered a new way of synthesizing carbon "onion" nanoparticles in situ in the carbonate eutectic TES material by adding 1%–5% by weight of surfactant (SDS) that led to enhancement of specific heat by 16%–55%
- Demonstrated first-order freeze/thaw cycle stability of composite TES materials
- Developed numerical models (using molecular dynamics simulations) to optimize the size and concentration of nanoparticles
- Developing a theoretical model to explain the observed enhancement of specific heat of nanofluid-eutectics
- Demonstrated 15% improvement in specific heat of chloride eutectic TES material by adding 1% by weight concentration of nanoparticles.

Future Directions

- Identify and evaluate nanoparticle materials that will remain in suspension in nitrate TES material
- Demonstrate long-term freeze/thaw cycle stability of composite TES materials
- Demonstrate corrosion compatibility of composite TES materials with stainless steel
- Demonstrate improved thermal conductivity of composite TES materials
- Determine the optimum size and concentration of the nanoparticles for enhancing thermophysical properties
- Develop a detailed cost and sizing model for a TES system using composite materials that balances cost and performance of nanoparticle composition and dimensions.

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1. Introduction

Reducing the cost of TES systems can both reduce the cost of electricity produced by CSP plants and increase their income by shifting their electricity output into more lucrative time periods. One approach to achieving these goals is to improve the thermophysical properties of the TES material. Previous research indicated that adding small amounts of nanoparticles to a fluid could dramatically improve the thermophysical properties of that fluid. We are investigating applying these findings to improve the specific heat and thermal conductivity of TES materials for CSP plants.

2. Technical Approach

The project team identified candidate materials, including the base materials (salts) and nanoparticles. We fabricated candidate materials using a variety of techniques, including dry mixing and aqueous solution mixing (using pool and film boiling techniques using a syringe pump). We measured the thermophysical properties of the candidate materials. The primary tool used in this task was a digital scanning calorimeter (DSC), which measures the specific heat of the material. We also used a laser flash analyzer for specific heat and thermal conductivity measurements. The main issue

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addressed in the first year of the program was demonstrating feasibility of the concept.

3. Results and Accomplishments

- Demonstrated 25%–75% improvement in specific heat of carbonate eutectic material at 0.5%–1.5% loading of SiO_2 nanoparticles (12/09)
- Demonstrated 20%–70% improvement in specific heat of carbonate eutectic material at 0.05%–0.1% loading of carbon nanotubes (CNT) (12/09)
- Demonstrated 10%–75% improvement in specific heat of nitrate material when Al_2O_3 added; still need to stabilize composite (11/09)
- Discovered a new way of synthesizing carbon onion nanoparticles in situ in the carbonate eutectic TES material by adding 1%–5% by weight of surfactant (SDS) that led to enhancement of specific heat by 16%–55%
- Demonstrated 15% improvement in specific heat of chloride eutectic material at 0.5%–1.5% loading of SiO_2 nanoparticles (12/09)
- Completed preliminary analysis of economics of improving TES material (11/09)
- Measured irregular results (up to 10%–20% improvement) for the specific heat of carbonates, chlorides, and nitrates at 0.1%–1% loading of cellulose nanocrystals (CNC).

We demonstrated the feasibility of improving the specific heat of a molten salt by adding small amounts of nanoparticles. We were able to show improvements in the specific heat in both the solid and liquid phases of the material. Our preliminary economic analysis showed that improving the specific heat of the TES material by 50% reduces TES system cost by 30%.

4. Planned FY 2010 Activities

- Refine and extend measurements of specific heat for composite materials (07/10)
- Demonstrate freeze/thaw cycling of composite materials (08/10)
- Demonstrate corrosion of stainless steel in composite material is no worse than it is in base salt (09/10)
- Demonstrate improvement in solid-phase thermal conductivity of composite materials (10/10)
- Identify means to stabilize nitrate-based composites (10/10)
- Reevaluate CNC nanoparticle composites (10/10)
- Improve economic model of TES system (11/10).

5. Major FY 2009 Publications

D. Shin and D. Banerjee, “Investigation of Nanofluids for Solar Thermal Storage Applications,” Paper No. ES2009-90465, *ASME Energy Sustainability Conference, San Francisco, CA, July 20–25, 2009*.

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Research and Development for Novel Thermal Energy Storage Systems (TES) for Concentrating Solar Power
(University of Connecticut)
Total Award: $1,687K ($1,290K DOE / $397K nonfederal)

Objectives

- Develop innovative heat transfer devices and methods for novel TES systems involving PCMs
- Develop new thermosyphons or heat pipes or both to reduce thermal resistances within the TES and improve performance of the CSP system
- Generate fundamental knowledge to enable system design through experimentation and modeling
- Enable reduction of LCOE by up to $0.06/kWh.

Accomplishments

- Identified candidate heat-pipe working fluids
- Designed and fabricated low-temperature multiple heat-pipe experimental apparatus
- Developed system-level TES model, including PCM, heat pipes, and heat transfer fluid
- Developed fundamental heat transfer and fluid dynamics model for PCM melting and solidification, including periodic melting and solidification.

Future Directions

- Identify specific PCM and heat-pipe working fluids
- Design and fabricate moderate/high-temperature heat pipes
- Design and fabricate moderate/high-temperature multiple heat-pipe experimental apparatus
- Finalize system-level and fundamental models
- Validate moderate/high-temperature models with experimental results
- Apply the system model to full-scale systems
- Optimize PCM/heat-pipe configurations.

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1. Introduction

The overall objective is to develop innovative heat transfer devices and methods for novel TES systems involving PCMs.

2. Technical Approach

The technical approach is to embed thermosyphons or heat pipes into PCMs to reduce thermal resistances between the PCM and the working fluid, to increase the overall efficiency of concentrating solar power generation plants. Experimental and modeling approaches are taken, and novel heat pipes and PCM modules will be fabricated to test their performance. Ultimately, computer programs will be made available to develop these components as well as to implement them in an optimal manner in actual concentrating solar power systems.

3. Results and Accomplishments

- Successfully identified a number of candidate working fluids for the heat pipes as well as candidate PCMs for incorporation in both current and future concentrating solar plants.
- Developed a system-level model, using a thermal element network approach, and used it to identify tradeoffs in the TES system. The effectiveness of adding heat pipes to improve performance was clearly shown and quantified. Companion experimental work with low-temperature PCMs and heat pipes has commenced with promising preliminary results.
- Developed a detailed simulation model to predict melting and solidification of the PCM. The model is capable of predicting both charging and discharging of thermal energy storage system; it uses no empirical models or input.

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4. Planned FY 2010 Activities

- In FY 2010, we will continue to identify and test candidate PCMs and heat pipe working fluids. Both the system model and the detailed models will be finalized and validated with detailed experimental measurements.
- High-temperature experiments will be designed and conducted for both the heat pipes and PCMs, individually as well as in an integrated module.

5. University and Industry Partners

- Virginia Polytechnic Institute and State University.

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Novel Molten Salts Thermal Energy Storage for Concentrating Solar Power Generation (The University of Alabama, Tuscaloosa)

Total Award: $1,895K ($1,500K DOE / $395K nonfederal)

Objectives

- Develop low melting point (LMP), molten salt, TES media with high TES density for sensible heat storage systems, with the following specific characteristics:
- Lower melting point compared to current salts (<222°C)
- Higher energy density compared to current salts (>756 MJ/m^3)
- Lower power generation cost compared to current salts: 2020 goals are to reduce the cost of TES to less than $15/kWh$_{thermal}$ and achieve round-trip efficiencies greater than 93%.

Accomplishments

- Confirmed the ternary eutectic mixture in the $LiNO_3$-$NaNO_3$-KNO_3 system by thermodynamic calculations and experimental verification to meet/exceed the specific targeted characteristics, offering good heat capacity and thermal stability
- Identified five additional salt mixtures that had the balance of properties to exceed the criteria; I identified 14 other novel mixtures that have attractive thermal properties
- Found that the six salt mixtures have melting temperatures in the range of 80°–116°C, and energy storage density from 1,000 to 1,500 MJ/m^3, which is a 30%–90% improvement over the current salt.

Future Directions

- Study the six proposed salt mixtures further; characterize all the necessary thermal and physical properties and optimize them for performance and cost based on their potential to meet the DOE 2020 goals
- Evaluate the additional identified salt mixtures to determine their thermal and physical properties, then optimize them for performance based on their potential.

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1. Introduction

Two key opportunities to reduce the cost of CSP plants are improved HTF and improved methods for TES. As part of this work, DOE awarded this contract to the University of Alabama (UA) to define and evaluate advanced HTF for CSP plant use.

The current molten salt, an HTF and thermal storage media, is a mixture of 60 wt% $NaNO_3$ and 40 wt% KNO_3. The liquid temperature range is 220°–600°C. The main disadvantage of this salt mixture is the high melting point. The UA program objective is to develop LMP molten salt TES media with high TES density for sensible heat storage systems. The media must also meet thermal stability criteria and be economically viable.

Preliminary work suggested that a ternary eutectic in the $NaNO_3$-$LiNO_3$-KNO_3 system had the required properties of lower melting point and higher TES density than the current salt system.

2. Technical Approach

To develop candidate LMP salt materials, the project team used thermodynamic calculations backed up by atomic and molecular modeling that estimated eutectic compositions melt points of mixtures, heat capacity, and density. From that work, energy storage density was calculated. Material properties were validated by using experimental techniques, including DSC for melt point and heat capacity, TGA and DSC for thermal stability, Brookfield viscometer for viscosity, and other characterization techniques. The potential impact of LMP materials on the TES facility is being evaluated by modeling the TES using MatLab®. Finally, costs are predicted by collecting current salt pricing and calculating salt mixture cost, and normalized mixture cost/energy stored ($/kWh$_t$). System costs are estimated by comparative ratioing with material capability and

cost predictions for an Andasol 1 TES-2 tank system as recently estimated by the Electric Power Research Institute (EPRI).

Thermodynamic calculations involve the minimization of the Gibbs energy of fusion expression for temperature and composition in a given system. Standard thermodynamic databases were used to input the thermodynamic parameters for the calculations. Regular solution approximation, which deals with expressing the excess Gibbs energy as a function of composition, was used for all the systems studied. Calculated eutectic points in binary systems were compared with the data available in the literature (phase diagram). Calculating the melting points of higher order systems involved extending the regular solution approximation employed for binary systems.

3. Results and Accomplishments

- Completed assessment of the base ternary eutectic system for melting point
- Predicted the melting point, density, heat capacities, and energy storage densities for more than 28 molten salt mixtures
- Completed the estimation of TES costs of the candidate LMP salt systems
- Completed identification of two or more potential salt system candidates that have lower melting points and higher energy density compared to current salts, and that are economically viable.

Thermodynamic calculation and experimental verification confirmed that the novel baseline UA ternary material, shown as the second material in Table 1, meets and exceeds the go/no-go goals. Using extensive thermodynamic calculations to predict melting point, density, and heat capacity, the project team identified 14 additional novel mixtures of molten salt with attractive thermal properties.

Melting points for all of these materials are well below the baseline UA ternary of 116°C, with one mixture predicted in the 80°C region. In addition, energy storage density for each of these materials is well above the solar salt. HTF compound costs were estimated based on the current supplier's price quotation, and TES system costs for a two-tank, direct approach were estimated for each of these materials. From the large set of qualifying materials, the team selected six specific mixtures further study; details are given in Table 1.

As shown in Table 1, the current solar salt price estimate is $1.08/kg, less than novel mixture costs of $1.27 to $2.21/kg. Because these novel materials offer much higher energy storage densities, however, both HTF material inventory and equipment (tank) size can be significantly reduced. Figure 1 also shows the resulting system cost estimates. Systems using the proposed materials approach the 2020 goal of $15/kWh$_{thermal}$. The UA baseline ternary showed a melting point significantly below the conventional solar salt and the Hitec salts. The calculated density and heat capacity for the UA baseline ternary showed improvements over the solar and Hitec salts.

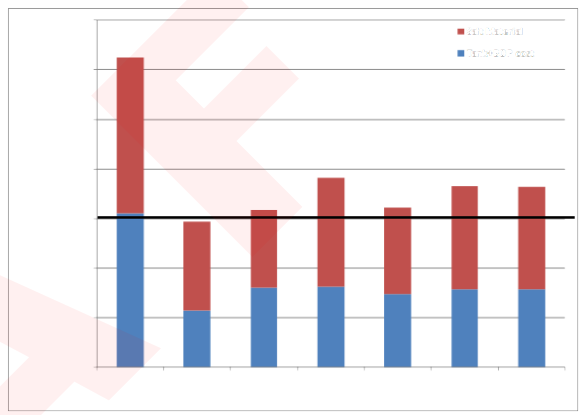

Fig. 1. Cost estimates for proposed HTF systems vs. solar salt baseline

The experimental melting point was 117°C and the experimental heat capacity of 2.3184 J/g.K was obtained at 500°C. These properties turn into a significant advantage for the UA baseline ternary's energy storage density, at 1524 MJ/m^3, nearly 100% greater than conventional solar salt (756 MJ/m^3) and significantly greater than values for the Hitec salt (955 MJ/m^3).

Thermal stability, shown in Figure 2, is good at 500°C. Weight loss of the salt at 500°C was less than 0.1%.

Fig. 2. TGA-DTA data showing the thermal stability of UA baseline ternary salt

4. Planned FY 2010 Activities

- Synthesize the six candidate salt mixtures proposed from year 1; study and optimized all the necessary thermal and physical properties for performance and cost based on their potential
- Further pursue additional salt mixtures that were identified to determine the necessary thermal and physical properties.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
The University of Alabama/ Ramana G. Reddy	Tuscaloosa, AL rreddy@eng.ua.edu	Develop LMP molten salts thermodynamic and transport property model, and experimental validation of the property data. Also develop LMP molten salt media with high TES system.	357.5	116
United Technologies Research Center/ James R. Irish	Hartford, CT irishjr@utrc.utc.com	Contribute atomic/ molecular and thermal modeling of system. Collaborate with UA in component attributes to evaluate improvements and cost reductions available in TES system.	142.5	35.6

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Development and Performance Evaluation of High Temperature Concrete for Thermal Energy Storage for Solar Power Generation
University of Arkansas
Total Award: $770K ($616K DOE / $154K nonfederal)

Objectives

- For the 2020 DOE goal for TES systems , achieve costs of less than $15/kWh$_{thermal}$ and achieve round-trip efficiency greater than 93%. Concrete as a material is inexpensive and the media cost/kWh$_{thermal}$ is reported to be $1. Hence this is a viable sensible heat solid media technology for TES. The objective is to develop and test high-performance concrete that can withstand temperatures up to 600°C.
- Develop computer model to study the heat transfer rate with and without fins.
- Test the developed concrete for TES using thermal cycling and evaluate the performance.

Accomplishments

- Developed a concrete mix that can withstand temperatures of greater than 600°C
- Developed and validated a 3D FEM model to study the heat transfer rate
- Used the model to study different fin arrangement effects on heat transfer rate.

Future Directions

- Develop a heating system to heat the concrete blocks up to 600°C
- Test the effect of heating rate on the performance of concrete as well as energy storage using concrete around a single steel tube
- Test a 4x4 steel tube system with concrete for energy storage and concrete performance.

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Reducing the Cost of Thermal Energy Storage for Parabolic Trough Solar Power Plants
Abengoa Solar, Inc.
Total Award: Phase 1 $625K ($500K DOE / $125K nonfederal)
Phase 2 TBD
Phase 3 TBD

Objectives

- Identify opportunities for cost reduction in near-term TES systems
- Identify two mid-term TES options with greater opportunities for cost reduction
- Demonstrate the TES options with the best cost reduction potential for parabolic troughs plants in the near term and midterm.

Accomplishments

- Completed design and model of 125 MWe_net baseline Therminol plant with 6 hours of two-tank molten salt storage
- Completed preliminary assessment of several TES concepts and chose three for more detailed investigation (advanced molten salt, phase change material, concrete)
- Completed transient performance models of TES concepts in TRNSYS.

Future Directions

- Finalize detailed technical and economic analysis of best three concepts
- Use Phase 1 results to illustrate reduced LCOE and make go/no go decision for further investigation.

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1. Introduction

State-of-the-art TES systems use a molten salt in a two-tank configuration. Although the two-tank systems are functional, the cost of such TES systems for parabolic trough plants must be reduced to be economically attractive. This work focuses on two approaches for reducing the cost of TES for trough plants:

- Research cost reduction opportunities for the indirect two-tank molten-salt design
- Develop alternative TES options that might be applicable for trough plants for midterm projects.

2. Technical Approach

- Develop sizing models in Engineering Equation Solver (EES) and transient performance models in TRNSYS to both assess plant performance and create bill of materials necessary for engineering, procurement, and construction cost estimates.

3. Results and Accomplishments

Abengoa developed a TRNSYS performance model for the 125 MWe_net baseline Therminol plant with 6 hours of two-tank molten salt storage, and obtained a cost estimate for such a plant. Researchers completed a preliminary assessment of several TES concepts, and selected three concepts for more detailed investigation (advanced molten salt, phase change material, and concrete). Transient performance models were developed in TRNSYS for each TES concept and attached to the plant model to account for system interactions and performance limitations. Performance analyses are being carried out for comparison with the baseline. Detailed cost estimates are also being obtained for each concept; these will be combined with performance results to calculate LCOEs for each concept.

4. Planned FY 2010 Activities

- Finalize detailed technical and economic analysis of best three concepts
- Select a concept and system development requirements for Phase 2
- Make a go/No Go decision on Phase 2
- Develop a prototype and scale-up if Phase 2 is approved.

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5. Major FY 2009 Publications

D.A. Arias, A. Gavilan, and R. Muren, "Pumping Power Parasitics in Parabolic Trough Solar Fields," *SolarPACES 2009, Berlin, Germany, September 15–18, 2009*.

D.J. Chapman and D.A. Arias, "An Assessment of the Supercritical Carbon Dioxide Cycle for Use in a Solar Parabolic Trough Power Plant," *Proceedings of SCCO2 Power Cycle Symposium 2009, Troy, NY, April 29–30, 2009*.

R. Muren, D. Arias, and B. Luptowski, "Performance Based Cost Modeling of Phase Change Thermal Energy Storage for High Temperature Concentrating Solar Power Systems," *Proceedings of the AMSE 2009 International Mechanical Engineering Congress & Exposition IMECE2009, Lake Buena Vista, FL, November 13–19, 2009.*

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Indirect, Dual-Media, Phase Changing Material Modular Thermal Energy Storage System
ACCIONA Solar Power, Inc.
Total Award: Phase 1 $625K ($500K DOE / $125K nonfederal)
Phase 2 TBD
Phase 3 TBD

Objectives

- Design, validate at prototype level, and then demonstrate a full-size TES system based on PCM TES modules; the

PCM TES module will be part of a TES system that can facilitate a decrease in LCOE by 2020.

Accomplishments

- Derived several different configurations
- Began developing heat transfer and fluid flow models that can be adapted to each design.

Future Directions

- Perform detailed heat transfer and fluid dynamic modeling
- Design the PCM TES module and the PCM TES system
- Fabricate and test a 100-kWht PCM TES module prototype.

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1. Introduction

An unsophisticated, modular, and scalable TES system could facilitate the attainment of a LCOE of $0.07/kWh by 2015.

The proposed design uses the inherent characteristic of molten salt to solidify during discharge to gain access to its latent heat properties. As discharging of the system concludes, the vat of salt will be fully solidified.

2. Technical Approach

The research team examined the design concept using value engineering criteria, consolidating the best configurations for the PCM TES module.

Also during FY 2009, the team created heat transfer and fluid dynamic models. These models will determine the heat storage capability and pumping capacity needed for the system and will provide a key go/no-go evaluation of the project.

3. Results and Accomplishments

The first achievement was to consolidate all of the design concepts that were examined for this project. Four different design concepts were derived. Next, TRNSYS was used to begin modeling the problem with standard program components. The current iteration can charge and discharge the storage system based on step functions and temperature-dependent flow control.

4. Planned FY 2010 Activities

- Continue modeling with standard components to simulate the latent heat portion of discharge (03/10)
- Begin building proprietary components (04/10)
- Begin translating the model elements into a physical design, which will segue into the lab unit design (06/10)
- Design the PCM TES module and the PCM TES system (11/10).

DRAFT

Innovative Application of Maintenance-Free Phase-Change Thermal Energy Storage (TES) for Dish Engine Solar Power Generation
Infinia Corporation
Total Award: $9,361K ($5,423K DOE / $3,939K nonfederal)

Objectives

- Provide preliminary design for 1-hour TES/dish Stirling demonstrator and preliminary LCOE estimate by the end of Phase 1 (FY 2009)
- Build and demonstrate 1-hour storage prototype based on the 3 kW commercial CSP system by the end of Phase 2 (FY 2010)
- Manufacture, deliver, and field test a statistically significant number of 4- to 6-hour storage TES/CSP systems by the end of Phase 3 (FY 2011 through FY 2012).

Accomplishments

- Completed the preliminary design of the 1-hour storage demonstrator
- Completed the preliminary LCOE estimate
- Finalized 50% of the design for the 1-hour storage demonstrator.

Future Directions

- Complete final design of the demonstrator
- Initiate design of an increased capacity dish for a 4- to 6-hour TES/CSP system
- Build and test prototype the demonstrator in FY 2010.

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1. Introduction

Integrating TES modules with dish Stirling systems will enable operation during cloud transients and provide dispatchable power for 4 to 6 hours after daylight hours, at a net incremental cost that can be shown to add a higher incremental value to the system, reducing LCOE in volume production.

2. Technical Approach

The TES system uses a PCM salt with a high melting point to maximize energy storage density by using both the latent heat of fusion and the sensible heat capacity over a wide range of operating temperatures. Heat will be conducted into and out of the salt via heat pipes. Thermal modeling analysis was used to optimize the configuration of heat pipes in the device.

3. Results and Accomplishments

Infinia completed the preliminary design and started final design of the 1-hour demonstration prototype. Researchers determined the size of the TES device, as well as the size, number, and placement of the heat pipes, required for optimal performance. The strategy for integrating the TES device with a commercial CSP system was defined, and a preliminary levelized cost of energy study was conducted. Figure 1 shows the demonstrator prototype.

4. Planned FY 2010 Activities

FY 2010 activities will focus on completing the final design of the demonstrator system, its fabrication, and testing. Preliminary design for a larger dish suitable for a 4- to 6-hour storage device will also be completed. Specific items include:

- Build the 1-hour TES demonstrator
- Demonstrate TES on-sun
- Complete larger dish design.

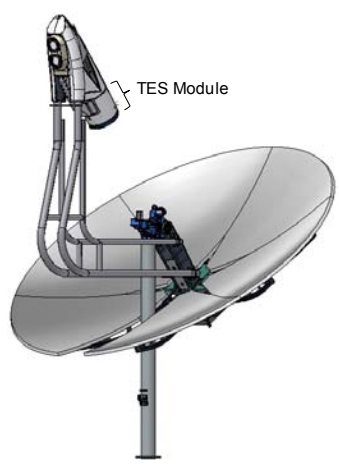

Fig. 1. Demonstrator prototype

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5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Infinia Corporation/ Songgang Qiu	Kennewick WA	Principal investigator, Stirling design	457	117
Penn State University Applied Research Lab/ Tim Miller	State College, PA	Thermal modeling and analysis	43	
Consultant/ Barry Penswick	Stevenson, WA	Stirling engine performance modeling	11	
Thermacore, Inc./ John Thayer	Lancaster, PA	Heat pipe design	74	

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CSP Energy Storage—Multiple Technologies Compared
US Solar Holdings, LLC
Total Award: $4,084K ($2,038K DOE / $2,046K nonfederal)

Objectives

- Provide a path to maximally cost-effective, commercially proven CSP energy storage technology
- Conduct further proof and cost reduction analysis for the thermocline TES technology
- Develop and prove a new, novel Sand Shifter TES technology.

Accomplishments

- Developed mathematical modeling tool for thermocline systems
- Detailed key design elements and identified the preferred design method for thermocline and Sand Shifter TES systems
- Generated initial cost estimates of the preferred design options for each technology.

Future Directions

- Validate design stage work through prototype construction, testing, and analysis
- Improve primary design approaches based on prototype testing and performance evaluation
- Refine cost estimates based on prototype performance analysis.

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1. Introduction

The goal is to develop and demonstrate TES systems that are competitive at the utility scale. To achieve this objective, the project examines innovative design approaches to lower the cost of TES technologies.

2. Technical Approach

2.1 Thermocline TES
Phase 1 focused on identifying and evaluating key design parameters in order to converge on a preferred thermocline system design approach. Selecting the preferred design approach involved a detailed evaluation of existing thermocline designs and an assessment of all key design parameters. An ideal heat storage system was first modeled to determine baseline system parameters (i.e., transfer fluid mass flow rate, total tank volume). Heat storage analysis was conducted to model the heat transfer between the transfer fluid and the solid heat storage filler material. This model was then used compare various system configurations to converge on a preferred design approach.

2.2 Sand Shifter TES
The Sand Shifter is an innovative idea requiring much time spent on modeling, basic R&D, and preliminary design. Both system and component design development was necessary. A comprehensive list of critical issues was identified and design development and testing were directed at resolving these issues, none of which now appear to make the concept infeasible. Heat transfer performance has been a special concern. Many approaches and detailed information remain proprietary pending patent execution, but an overview of the results and accomplishments is given here.

Attention has focused on the adverse capital cost and energy consumption of the auxiliary materials handing equipment (MHE). Design improvements explored and testing indicates that MHE energy consumption will be acceptable. Also, some structural design issues are critical and several promising designs are now under development.

3. Results and Accomplishments

3.1 Thermocline TES

- Evaluated key design parameters and compared various system configurations to select a preferred design approach (07/09)
- Developed a model to predict heat storage performance for different thermocline conditions and configurations (05/09)
- Designed and partly constructed a lab-scale heat storage test loop prototype (09/09)
- Consulted expert vendors for initial cost estimate of preferred design approach (08/09).

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3.2 Sand Shifter TES

- Demonstrated basic concept with a preliminary 50-inch diameter prototype (12/08)
- Identified alternative mineral sand, which is under consideration (02/09+)
- Identified an alternative storage volume with multiple advantages (02/09)
- Continued sand erosion tests, which show negligible wear (03/09+)
- Completed preliminary designs, with favorable cost analyses (03/09)
- Verified heat transfer results (03/09+)
- Developed Various heat exchanger surface designs (02/09+)
- Performed sand distribution tests (09/09).

4. Planned FY 2010 Activities

3.1 Thermocline

- Construct prototype system and perform testing plan
- Refine initial cost estimate incorporating design updates.

3.2 Sand Shifter

- Construct a fully integrated Sand Shifter prototype system
- Perform testing plan to evaluate and update key design components
- Refine initial cost estimate incorporating design updates.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
US Solar Holdings LLC/ Jake Stephens	Tucson, AZ jstephens@ussolarholdings.com	Principal investigator and project manager providing industry perspective and business analysis	47.4	0
Georgia Tech/ Sheldon Jeter	Atlanta, GA Sheldon.jeter@me.gatech.edu	Lead role in Sand Shifter subproject design, development, and prototyping efforts	131.8	0
University of Arizona/ Perry Li	Tucson, AZ peiwen@email.arizona.edu	Lead role in thermocline subproject design, development, and prototyping efforts	86.2	0
Arizona Public Service/ Phil Smithers	Phoenix, AZ phil.smithers@aps.com	Project oversight, utility scale development perspective, and technical assistance		
IroncCo Enterprises/ Jeff Krauss	Phoenix, AZ jeff.krauss@ironco.net	Steel fabrication consultant, prototype construction	20.6	0
Klondyke Construction/ Steve McClain	Phoenix, AZ smcclain@klonykeinc.com	Construction consulting	9.6	0
Harris Group/ Steve McCormick	Denver, CO Steve.mccormick@harrisgroup.com	Engineering analysis and cost estimating	33	0
Arizona State/ Kenneth Sullivan	Tempe, AZ Kenneth.Sullivan@asu.edu	Construction management and project planning controls	9	0

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Advanced CSP Concepts Summary

Advanced Concepts task is recognized by the solar industry as the world's leader because of its work in optical characterization and accelerated and outdoor testing of advanced solar reflectors and its repository of material durability data. Optical characterization and accelerated and outdoor testing are not duplicated by private industry work.

Low-cost, high-performance, durable advanced optical materials are necessary to meet the demands of advanced system designs and to achieve the cost and performance goals that are needed to commercialize CSP technologies. The overall objective is to develop, validate, and aid the commercialization of advanced reflector systems that can dramatically reduce the cost of concentrating solar power.

	NREL Total $K	SNL Total $K	Other Total $K	Solar Total $K
Advanced CSP Concepts	**725**	**900**	**2910**	**4535**
Advanced Materials & Concepts	**475**	**0**	**0**	**475**
Power Tower R&D	**0**	**850**	**500**	**1350**
CSP Funding Opportunity Announcement – Advanced Concepts	**250**	**50**	**2410**	**2710**

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Advanced Materials and Concepts

Performing Organizations:	Sandia National Laboratories (SNL) National Renewable Energy Laboratory (NREL)
Key Technical Contacts:	Clifford K. Ho (SNL, Primary Contact), 505-844-2384, ckho@sandia.gov Cheryl Kennedy (NREL, Primary Contact), 303-384-6272, cheryl.kennedy@nrel.gov Gregory J. Kolb (SNL), 505-844-1887, gjkolb@sandia.gov Nathan P. Siegel (SNL), 505-284-2033, npsiege@sandia.gov
DOE HQ Technology Manager:	Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2009 Budgets:	$750K (SNL), $475K (NREL)

Objectives

- Develop advanced cross-cutting technologies and modeling and analysis tools that will aid in the development, validation, and commercialization of concentrating solar power (CSP) components and systems to increase performance and dramatically reduce costs to less than 10¢/kWh by 2015
- Create probabilistic performance model to assess levelized cost of energy (LCOE), validation of solid particle receiver model, and develop CAD models for detailed coupled-process evaluation (SNL)
- Reduce by half the cost of the mirrors 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 the durability of optical materials to determine the lifetime of solar reflector materials (NREL).

Accomplishments

- Performed review of existing codes and software for CSP technologies; identified deficiencies and needs (SNL)
- Developed and implemented probabilistic methods to quantify uncertainties and sensitivity analyses for assessing the system performance and economics (LCOE) of a central-receiver power plant (SNL)
- Acquired tools and methods to develop integrated models to assess the impact of wind, gravity, and thermal loads on optical performance of collector/receiver systems (SNL)
- Developed and validated model of a solid particle receiver for advanced high-temperature power-cycle and thermal-storage capabilities (SNL)
- Worked with California Energy Commission (the Commission) to develop analyses for glint and glare hazard assessments of solar thermal power plants (SNL)
- Published five papers on these topics at international conferences (SNL)
- Performed durability testing and published results of optical materials that potentially reduce 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).

Future Directions

- Implement probabilistic modeling into existing tools used by industry (e.g., Solar Advisor Model, or SAM) (SNL)
- Continue developing integrated models (CAD/fluid/thermal/structural/optical) to understand and optimize system design and performance under normal and off-normal conditions (SNL)
- Continue durability testing of optical materials to determine the lifetime of solar reflector materials (NREL)
- Continue optical characterization of advanced reflector materials and accelerated and outdoor testing of commercial and experimental reflector materials, as well as those developed under CSP funding opportunity announcements (FOAs), the CSP industry, and cooperative research and development agreements (CRADAs) to determine the lifetime of solar reflector materials and to support industry/program needs (NREL)

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- Analyze and publish testing results of reflector materials applied to CSP technologies (NREL).

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1. Introduction

Modeling and analyses are critical to understanding and improving the performance and economics of CSP systems. Because these systems are complex, multiple models of components at various scales are needed. Information from detailed smaller scale models and tests are often distilled into larger scale, total-system models.

SNL's work focuses on the need to develop and integrate rigorous models and analyses of detailed components and processes to make large-scale, total-system models more accurate and reliable. Probabilistic models are needed to quantify uncertainties and to identify parameters and processes that have the most impact on system performance and cost. In addition, coupled processes such as the impact of wind and gravity loads on optical performance of heliostats or other collectors are needed to better predict performance in normal and off-normal conditions. Finally, models of emerging technologies that can improve system performance (e.g., solid particle receivers for advanced high-temperature power cycles and thermal storage) and cross-cutting analyses that will enable certification of CSP systems are described.

NREL is conducting R&D to meet the DOE SETP goal, which is for CSP technologies to be cost competitive in the intermediate power market at 8–9¢/kWh with six hours of storage by 2015. The long-term goal is for CSP systems to be cost competitive in the baseload power market with 12 to 17 hours of thermal storage by 2020. CSP systems cannot hit these targets without aggressive cost reductions and revolutionary performance improvements from technology advances. The SETP Multi-Year Technical Plan targets cost reductions of up to 50% for the solar concentrator. Reducing the field labor and collector support structure costs will have a significant impact. Commercialization of CSP technologies requires the development of advanced reflector materials such as lightweight, easy-to-install, front-surface reflectors with antisoiling coatings. The objective of NREL's research is to identify new, cost-effective advanced reflector materials that are durable with weathering.

2. Technical Approach

SNL performed a review of existing CSP codes and software to identify gaps and needs in modeling and analysis. Based on this review, researchers recommended and demonstrated probabilistic modeling. In addition, the investigators started using integrated CAD-based software (Solidworks®), computational fluid dynamics software (FLUENT® and Cosmos FloWorks®), stress analysis software (Cosmosworks®), and advanced optical modeling software (ASAP®) to model detailed components and coupled processes. The results of these codes and models will enable a more thorough characterization of uncertainties and focus research on areas that are most important to enable more reliable total-system model predictions.

NREL is working on the following:

- Developing advanced reflector materials that are low in cost (<$2.50/ft^2) and that maintain high specular reflectance (>95% into a 2- to 4-mrad cone angle) for long lifetimes (30 years) under severe outdoor environments
- Testing the durability of optical materials to determine the lifetime of solar reflector materials.

Researchers identify candidate reflector materials based on their potential for high optical performance, long outdoor durability, and low cost. To assess their optical durability, materials are optically characterized at the outset and re-measured periodically as a function of exposure time after being subjected to real and simulated weathering environments. Candidate solar reflectors being tested include thick and thin glass, silvered polymer, aluminum, and front surface reflectors. The optical materials database contains more than 20,000 samples encompassing more than 300,000 measurements over a 23-year time span of optical durability results.

3. Results and Accomplishments

SNL achieved the following accomplishments:

- Researchers developed probabilistic models of a 100-MWe power tower to quantify uncertainties associated with LCOE predictions. Stepwise linear regression sensitivity analyses revealed specific features and processes that were found to be important to the LCOE, including costs, component reliability, parasitics, receiver absorption, and heliostat performance.

- SNL recently designed and tested a prototype solid particle receiver. Researchers developed computational fluid dynamics models to simulate the performance of a prototype solid particle receiver being operated at SNL. The simulations included irradiation from the concentrated solar flux, two-band re-radiation and emission within the cavity, discrete-phase particle transport and heat transfer, gas-phase convection, wall conduction, and radiative and convective heat losses. The investigators compared the simulated and measured temperatures of the particles and cavity walls and calibrated solar flux parameters. This validated model will be used to develop next- generation receivers that allow higher temperature power cycles and energy storage for increased efficiency. The solid particle receiver enables both high-temperature operation and low-cost thermal energy storage that can potentially meet DOE cost goals and generate baseload solar power for industry.

- Applications and certifications for solar thermal power plants often require an assessment of "visual resources" at the site, which include an evaluation of general health and safety issues associated with potential glint and glare. Rigorous and uniform treatment of glint and glare, however, is lacking. In FY 2009, SNL compiled safety metrics and developed a hazard evaluation method. Models are being developed to assess potential hazards associated with glint and glare in each of the primary CSP technologies: (1) power tower systems, (2) linear concentrator systems (e.g., parabolic troughs), and (3) dish/engine systems. Once developed, these cross-cutting analyses can be used by applicants seeking certification of concentrating solar thermal power plants.

Selected NREL accomplishments follow:

- The Advanced Concepts R&D project was awarded a rank of 3.7 at the March 2009 SETP Peer Review meeting. The review team specifically recognized the work of NREL's Advanced Materials task and its importance to industry. The team strongly recommended that the project be expanded with additional space, equipment, and personnel resources allocated for this activity.
- Researchers provided significant industry support (i.e., technical assistance and data) to more than 180 CSP and CPV industry partners on solar reflectors.
- NREL signed a CRADA with Schott Solar in April 2009 to rapidly commercialize NREL's solar selective coating for parabolic trough receiver tubes in CSP systems.
- NREL and 3M signed a CRADA in July 2009 to develop silvered polymeric mirrors as low-cost replacements for glass mirrors in CSP systems.
- Capabilities that had been degraded after five years of significantly constrained budgets continue to be restored. NREL is hiring new staff members and purchasing and installing new optical measurement and accelerated weathering equipment.
- A subcontract to modernize the optical materials database and make it accessible via the Web was placed with EMagnit, and development work has begun.
- NREL staff members participated in DOE Glass Standard committee meetings and assisted with inclusion of Solar Glass standards (for PV, CSP, and SH applications) into the ASTM E44 Solar Applications working group.
- NREL scientists also participated (by presenting and chairing) in SolarPACES Task III meetings on reflectance characterization and standards, receiver characterization and standards, and lifetime and durability. NREL staff also attended a session on mirror/module characterization and standards.

4. Planned FY 2010 Activities

SNL will work on the following:

- Advanced trough analysis
- Optical facet/method lab development
- Advanced modeling
- Solid particle receiver analysis
- Molten salt heat transfer for advanced power cycles
- Selective absorbers for power tower receivers.

NREL's work in advanced reflectors will entail the following:

- Continue to perform durability testing of optical materials and publish results of durability testing of solar mirrors (09/10).
- Implement Web-accessible database (03/10).
- Build 2-mrad spectral specular reflectance laboratory instrument (09/10).
- Demonstrate and report on low-no H_2O cleaning design project by CU team (06/10).

- Complete and document review of existing procedures to form basis for identifying and developing CSP testing standards. Perform round robin reflectance measurements for standard development (03/10).

In the area of advanced reflector FOA support, NREL will perform the following tasks:

- Report on application of SLP methodology to 3M silvered polymer and glass mirror samples (09/10).
- Report on status of FOA projects (09/10).
- Report on VSHOT and two-axis tracking for Alcoa and PPG collector (09/10).

NREL's work in advanced absorbers will include the following:

- Report on optimized NREL coating generated by sputtering and test optical properties and results of stability tests (03/10).
- Generate Ashby diagrams and report on potential systems (09/10).
- Complete and document review of existing procedures for receiver testing to form basis for identifying and developing CSP testing standards (03/10).

5. FY 2009 Special Awards

The SkyTrough™ Parabolic Trough Solar Concentrating Collector was awarded an R&D 100 award (bestowed by *R&D Magazine*) in August 2009. The SkyTrough™ uses ReflecTech® Mirror Film, a lightweight, weatherproof, glass-free, slide-in mirror developed by NREL Advanced Materials task members and SkyFuels.

6. Major FY 2009 Publications

SNL published the following in FY 2009:

C.K. Ho, Software and Codes for Analysis of Concentrating Solar Power Technologies. SAND2008-8053. Albuquerque, NM: SNL (2008).

C.K. Ho and G.J. Kolb. "Incorporating Uncertainty into Probabilistic Performance Models of Concentrating Solar Power Plants." *Proc. 2009 ASME 3rd International Conference on Energy Sustainability, San Francisco, CA, July 19–23, 2009.*

C.K. Ho, C.M. Ghanbari, and R.B. Diver, "Hazard Analyses of Glint and Glare from Concentrating Solar Power Plants." *Proc. SolarPACES 2009, Berlin, Germany, September 15–18, 2009.*

C.K. Ho, S.S. Khalsa, and G.J. Kolb, "Tools for Probabilistic Modeling of Concentrating Solar Power Plants." *Proc. SolarPACES 2009, Berlin, Germany, September 15–18, 2009.*

C.K. Ho, S.S. Khalsa, and N.P. Siegel, 2009, "Modeling On-Sun Tests of a Prototype Solid Particle Receiver for Concentrating Solar Power Processes and Storage." *2009 ASME 3rd International Conference on Energy Sustainability, San Francisco, CA, July 19–23, 2009.*

C.K. Ho, M. Roeger, S.S. Khalsa, L. Amsbeck, R. Buck, N. Siegel, and G. Kolb, "Experimental Validation of Different Modeling Approaches for Solid Particle Receivers." *Proc. SolarPACES 2009, Berlin, Germany, September 15–18, 2009.*

NREL published the following in FY 2009:

C.E. Kennedy, "The Potential of Concentrating Solar Power." *Association of Industrial Metallizers, Coaters and Laminators (AIMCAL) Fall Technical Conference 2008 and 22nd International Vacuum Web Coating Conference, Myrtle Beach, SC, Oct.22, 2008.*

C.E. Kennedy, "Reliability Testing of Optical Materials." *5th International Conference on Solar Concentrators for the Generation of Electricity (ICSC5), Palm Desert, CA, Nov. 18, 2008.*

C.E. Kennedy, "Requirements & Potential for Concentrating Solar Power Mirrors." *Glass Week 2009 for the Glass Association of North America (GANA), Las Vegas, NV, Feb.13, 2009.*

C.E. Kennedy, "CSP Applied Research." *DOE SETP Peer Review Meeting, Denver, CO, March 9, 2009.*

C.E. Kennedy, "Market Potential for Concentrated Solar Power and Photovoltaics." *2009 SEMICON West & Intersolar North America Analytical Symposium: Analysis of Photovoltaic & Semiconductor Materials, San Francisco, CA, July 15, 2009.*

C.E. Kennedy, "Development Path for an Advanced Solar Selective Coating." *SolarPACES 2009 Symposium, Berlin, Germany, Sept. 16, 2009.*

C.E. Kennedy, "Advanced Mirrors for Concentrating Solar Power." *SolarPACES 2009 Symposium, Berlin, Germany, Sept.16, 2009.*

7. University and Industry Partners

SNL

The following institutions provided in-kind participation in the Advanced Concepts activities: DLR, U. Wisconsin-Madison, UNLV, California Energy Commission, and NREL.

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NREL
During 2009, a partial list of industry interactions occurred with CSP reflector manufacturers and CPV manufacturers on the durability of solar mirrors includes: 3M, A Better Focus, Abengoa, ACA, Acciona, AGC (AFG, Glaverbel), Ahuru Energy, Airlight Energy, AIST-NEDO-METI, Alanod, Alcan, Alcoa, Ammonix, Arch Aluminum & Glass, Arontis, Atlas, Ausra, Bayer Material Science, BEI Space, Blach & Vetch, Boeing, BrightSource, Capitol Sun Group, Cardinal Glass, CENIM/CSIC, Ceplast Metallized Product, Chevron, Chisso, CNRC, Concentrator Optics, Convergent Solar, Cool Earth, Cooper Lighting, Copeland, Corning, Cosmo Films, Cyanto, Depostion Systems, Dow Chemical, Dow Corning, Energy Innovations, Enfocus, ESG, eSolar, Evonik, Fenzi, Flabeg (Naugatuck), Gardner Glass, Gear Solar, GE Energy, General Atomics, GlassTech, Google, Gossamer Space Frame, GreenVolts, Guardian, Honeywell, Hydro Aluminum, Imat SpA, Infinia, International Solar Technologies, ITRI, JDS Uniphase, Kearney & Assoc., KERI, Light Prescription Innovators, LLNL, Lockheed Martin, Lux Research, Luz II, Magna Mirrors, Micro Engineered Metals, McKinsey & Co., MegaWatt Solar, Mohave Sun Power, Momentive Performance, Nanotron, Naugatuck, Nitinol, Northside, Olymco, Pent-ht-optics, Pilkington, PPG, Pratt & Whitney, Praxair, QPanel, RAflector, RavenBrick LLC, Raytheon, ReflecTech, Replex, Rio Glass, Rocky Development, Rohm & Haas, SAES Getters, SAIC, Saint Gobain, Sandia, Sandvik, Schott Solar, SEIA, SkyFuel, Skyline Solar, Spraylat, SolarGenix, Solaria, SolarReserve, Solar Systems, SolarTech USA, Solarversa, Solel, SolFocus, Soliant, Solucar, Solyndra, Southwall, SPAWAR, Spinnaker Energy, Spraylat, SRI International, Stanford, Stirling Energy Systems, Sub-One, SunCube, SunPower, Sunray, SunTechnics, Surface Optics, Symmorphix, Texas A&M, The Boston Consulting Group, The Winslow Group, Uniaxis, United Solar, University of Baleric Islands, University of California Merced, University of Colorado, University of Hartford, University of Minnesota, Valspar, VaporTech, Veridian, Vitro America, Von Ardenne, Vulvox, Wavefront Technologies, West Virginia University, Wooly Parsons, Xandex, Xcel Energy, and Xerocoat.

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
3M Dr. Susannah Clear	St. Paul, MN scclear@mmm.com	To replicate SLP with 3M's new improved "Solar Reflector 1000" and perform 250 hour of on-sun ultra-accelerated natural sunlight testing	90	640
Schott Solar Dr. Alex Marker	Duryea, PA alex.marker@us.schott.com	To rapidly commercialize NREL's advanced solar selective coating	435 (TCD)	1,085

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Power Tower R&D

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contacts: Gregory J. Kolb, 505-844-1887, gjkolb@sandia.gov
Cheryl M. Ghanbari, 505-845-3426, cghanba@sandia.gov
Clifford K. Ho, 505-844-2384, ckho@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2009 Budget: $900K (SNL)

Objectives

- Perform R&D to support development of power tower systems.

Accomplishments

- Supported the development and test of Rocketdyne's first-generation heliostat
- Developed and tested a heliostat beam-characterization system
- Updated SOLERGY software to better predict annual performance of steam receivers
- Replaced NSTTF heliostat software and developed an algorithm to improve tracking accuracy
- Worked with the National Renewable Energy Laboratory (NREL) to release the first power tower model, NREL's Solar Advisor Model (SAM).

Future Directions

- Work with industry to develop and test components to be used in commercial projects
- Perform studies of next-generation power towers.

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1. Introduction

Five companies are pursuing commercial power-tower projects: Solar Reserve, eSolar, BrightSource, Abengoa, and SENER. Two new commercial projects (25 MW total) began operation in 2009, and power purchase agreements to build thousands of future megawatts were established. Most of SNL's power tower R&D supports industries efforts to develop successful near-term projects with the remainder devoted to R&D on next-generation technology.

2. Technical Approach

SNL interacts with the U.S. power tower developers to determine critical technology needs. Tasks that could be performed within the limits of the DOE budget allocation were defined.

3. Results and Accomplishments

3.1 Help Rocketdyne Develop a Prototype Heliostat

Solar Reserve and Rocketdyne are commercializing Solar-Two-type power tower technology. Rocketdyne has a long history in power tower development and were responsible for the construction of the Solar One steam receiver and Solar Two salt receiver. In 2008 Rocketdyne made a business decision to expand their scope of supply to include heliostats.

In FY 2009, SNL performed tech transfer activities with the Rocketdyne heliostat team. We made sure they were aware of the main conclusions of the heliostat R&D conducted over the years. SNL also sent Rocketdyne several mirror facets and loaned them two azimuth drives to help them evaluate heliostat technology options.

In late FY 2009, Rocketdyne installed their initial 62-m^2 prototype at the NSTTF and successfully tracked its beam on the solar tower for several days.

3.2 Develop a Heliostat Beam-Characterization System

SNL developed a user-friendly beam-characterization system that will allow industry to evaluate the optical quality of their heliostats and determine tracking accuracy. Lab-view-based

software reads inputs from a digital camera and solar-flux gauge. Flux contours and beam centroids are displayed in real time and recorded for further analysis.

The system is now routinely used at the NSTTF. Rocketdyne also ran the software to evaluate their prototype heliostat. The system is relatively portable and could be moved to non-SNL test sites selected by industry.

3.3 Update SOLERGY to Better Predict the Performance of Steam Receivers

SNL's SOLERGY code is used to simulate a power tower for a full year. SOLERGY uses 15-minute weather data and plant performance models to calculate the power flowing through each part of the solar plant.

Code predictions were compared with data from the Solar One steam receiver plant and the Solar Two salt receiver plant. The code does a better job of simulating a salt plant because the receiver and turbine-generator are able to operate during partly cloudy weather and using 15-minute average direct-normal insolation (DNI) data adequately represents insolation transients. Steam receivers, on the other hand, typically trip offline within a few minutes during partly cloudy conditions because of rapid degradation of steam temperature and pressure. Receiver trip leads to a turbine trip because there is no buffer storage between the receiver and turbine. During our validation effort conducted in the late 1980s we found that using 15-minute average DNI data caused SOLERGY to overpredict Solar One's actual annual performance by 16%. We showed that using 3-minute data gave a much better estimate, but 3-minute data are not generally available for many sites.

Because eSolar and Brightsource are resurrecting water-steam receiver technology, SNL improved SOLERGY's model of steam receiver plants and revalidated this new model with Solar One data. The new model will trip the receiver when insolation within a given time step is less than XX% of the clear-sky value that is predicted for that time step. We found that a value of 60% allows SOLERGY to achieve a much better prediction of actual Solar One performance. The new model was used during an evaluation of eSolar's distributed power tower system under a work-for-others contract that SNL established with eSolar.

3.4 Improved Heliostat Software

All of the controls for the heliostats at the NSTTF were replaced. This involved deploying software for sun tracking of each heliostat at each heliostat. Heliostat aiming, scram, and failsafe commands are sent from computers in the control room. The software deployment at each heliostat was completed as well as about a third of the software required for operation in the control room.

Ten of the dish Stirling systems currently operating at the NSTTF employ advanced tracking software that eliminate sun-tracking errors caused by several potential installation and manufacturing errors (e.g., a tilted pedestal). These algorithms were adapted for heliostat application during FY 2009.

3.5 Support Development of SAM Power Tower Model

A power tower module was incorporated into NREL's SAM in FY 2009. SNL's DELSOL code is used by SAM to define the optical design of a power tower. SNL worked with NREL to integrate DELSOL into SAM. SNL also performed detailed computational fluid dynamics modeling to evaluate the heat loss model implanted in SAM.

4. Planned FY 2010 Activities

- Rocketdyne will complete testing of their prototype heliostat and test three additional second-generation models.
- Improved heliostat tracking software will be tested on several heliostats at the NSTTF.
- We will evaluate next-generation power towers.

5. Major FY 2009 Publications/Presentations

G.J. Kolb, "Point-Focus Systems," Plenary Session of *SolarPACES 2009, Berlin, Germany, September 15-18, 2009*.

6. University and Industry Partners

Solar Reserve/Rocketdyne and eSolar were SNL's industry partners in FY 2009. A $30K work-for-others contract was established with eSolar. Rocketdyne worked side-by-side with SNL at the NSTTF under a user-facility agreement.

Advanced CSP Concepts Industry Projects

Performing Organizations: PPG Industries, Inc.; 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
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 2009 Budget: $2,881K (DOE/GO)

Objectives

- Develop reliable, affordable, and environmentally sound energy supply technologies to expand national electricity generation options and increase energy security by increasing domestic energy supply options.
- Identify advanced systems or components that can generate low-cost power (less than 7¢/kWh) with storage (12–17 hours) by 2020.

Accomplishments

- Continued five Concentrating Solar Power (CSP) Advanced Systems and/or Component awards
- Completed two Phase I go/no-go reviews (both awardees received "go" decision)
- Continued to assess CSP Advanced Systems and/or Component awards against the Solar Energy Technologies Program (SETP)/CSP subprogram goals and objectives.

Future Directions

- Evaluate each of the CSP Advanced Systems and/or Component awards to ensure they are progressing to meet the SETP/CSP objectives.

1. Introduction

CSP is of the most attractive renewable energy option in the southwestern United States. 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, Principal Investigator, and Agreement Title	FY 2009 Budget ($K)
PPG Industries, Inc., James McCamy, High Performance Reflector Panels for Concentrating Solar Power Assemblies	531
SkyFuel, Inc., Randy Brost/Randy Gee, Commercial Development off an Advanced, High-Temperature, Linear-Fresnel Based Concentrating Solar Power Concept	0*
3M Company, Susannah Clear, Cleanable and Hardcoat Coatings for Increased Durability of Silvered Polymeric Mirrors	996
Hamilton Sundstrand Corporation, Michael McDowell, Solar Power Tower Receiver Development	795
Solar Millennium, LLC, Ray Dracker, Advanced High Temperature Trough Development	559

*Funded in FY 2008 with additional funding planned in FY 2010.

PPG Industries, Inc.
High Performance Reflector Panels for Concentrating Solar Power Assemblies
Total Award: $3,639K: $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 Pb-free protective coatings and associated application process for long-life field deployments
- Develop mirrors with different (flat/bent) geometries and mechanical strengths for deployment in power tower, CLFR, and trough CSP applications.

Accomplishments

- Demonstrated feasibility of large-area mirror fabrication with PPG's technology for both bent and flat geometries
- Identified Pb-free coating and encapsulant materials and stack design for significantly improved durability under exposure to damp heat (85°C/85% relative humidity [RH]) and CASS accelerated testing conditions
- Completed 60 weeks of exposure to damp heat accelerated testing conditions, for mirror samples with no loss of reflectivity
- Completed initial fabrication process design and engineering study
- Completed initial cost study and validated SAM inputs supporting LCOE reduction of more than 7%.

Future Directions

- Focus on process development for low-cost manufacturing of large-area mirrors with 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 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 reduction to the CSP systems builder of the overall capital expenditure.

2. Technical Approach

PPG is investigating alternate materials, structures, and fabrication processes for reflector components. PPG is evaluating various materials and stack designs for the reflecting layers with protective back coatings and whether it is possible to bend the resulting mirror into parabolic or other advantageous shapes.

3. Results and Accomplishments

PPG completed the use of damp heat (85°C/85%RH) testing as the initial screening to determine potential materials candidates and moved to CASS accelerated as the primary tool for determining durability. This change in test protocol focus was confirmed with outdoor field testing at our research facility. Progress was made in new coating stack designs and materials for the reflective layer and encapsulant back coat. Researchers also investigated and demonstrated several different application methods and fabrication techniques using standard industrial equipment, as well as new methods for applying the back protective coating. These fabrication subprocesses were included in an initial process design and engineering study that investigated all the unit operations necessary to fabricate mirrors of different geometries. The study results confirm this approach is viable as a method for producing a high-value reflector for the CSP solar field.

During 2009, we demonstrated the feasibility of large-area mirror fabrication for both bent and flat geometries, using commercially available industrial-scale equipment. With this equipment we were successful in bending 20 samples with a 18 x 24 in. size, 10 samples with 36 x 48 in. size, and 6 samples with an LS-4 (61.8 x 74.8 in.) size.

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All were bent with a cylindrical radius of 160 inches. Figure 1 shows an LS-4 size mirror produced using this approach.

Fig. 1. Six samples of mirror coated glass bent to the LS-4 geometry (61.8 x 74.8"; 160" radius).

Gen 3 mirror samples completed more than 60 weeks of testing under damp heat conditions with no reduction in reflectivity. Figure 2 shows the front surface of these mirrors. The mirror on the left had no back protective coating, and the one on the right had a two-layer organic back protective coating that was developed by PPG.

Fig. 2. Glass side physical appearances of encapsulated (right) and unencapsulated (left) mirrors after 60 weeks of exposure under 85°C / 85% RH conditions. The straight line on the left of each sample is a scratch made in the mirror layers.

Substantial progress was made in improving the durability of the mirror when exposed to CASS accelerated testing conditions. This was achieved by improving the intrinsic durability of the reflective coating stack and the protection of the back protective coating. This protective coating was a two-layer, Pb-free paint system with a heterogeneous organic/inorganic base layer. Figure 3 shows the improved CASS durability with this system compared with an earlier (85/85 durable) material.

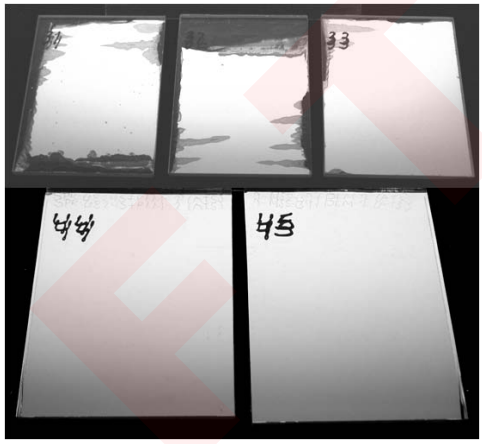

Fig. 3. Comparison of an all-organic back encapsulant system (top) and two-layer encapsulant system developed this period after 120 hours of exposure to CASS.

4. Planned FY 2010 Activities

- Down select the coating materials and designs for development in Phase 3
- Develop these materials and focus on low-cost processing for both flat and bent geometry mirrors
- Demonstrate all the fabrication unit operations for a set of large-area prototype mirrors
- Field test large-area prototype mirrors at multiple outdoor locations.

5. FY 2009 Special Awards and Patents

The High Performance Reflector Panels for Concentrating Solar Power Assemblies project won the 2009 PPG INNOVA award. This award is the highest recognition for an early-stage project and recognizes both technical achievement and expected market impact.

6. Major FY 2009 Publications

Product development results were presented to the solar community at the Solar Power International Conference 2009 meeting.

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SkyFuel, Inc.
Commercial Development off an Advanced, High-Temperature, Linear Fresnel Concept
Total Award: $4,139K: $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

- Completed analysis and optimization of linear power tower collector design and power plant configuration using linear Fresnel reflectors and direct molten salt thermal energy storage
- Produced conceptual designs of key collector hardware components
- Assessed overall performance and economic efficacy of the linear power tower design relative to a state-of-the-art parabolic trough concentrator.

Future Directions

- Implement and test collector components using the low-cost, high-performance designs developed in Phase 1
- Demonstrate efficient fabrication and installation processes for the linear power tower collector
- Estimate expected linear power tower economic performance, based on measured results
- Implement pilot linear power tower power plant in Phase 3.

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1. Introduction

The objective of SkyFuel's proposed multiphased 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. Technical Approach

The linear Fresnel collector architecture allows the design of solar collectors with large apertures, while keeping the bulk of the collector low to the ground. This reduces wind loads, which in turn allows the design of mirrors with significantly reduced material content. A key component of our design approach is to use ReflecTech® polymer film to produce low-cost yet high-performance mirror components.

Although Fresnel collector architecture offers inherent structural advantages allowing low-cost mirrors, it also entails numerous configuration options and design freedoms, leading to increased complexity. SkyFuel uses advanced computational optimization methods.

3. Results and Accomplishments

SkyFuel explored several different design concepts for key linear power tower collector components and developed efficient designs for each component, with two leading mirror concepts carried forward for competitive testing in Phase 2. Both designs substantially reduce material content compared to parabolic trough while avoiding the high part count and complexity characteristic of central receiver technologies.

SkyFuel developed in-house optimization software to generate and evaluate thousands of candidate collector and solar plant designs. These models were used to identify optimum designs for the collector geometry, plant layout, and storage system, using economic return as the optimization criterion. The models predict that a linear power tower using molten salt HTF will produce economic performance substantially higher than state-of-the-art parabolic troughs, and will support energy storage capacities in excess of 10 hours.

4. Planned FY 2010 Activities

Construct prototype LPT collector components and evaluate their cost and performance.

3M Company
Cleanable and Hardcoat Coatings for Increased Durability of Silvered Polymeric Mirrors
Total Award: $3,614K: $2,312K (DOE), $1,302K (Recipient)

Objectives

- Develop durable and cleanable coatings specifically for silvered polymeric mirrors with polymethylmethacrylate (PMMA) front surfaces
- Demonstrate manufacturing processes for these durable and cleanable coatings
- Evaluate and validate the performance of these mirrors and associated effect on LCOE.

Accomplishments

- Passed go/no go decision at end of Budget Period 1
- Identified, from accelerated weathering, three classes of coating chemistries compatible with PMMA substrates with good balance of abrasion resistance and durability that significantly improve abrasion resistance of PMMA
- Identified critical process spaces for coating chemistries that affect durable adhesion of coating after accelerated weathering
- Established preliminary understanding of coatings as technology that plays a role in enabling 15%–25% LCOE reduction.

Future Directions

- Optimize coating formulations and process conditions for durability, optical properties, cleanability, and adhesion
- Optimize coating conditions on a roll-to-roll coater for the top candidates based on accelerated aging and performance testing
- 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 are promising alternative low-cost replacements for thick glass mirrors in parabolic trough CSP installations, with the potential to reduce the installed system cost and LCOE for a trough installation. 3M is studying two aspects of silvered polymeric mirror films related to long-term durability–abrasion and soiling resistance of the acrylic protective layer.

2. Technical Approach

3M's approach in Budget Period 1 was to screen candidate hardcoat and cleanable coatings, use accelerated aging to test for durability and performance, and develop process optimization on samples with the best balance of abrasion and soiling resistance, optical properties, durability, and durable adhesion. Researchers evaluated top candidates to determine their feasibility for manufacturing and roll-to-roll coating processes. During Budget Period 2, 3M is optimizing formulations and pilot-scale processes for selected coatings. Results from bench and pilot work will be incorporated into an economic model. Final candidates will be selected for scale-up to large width, manufacturing scale, mirror coating in Budget Period 3. Coated mirror film from this phase will undergo field trial weathering, and results will be analyzed and incorporated into LCOE calculations.

3. Results and Accomplishments

3M successfully passed the Budget Period 1 go/no-go decision. Screening work and performance testing, both before and after accelerated weathering, narrowed a list of suitable coating chemistries to three classes of materials. Optimal classes of chemistry completed a minimum of 2,000 hours of accelerated weathering, and top coating candidates completed more than 3,000 hours. Preliminary pilot-scale process settings were demonstrated for top candidates. Continued optimization to improve the durability of adhesion, abrasion resistance, and cleanability is ongoing in parallel with pilot-scale process optimization. Preliminary cost analysis

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demonstrated the value of coatings as enabling technology for silvered polymeric mirrors, which in turn are enabling technology for advances in trough size and system heat load that have the potential to decrease LCOE by 15%–25%.

4. Planned FY 2010 Activities

- Optimize formulations and process conditions for best abrasion resistance, cleanability, and durable adhesion
- Test field and accelerated aging of pilot-scale coated silvered polymeric mirrors
- Incorporate field results into LCOE evaluation.

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Hamilton Sundstrand Corporation
Solar Power Tower Receiver Development
Total Award: $2,881K: $1,856K (DOE), $1,025K (Recipient)

Objectives

- Complete the following in Phase 1: panel sizing, preliminary design, cost evaluation, and go-forward plan
- Work on Phase 2 objectives: comprehensive panel design, cost estimates, manufacturability assessment, roadmap, and procurement.

Accomplishments

- Completed preliminary design review (PDR) and Phase 1 report
- Achieved a preliminary design that reduced the LCOE of solar power plants
- Received go ahead to proceed to Phase 2.

Future Directions

- Complete Phase 2 objectives
- Start Phase 3: panel fabrication, panel testing, and production scenarios
- Apply lessons learned from this receiver development to production-level CSP receivers.

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1. Introduction

The objective is to validate the manufacturability of a large-scale molten salt receiver panel and then confirm its operation in prototypic solar flux to reduce the LCOE from a central receiver solar power plant. The key technical risk to building larger power towers is in building the larger receiver systems, specifically the issues involved with key receiver panel features such as the large headers and longer tubes. This work involves designing, fabricating, and testing an advanced, molten salt, prototypic, subscale receiver panel for a large receiver system.

2. Technical Approach

Phase 2 of this three-phase project is ongoing. During Phase 1, researchers completed the preliminary design and cost evaluation. In Phase 2, the preliminary design is moving to critical design drawings. Long lead hardware has been ordered and the design is being reviewed for manufacturability, along with a final cost breakdown and a roadmap to reach 2020 cost goals. During Phase 3, the receiver will be fabricated and tested at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories.

Specific tasks completed during FY 2009 were panel sizing, preliminary design, cost evaluation, and go-forward plan. A PDR was held on March 5, 2009.

Phase 2 was delayed until October 2009 while Phase 1 progress was reviewed and verified. The Phase 2 schedule now extends into the summer of 2010.

3. Results and Accomplishments

The first major accomplishment of Phase 1 was the PDR completion. The PDR was presented to a panel of senior members of Pratt & Whitney Rocketdyne, responsible for supplying technical critique on the receiver design. They reviewed all aspects, including design requirements and features; manufacturing techniques; structural, thermal and materials analysis; electrical system details; quality plan details; risk analysis; and schedules/plans for the remaining phases. The PDR was well received and all attending believed the review was a comprehensive summary of the design to date.

Five actions were submitted that indicated areas for further iteration on the design. The main area of the design that the review board did not like was the tube clip retention system. The design presented in the PDR featured a snap-in feature that upon further reflection makes it inconvenient for easy installation and assembly. Therefore, the snap-in idea will not be incorporated and the design evaluated for a more technically sound and

easily installed clip assembly. Other recommendations were questions about the headers, tubes, and structural analysis. Five actions are entered into an action control system to track and manage each item.

The second major accomplishment of Phase 1 was completing the Phase 1 report. The report covered a summary of the work completed, including a discussion of the design and a summary of the cost evaluation of the project and the receiver hardware.

Fig. 1. Group of pictures showing fabrication and installation of a Solar II receiver at Daggett, CA.

The pictures in Figure 1 represent the progression and growth of the CSP receiver from the Solar II project in the 1990s to this current development receiver. The current design has larger tubes and headers to enable increased flow rate and a lower chance of tube blockage. Note that the DOE receiver is shorter than Solar II, on purpose, so that it can fit into the Sandia test facility. The full-scale receiver will be more than twice the size of the Solar II version.

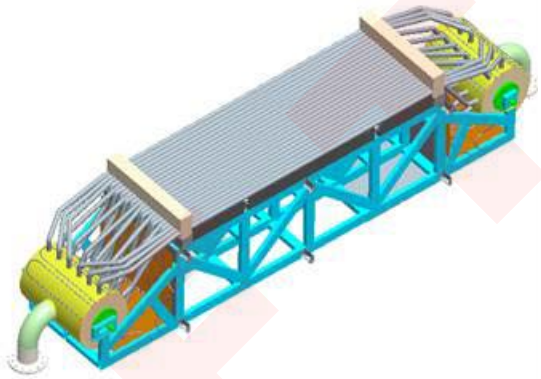

Fig. 2. Receiver being developed on this contract for testing at NSTTF.

4. Planned FY 2010 Activities

FY 2010 activities include completing Phase 2 tasks. The highlights of the schedule are as follows:

- Complete the 3D model (02/10)
- Order long lead hardware (04/10)
- Complete all the drawings (06/10)
- Perform Critical Design Review (06/10)
- Complete the Phase 2 final report (07/10)
- Expose the receiver to a heat flux of 1050 suns from the Sandia facility to reach the maximum temperature of 1050°F.

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Solar Millennium, LLC
Advanced High Temperature Trough Development
Total Award: $5,919K: $3,311K (DOE), $2,608K (Recipient)

Objectives

- Design, construct, and demonstrate an advanced parabolic trough collector loop at Kramer Junction Power Plant
- Modify test loop to be a molten salt parabolic trough test system
- Evaluate benefits and costs of molten salt as an HTF in a full-sized solar field.

Accomplishments

- Completed detailed design of all components and systems for the Kramer Junction HelioTrough loop.
- Successfully organized a large, international, competitive procurement process for all the collector and loop components. Schott and Flabeg were chosen vendors for solar components. Schott was selected as the HCE vendor because they can produce the larger diameter (89 mm) heat collection element (HCE) tube required for the HelioTrough. Likewise, Flabeg was the only mirror vendor that could manufacturer mirrors large enough for the HelioTrough design. Baotou Hydraulics Machinery Co. Ltd. was the low-cost bidder and therefore selected as the steel vendor.
- Determined from photogrammetry and deflectometry results that the collector has an intercept factor range of 98.9%–99.1% for 89.9 diameter HCEs
- Successfully built and commissioned the new HelioTrough loop.

Future Directions

- Conduct detailed tests of the full loop in 2010.

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1. Introduction

Flagsol designed a new high-temperature parabolic trough collector, the HelioTrough, to operate with a variety of HTFs. The HelioTrough has a larger collector aperture and HCE tube diameter compared to that of the Skal-ET. Also, the HelioTrough has a metal structure significantly different from the previous Skal-ET collector. Unlike the torque box design of the Skal-ET, the HelioTrough uses a flanged torque tube for supporting the cantilever arms. These improvements allow for a smaller solar field design with a larger thermal output.

To achieve high optical efficiency, the geometry of the reflector surface and position of the HCE tube must be extremely precise. To achieve such tight tolerances, the HelioTrough collector was built on a series of high precision aligned jigs. Before the work in Kramer Junction, the first HelioTrough prototype was erected in a warehouse in Dortmund, Germany. The work in Dortmund tested the drive pylon and offered jig and collector erection experience. This was to validate the construction of 40 HelioTrough collectors in Kramer Junction.

2. Technical Approach

This project is divided into four phases. Phase 2 highlights were procurement, erection, and commissioning in 2009. Phase 2 consisted of the completing the detailed engineering of the HelioTrough-VP1 Reference Loop, new assembly tools, and procurement, erection, and commissioning.

3. Results and Accomplishments

In addition to successfully constructing and commissioning the advanced HelioTrough loop, CSP Services conducted photogrammetry and deflectometry during HelioTrough construction to evaluate the optical precision of the collector and assembly jigs.

3.1 Photogrammetry and Deflectometry
Photogrammetry evaluates the alignment quality of the mirror assembly jig and twist of the HelioTrough. deflectometry evaluated the

parabolic shape and alignment of SCE 3 (before mirror jig realignment) and SCE 27 (after realignment). The deflectometry results indicate:

- Deviation from the ideal shape RMS 2.1–2.2 mrad
- Intercept factors: 98.9%–99.1% for 89.9 diameter HCE.

Tests indicated that the RMS deviation values for each mirror of SCE 3 (before mirror jig realignment) are low except in Row 2. Higher deviations in Row 2 can be attributed to gravitational influences in the measurement position of SCE 3. Figure 1 shows the local intercept factor (in percent) for SCE3. Green indicates all reflected rays hit the absorber tube. Red indicates part of the reflected rays miss the absorber tube, and blue indicates reflected rays will most likely miss the absorber tube. Total intercept factor with the sun-shape is calculated to be 98.9%.

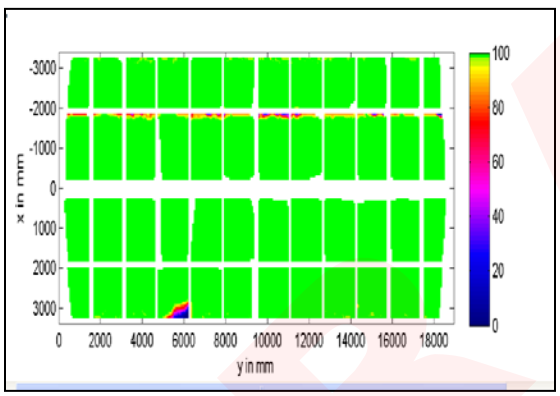

Fig. 1. Local intercept factor (in percent) for SCE3.

Similarly, deflectometry was performed on SCE 27 after realignment of the mirror jig. According to CSP results, the RMS deviation values for each mirror of SCE 27 are low except in Row 3. The lower edges of Row 3 were bowed, which most likely was caused by gravitational influences. Figure 2 depicts the local intercept factor (in percent) for SCE27. The color reference remains the same. Total intercept factor with the sun-shape is calculated to be 99.1%.

The optical design goals were fully achieved. In addition to these results, the jig assembly line is highly efficient with simple construction.

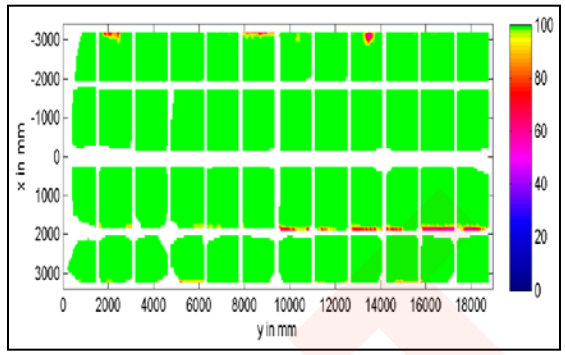

Fig. 2. Local intercept factor (in percent) for SCE27

3.2 Phase 2 Hydro, Electrical, and Mechanical Test

After all collectors were installed, researchers performed a hydro test to check for leaks and ensure the system is mechanically sound. A mechanical checkout package was completed and includes:

- Hydro completion report
- Weld map
- Pneumatic testing report
- 10% x-ray including film.

Additionally, an electrical completion package includes:

- Continuity report for every wiring run to ensure proper functionality
- Calibration data documents for all instruments
- Flow meters 100% tested and fully installed
- RTDS 100% tested and fully installed
- Differential pressure transmitters 100% tested and calibrated, tubing connection fully installed.

4. Planned FY 2010 Activities

Detailed test and evaluation of the full loop will be conducted. Advanced HCE tubes will be installed and performance metrics measured.

5. Major FY 2009 Publications

K.-J. Riffleman, “HelioTrough—A New Collector Generation for Parabolic Trough Power Plants,” presented at *Solar Paces 2009*.

Southwest Stakeholder Outreach

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contact: Thomas R. Mancini, SNL, 505-844-8643, trmanci@sandia.gov

DOE HQ Technology Manager: Charles Hemmeline, 202-586-6646, charles.hemmeline@ee.doe.gov

FY 2009 Budget: $250K (SNL)

Objectives

- Act as an information resource to concentrating solar power (CSP) stakeholders in accordance with the U.S. Department of Energy (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 a workshop for the SEPA Conference in San Jose, CA, Oct. 13–15, 2008
- Presented at the U.S. Environmental Protection Agency Brown to Green Conference in Santa Fe, NM, Dec. 10–12, 2008
- Presented at Green Energy Conference on CSP, Las Vegas, NV, Jan. 21–22, 2009
- Presented at Solar Today CSP Conference, Barcelona, Spain, Feb. 20–26, 2009
- Presented at World Bank CSP meeting, Washington, DC, Apr. 8–9, 2009
- Participated in SEIA Utility Scale Division Meeting, Washington, DC, Apr. 26–28, 2009
- Attended Schott Solar Dedication, Albuquerque, NM, May 11, 2009
- Presented at Concentrating Solar Thermal Conference, San Francisco, CA, June 3–5, 2009
- Presented on at ASME HT and Renewable Conference, San Francisco, CA, July 27–29, 2009
- Presented at SEPA Utility Scale Conference, San Jose, CA, July 31, 2009
- Presented at EUCI CSP Conference, Denver, CO, Aug. 24–26, 2009
- Presented at BLM Renewables Conference, Las Vegas, NV, Aug. 31, 2009
- Reviewed more than 20 proposals for CSP projects on BLM land in Arizona.

Future Directions

- Support outreach activities; include accelerated support of the BLM land lease evaluations.

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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 base load 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 on work funded under the market analysis/grid integration, resource assessment, and solar advisor support within the CSP market transformation activities.

2. Technical Approach

The general approach involves presenting at CSP conferences and supporting the Bureau of Land Management with deployment of CSP projects on public lands.

3. Results and Accomplishments

- Presented at more than 12 conferences
- Supported of reviews of more than 20 BLM proposals for CSP Projects in Arizona.

CSP Resource Assessment

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Mark Mehos (NREL), 303-384-7458, mark.mehos@nrel.gov

DOE HQ Technology Manager: Tex Wilkins, 202-586-1684, frank.wilkins@hq.doe.gov

FY 2009 Budget: $950K (NREL)

Objectives

- Obtain high-quality, site-specific measurements for model validation studies
- Develop best practices in using solar data for system siting and operations
- Develop satellite-based, large-area, direct normal solar irradiance (DNI)data sets
- Evaluate solar resource forecasting schemes.

Accomplishments

- Installed 11 SOLRMAP stations in the southwestern United States
- Hosted Concentrating Solar Power (CSP) Resource Assessment Workshop, and started writing Best Practices Handbook
- Further developed in-house capability of modeling solar resources using satellite imagery at high spatial resolution (5–10 km)
- Through IEA/SHC Task 36, continued to evaluate various methods for determining 1–3 day ahead solar resource (DNI) forecasting
- Made a strategic new hire (Manajit Sengupta) to lead our in-house capabilities in resource modeling, forecasting, and benchmarking.
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Future Directions

- Finalize Best Practices Manual and update as required
- Develop various empirical and physically based satellite modeling and solar resource forecasting capabilities (in combination with photovoltaics [PV] task)
- Continue to provide technical and OA support to IEA/SHC Task 36 and future tasks
- Produce periodic updates to the NSRDB (in combination with PV).

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1. Introduction

Assessing the amount and characteristics of DNI, including historical values as well as predicted future values, has been identified as a priority for CSP developers and utilities alike. Developers are becoming increasingly dependent on high-resolution hour-by-hour DNI data derived from satellite imagery. Although annual maps have been useful for identifying potential locations for near-term projects, accurately predicting the hour-by-hour (resource forecasting), month-by-month, and year-by-year (performance/revenue forecasting) DNI at locations of interest to developers and utilities is critical to large-scale deployment of CSP.

2. Technical Approach

Bankable Data and GIS Support: NREL works with interested developers and utilities through its SOLRMAP program to install up to 12 additional ground-based stations at targeted locations for site selection and system performance evaluation. The data support stakeholders and are available for NREL's further validation of satellite remote sensing model estimates of DNI, for producing high temporal resolution (up to 1-minute) measured solar and meteorological data needed for resource model development, and for use in projecting short-term in-situ data sets to long-term data that address seasonal and interannual variability of the solar resources.

Resource Data Modeling and Forecasting: NREL evaluates several solar resource forecasting methods that could meet the needs of CSP plant operators. In parallel with a task within the NCPV,

this task develops an in-house capability for producing site-time specific estimates of DNI solar resources using satellite imagery. This task also benchmarks various modeled DNI data sets against ground data stations to achieve several purposes. These procedures will be documented in a Best Practices Manual.

3. Results and Accomplishments

We installed 11 SOLRMAP stations, using the rotating shadowband radiometer configuration, in the southwestern U.S. SOLRMAP involves using cooperative research and development agreements to partner with industry to establish high-quality ground measurement stations in targeted locations. NREL uses the data for model development and other research; industry benefits from credible data sets validated by NREL solar resource assessment experts. Installing 11 stations completes an FY 2009 milestone.

NREL hosted a CSP Resource Assessment workshop to show stakeholders the quality, completeness, and bankability of data sets being produced. About 80 participants attended the 2-day meeting, and the outcome was a plan to develop a Best Practices Manual for applying solar resource data to CSP project design and implementation. A first draft of this manual is planned for completion in early FY 2010.

In collaboration with the PV task, we established procedures to access geostationary satellite data (both visible and IR channels), and are finalizing a procedure for converting this imagery into high resolution (5—10 km and 15—30 min) solar resource estimates, both GHI and DNI. The empirical modeling approach is nearing completion and will be tested in FY 2010. We are also developing a more physically based satellite model, to be used for research and benchmarking, through collaboration with NOAA, University of Wisconsin, and Colorado State University. Our efforts in FY 2009 focused on developing a scope of effort and establishing partnerships with the key researchers involved in NOAA's Geostationary Satellite Insolation Program.

Through IEA/SHC Task 36, we are gaining critical information and data on DNI solar resource forecasting techniques being examined in several regions around Europe. NASA/LaRC previously evaluated some of these techniques, and this work will continue under SETP support in FY 2010. Although mesoscale model input improves the result of solar resource forecasts using National Weather Service forecast products, considerable work needs to be done to obtain sufficient reliability of these forecasts for utility-scale operations. This task is cost-shared with the PV program.

4. Planned FY 2010 Activities

The CSP and PV tasks will be consolidated. CSP work will focus on four areas:

- Continue SOLRMAP station installations and data processing
- Finalize the Best Practices Manual, and periodically update the manual based on R&D results and user feedback
- Further develop high-resolution satellite-based DNI models, taking into consideration physical processes in the atmosphere; these models will be used to guide R&D efforts in resource assessment methods, benchmarking against other methods, and analytical studies at NRE.
- Continue further benchmarking and identification of research priorities of solar resource forecasting schemes.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Solar Consulting Services/Dr. Christ Gueymard	New Hampshire chris@solarconsultingservices.com	Develop high-quality spatial and temporal aerosol optical depth data for use in NREL-developed and external satellite-derived models	50	
State University of New York, Albany/: Dr. Richard Perez	Albany, NY perez@asrc.cestm.albany.edu	Test and evaluate various 1–3 day ahead solar forecasting methods	25	50**

* To be awarded in FY 2010.
** Cost share with PV Solar Resource Characterization task.

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Market Analysis & Grid Integration

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Craig Turchi (NREL, Primary Contact), 303-384-7565, craig.turchi@nrel.gov
Mark Mehos, 303-384-7458, mark.mehos@nrel.gov

DOE HQ Technology Manager: Tex Wilkins, 202-586-1684, frank.wilkins@hq.doe.gov

FY 2009 Budget: $1,418K (NREL)

Objectives

- Support development and use of tools for analyzing concentrating solar power (CSP) market penetration and grid integration to promote deployment of utility-scale CSP in the southwestern United States For FY 09 the agreement includes the following tasks: (i) CSP Market Analysis, (ii) Grid Integration and Optimized Dispatch Analysis, (iii) Transmission and Policy Support
- Support western transmission analysis and renewable energy study groups with CSP-specific analysis
- Support U.S. Department of Energy and Energy Information Administration analysis requests.

Accomplishments

- Updated Renewable Energy Deployment System (ReEDS) code to maintain current system costs for CSP technologies
- Used ReEDS model to produce a correlation map of solar generation potential, wind generation potential, and load for the 356 ReEDS regions
- Completed and published a life-cycle assessment (LCA) of the state-of-the-art thermal energy storage systems for parabolic trough plants
- Estimated the water consumption for wet-cooled parabolic trough plants and modeled the performance and cost of dry-cooled alternative designs
- Completely revised and updated the cost model for NREL's representative parabolic trough plant
- Assisted Bureau of Land Management (BLM) and Western Governors' Association (WGA) with identifying and mapping potential solar energy zones
- Analyzed the role and value of thermal energy storage for maximizing revenue from representative CSP plants in different utility markets
- Added U.S. Environmental Protection Agency brownfield sites and proposed renewable energy zones to Solar Power Prospector
- Modeled CSP with storage contribution in Western Wind and Solar Integration Study (WWSIS), demonstrating optimum storage capacity and showing increased CSP plant revenue when storage is used to match dispatch to load.

Future Directions

- Separate this project into CSP System Analysis, Market Transformation, and Grid Analysis activities to better focus activities and match staff expertise
- Complete and publish the parabolic trough LCA, followed by initiation of a similar activity for power towers
- Publish parabolic trough cost update and cooling studies
- Support Solar Vision Study
- Develop financial models representing current or proposed financial vehicle for utility-scale solar plants; incorporate the best models in the Solar Advisor Model (SAM)
- Investigate the potential of solar/fossil hybrid plant designs to reduce project risk and facilitate deployment of CSP technologies; this work will be undertaken with the Electric Power Research Institute (EPRI).

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1. Introduction

The 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 technology R&D to improve performance and reduce component costs, solar plant scale-up to minimize project development and O&M costs, and deployment to take advantage of volume production and learning. The CSP Market Transformation Project supports outreach and analysis intended to encourage the last two avenues for cost reduction.

2. Technical Approach

Task 1, CSP Market Analysis, includes continued development of ReEDS and use of the model to support internal and external requests for analysis. Additional activities include updating and tracking CSP system costs, examining the correlation of CSP and wind energy generation, and investigating environmental impacts of CSP deployment.

Task 2, Grid Integration and Optimized Dispatch Analysis, examined the optimum storage amount and dispatch plan for CSP plants with thermal energy storage.

Task 3, Transmission Policy Support, includes CSP support of regional transmission study groups, including the WGA/Western Renewable Energy Zone (WREZ) analysis teams.

3. Results and Accomplishments

- The ReEDS model was maintained with updated cost and configuration data for CSP technologies and used to produce a correlation map of solar energy potential, wind energy potential, and load for the 356 regions that represent the United States. This spreadsheet-based model can be used to show regions where solar and wind power are complementary in their ability to cover the regional load. Such interaction can offset the variable nature of both technologies, promoting higher renewable energy penetration.
- NREL analysts completed a life-cycle assessment of the thermal storage systems within a state-of-the-art parabolic trough plant. A large mass of nitrate salt is required for current thermal storage designs. The source of the nitrate salt has a significant effect on its carbon footprint, with mined salt producing much less greenhouse gas emissions than synthetically produced salt. The estimated carbon payback time for a thermal storage system with mined salt is approximately two months.
- Parabolic trough and power tower plants can be dry-cooled to reduce water consumption by more than 90%. However, dry-cooling is less efficient and leads to higher capital costs and levelized cost of electricity (LCOE). Analysis of wet-cooled and dry-cooled parabolic trough plants by subcontractor WorleyParsons indicated that larger than normal air-cooled condensers can minimize the efficiency penalty for dry-cooling and reduce the LCOE impact to 1¢/kWh or less.
- NREL also worked with WorleyParsons to update the cost estimates for parabolic trough power plants. The cost study used a reference plant with a 100-MWe capacity and 6 hours of thermal energy storage. Wet-cooling and dry-cooling configurations were considered. NREL developed a spreadsheet model that includes capital and operating costs by component, e.g., mirrors, heat transfer fluid, and operators, to allow users to estimate the effect of changes in component costs. Costs estimated by WorleyParsons were adjusted for a slight change in plant size and relocation to southwestern Arizona. The spreadsheet also allows users to estimate the costs of different-size plants and to take into account changes in commodity prices. The model is designed to work with SAM.
- NREL's analysts continued to assist working groups on the WGA/WREZ team and with the Solar Environmental Impact Statement. Both programs issued maps of proposed renewable energy zones to promote the siting of solar projects in locations that have better access to transmission and minimize the environmental impact of the facilities.
- NREL examined the value of thermal energy storage with respect to revenue generation for hypothetical trough plants in three different utility power markets. The analysis examined plants selling power into Arizona, Texas, and California markets and used historical

electricity price data to estimate the revenue from different dispatch schemes. Locational profit differences were shown to be mainly caused by differences in energy prices in the different system operator and utility systems considered, with differences in solar resource being a smaller determinant of CSP value. For example, a CSP plant in Texas was estimated to have higher profitability than a similar plant in Arizona or California despite the lesser solar resource in Texas. We showed that TES can increase CSP value both by allowing generation to be shifted to higher-priced hours and by increasing the use of thermal energy from the solar field. The operating profits of the CSP plant seemed relatively insensitive to the assumption that TES dispatch decisions are made a day at a time, which suggests that most generation shifting is done within a day or between adjacent days. A simple backcasting dispatch technique achieved at least 87% of the revenue that are possible with perfect foresight of energy prices and solar availability, indicating day-ahead forecasting will not be too challenging and including price and weather forecasts in the dispatch process can further improve the profitability of a real CSP plant. Despite these benefits, our analysis suggested that with current capital costs TES cannot be justified on the basis of energy value alone and further improvement in TES cost and performance are necessary. As overall CSP costs fall, the benefits of TES will be instrumental in helping CSP achieve higher market penetration and eventual cost parity with other generation sources.

- Analysis under the WWSIG resulted in similar conclusions with respect to CSP storage value, with the significantly higher capacity value of CSP highlighting the benefits of the CSP with thermal storage in meeting peak demand.

4. Planned FY 2010 Activities

- Divide this topic area into separate projects focusing on CSP System Analysis, Market Transformation, and Grid Analysis. This separation will clarify the activities and allow staff with relevant expertise to be engaged. For example, transmission experts from NREL's wind program area will be tapped to support analysis of CSP transmission issues.
- The LCA for an entire parabolic trough plant will be completed, adding to the TES analysis performed in FY 2009. NREL will leverage the plant design information compiled under the FY 2009 WorleyParsons contract to update trough plant costs. The detailed data used to estimate plant size and cost will produce much of the information necessary to accurately estimate facility LCA. Following completion of the trough plant LCA, NREL will begin a similar activity for power towers, with a planned completion in FY 2011.
- The parabolic trough cost update, trough plant LCA, and trough plant cooling studies will be published.
- The NREL CSP analysis team will support the Solar Vision Study by providing insight and information on CSP costs, CSP generation potential, and CSP environmental impact. The Solar Vision Study will assess the potential of solar power to produce 10% and 20% of the nation's electricity needs by 2030.
- Members of NREL's financial analysis group will examine financial vehicles being proposed for utility-scale solar power projects, develop spreadsheet models to assess the value of each approach. and incorporate the best models in SAM.
- NREL will release the first non-beta version of the Solar Power Prospector, incorporating enhanced data download capability, CSP plant data, and updated renewable energy zone information.
- Building on a relationship developed in FY 2009, NREL will work with EPRI to determine the potential of solar/fossil hybrid plant designs. Such designs can reduce the cost and project risk associated with large CSP projects. Solar/fossil hybrids are viewed favorably by the utility sector and can expand the deployment of CSP technologies, thereby accelerating learning rates and reducing CSP costs. NREL and EPRI will jointly develop a database of existing fossil plants that ranks suitability for solar augmentation. The team will also explore greenfield solar/fossil hybrid designs.

5. Major FY 2009 Publications

G.C. Glatzmaier and C.S. Turchi, "Supercritical CO_2 as a Heat Transfer and Power Cycle Fluid for CSP Systems," Paper ES2009-90332, *ASME Energy Sustainability 2009, San Francisco, CA, July 19-23, 2009.*

H. Garvin, C.S. Turchi, T. Decker, J. Burkhardt, and C. Kutscher, "Life Cycle Assessment of Thermal Energy Storage: Two-Tank Indirect and

Thermocline," Paper ES2009-90402, *ASME Energy Sustainability 2009, San Francisco, CA, July 19-23, 2009*.

D. Lew, M. Milligan, G. Jordan, L. Freeman, N. Miller, K. Clark, and R. Piwko, "How do Wind and Solar Power Affect Grid Operations: The Western Wind and Solar Integration Study," NREL/CP-550-46517, Golden, CO: NREL (2009).

Western Renewable Energy Zones—Phase 1 Report, Western Governors' Association and U.S. DOE (June 2009).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
WorleyParsons/ Rodney Gartner	Golden, CO Rodney.Gartner@WorleyParsons.com	Parabolic Trough Plant Cost Model	181	0
WorleyParsons/ Ryan Bowers	Golden, CO ryan.bowers@WorleyParsons.com	Parabolic Trough Cooling Studies	100	0
University of Colorado/ Dr. Jana Miford	Boulder, CO	CSP life Cycle Assessment	22	0
Ohio State University/ Ramteen Sioshansi	Columbus, OH sioshansi.1@osu.edu	Energy Storage and CSP Penetration Analysis	22	0
Western Governors Association		Support for Western Renewable Energy Zones Initiative	313	

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Solar Advisor Support

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Nate Blair (NREL), 303-384-7426, nate.blair@nrel.gov

DOE HQ Technology Manager: Tex Wilkins, 202-586-1684, frank.wilkins@hq.doe.gov

FY 2009 Budget: $380K (NREL)

Objectives

- Enhance the 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 with the best available concentrating solar power (CSP) models.

Accomplishments

- Reconstructed the entire SAM core code in C++ for several reasons:
  - Is significantly faster
  - Allows greater interaction with risk-assessment tools such as @Risk and CrystalBall
  - Incorporates Monte Carlo analysis (in conjunction with Sandia National Laboratories)
  - Enables SAM as a WebApp and an Apple Mac Version
  - Allows easier interaction with Excel, Matlab, and other web tools
  - Has improved maintainability.
- Released new SAM versions with:
  - Power tower model (based on sponsored university research) incorporated
  - Improved dispatch model for trough systems added
  - Enhanced GUI and greater graphical output capability, including tornado-chart analysis
  - Added time-of-use utility rates and automated IPP financing optimization.
- Conducted multiple in-person and web-based trainings for SAM.

Future Directions

- Continue DOE and user support and hold a full-day user forum
- Add additional CSP technologies to SAM, including a detailed, thermodynamic trough model and a generic optical model.

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1. Introduction

The objective of this project is to combine photovoltaics (PV), CSP, and thermal solar technologies into a single model using high-quality performance models developed by NREL, Sandia, and other partners. This will facilitate comparison by handling performance, costs, and financing consistently across technologies. Emphasis will be on a quality user interface to promote greater usage of quality tools by industry and the U.S. Department of Energy (DOE).

2. Technical Approach

The system modeling task consists of systems performance and cost modeling and validation projects. The primary function of SAM is to allow users to investigate the effect of variations in physical and financial parameters to better understand their effect 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, levelized cost of energy, and system capital and O&M costs. SAM is used not only by DOE, laboratory management, and research staff, but also 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.

3. Results and Accomplishments

A great deal of SAM development was accomplished in FY 2009. The primary activity was developing and releasing a rebuilt code base for SAM, which was done for a variety of reasons, including ongoing problems with the original platform chosen and its speed. Although not a planned deliverable, this activity was completed while still accomplishing the other planned deliverables (and some originally slated to be enhanced activities).

With more than 11,000 individuals having downloaded SAM, user support continues to be a growing issue, especially as some long-time users delve ever deeper into the capabilities.

Specific CSP SAM Accomplishments:

- Held a specific annual one-day workshop at Solar Power International covering CSP and PV
- Incorporate detailed modeling of a power tower system into the SAM model
- Added a significantly enhanced dispatch model SAM as well for trough systems
- Enhanced IPP financing and other utility-scale issues.

4. Planned FY 2010 Activities

Task #1: DOE and Industry User Support-SAM.

- Maintain user support for SAM via an email address supported by a subcontractor, a significant effort with more than 11,000 users
- Rework the SAM website to incorporate capabilities of our current Google Group site.

Task #2: *SAM Model Enhancement (Core*).

- Incorporate direct access to DSIRE incentive web feed.
- Complete SAM code restructuring:

Task #3: This task contains activities that are specific to CSP modeling within SAM:

- Debug and update CSP portion of model
- Incorporate thermodynamic model of steam Rankine cycle into parabolic trough
- Improve data exchange between SAM and Solar Power Prospector to facilitate CSP system feasibility studies
- Improve SAM interface for modeling integrated solar-fossil plants
- Develop generic optical efficiency model to allow for analysis of nonstandard CSP designs and importation of SolTrace model outputs.
- Incorporate enhancements to power tower model (DSG and cavity receiver)
- Collaborate with Cliff Ho at Sandia on their stochastic modeling efforts (using SAM as the engine)
- Integrate NREL cost model into SAM as a standard option.

5. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
Janzou Consulting/ Steve Janzou	Evergreen, CO Steve_janzou@nrel.gov	program the front-end and basic engine of the Solar Advisor Model	40	0
University of Wisconsin-Madison/ Prof. Sanford Klein	Madison, WI Klein@engr.wisc.edu	Development of Cavity Receiver Model	105	0
Paul Gilman/ Paul Gilman	Chicago, IL PaulGilman@earthlink.net	user support and technical writing support	20	0

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Solar Energy Development
Programmatic Environmental Impact Statement (PEIS)

Performing Organization: Argonne National Laboratory (ANL)
National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Heidi Hartmann (ANL, Primary Contact), 630-252-6487, hmhartmann@anl.gov
Doug Dahle (Primary Contact), 303-384-7513, doug.dahle@nrel.gov
Craig Turchi, 303-384-7565, craig.turchi@nrel.gov

DOE HQ Technology Manager: Frank (Tex) Wilkins, 202-586-1684, Frank.wilkins@ee.doe.gov

FY 2009 Budgets: $2,081K (ANL), $125K (NREL)

Objectives

- Develop environmental strategies and mitigation measures applicable to DOE-supported solar energy development projects, and utility-scale projects to be located on lands administered by the Bureau of Land Management (BLM) in six southwestern states (Arizona, California, Colorado, Nevada, New Mexico, and Utah)
- Evaluate and compare environmental impacts of utility-scale solar technologies, including parabolic trough, power tower, dish engine, and PV systems
- Identify BLM-administered lands suitable for utility-scale solar energy development from an environmental impact perspective
- Meet regulatory requirements of National Environmental Policy Act (NEPA).

Accomplishments

- Conducted second scoping period to solicit public comment on 24 solar energy study areas on BLM-administered lands; expanded scope of the PEIS to include detailed environmental impacts analyses in these areas (ANL)
- Distributed drafts of introductory chapters, affected environment description, impact analyses, and technical appendices for DOE, BLM, and Cooperating Agency review (ANL)
- Compiled extensive geographic information system (GIS) dataset (ANL)
- Participated in ongoing work with Cooperating Agencies and staff of related projects (Western Governor's Association Renewable Energy Zones [WREZ] study; California Renewable Energy Transmission Initiative [RETI] study) to coordinate analyses (ANL)
- Provided GIS solar data and recommended exclusions for ANL development of maps (NREL)
- Performed technical review of PEIS Solar Technology Overview appendix (NREL)
- Provided consultation and advice for Argonne/BLM/DOE solar project planning meetings and solar power plant tours. Ran ReEDS model simulations for proposed solar energy study areas (NREL)
- Maintained Solar PEIS Information Center website at http://solareis.anl.gov (ANL).

Future Directions

- With DOE and BLM, establish suite of strategies and mitigation measures applicable for DOE-supported projects (ANL)
- Publish PEIS Draft for public comment December 2010 (ANL)
- Respond to public comments; publish Final PEIS December 2011 (ANL).

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1. Introduction

Executive Order 13212 requires that federal agencies and executive departments take appropriate actions "to expedite projects that will increase the production, transmission, or conservation of energy." Executive Order 13514 requires that federal agencies take efforts to

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align their policies to advance local planning efforts for energy development, including renewable energy. Both DOE and BLM are undertaking various actions to comply with these orders. As part of these efforts, DOE and BLM are jointly preparing the Solar Energy Development PEIS to assess the environmental, social, and economic impacts associated with utility-scale solar energy development. Through the PEIS, the agencies will develop a comprehensive set of mitigation strategies and measures for various resources that will be applicable for utility-scale solar energy development projects supported by DOE, or on BLM-administered lands. The PEIS will also result in the amendment of BLM land use plans, a prerequisite for the granting of right-of-way (ROW) authorizations for solar developments on BLM-administered lands (see below).

The BLM administers approximately 256 million acres (1 million km^2) of public lands. As of March 1, 2010, the BLM was processing about 130 active applications (totaling about 74,000 MW of power) for ROW authorizations for utility-scale solar energy projects on BLM-administered lands; additional applications are being received and evaluated. For any of these projects to proceed, the BLM must issue ROW authorizations in accordance with the requirements of the Federal Land Policy and Management Act of 1976 (FLPMA). Prior to issuance of ROW authorizations, BLM land use plans must be amended to designate specific areas as available for application for solar developments.

2. Technical Approach

ANL

Environmental impact statements compare the impacts of various alternatives that the lead agency or agencies are considering implementing. For the Solar Energy Development PEIS, DOE's proposed action alternative is to amend its current investment and deployment strategy to more effectively integrate environmental considerations into technology investment and technical assistance decisions. Elements of this include (1) establishing technology performance program goals and prioritizing investments that minimize environmental impacts; (2) preferentially investing in grouped (such as state and regional focused renewable energy zone efforts) or dispersed solar projects based on the potential for minimizing environmental impacts; and 3) amending the current financial assistance strategy to incorporate environmental considerations earlier in the process, by developing and implementing a program of policies and mitigation requirements that DOE financial assistance recipients would be required to adopt when applying for DOE funding.

Alternatives being evaluated by BLM involve the identification of specific lands as available for ROW application, including potential designation of solar energy zones (SEZs) within which solar energy development would be prioritized over other land uses. In addition, BLM proposes to implement a program of policies and mitigation measures applicable to ROW authorizations for solar energy development. Certain BLM-administered lands would be excluded from solar development under all alternatives, including specially-designated lands (e.g., federally designated wilderness areas, wilderness study areas, national monuments, national conservation areas, national trails, and wild and scenic rivers) and lands with slope of greater than 5%.

In the PEIS, the impacts of the alternatives are assessed for the following resource areas and values: land use, water resources and availability, air quality (including emissions avoided), ecological resources and threatened and endangered species, visual resources, the acoustic environment, socioeconomics, environmental justice, paleontology and cultural resources, geologic setting and seismic hazard, transportation impacts, and health and safety. Assessments consider applicable regulations and BLM guidance, and compare the impacts of parabolic trough, power tower, dish engine, and PV technologies. Two parameters that are key for the comparison of impacts are land use (and associated habitat disturbance) and water use.

Potential mitigation measures for impacts are identified. Some potentially applicable mitigation measures will be recommended for consideration on a project-specific, location-specific, or technology-specific basis. Additionally, a subset will be identified as applicable and reasonable for all solar energy development projects; this subset will be identified as the agencies' environmental strategy, and included as requirements for projects over which each agency has jurisdiction. This set of mitigation measures will

be comprehensive and will be consistently applicable for utility-scale solar energy development projects supported by DOE or on BLM-administered lands.

The PEIS will also evaluate the potential cumulative impacts of solar energy development over the twenty year period through 2030. NREL is aiding in this task, through the provision of state-specific projected development levels (in megawatts).

NREL
Under this agreement, NREL staff support the needs of the PEIS team at ANL. NREL activities include providing information related to solar technology operating conditions, operating requirements, and performance, as well as modeling potential solar deployment using the Renewable Energy Deployment System model (ReEDS). NREL staff have attended public scoping meeting and continue to attend project meetings as requested by DOE and ANL. NREL GIS experts assist the Argonne team and BLM with mapping of potential solar energy study areas. NREL provides technical review of PEIS documents and assists the team with questions and concerns related to the operational needs of solar power plants.

3. Results and Accomplishments

ANLThe PEIS public involvement process is driven by NEPA regulatory requirements. To date, the Solar Energy PEIS effort has met and exceeded these requirements.

Drafts of a significant portion of the PEIS were delivered to DOE, BLM, and their Cooperating Agencies for review. These included the introductory chapters, description of the affected environment in the six-state study area, description of potential impacts and mitigation measures for each technology, and technology overviews. Review comments were incorporated into revised drafts.

In March 2009, BLM initiated changes to the scope of the PEIS in response to Secretarial Order 3285 issued by the Department of the Interior Secretary Salazar. This order established a goal of identifying which BLM-administered lands are best suited for utility-scale solar energy production and prioritizing development in these areas. This change in scope included the identification of 24 solar energy study areas, a second public scoping period (from June 30 to Sept. 14, 2009), and the addition of detailed impact assessments of these areas. Based on public comment, the 24 solar energy study areas have been modified slightly and are now being assessed as potential SEZs.

Work is under way to revise earlier draft sections of the PEIS to incorporate these changes in scope and to include the detailed impact assessments.

4. Planned FY 2010 Activities

ANL
PEIS staff will complete analysis of the impacts of the 24 SEZs and revisions to the previously drafted sections of the PEIS. In addition, analysis of the agency proposed actions and alternatives will be prepared. The preliminary draft PEIS is scheduled for completion at the end of August 2010, at which time it will be reviewed and commented on by the Agencies and by Cooperating Agencies. Comments will be incorporated as appropriate for release of the Draft PEIS in FY11 (12/10).

NREL
NREL will continue to assist the PEIS team as the activity continues in FY 2010 through FY 2012. Public comments will be posted in October 2009, and NREL will assist with reviewing and addressing these concerns, specifically as they relate to technology issues. NREL analysts will provide deployment modeling support via the ReEDS model to estimate where solar power plants are likely to be built and assess the value of proposed solar energy study areas with respect to transmission availability. A draft EIS that addresses public comments will be issued by Argonne in December 2010. This will be followed by another 90-day public comments period. NREL will again assist with addressing public comments prior to release of the final EIS in FY 2012 (12/11).

5. Major FY 2009 Publications

Solar Energy Study Area maps published. Announcement in *Federal Register* **74**, 124, June 30, 2009. Available at http://solareis.anl.gov/eis/maps/index.cfm.

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Operations & Planning Overview

The operations and planning section includes activities that cut across all subprograms. The activities reflected below support the funded subprograms to achieve the program's goals.

The Program Management project includes all of the management oversight at the national laboratories – National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) - as well as the support service efforts that are provided by New West and Sentech.

Equipment and Facilities includes equipment purchases at the labs that need to be funded through specially marked capital equipment accounts, as well as operations and maintenance (O&M) support for the National Solar Thermal Test Facility at SNL. The equipment purchase at NREL included an Atlas Weatherometer and an Oxygen Permeation device used for concentrating solar power (CSP) research and development (R&D).

Communications efforts include laboratory support for the solar communications as well as various communications tasks funded directly through HQ. These include several solar-related studies by the National Academy of Sciences (NAS), support for the American Solar Energy Society (ASES) Solar Tour, and the Solar Electric Power Association (SEPA) Conference.

International activities include both PV & CSP International Energy Agency (IEA) efforts (SolarPACES), as well as direct support for a project in India.

PBA Crosscut activities are managed by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's (EERE's) Office of Planning Budget and Analysis, which totaled 3.3% of solar program funding. Activities include cross-cutting analysis, the Renewable Electricity Futures Study, Green Power, and projects in Hawaii, Alaska, Brazil, and Israel.

The DOE SBIR activity funds Small Business Innovative Research projects that are managed by DOE's Office of Science. This came to 1.5% of Solar Program funding in FY 2009, however, the Solar Program benefits from specific solar projects that are selected under this solicitation.

Operations & Planning	NREL	SNL	Other	Total
Program Management	**1417**	**1531**	**3560**	**6508**
PV Program Management	1112	811	0	1923
CSP Program Management	305	720	0	1025
HQ Support Services	0	0	3560	3560
Equipment & Facilities	**202**	**800**	**0**	**1002**
CSP Equipment & Facilities	202	800	0	1002
Communications & International	**1247**	**200**	**1461**	**2908**
Lab Communications	834	200	0	1034
HQ Communications	0	0	1461	1461
International	413	0	0	413
PBA Crosscut	**0**	**0**	**5748**	**5748**
DOE SBIR	**0**	**0**	**2586**	**2586**
Total	2866	2531	13355	18752

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CSP Program Management

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

Key Technical Contacts: Thomas R. Mancini (SNL) 505-844-8643, trmanci@sandia.gov
Mark S. Mehos (NREL) 303-384-7458, mark.mehos@nrel.gov

DOE HQ Technology Manager: Tommy Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov

FY 2009 Budgets: $750K (SNL), $305K (NREL)

Objectives

- Effectively plan, administer, manage, and review the NREL and SNL Concentrating Solar Power (CSP) budgets
- Provide technical analysis and support services to the Department of Energy's (DOE's) Solar Energy Technologies Program (SETP or the Solar Program)
- Provide technical support for grid integration activities.

Accomplishment

- Successfully implemented CSP R&D and market transformation activities, as directed by DOE through the fiscal year (FY) 2009 Annual Operating Plan (AOP).

Future Directions

- Support SETP management of the CSP efforts
- Plan, administer, manage, and review the Solar Program at the national labs (NREL/SNL)
- Continue to support market transformation and grid integration activities, risk analysis, and CSP/Bureau of Land Management support.

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1. Introduction

The CSP activities are managed collaboratively. SETP leads the CSP work, which is carried out through SNL and NREL.

2. Technical Approach

At SNL, all CSP activities are overseen by Jeffrey Nelson. Thomas Mancini and Joe Tillerson are responsible for day-to-day CSP management and Charles Hanley manages the PV activities. Mark Mehos manages CSP activities at NREL.

3. Results and Accomplishments

- Completed development of the FY 2009 AOP and ensured that all FY 2009 CSP milestones were completed
- 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 the planning and implementation of all appropriate program meetings, such as the annual review, the FY 2010 AOP development meetings, and other related events.

4. Planned FY 2010 Activities

SNL and NREL will continue to support DOE's management of the CSP Program by providing analysis and recommendations for future direction. Specifically, we will

- Participate in all future program management activities in close coordination with SETP
- Work with DOE CSP leadership to develop strategic and near-term plans that support accelerated commercial development and deployment of CSP systems
- Hire new staff to support expanded R&D, systems integration, market transformation funding and testing at the SNL and NREL test facilities, as well as to meet current and future program commitments.

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New West Technologies Programmatic Support

Performing Organization: New West Technologies, LLC (NWT)

Key Technical Contacts: John Bartlett (NWT), 202-586-8196, john.bartlett@ee.doe.gov
Charlie Coggeshall (NWT), 202-470-6375, ccoggeshall@nwttech.com

DOE HQ Technology Manager: John Lushetsky, 202-287-1685, john.lushetsky@ee.doe.gov

FY 2009 Budgets: $2,572K (Task #3); $150K (Task #16); $216K (Task #29); $131.5K (Task #31); $120K (Task #33)

Objectives

- Provide technical, engineering, analytical, and management support to the U.S. Department of Energy's (DOE's) Solar Energy Technologies Program (SETP, or Solar Program) by developing program plans and evaluations, coordinating meetings and documents, reviewing scientific and engineering studies and analyses, offering technical expertise in various program and project evaluations, and managing projects (Task #3)
- Provide technical and programmatic support for the Solar Program's Grid Integration Program activities (Task #16)
- Provide technical support for the Solar Program's 2009 peer review (Task #29)
- Provide support for the Solar Program's headquarters (HQ) communications (Task #31)
- Support the Solar Program in monitoring technical progress and project costs (Task #33).

Accomplishments

- Provided the Solar Program with technical, engineering, analytical, and management support in all efforts related to the program goal of achieving cost competitiveness for photovoltaic (PV) and concentrating solar power (CSP) technologies by 2015;this task (#3) was supported through the accomplishment of seven subtasks
- Provided technical support for stakeholder engagement activities and assisted in strategic planning activities for the Solar Program's Grid Integration Program, as well as a DOE strategy document on interconnecting renewable energy systems onto the grid (Task #16)
- Provided technical support to the peer review organizer at HQ in achieving a well-organized, well-run, technically superior Solar Program Peer Review (Task #29)
- Provided a marketing communication manager who met all Solar Program HQ communications needs and developed and identified communications and marketing opportunities (Task #31)
- Enabled Solar Program staff members to more effectively monitor project information via access to critical, real-time information about their projects in EERE's Corporate Planning System (CPS; Task #33).

Future Directions

- Continue supporting the Solar Program's goal of achieving cost-competitiveness for PV and CSP technologies by 2015
- Continue providing technical support for stakeholder engagement activities
- Support development of the DOE Solar Vision Study
- Continue providing strategic planning support and analyses for all subprograms (Grid Integration, Market Transformation, and PV and CSP technology programs)
- Provide technical support for the Solar Program's 2010 peer review.

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1. Introduction

DOE's Solar Program contracted with NWT to support five separate tasks with a cumulative budget of $3,189.5K. This report summarizes basic points in the agreements for each task and the corresponding results of those tasks as of the end of FY 2009, and looks forward at directions and expectations for FY 2010.

2. Technical Approach

The Technology Development (TD) support (Task #3) accounted for the bulk of the total contract work budgeted for NWT. NWT subcontracted much of this work to SENTECH, Inc. The wide spectrum of support provided by NWT and SENTECH is broken down into the following seven subtasks, which the Solar Program identified as key areas requiring assistance:

- Subtask #1: Solar Program working group activities
- Subtask #2: Simulation-based risk analysis development
- Subtask #3: Promotion of solar energy production capacity in the United States
- Subtask #4: Various policy, economic, and engineering analyses
- Subtask #5:2009 Solar Program Peer Review
- Subtask #6: All major market transformation activities
- Subtask #7: All CSP Program activities.

Task #29, which required support for the 2009 peer review, was subcontracted to Kevin DeGroat of Antares.

Task #33, which required support for monitoring Solar Program technical progress and project costs, was subcontracted to BCS, Inc.

3. Results and Accomplishments

3.1 Task #3

Successfully supported the Solar Program's goal of achieving cost competitiveness for PV and CSP technologies by 2015. This task (#3) was addressed through the following subtask accomplishments:

- Subtask #1:Assisted in the planning, facilitating, and implementing of Solar Program working group activities
  - Led Workforce Development activities (04/09)
  - Provided technical assistance to the General Services Administration (GSA) throughout the year. SENTECH provided input on GSA's solar request for proposals and supporting documentation, reviewed solar installation plans, and performed and provided oversight for site feasibility studies.
- Subtask #2: Assisted DOE in conducting detailed, systems-level simulation-based risk analysis
  - Wrote content for the final report of the 2009 Solar Technical Risk and Uncertainty Analysis (09/09).
- Subtask #3: Assisted in implementing the Solar Program's plan for promoting America's solar energy production capacity
  - Established communication with principal solar analysts on Wall Street to facilitate flow of research from DOE to Wall Street (11/08)
  - Wrote sections and edited all of Appendix B of the IRS 48C Notice (07/09)
  - Successfully launched and maintained development of the Solar Vision Study (06/09–present)
  - Offered leader and member contributions to Solar Vision Study chapters (09/09)
  - Provided background research on PV manufacturing consortia in support of PV Manufacturing Initiative (07/09)
  - Contributed to the Annual Report on US Solar Energy Markets: 2008
  - Participated in numerous solar conferences including the following: Solar Energy Consortium Solar Summit in New York City, NY (10/08); Solar Power International in San Diego, CA (10/08); IREC Annual Meeting in San Diego, CA (10/08); ASES Annual Conference in Buffalo, NY (05/09); SolarTech Performance Symposium/Intersolar in San Francisco, CA (07/09); National Association of State Energy Offices (NASEO) Annual Meeting (09/09); USGWPC Water/Energy Sustainability

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Symposium in Salt Lake City, UT (09/09); and Solar ABCs stakeholder meetings (throughout FY 2009).

- Subtask #4: Assisted in preparation and drafting of policy, economic, and engineering analyses in response to administration, congressional, and stakeholder requests
  - Analyzed the financial assumptions in the Solar Advisor Model (SAM; 12/08)
  - Modeled and analyzed costs and benefits from SEIA's stimulus proposals (01/09)
  - Modeled number of applications Department of Treasury should expect from solar projects (2009–2011) for Section 1603 grants in lieu of tax credits (05/09)
  - Completed the internal and external reviews for an NREL technical report, *The Effects of the Financial Crisis on Photovoltaics: An Analysis of Changes in the Market Forecasts from 2008 to 2009*
  - Developed a gap analysis for the market transformation analysis effort with NREL.
- Subtask #5: Assisted the Solar Program in planning the scope, schedule, and technical requirements of the 2009 Program Peer Review
  - Finalized contact list for principal investigators (PIs)
  - Prepared project feedback summary reports
- Subtask #6: Provided support for major market transformation activities including Solar America Cities, Education and Training, Codes and Standards, Solar America Showcase, and State and Utility Outreach
  - Completed guide for Solar America Cities: Managing Solar in America's Cities (12/08)
  - Provided a speaker at the Intersolar Conference, who discussed the effect of codes and standards on the LCOE of solar systems (07/09)
  - Led coordination of Solar America Cities 2nd Annual Meeting
  - Led weekly calls on Cities and Showcase work (03/09)
  - Participated in the Edison Electric Institute Annual Convention (06/09)
  - Issued a notice of technical assistance for Solar America Showcase awards each quarter and reviewed project applications.
  - Assisted the Market Transformation team and the National Association of Regulatory Commissioners (NARUC) with selection and management of technical assistance NREL provided to NARUC members (NARUC made nine awards in 05/09).
  - Supported the Market Transformation team in issuing a funding opportunity announcement (FOA) for Solar America Cities Special Projects and Solar Workforce Development released 05/09–08/09; reviewed subsequent responses to FOA.
- Subtask #7:Supported major CSP Program activities including the development of a Programmatic Environmental Impact Statement (PEIS), the development of a Congressionally directed Water Usage study, participation and review of the Western Governors' Association activities, and development of the Program's Technology Roadmap
  - Created two CSP technical risk and uncertainty analysis documents for trough and tower technology (06/09)
  - Participated in kickoff meeting for the ASME Performance Test Code for Concentrating Solar Power (07/09)
  - Reviewed the Solar Program's purpose and needs statement about the solar PEIS (03/09)
  - Reviewed and provided feedback on the U.S. Bureau of Land Management (BLM) on solar companies' development plans for constructing utility-scale plants in the southwestern United States
  - Supported the Solar Program's preparation and presentation to EERE management on the expanded initiative for the CSP Demonstration Project
  - Provided technical review for several funding opportunities for CSP technologies including ARPA-e, Loan

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Guarantee Program, Community Block Grants, and Small Business Innovation Research (SBIR) program.

3.2 Task #16

Provided technical support for stakeholder engagement activities and assisted in strategic planning activities for the Solar Program's Grid Integration Program, as well as a DOE strategy document on interconnecting renewable energy systems onto the grid. Specific examples of some, but not all, accomplishments achieved under this task follow:

- Developed Renewable Systems Integration Program white paper (01/09)
- Conducted DOE Workshop on High Penetration of PV into the Distribution Grid (02/09)
- Prepared presentations for SEGIS-ES workshop (06/09)
- Completed draft report summarizing SEGIS-ES workshop (07/09).

3.3 Task #29

Provided technical support to the Solar Program 2009 peer review organizer at HQ to achieve a well-organized, well-run, technically superior Solar Program peer review. Specific examples of some, but not all, accomplishments achieved under this task follow:

- Selected and confirmed chairperson and reviewers (01/09)
- Developed agenda and logistics for process (01/09–03/09)
- Facilitated and recorded peer review sessions (03/09)

3.4 Task #31

- Provided a marketing communication manager who met all Solar Program HQ communications needs and developed and identified communications and marketing opportunities. Specific examples of some, but not all, accomplishments achieved under this task follow: Directed Solar America Cities (SAC) logo creation and development process (01/09)
- Provided SAC team members with new PowerPoint template slides (03/09)
- Collaborated with NREL and the DOE Golden field office on development of the Solar Program's Recovery page (04/09)
- Wrote numerous press releases for AARA FOAs (04/09)

3.5 Task #33

- Supported the Solar Program in monitoring technical progress and project costs. Enabled Solar Program staff members to more effectively monitor project information via access to critical, real-time information about their projects in EERE's CPS. Specific examples of some, but not all, accomplishments achieved under this task follow: Provided technical input to Solar Program to coordinate and execute legislative requirements (05/09)
- Facilitated use of contacts database and provided training on its use (05/09)
- Provided program management and budget support to the Solar Program, including technical inputs for FY 2010 and ARRA financial planning and budget execution effort (09/09).

4. Planned FY 2010 Activities

- Continue supporting the Solar Program's goal of achieving cost competitiveness for PV and CSP technologies by 2015
- Continue providing technical support for stakeholder engagement activities
- Continue providing support for the DOE Solar Vision Study
- Continue providing strategic planning support and analyses for all subprograms Provide technical support for the Solar Program's 2010 peer review.

5. Major FY 2009 Publications

M. Coddington, B. Kroposki, T. Basso, K. Lynn, D. Sammon, M. Vaziri, and T. Yohn, "Photovoltaic Systems Interconnected onto Secondary Network Distribution Systems—Success Stories," *34th IEEE Photovoltaic Specialists Conference, Philadelphia, June 7-12, 2009.*

J.E. Bartlett, R.M. Margolis and C.E. Jennings, The Effects of the Financial Crisis on Photovoltaics: An Analysis of Changes in Market Forecasts from 2008 to 2009. Golden, CO: National Renewable Energy Laboratory (September 2009).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)	Cost Share ($K)
SENTECH	Bethesda, MD jmcveigh@sentech.org	Task #3/Assistance to SETP	2,256	0
Antares Group, Inc.	Landover, MD kdegroat@antares.org	Task #29/SETP 2009 Peer Review	216	0
BCS, Inc.	Laurel, MD kboras@bcs-hq.com	Task #33/Monitoring Technical Progress & Cost Support	120	0

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Sentech Programmatic Support

Performing Organization: Sentech, Inc.

Key Technical Contacts: Jim McVeigh, 240-223-5528, jmcveigh@sentech.org,
Sarah Truitt, 240-223-5571, struitt@sentech.org

DOE HQ Technology Manager: John Lushetsky, 202-287-1685, john.lushetsky@ee.doe.gov

FY 2009 Budget: $615K on Business Administration support contract

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Objectives

- Provide marketing and outreach support to the U.S. Department of Energy (DOE) Solar Energy Technologies Program (SETP) by preparing presentations and speeches, responding to controlled correspondence, updating Web sites, developing Webinars, creating outreach materials, supporting event logistics, and preparing for meetings and other outreach related activities.

Accomplishments

- Supported the SETP Market Transformation team in addressing key industry issues to technology deployment with critical stakeholder audiences including state and local governments, workforce training and educational institutions, nationally recognized testing laboratories, and utilities
- Coordinated many internal and external SETP events and meetings including Solar Program Peer Review, Solar America Cities Annual Meeting, Tiger Team Retreats, and High Penetration Workshops.

Future Directions

- Continue to support SETP in its endeavor to reduce solar technology system costs, increase efficiency, and address barriers to the widespread adoption of solar energy technologies
- Continue to provide logistical support for SETP meetings and events.

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1. Introduction

In fiscal year (FY) 2009, SENTECH provided administrative, programmatic, technical, and analytical support services to DOE's SETP. In addition to providing overall support for SETP program management, communications, and administration, SENTECH supported multiple areas of SETP, including Budget and Operations, Market Transformation, and Concentrating Solar Power (CSP).

2. Technical Approach

SENTECH provided turnkey support services in the areas of program administration, Web site development, meeting and event coordination, and communications and outreach.

SENTECH partnered with Project Performance Corporation (PPC) to provide Web development services, Courtesy Associates for meeting and event logistics, and Christina VanVleck for graphics design services.

SENTECH provided six full-time staff members dedicated to supporting various areas of SETP, including Budget, Planning and Operations, CSP, and Market Transformation. SENTECH also provided four part-time staffers to support SETP communications and analyses tasks. Half of the contractors who provided support hold an advanced degree in engineering, business, or public administration and policy. A majority of SENTECH contractors were co-located at DOE to facilitate responsive, on-site support to federal staff.

3. Results and Accomplishments

Because SENTECH staff members assist DOE in carrying out activities to meet programmatic goals, our major accomplishments mirror those of SETP. Highlights from our support in FY 2009 are listed below:

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3.1 Technical Outreach Support

- Coordinated the peer review process for the *American Recovery and Reinvestment Act of 2009* (the Recovery Act) FOAs and SBIR phase I funding round
- Provided content development, review, and project management for publications throughout the year, including *Use of Municipal Assistance Programs to Advance the Adoption of Solar Energy Technologies,* published by the American Solar Energy Society (ASES) in May 2009 and *Solar Powering Your Community: A Guide for Local Governments,* published by SETP in July 2009
- Provided volunteer assistance as technology experts and VIP tour guides for the 2009 Solar Decathlon
- Represented SETP at numerous Solar America Cities (SAC) Program ribbon cutting and media events and staffed exhibit booths at numerous conferences.

3.2 Communications and Administrative Work

- Developed or modified Web site content for Market Transformation pages on EERE Web site
- Compiled, edited, and distributed the SETP quarterly newsletter and SAC e-bulletin
- Developed and maintained SAC public Web site and intranet portal
- Wrote press releases and progress alerts for SETP, assisted with controlled correspondence and budget tracking.

3.3 Meeting and Event Coordination

- High Penetration Workshop (02/09)
- Solar Program Peer Review (03/09)
- SAC Annual Meeting (04/09)
- SAC Train the Trainers Workshop (07/09)
- Market Transformation Analysis Meeting (09/09)
- Workforce Development/SAC Special Projects Merit Review (08/09).

4. Planned FY 2010 Activities

SENTECH will continue to support SETP in advancing solar technology, industry, and market development. SENTECH will provide administrative, analytical, and technical support to federal staff.

5. Major FY 2009 Publications

K. Lynn and S. Truitt, *Use of Municipal Assistance Programs to Advance the Adoption of Solar Technologies,* American Solar Energy Society (ASES) May 13-15, Buffalo, NY, 2009.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2009.

Organization/ Principal Investigator	Location/E-mail	Description/Title of Research Activity	FY 2009 ($K)
Courtesy Associates	Washington, DC lthornton@courtesyassociates.com	Meeting and event logistics coordination	235
PPC	McLean, VA Janis.adkins@ppc.com	Web site development services	200
Christina VanVleck (Graphic Designer)	Boston, MA vanvleck@rcn.com	Graphics design services.	20

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CSP Capital Equipment & Facilities

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

Key Technical Contacts: Mark S. Mehos (NREL), 303-384-7458, mark.mehos@nrel.gov
Thomas Mancini (SNL), 505-844-8643, trmanci@sandia.gov
Joe Tillerson (SNL), 505-844-1806, jrtille@sandia.gov

DOE HQ Technology Manager: Tommy Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov

FY 2009 Budgets: $800K (SNL), $200K (NREL)

Objectives

- Maintain core capabilities of the Concentrating Solar Power (CSP) Program through operation and maintenance of the NREL and SNL CSP research facilities
- Maintain safe operational conditions for the test facilities at NREL and SNL
- Build advanced capabilities at NREL and at SNL's National Solar Thermal Test Facility (NSTTF) using funding from the *American Recovery and Reinvestment Act of 2009* (the Recovery Act).

Accomplishments

- Achieved Nationally Recognized Testing Laboratory (NRTL) compliance for 95% of the NSTTF site (SNL)
- Developed a detailed plan for Recovery Act funding (SNL)
- Awarded Recovery Act funds through competitive call for laboratory test and evaluation and storage concepts (NREL).

Future Directions

- Begin major upgrades in facilities at the NSTTF in fiscal year (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, ensuring preparedness for upcoming R&D opportunities and challenges (SNL)
- Continue to replace aging and largely unserviceable equipment (SNL and NREL)
- Complete fabrication of optical test and thermal storage test labs at Energy Systems Integration Facility (ESIF;NREL)
- Complete construction of pilot-scale thermal energy storage test facility at SolarTAC (NREL)
- Complete upgrade of High Flux Solar Furnace (HFSF) test facility (NREL).

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1. Introduction

DOE uses the test facilities at SNL and NREL extensively for evaluating CSP components and systems. SNL's facilities include a 5-MWth CRTF, a 75-kWth solar furnace, a rotational facility for testing trough collectors over their operating temperature range, an engine test facility, a dish test facility, and associated data acquisition and technical test equipment needed by the technicians who support the evaluations. NREL's facilities include several optical materials research laboratories, an optical systems characterization laboratory, a thermal storage materials laboratory, a large-payload two-axis tracker for testing parabolic trough performance, and an HFSF. SNL and NREL are responsible for maintaining world-class testing and evaluation capabilities for use by DOE and the CSP industry.

2. Technical Approach

2.1 Operations

Ongoing activities at the NSTTF and NREL laboratory and test facilities include safety and readiness testing and inspection associated with chemicals, confined spaces, cranes and rigging, electricity, environmental management and

regulations, evacuation, fire, 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 maintaining OUO, site and computer security, safety, monitor site access, coordinate maintenance and deliveries, Foreign Corrupt Practices Act, counterintelligence, EEO/AA, ethics, drug free workplace, export control, property, diversity, annual review of site security plan, SNL satellite badge office, process foreign national requests, coordinate tours, and process after-hours access.

2.2 NRTL Certification at the NSTTF

All NREL and SNL facilities must be certified as 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 had never been tested or certified by an NRTL. At this point, however, virtually all of the equipment has been evaluated and certified as compliant.

3. Results and Accomplishments

SNL accomplished the following at the NSTTF:

- Upgraded motors and controls on the heliostat field
- Continued testing ten 25-kW Stirling Energy Systems (SES) dish Stirling systems
- Continued testing of four 3-kW Infinia dish Stirling systems
- Disassembled old molten-salt test facility
- Started testing the SkyFuel SkyTrough™
- Installed and tested PWR heliostat

NREL accomplished the following facilities-related work:

- Completed advanced thermal storage materials characterization laboratory
- Awarded Recovery Act funds through competitive call for laboratory test and evaluation and storage concepts
- Tested SkyFuel and Acciona collectors
- Tested Schott and Solel heat-collection elements
- Tested advanced polymer and glass mirror samples and facets.

4. Planned FY 2010 Activities

NREL and SNL will continue ongoing testing and facilities upgrades: Specifically, we will

- Continue testing of SES and Infinia dish Stirling Systems
- Continue testing of the PWR heliostat
- Complete testing of the SkyTrough
- Conduct design testing of PWR receiver panel
- Complete testing of SkyFuel, Alcoa, and Abengoa advanced collector designs
- Complete testing of alternative mirror facets designs supplied by Rioglass, Guardian Industries, and PPG.
- Implement upgrades associated with Recovery Act funding.

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Communications

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Terri Jones (NREL), 303-275-4217, terri.jones@nrel.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2009 Budget: $834K (NREL)

Objective

- Provide communications strategy, execution, production, and evaluation to meet the communications needs of the Solar Energy Technologies Program (SETP).

Accomplishments

- Made improvements to, updated, and maintained SETP Web site (approximately 300 pages and 1,000 files) with changes to better reflect the current activities and increase usability.
- Produced eight new documents, including the FY 2008 SETP Annual Report, and contributed to programmatic documents, such as the quarterly newsletter.
- Represented the program at the International Builders' Show (IBS) and the National Conference of State Legislators, completed all preparations for the Solar Power International conference, and provided communication support for the first annual Utility Solar Conference.

Future Directions

- Conduct strategic planning to ensure communications tactics meet the most current and essential needs of the program.
- Conduct usability studies with key stakeholders within the industry to assess their needs and subsequently make significant changes to the Web site to better meet those needs.
- Evaluate efficacy of and make changes to exhibiting activities to ensure current needs of the program are being met.
- Support Market Transformation to ensure that critical information about these activities is captured and available to its stakeholders, so they can better emulate these activities within their sphere of influence.
- Enhance support of Photovoltaic, Concentrating Solar Power, and Systems Integration subprograms: target specific conferences, develop new exhibits, and create outreach materials.

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1. Introduction

NREL provides comprehensive communications services to SETP including:

- Strategic planning to ensure specific activities are necessary and 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.

2. Results and Accomplishments

<u>Core/Cross-Cutting</u>

- Produced FY 2008 SETP Annual Report, coordinating individual reports on all SETP activities. Edited, produced, printed, and distributed the report.
- Developed a new fact sheet for utilities and distributed an e-blast to attendees of the first annual Solar Energy Power Association's Utility Solar Conference, which the Solar Program co-sponsored.
- Managed program presence at Solar Power International, which included creating new fact sheets, producing an updated exhibit, and coordinating booth staffing.
- Added a new rotating flash feature on the SETP home page to promote key activities.

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- Established two new mechanisms to increase awareness of solar financial opportunities on the Web site: an RSS feed and email subscription.
- Responded to ~100 Webmaster inquiries from a wide range of users and developed a comprehensive maintenance plan to ensure every Web page is updated regularly. Completed ongoing posting requests such as funding announcements.
- Developed new Systems Integration content on the SETP Web site to better represent the program activities.
- Launched two new Web pages, under the direction of EERE, on the solar projects funded by the American Recovery and Reinvestment Act and the Solar Program's Planning, Implementation, and Results.
- Provided editorial and graphical support to technical publications, concept papers, and reports.

Market Transformation

- Promoted 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 more than 60,000 IBS attendees, the pavilion garnered new leads from attendees interested in solar. One new publication was produced for the builder audience.
- Supported Solar America Cities (SACs) and Solar America Showcases (SASs) in a variety of ways. Updated Web content timed to go live with the Secretary's announcements of solar awardees. Developed publications to assist cities in understanding the technical assistance process.
- Collaborated with other SETP staff and contractors to develop a unique brand/identity for SACs, produced guidance for use of the brand both internally and externally, and presented the brand at SAC's Annual Meeting.
- Produced a 100-page guide, in collaboration with the Market Transformation Team, that helps state and local governments develop and implement solar programs, titled "Solar Powering Your Community: Guide for Local Governments."
- Collaborated with Market Transformation partners to develop "histories" publications to highlight the evolution of the Solar Program's involvement in each of the 25 SACs (i.e., one for each city and one for SACs overall).
- Served as a solar expert for the program booth at the National Conference of State Legislators.

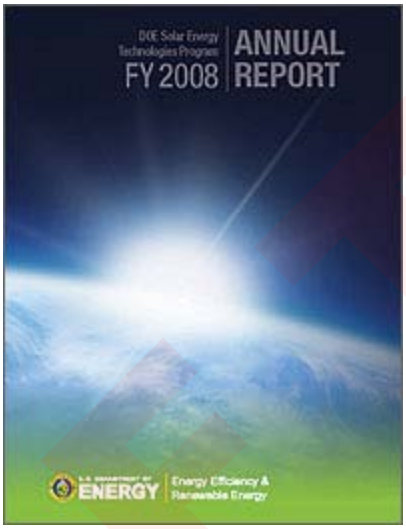

Fig. 1. The Annual Report was a key publication.

3. Major FY 2009 Products

Web site: www.solar.energy.gov

Publications:

- "A Homebuilders Guide to Going Solar," www.solar.energy.gov/pdfs/44792.pdf
- "Advancing Clean Energy," www.eere.energy.gov/office_eere/pdfs/solar_fs.pdf
- "Solar Energy Technologies Program: Photovoltaics" fact sheet, www.solar.energy.gov/pdfs/46660.pdf
- "Solar Energy Technologies Program: Concentrating Solar Power" fact sheet, www.solar.energy.gov/pdfs/46661.pdf
- "Solar Energy Technologies Program: Market Transformation" fact sheet, www.solar.energy.gov/pdfs/46662.pdf
- "Solar Energy Technologies Program: Systems Integration" fact sheet, www.solar.energy.gov/pdfs/46663.pdf
- "Solar: A Clean Energy Source for Utilities" fact sheet, www.solar.energy.gov/pdfs/46259.pdf
- "Solar America Cities Awards" fact sheet; DOE/GO-102009-2825.
- "Solar Powering Your Community: Guide for Local Governments," www.solaramericacities.energy.gov/pdfs/Solar-Powering-Your-Community-Guide-For-Local-Governments.pdf

International Activities

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

Key Technical Contacts: Carol Anna (NREL), 303-275-3655, carol.anna@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 2009 Budgets: $188K (NREL), $100K (SNL)

Objectives

International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) Programme

- Act as operating agent for Task 10, Urban Scale PV Applications
- Represent the United States 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
- Coordinate activities of Task 1, CSP Electric Power Systems
- Organize and chair two meetings.

Accomplishments

PVPS Programme

- Produced the U.S. content for the *Photovoltaic Power Systems Programme Annual Report 2008* and the *National Survey Report of PV Power Applications in the United States 2008* (Task 1)
- Represented the United States at the Task 1 Experts Meeting in Kota Kinabalu, Sabah, Malaysia (Task 1)
- Represented the United States at Executive Committee and operating agent meetings in Vienna, Austria, and Lisbon, Portugal; and technical expert meetings in Sydney, Australia, and Rome, Italy (Task 10).

CSP SolarPACES

- Completed and submitted annual report
- Completed the IEA's midterm review of SolarPACES.

Future Directions

- Complete 2009 IEA PVPS Annual Report and 2009 National Survey Report (Task 1)
- Support IEA PVPS Web site activities and disseminate information to U.S. audiences (Task 1)
- Attend Task 1 meetings in Seville, Spain
- Close out Task 10 activities
- Complete review and revision of the implementing agreement.

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1. Major FY 2009 Publications

IEA PVPS. *Photovoltaic Power Systems Programme Annual Report 2008* (April 2009). Available at http://www.iea-pvps.org/products/download/rep_ar08.pdf, accessed March 2010.

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IEA PVPS. *National Survey Report of PV Power Applications in the United States 2008* (June 2009). Available at http://www.iea-pvps.org/countries/download/nsr08/NSR%20USA%202008.pdf, accessed March 2010.

SolarPACES Semi-Annual Review, October 2009, Stockholm, Sweden.

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Small Business Innovation Research

Performing Organization: DOE Solar Energy Technologies Program (SETP)

DOE HQ Technology Manager: Alec Bulawka, 202-586-5633, alec.bulawka@ee.doe.gov

FY 2009 Budget: $12,000K

Objectives

- Support small business energy 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) SETP
- Effectively support American Recovery and Reinvestment Act of 2009 (Recovery Act) initiatives.

Accomplishments

- Increased the efficiency of existing multijunction (MJ) cells with a solar concentrating coating that focuses incoming sunlight to the appropriate junction
- Solved the problem of encapsulation coatings with a material matrix, resulting in a polymer-based glass-like sol-gel high barrier coating against oxygen and water penetration
- Recycled swarf from slicing silicon using fixed abrasive slicing technology (FAST) to reduce waste and increase silicon supply
- Developed lightweight, mechanically robust, highly reflective membrane materials and environmental coating materials for antireflective, self-cleaning mirror surfaces
- Developed a photovoltaic (PV) manufacturing diagnostic system using hyperspecial imaging techniques enabling fast, in-line PV diagnostics
- Developed fast, real-time diagnostics of mechanically fragile silicon (Si) wafers and cell for PV production
- Using Al, Cu and Ni nanoparticle inks; increased control over film thickness and conductivity compared with conventional screen-print pastes
- Developed first-of-a-kind “flat-plate” high-concentration PV panel based on III-V cells with novel optical design and flattening concentrator structure to a panel
- Synthesized and tested new fullerene derivatives for use in bulk heterojunction organic PV (BHJ OPV), incorporation of electron-rich atoms to increase power conversion efficiency.

Future Directions

- Enter solar cell original equipment manufacturing (OEM) market in 2012
- Develop promising coating technology that will prolong the life of existing and future flexible solar cells without impeding efficiency
- Demonstrate ability to convert FAST swarf to high-quality Si feedstock, and demonstrate FAST ability to slice Si
- Improve reflectivity of flexible mirrors by 2% and increase spectral bandwidth to include ultraviolet
- Achieve a 5% improvement in PV yield (through diagnostics) with a potential annual savings of about $300 million
- Continue to study ultrasonic resonance vibrations diagnostic methodology, which will improve solar cell and module manufacturers
- Expect potential increases in efficiency through reduced front shadowing and lower Si-PV cost through material waste reduction, thinner substrates, and increased yield
- Create a prototype CPV system with a potential of lowest levelized cost of energy (LCOE) on the market with higher efficiency and lower cost/footprint than conventional PV panels, utility-scale and rooftop potential

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- Develop new fullerene derivatives in bulk heterojunction OPV, approaching an 8% to 10% efficient laboratory device.

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1. Introduction

Solar energy is our largest energy resource and can provide clean, sustainable energy supplies, including electricity, fuels, and thermal energy. The Recovery Act) emphasized solar energy, among others, as a key element in combating global climate change. The cost-effective capture of the enormous solar resource is, however, problematic. The Small Business Innovation Research (SBIR) Program seeks to develop novel, commercially feasible solar systems and production techniques. As such, SETP is submitting an unprecedented extensive topic and subtopic opportunity to the small business community. These topics emphasize novel, previously untried but commercially feasible solar concepts and devices.

Each year, 10 federal departments and agencies, including DOE, are required by the 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 $20 million and received $53 million in research funding. Last year, because of ARRA funding, the return on investment was exceptionally significant.

As in the past, the Solar Program 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 2008. The 2009 Solar Program is nested mainly in the Advanced Solar Technology (Topic 8) SBIR-Recovery Act category as well as the conventional annual solicitation. Once again, the SBIR activities complement 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. Based on an unprecedented return response volume to the ARRA solicitation, the community is involved very actively in the President's ARRA Initiative.

2. Technical Approach

Renewable energy technologies, as before, 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 involve solar electric, PV, and concentrating solar power (CSP) systems as well as solar-assisted alternate fuel generation. Much activity has also focused on organic material improvement. Grant applications for FY 2009 (in two separate solicitations) were required to clearly demonstrate the applicants' ability to proceed to hardware development fabrication, testing, and manufacture of technologies.

3. Results and Accomplishments

More than ever before, SBIR awards advanced their goals and produced very encouraging results of their R&D to date (see Section 6 table).

4. Planned FY 2010 Activities

Further development of PV and CSP systems, as well as systems integration, will be accomplished through creative and innovative approaches in engineering and design, new materials, alternative fuels, and new processes. Much attention has been given to accelerate the idea of production and manufacture.

4.1 Hybrid Solar Energy Systems —Combination of PV, Solar Heat, and/or Solar Cooling

Hybrid solar technologies, which combine electrical and thermal power generation, promise to significantly increase the total operating efficiency of solar panels and reduce system costs and size where the cogeneration of heat and electrical power is needed. This approach also offers a variety of secondary benefits such as load shifting (e.g., thermal cooling, electrical/thermal ratio adjustment) and synergistic performance benefits (e.g., allowing cells to run cooler, removing snow melting). Currently, solar water heating is funded in the Building Technologies Program and PV technologies are funded through the Solar Program. This category enables cross-cutting applications, which are currently not fundable under EERE.

4.2 Innovative Applications of Solar Energy for Fuels and Industrial Processes, Not Electricity, HVAC, or Residential Water Heating

Solar energy can be used to produce fuels or to power industrial processes. Production of fuels allows solar energy to be stored and used at

controlled times and places. Much research has been done by the international community in such production, with, as yet, no cost-effective technology found. For industrial processes, only a few large solar-powered systems are in use worldwide, even though among industry, transportation, household, and service sectors in the developed world, industry has the highest share of energy consumption. Innovative design and development of solar-powered systems that either produce fuels or power industrial processes is highly desirable.

4.3 CSP Systems for Distributed Applications
The CSP subprogram focuses on large-scale systems that can supply power on demand. There is also a market for smaller scale CSP technologies, however, that can supply power for residential and commercial applications. These could be either rooftop community based systems that do not require a lot of land and can be sited close to load centers. System design would be undertaken in Phase 1 and move on to prototype scale in Phase 2.

4.4 Organic PV and Nanotech/Photonics
Concise methods and subassemblies for large-scale, molecular manufacturing of fullerenic and other dopant material for organic semiconductors, specifically for PV, are being pursued. Variations on the theme are welcome whereby nanotechniques will also be explored and pursued that contribute to increasing the efficiency of organic PV beyond the 10% level, thereby leading to cost-effectiveness and commercial viability. Material nanotransformational contributory techniques and passive photonic nano-particle/crystal augmentation are sought likewise.

4.5 Manufacturing Tools for Reliability Testing
Tools to conduct reliability testing in PV module manufacturing environments can be developed. For example, tools such as light soaking equipment are used to prepare modules or components for accelerated lifetime testing, which is frequently conducted in-house at the module manufacturing facility or by service companies before sending for official third party certification. New tools are needed for the testing components (e.g., modules, inverters) or subcomponents (e.g., cells, microinverters, individual layers of a module), and should combine high performance, low cost, and a small floor footprint.

4.6 Module and System Manufacturing Metrology and Process Control
The rapid scale-up of the manufacturing of PV, particularly for new thin-film technologies, is challenging the possibility of using conventional technologies to make real-time non-destructive measurements of material characteristics in high-volume, high-production-rate environments and then using this information to implement real-time process control of the manufacturing process. The development of novel, advanced, real-time non-destructive materials characterization tools for use in high-volume manufacturing lines for PV systems is thus essential.

4.7 PV System Diagnostic Tools
The current rapid growth of the PV industry has led to diverse and innovative product designs, which frequently require non-traditional tests for reliability and performance. Examples of these non-traditional tests include performance testing and tracking requirements for concentrating PV modules, and software-based system diagnostic tools. Innovative methods are needed to monitor PV system and component performance in order to identify failures and loss mechanisms and to minimize system down time. Approaches of interest include the development of diagnostic tools that are process-oriented and internal to the system components, or those that can be integrated—i.e., “piggy-backed”—through ancillary application.

5. Major FY 2009 Publications

SBIR holds the awardees responsible for a final report at the end of both Phase 1 and Phase 2. The SBIR Office in Germantown, MD, has the final reports for all projects awarded in the past.

6. Industry Partners

The following organizations partnered in the project’s research activities during FY 2009.

Company Name	Company Address	Amount	PI	Title
Nanosolar, Inc.	2440 Embarcadero Way, Palo Alto, CA 94303	750,000	Chris Eberspacher	Printed Solar Cell Using Nanostructured Ink

Company Name	Company Address	Amount	PI	Title
TDA Research, Inc.	12345 W. 52nd Ave., Wheat Ridge, CO 80033-1916	750,000	Michael D. Diener	Improved Fullerenes for OPV
NanoSonic, Inc.	1485 South Main Street, Blacksburg, VA 24060-5556	750,000	Michelle Berg	High Performance, Low-Cost Nanostructured Mirror Surfaces
Midwest Optoelectronics, LLC	2600 Dorr Street, Toledo, OH 43607	746,325	Aarohi S. Vijh	Novel Interconnection Process for Lightweight Flexible Photovoltaic Modules
Luminit, LLC	1850 W. 205 Street, Torrance, CA 90501-1526	750,000	Kevin Yu	Flexible Spectrum Splitting Holographic Concentrator
SVV Technology Innovations, Inc.	10027 E. Taron Dr., Elk Grove, CA 95757-8190	749,882	Sergiy Vasylyev	High Performance PV Concentrator
Luna Innovations Incorporated	1 Riverside Circle, Suite 400, Roanoke, VA 24016-4962	749,993	Kevin Flanagan	High-Throughput In-Line PV Manufacturing Diagnostic System
Ultrasonic Technologies, Inc.	3650 Spectrum Boulevard, Suite 170, Tampa, FL 33612-9446	737,279	Sergei Ostapenko	In-line Crack Detection in Silicon Solar Cell Production Using Resonance Ultrasonic Vibrations
Applied Nanotech, Inc.	3006 Longhorn Blvd., Suite 107, Austin, TX 78758-7631	749,997	James Novak	Non-Contact, Printable Metallic Inks for Silicon Solar Cells
Luminit, LLC	1850 W. 205 Street, Torrance, CA 90501-1526	750,000	Kevin Yu	Multifunctional UV Curable Sol-Gel Organic Hybrid Nanocomposite Encapsulation System
Crystal Systems, Inc.	27 Congress Street, Salem, MA 01970	745,586	David Brian Joyce	Material Utilization and Waste Reduction through Kerf Recycling
Gratings, Inc.	2655A Pan American Freeway NW, Albuquerque, NM 87107-1639	100,000	Saleem H. Zaidi	Microstructured Crystalline Silicon Thin-Film Solar Cells
Luna Innovations Incorporated	1 Riverside Circle, Suite 400, Roanoke, VA 24016-4962	99,981	Martin Drees	Highly Efficient Organic Solar Cells Using Low Band Gap Polymers and Novel Acceptor Materials
TDA Research, Inc.	12345 W. 52nd Ave., Wheat Ridge, CO 80033-1916	100,000	Michael D. Diener	A New Three-Part Architecture for Efficient and Stable Bulk Heterojunction OPV Devices
Aspen Aerogels, Inc.	30 Forbes Road, Bldg, B, Northborough, MA 01532-2501	100,000	Roxanna Trifu	Transparent Aerogel Insulation for Solar Heat Concentration Elements
NanoSonic, Inc.	1485 South Main Street, Blacksburg, VA 24060-5556	100,000	Michelle Berg	Low-Cost Solar Coatings for Improved Thermal Performance of Components in Concentrating Solar Power Systems
ReflecTech	18200 West Highway 72, Arvada, CO 80007	99,964	Randy Gee	Low-Cost, Durable, High-Performance Reflectors for Utility-Scale Solar Thermal Energy Collection

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Company Name	Company Address	Amount	PI	Title
SVV Technology Innovations, Inc.	10027 E. Taron Dr., Elk Grove, CA 95757-8190	99,997	Viktor Vasylyev	Concentrator PV Receiver Based on Crystalline Si Cells
MicroLink Devices	6457 West Howard St., Niles, IL 60714-3301	100,000	Chris Youtsey	Backside Contact Multijunction Solar Cells for Concentrator Applications
Fractal Systems Inc.	108 4th Street, Belleair Beach, FL 33786-3213	149,718	Matt Aldissi	Recovery Act— Enhanced Charge Transport towards High Efficiency Organic Photovoltaics
SVV Technology Innovations, Inc.	10027 E. Taron Dr., Elk Grove, CA 95757-8190	95,929	Viktor Vasylyev	Recovery Act—Hybrid Slat-Array PV System with Thermal Co-Generation
Plextronics, Inc.	2180 William Pitt Way, Pittsburgh, PA 15238-1357	150,000	Shawn Williams	Recovery Act—High Performance Organic Photovoltaics via Novel Materials Combinations
Cobb Design Inc.	2595 27th Avenue. North Saint Petersburg, FL 33713-3934	145,472	William Cobb, Jr.	Recovery Act— Design and Demonstration of a Solar Array for a Modular Distributed Concentrating Solar Power (CSP) System
Weidlinger Associates, Inc.	375 Hudson Street. New York, NY 10014-3656	149,041	Huiming Yin	Recovery Act—Hybrid Building Integrated Solar Energy System for Photovoltaic, Thermoelectric, and Heat Utilization
Versatilis LLC	488 Ridgefield Road, Shelburne, VT 05482-6311	150,000	George A. Powch	Recovery Act—Electret Field Enhanced Organic Solar Cells
Physical Sciences Inc.	20 New England Business Center, Andover, MA 01810-1077	149,816	Juan Montoya	Recovery Act—SolarFlex (Surface Plasmon Energy Trapping on Organic Solar Cell)
Physical Optics Corporation	20600 Gramercy Place, Bldg. 100. Torrance, CA 90501-1821	149,987	Xiaowei Xia	Recovery Act— Hybrid Electrical And Thermal Energy System
Luna Innovations Incorporated	1 Riverside Circle, Suite 400. Roanoke, VA 24016-4962	150,000	Steve Joslin	Recovery Act—Advancement of Nano-Material Production for OPV Acceptors
Nano-C, Inc.	33 Southwest Park, Westwood, MA 02090-1524	148,771	Henning Richter	Recovery Act—Nanocomposite Structures for OPV Devices
Structured Materials Industries, Inc.	201 Circle Drive North, Unit 102, Piscataway, NJ 08854-3723	150,000	Gary S. Tompa	Recovery Act—ZnO/ZnS/P3HT Core-Shell Heterostructure Organic Hybrid Solar Cells
Luminit, LLC	1850 W. 205 Street, Torrance, CA 90501-1526	149,999	Kevin Yu	Recovery Act—Solar Photovoltaic Holographic Cogeneration System
Giner Electrochemical Systems, LLC	89 Rumford Avenue, Newton, MA 02466-1311	149,684	Simon G. Stone	Recovery Act—Advanced Membrane Technology for the Hybrid Sulfur Process Electrolyzer

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Company Name	Company Address	Amount	PI	Title
Asylum Research Corporation	6310 Hollister Ave., Santa Barbara, CA 93117-3115	146,777	Roger Proksch	Recovery Act—Nanoscale Probe System for Organic Photovoltaics
Covalent Solar, Inc.	1 Broadway, 14th Floor, Cambridge, MA 02142-1187	149,813	Jon Mapel	Recovery Act—Organic Solar Concentrators for Low-Cost Solar Power Generation
InnoSense LLC	2531 W. 237th Street, Suite 127, Torrance, CA 90505-5245	150,000	Uma Sampathkumaran	Recovery Act—Nanostructured Photovoltaic Device
Solarno Inc.	153 Hollywood Dr., Coppell, TX 75019-7306	149,000	Anvar Zakhidov	Recovery Act—Parallel Tandem Organic Solar Cells with Carbon Nanotube Sheet Interlayers
Physical Optics Corporation	20600 Gramercy Place, Bldg. 100. Torrance, CA 90501-1821	149,989	Juan Hodelin	Recovery Act—Thermally Assisted Photoelectrochemical Hydrogen Generation using a Holographic Concentrator
Phasiks, Inc.	10842 Noel St., Suite 106. Los Alamitos, CA 90720	150,000	Richard Welle	Recovery Act—Segmented Fresnel CSP for Community and Business Applications

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Solar Congressional Earmarks

Performing Organizations: CEC Stuyvesant Cove, Inc. (CEC); CENTRIA, Inc.; Crowder College; Eikos, Inc.; Greenfield Community College; Nevada Institute for Renewable Energy Commercialization (NIREC); North Dakota State University (NDSU); Nye County, NV; Regents of New Mexico State University (NMSU); Rural Development, Inc.; San Francisco Public Utilities Commission (SFPUC); The Solar Energy Consortium (TSEC): 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 (UNLV) Research Foundation; Bexar County; Utah State University USU); Omega Optical, Inc.; City of Beacon, NY; St. Clair Community College; Vermont Department of Education; Salt Lake County.

Key Technical Contacts: Carolyn Elam (DOE/GO, Primary Contact), 303-275-4953, carolyn.elam@go.doe.gov
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Brian Hunter (DOE/GO), 303-275-4934, brian.hunter@go.doe.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, Thomas.rueckert@ee.doe.gov

FY 2009 Budget: $7,247K (DOE/GO) awarded; $23,291 (DOE/GO) in negotiation

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Objectives

- Manage 28 congressional earmarks and 10 new awards through the Consolidated Appropriations Act, 2009
- Conduct research related to DOE Solar Energy Technologies Program objectives.

Accomplishments

- Awarded 10 new congressional earmarks.

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1. Introduction

We negotiated and funded 10 of 29 congressionally directed projects. These funds were directed by the Consolidated Appropriations Act, 2009. The projects were fully funded this year, although several are multiyear.

2. Technical Approach

In addition to the 10 projects funded in 2009, all projects from prior years were active during FY 2009. The awards are summarized in the tables.

Agreement Title	FY 2008 Budget ($K)
CEC; Christopher Collins	492

Agreement Title	FY 2008 Budget ($K)
(Solar 2 Green Energy, Arts & Education Center)	
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 (Sustainable Energy Model Greenhouse)	394
NIREC; Jim Croce	1,476

Agreement Title	FY 2008 Budget ($K)
(Renewable Energy Research and Development)	
NDSU ; Philip Boudjouk (Center for Nanoscale Energy)	5,904
Nye County; Pam Webster (Nye County Renewable Energy Feasibility Study)	492
NMSU: Shuguang Deng (High Efficiency Cascade Solar Cells)	984
Rural Development, Inc.; Anne Perkins (Wisdom Way Solar Village)	394
SFPUC; John F. Doyle (MUNI Ways and Structures Building Integrated Solar Membrane Project)	610
TSEC; 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
UALR; Alexandru Biris (Novel Photovoltaic Devices Based on Polymeric and Carbon Nanostructured Materials)	1,181**
University of Hartford; 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*
UNLV; Biswajit Das (Solar Cell Nanotechnology)	738

* Funded with prior year funds
** Continuation of existing (prior year) Congressional Earmark

Agreement Title (Awarded)	FY 2009 Budget ($K)
Bexar County; Golda Weir (Bexar County Parking Garage Photovoltaic Panels)	475
TSEC; Petra Klein (Comparative Analysis of Turnkey Silicon Solar Cell Processes and Equipment)	594
USU; Jeff Muhs (Multi-functional Solar Energy Research Systems Research)	1,665
Omega Optical, Inc; Gary Carver (Solar Power Generation Development)	1,427
City of Beacon; Mayor Steve Gold (Solar Electric Power System)	66
St. Clair County Community College; Denise McNeil (Solar Electric and Wind Power Systems)	190
Vermont Department of Education; Cathy Hilgendorf (Sustainable Energy for Vermont Schools)	500
TSEC; Petra Klein (Photovoltaic Innovation)	1,903
Salt Lake County; Teresa Young (Energy Efficient Buildings)	618
Nevada Institute for Renewable Energy Commercialization; Jim Croce (Renewable Energy Research and Development)	475

Agreement Title (In Negotiation)	FY 2009 Budget ($K)
Creighton University	1,141
NDSU	4,757
Oregon Department of Energy	380
Xunlight Corporation	1,189
Rochester Institute of Technology	951
Isles, Inc.	237
Sandia National Laboratories	1,903
Lehigh Valley Hospital and Health Network	951
Crowder College	951
ULAR	1,189
Oregon Department of Transportation	951
Islip Town Hall	475
City of Trenton	475
Orange County Florida Government	237
Essex County	951
Township, Cherry Hill, NJ	285
Clark County School District	1,189
City of St. Petersburg	1,427
Vermont Department of Public Service	713
UNLV	951
Rural Development, Inc.	570
Andre Agassi Charitable Foundation	1,189

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 in New York.

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Accomplishments

- Completed Acoustic Site Survey, investigation and sizing of battery backup system, and study of potential "pre-fab" options. Received report on power consumption for Building Exhibit and developed new energy analysis Report
- Completed schematic design, design development and preconstruction documents phases (including new renderings) and achieved 86% completion on construction documents, including a new design and drawing Set at 75% completion
- Completed 100% of engineering and foundation documents.

3.2 Building-Integrated Photovoltaic (BIPV) Solar Energy System (CENTRIA—Mowrey)

Objectives

- Increase adoption of solar energy by developing standard BIPV designs
- 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
- Work with BIPV metal roofing companies to promote products and adoption into building designs to grow market.

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, renewable business incubation, and consumer education.

Accomplishment

- 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 environmental stability of coatings
- Evaluate cost-performance-processing tradeoffs.

Accomplishments

- Determined gravure/roll coating is a suitable method for CNT/binder deposition for PV applications
- Developed reliable method to purify good-quality metallic NW
- Synthesized nanomaterials for TCCs. Eikos has developed CNT ink with excellent RT performance from two new suppliers, enabling us to meet current and future orders. One of these new companies is U.S.-based, ensuring material supply for sensitive government applications
- Utilized Eikos CNT coatings as a back contact in a cadmium telluride (CdTe) multi-junction device. Work presented at the 34th IEEE PV Specialists Conference
- Successfully developed a CNT/triple binder coating capable of meeting RT specifications and weathering environmental conditions
- Adapted ink formulations and developed new printing protocols to enable a more reliable deposition of complex and conductive CNT patterns of variable sizes by ink-jet printing
- Developed a new AR binder system that enables CNT-based TCC to meet all PV specifications. This new formulation also simplifies processing and reduces costs
- Conducted heat treatment experiments to purify and characterize CNT from multiple suppliers.

Future Directions

- Work with prescreened SWCNT suppliers to improve the quality of as-produced CNT material
- Integrate coatings into thin-film organic and polycrystalline PV
- Integrate binder top coats into CNT TCC for use in PV cells
- Improve CNT ink RT performance and stability.

3.5 Sustainable Energy Model Greenhouse (Greenfield Community College—Haywood)

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Objective

- 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.

Accomplishment

- Completed contracting process with consultant to develop design feasibility study for greenhouse.

Future Directions

- Complete design plans with bid documents; scheduled for late spring/summer 2010 construction
- Create teaching and learning environment to support biology and renewable energy curricula with carbon-neutral greenhouse equipped with passive solar, PV, solar thermal systems, and interface with geothermal system.

3.6 Renewable Energy Research and Development (NIREC—Croce)

Objective

- Select and fund clean energy research and development, and support the transformation of these ideas into sustainable enterprises.

Accomplishments

- Successfully launched two competitive Requests for Proposals (RFPs).
- Selected and began process of awarding approximately $300,000 in research and technology development projects
- Successfully completed two R&D projects (awarded in 2008) on time and on target
- Presented and participated in numerous outreach activities to educate the clean energy innovation community on the challenges, potential solutions, and significant economic benefits to clean energy technology development and deployment.

Future Directions

- Search for, assess, and award funds to deserving projects:
    - Fund at least six new R&D projects and support the development of their commercialization road map
    - Continue to nurture a robust network of innovation ecosystem partners
- Conduct education and outreach activities to facilitate interest in the need for clean energy technologies.

3.7 Center for Nanoscale Energy (NDSU—Boudjouk)

Objectives

- Evaluate efficacy of NDSU liquid silanes and atmospheric-pressure deposition technologies in PV device manufacturing
- Develop routes for effective catalytic conversion of plant-derived olefins and other renewables into high-value chemicals and materials
- Evaluate new catalyst compositions in carbon-nanotube-based membrane electrode assemblies (MEAs) in polymer electrolyte fuel cells (PEMFCs) to improve the performance and reduce the costs of the catalysts for oxygen reduction.

Accomplishments

- Achieved a breakthrough in the synthesis of cyclohexasilane (Si_6H_{12}), where yields have been improved to >90%
- Achieved ultrahigh-rate silicon deposition rates (8Å/s) by using P_EC_{VD} using Si_6H_{12} as the silicon source, potentially enabling higher production rates for Si thin-film PV cells
- Achieved aerosol printing of an Ag $cu_r r_{en}$t-collecting grid on c-Si cells, where fine resolution (less than 5 μm) minimizes shadowing losses
- Achieved high selectivity in the oxidative cleavage of monounsaturated carboxylic acids derived from oil seeds, yielding high-value polymer precursors.

Future Directions

- Conduct a technoeconomic analysis of Si_6H_{12}-based processes for producing Si-based thin films needed in PV devices
- Probe the mechanism of transformation of Si_6H_{12}-based inks into thin-film Si
- Utilize high-throughput combinatorial (HTC) methodologies to investigate high-value polymer materials that can be synthesized from plant-derived chemicals
- Evaluate the activity and stability of carbon-nanotube-supported platinum alloy catalysts for electrochemical oxygen reduction.

3.8 Nye County Renewable Energy Feasibility Study (Nye County—Webster)

Objectives

- Develop land use and community preparedness plans that support responsible and sustainable renewable energy development in areas targeted by project developers
- Measure and report solar and wind characterization data to assess generation potential

- Provide comprehensive liaison, environmental regulation, and support services to energy developers and government agencies involved in Nye County.

Accomplishments

- Completed an *Amargosa Valley Area Plan* to guide the design and permitting of solar thermal power plants in the valley. The plan has been approved, and two 500-MW projects have progressed to the EIS phase
- Evaluated the former Barrick Mine site for suitability for a 20- to 30-MW PV power generation facility
- Installed Internet-monitored solar intensity and weather monitoring instrumentation on county building rooftop sites in Pahrump (2,693 ft elevation) and Tonopah (5,863 ft elevation). The UNLV Center for Energy Research carried out this work.
- Set in motion three lease-option agreements for PV solar projects on the Tonopah Airport site

Brought a 100-MW solar thermal power-tower project using molten salt technology to the EIS phase. The site is northwest of Tonopah Future Directions

- Assist developers with the BLM permitting and agency approval processes to move projects toward construction
- Redirect landfill study earmark funds toward a new transmission for export study that will propose transmission corridor upgrades and expansions to support the delivery of Nye County renewable energy generation capacity to the California market.

3.9 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

- Synthesized high-purity SWNT, DWNT, MWNT, N-SWNT and Nanolance chains
- Built first generation of vertical cells and generated IP associated with it
- Produced new all-organic optical limiting composites
- Produced new hybrid optical limiters with the highest nonlinear limiting values in the visible and near-IR region.
- Developed new thin-film sensors from nanocomposites that have broadband responses in the GHz region (for wind turbine blade sensor coating)
- Completed theoretical studies of functionalized and doped carbon nanotubes in self-assembled complexes
- Initiated studies of core-shell semiconductor nanoparticles embedded in electroactive polymers

Future Directions

- Complete first stage of vertical cells by developing a 1-cm^2 cell composed of multiple devices
- Demonstrate new vertical cells operating in air
- Deliver new nanocomposites for potential use as new n-type semiconductors
- Calculate the electronic and optical properties of nanoparticles embedded in polymers
- Study the absorption characteristics and the efficiency of charge transport of nanocomposite materials
- 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 and develop new cells.

3.10 Wisdom Way Solar Village (Rural Development, Inc.—Perkins)

Objectives

- Enhance Wisdom Way Solar Village, a development of 20 prototypical 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).

Accomplishments

- Completed and sold eight near zero net energy homes,
- Installed high efficiency windows for 16 units
- Installed 16 solar hot water systems
- Began monitoring 4 homes for performance.

Future Directions

- Complete remaining 12 units
- Rent 2 units to households with disabled members
- Sell final 10 units by December 2010.

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3.11 MUNI Ways and Structures Building Integrated Solar Membrane Project (SFPUC—Doyle)

Objectives

- Install BIPV system using best available, highest efficiency technology to meet about 25% of the building's total facility load, which averages 52,560 kWh per month.

Accomplishments

- Completed preliminary roof structural and electrical evaluation, taking California Environmental Quality Act (CEQA) requirements into account
- Completed preliminary designs for a BIPV installation on the facility roof and specified monitoring of BIPV system
- Revised and streamlined city RFP contract documents to make bidding process easier for solar contractors
- Selected eight qualified firms to receive RFP.

Future Directions

- Issue and advertise RFP 02/10
- Start construction in late summer 2010 with completion estimated for December 2010.

3.12 Solar Consortium of NY PV R&D Center (TSEC—Cozzolino)

TSEC is an industry-led nonprofit dedicated to eliminating the technical and economic barriers to the widespread use of solar energy in New York State.

Objectives

- Enable TSEC's Solar Innovation and Solar Solutions teams to work with public and private entities, industry, and universities to overcome technical and technology barriers to solar energy use
- Facilitate TSEC's Enable Manufacturing Teams as they work with industry partners to grow and retain jobs in renewable energy in New York State and to bring new products to market.

Accomplishments

- Worked with the Federal Prison system and the U.S. Department of Justice, along with two industry partners, to establish a manufacturing capability within the prison system
- Assisted EarthKind Energy, a solar hot water collector company with R&D and manufacturing capability, during its relocation to New York State.
- Initiated and coordinated the work of four NYS county workforce agencies and the State University of New York (SUNY). Thirteen companies with about 50 job openings attended the session, along with 400 job seekers
- Coordinated SUNY New Paltz Solar usage projects (three hospital in Ulster County, NY, and an off-grid PV Air National Guard installation in Newburgh, NY)
- Provided technical support to SUNY New Paltz solar car team for the Formula Sun Grand Prix Race in Cresson, Texas
- Received NYSERDA grant for Advance Energy System Mass Transit
- Assisted Prism Solar Technology to manufacture its proprietary solar concentration film
- Established a daily renewable energy e-bulletin reaching a diverse and growing number of readers.

Future Directions

- Expand use of off-grid applications of solar energy products
- Increase focus on solar farming in NYS
- Increase focus on solar thermal applications
- Continue collaborations between industry and academia for technology transfer and new product commercialization
- Conduct solar education and outreach activities.

3.13 Development of Concentrator PV Systems for Solar Electricity (University of Arizona—Angel)

Objectives

- Cost-competitive generation of solar electricity
- Demonstrate a new approach to concentrating PV generation in a working prototype
- Develop new manufacturing methods aimed at mass production at low cost.

Accomplishments

- Constructed prototype with multijunction PV cell at 1,000 x concentration; end-to-end test shows 27% conversion efficiency.
- Developed a new manufacturing method for back-silvered solar reflectors demonstrated in segmented unit 3 m in diameter
- Constructed a low-cost, low-mass 2-axis tracker to carry 70 m^2 of glass reflectors

Future Directions

- Build and demonstrate a 20-kW prototype unit
- Develop and demonstrate production at 1 MW/year rate
- Facilitate transition to industrial production.

3.14 Novel PV Devices Based on Polymeric and Carbon Nanostructured Materials (UALR—Biris)

Objectives

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- Develop highly efficient and cost-effective solar devices using the unique optical and electronic properties of carbon nano-structured materials and photosensitive polymers.

Accomplishments

- Harvested light using high-density, p-type, single-wall carbon nanotube/n-type silicon heterojunctions.
- Developed polymer Functionalized n-Type Single Wall Carbon Nanotube PV Devices
- Investigated the electrical, optical, and morphological properties of P3HT-MWNT nanocomposite prepared using in situ polymerization
- Characterized pristine G-PANI films for electrodes to replace Ca and Al
- Fabricated and tested carbon nanotube (SWNT-P3HT) composite cell structures
- Characterized SSDP-PANI thin films for HTMs
- Synthesized boron-doped SWNTs and fabricated and tested a B-SWNT/n-Si structure.

Future Directions

- Develop PANI/n-Si-based solar cell
- Fabricate p-SWNT/n-SWNT cell with 3D networked junction
- Direct the self assembly of functional nanoparticles using polymer tethers
- Use enhanced lifetime of triplet exciton to create bulk heterojunction PV
- Continue to work on hybrid thin-film PV cells
- Modify graphene and fabricate graphene-carbon nanotube-based solar cell.

3.15 Evaluation of Economic Benefits of Distributed PV Systems (University of Hartford—Lubin)

Objectives

- Concentrate on economic benefits of distributed PV systems and adding support of investigations into the effect on faults that could affect meeting load requirements.
- Use existing research to develop economic and engineering models and existing PV installations to obtain data on both generation and load
- Use simulation models to determine the influence of distributed PV systems on operational faults on the inverters and load
- Determine net loss or gain in economic values based on effect of PV systems on reliability of meeting load requirements.

Accomplishments

- Acquired advanced dynamic simulation code to model both the solar generation and the loads of operating systems
- Used the university's PV system to verify the simulations and effects of the system
- Initiated an agreement with Connecticut companies to gather operating information from installed systems to compare with the model.

Future Directions

- Complete work to develop and validate simulation model of the PV installation at the university
- Initiate planning for data acquisition with owner-operated PV installations
- Evaluate data for indications of fault generation.

3.16 Sustainable Buildings: Using Active Solar Power (University of Louisville—Sharp)

Objectives

- Demonstrate to public officials, developers, commercial establishments, industries, and citizens the benefits of using solar technologies, including PV streetlights, daylighting, and solar water heating.
-
- Conduct simulations, bench-scale testing, and full-scale prototype testing on heat pipe-augmented passive solar heating system
- Explore thermochemical energy storage for concentrating solar systems through simulations.
- Develop training for installers of solar PV and water heating systems; design and construct a heliodon.

Future Direction

- Collaborate with Kentucky Solar Partnership to conduct educational outreach and support the installation of solar water heating systems and construction of zero energy homes.

3.17 CIBS Solar Cell Development (University of Nebraska at Kearney—Exstrom)

Objectives

- Fabricate and study new PV material, copper indium boron diselenide, $CuIn_xB_{1-x}Se_2$ (CIBS)
- Exceed $CuIn_{1-x}Ga_xSe_2$ (CIGS) PV efficiencies with CIBS goals of 25% (single-film) and 15% (module) through chemical composition changes.

Accomplishments

- Deposited $Cu_{.45}In_{.55-x}B_x$ precursor films of varying boron concentrations (22% to 63%) on molybdenum-coated quartz. These films

remained adherent and appear to have a wide bandgap because they are transparent

- Demonstrated that in solvothermal CIBS preparations from oleylamine solvents, boron reagent amounts do not have an effect on nanocrystalline product material properties. Raman spectra and XRD patterns are consistent with $CuInSe_2$ regardless of boron amount. Boron ions may be occupying interstitial sites in the crystal lattice
- Developed a new room-temperature aqueous solution-based preparation method for nanocrystalline $CuInSe_2$. In this method, all reagent species are solubilized. This may facilitate boron incorporation into the chalcopyrite lattice structure if this method proves viable for CIBS synthesis.

Future Directions

- 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
- Generalize the room-temperature aqueous solution-based preparation of CIBS.

3.18 Solar Cell Nanotechnology (UNLV—Das)

Objectives

- Develop low-cost nonlithographic nanofabrication technology to fabricate thin-film porous templates as well as uniform arrays of semiconductor nanostructures to make high- efficiency solar cells.

Accomplishments

- Optimized thin-film structure for creation of uniform arrays of nanostructures
- Optimized aluminum deposition process by investigating sputtering and e-beam deposition techniques
- Investigated buffer materials for ITO-coated glass substrates
- Investigated and optimized aluminum layer thickness
- Designed and implemented a new anodization apparatus
- Investigated anodization process to optimize process parameters.

Future Directions

- Optimize process parameters for desired template parameters
- Develop the two-step anodization process for improved structural control
- Design and implement electrochemical synthesis apparatus
- Investigate and optimize electrochemical synthesis process
- Develop and optimize the electrophoretic synthesis process
- Implement and characterize nanostructure-based solar cells.

3.19 County Parking Garage Photovoltaic Panels (Bexar County—Weir)

Objectives

- Promote the use of renewable energy while minimizing the impact of vehicle emissions
- Help sustain Bexar County's ongoing goal of energy efficiency

Accomplishment

- Complete design development.

Future Directions

- Develop construction documents for PV systems
- Install PV system.

3.20 Comparative Analysis of Turnkey Silicon Solar Cell Processes and Equipment (TSEC—Cozzolino)

Objectives

- Assist IBM with preparing a comprehensive report showing the advantages and disadvantages of currently available Si PV technology and developing a technology road map
- Carry out a full cost and technology comparison of currently available crystalline (mono, multi, poly) Si PV technology and create a technology road map to set forth ways to compete (on a cost basis) with traditional methods for generating electricity.

Accomplishments

- Completed an initial evaluation of road maps and prepared a preliminary report for use in driving remaining work.

Future Directions

- Complete engineering analysis of the most promising turnkey crystalline Si lines available from commercial providersEvaluate and compare the total "cost of ownership" among various turnkey providers
- Generate turnkey producers from a common set of characterized Si based substrates which to be analyzed and measured using many techniques.
- Evaluate each turnkey line for applicability of thin Si as a starting material
- Gain a thorough understanding of the technology, allowing a qualified, multientity team (national labs, academia, and industry)

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to move forward on reducing costs and heightening efficiency to compete with traditional power generation techniques.

3.21 Multi-functional Solar Energy Research Systems Research (USU—Muhs)

Objectives

- Strengthen and diversify USU energy R&D capabilities by exploring pathways to combine novel solar and biofuels production technologies with innovative co-located energy systems capable of simultaneously producing electricity or process heat.

3.22 Solar Power Generation Development (Omega Optical, Inc—Carver)

Objectives

- Create a solar cell prototype with low cost and high efficiency while avoiding both scarce and toxic materials
- Optimize the electronic properties of organic thin films
- Deposit organic-based Schottky cells
- Implement spectral splitting
- Integrate PV and photothermal (PT) collection mechanisms.

Accomplishments

- Assembled team and established lab space (late August 2009)
- Installed and dedicated two thin-film deposition systems to this program
- Deposited and evaluated several organic materials Installed test equipment
- Collected preliminary data including SEM images, x-ray diffraction, optical transmittance, resistivity, and mobility.

Future Directions

- Optimize PV and PT cell collection efficiency
- Fabricate PV and PT modules
- Optimize module reliability
- Integrate PV and PT collection into residential building materials.

3.23 Solar Electric Power System (City of Beacon, NY—Gold)

Objectives

- Purchase PV system for the City of Beacon's Municipal Building's southwest-facing roof, as large as 14 kW
- Install a public real-time monitoring system display and an educational display to demonstrate how the system works, present the cost savings, and outline the environmental benefits.

3.24 Solar Thermal, Solar Electric and Wind Power Systems (St. Clair Community College—McNeil)

Objectives

- Purchase equipment to advance student and community studies in alternative energy and energy management. This will be partnered with existing and proposed curricula to create a "living lab," along with fixed and mobile simulated hands-on experimentation units. Students will be able to attain an associate's degree in alternative energy.

3.25 Sustainable Energy for Vermont Schools (Vermont Dept. of Education—Hilgendorf)

Objectives

- Work with 10 Vermont public schools to develop solar power educational programs. This will fund the site feasibility and initial design, and the installation of PV systems on schools. PV installations (5 kW) at schools will be used to promote K-12 cross-discipline curriculum modules, teacher professional development, and workforce development initiatives.

3.26 TSEC Photovoltaic Innovation NY (TSEC—Klein)

Objectives

- Advance solar innovation and R&D by advancing solar technology in partnership with industry and academia
- Develop solar solutions to overcome barriers to solar implementation in various unique solar applications
- Enable manufacturing in partnership with state/local economic development agencies, industry, and academia to yield technical and economic resources that renewable energy companies need to grow; in addition, support job growth in the renewable energy field
- Assist IBM with preparing a comprehensive report showing the advantages and disadvantages of currently available Si PV technology and developing a technology road map
- Assist Prism Solar Technology in the maximum conversion of plasma display manufacturing equipment for PV cells and modules and Prism's patented Holographic Optical Elements (HOE).

Accomplishments

- Assisted subrecipients in project management and collaboration

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- Used the SEMILAB mapping tool to obtain lifetime maps on selected upgraded metallurgical grade (UMG) solar cells from Schmid, a German turnkey cell manufacturer
- Compared lifetime maps and diffusion length maps to UMG solar cell efficiencies. Results indicate weak correlation of cell performance with lifetime and with UMG alloy blend
- Took preliminary quantum efficiency measurements, which also indicate weak dependence on lifetime/diffusion length
- Set up and calibrated a PV characterization workstation equipped with a solar simulator for studying cells with areas of 2"×2"Obtained initial results for AC and DC PV parameters for a reference Si solar cell to standardize measurement procedures and to benchmark UMG-Si cell performance
- Presented initial findings at a CAMP symposium in October 2009. Submitted a paper on this work for presentation at the Semicon China 2010 Conference in Shanghai, China, March 16–18, 2010.

Future Directions

- Continue to advance solar innovation for solar solutions and to enable manufacturing
- Fabricate and characterize composites of UMG Si with PV solar grade Si to allow for a full cost and technology comparison of available crystalline (mono, multi, poly) Si PV production to result in a technology road map (work to be done by IBM & Clarkson)
- Maximize Prism Solar Technologies' conversion of plasma display manufacturing equipment line and area to manufacture PV cells and modules, along with Prism's HOE.

3.27 Energy Efficient Buildings (Salt Lake County—Young)

Objectives

- Install solar PV (approximately 300 kW) on selected county facilities using a Power Purchase Agreement (PPA) model. This will allow for increased energy efficiency with each facility. These installations will also demonstrate renewable technologies to communities in the county.

4. FY 2009 Special Recognitions and Patents

NMSU

- "Versatile Unfolding Solar Deployment System," S. Curran et al., U.S. patent application filed.
- "Organic Photovoltaic Pixel Tandem Wrap Cell," S. Curran et al., U.S. patent application filed.
- Filed patent application for "Vertically Stacked PV and Thermal Solar Cell," S. Curran et al., U.S. patent application filed.

UALR

- Z. Li and A.S. Biris, "Light-Harvesting with Single Wall Carbon Nanotubes/n-Silicon Heterojunctions." UALR ID #: 09-14; U.S. patent application 61/211,825, pending.

NIREC

- University of Nevada Reno, U.S. patent application 61169496.
- University of California, Davis, U.S. patent application # 12/404.

University of Arizona

- "Solar Concentrator Apparatus with Large, Multiple, Co-Axial Dish Reflectors," U.S. patent application 12/463,001, pending.
- "PV Generator with a Spherical Imaging Lens for use with a Paraboloidal Solar Reflector," U.S. patent application 12/463,016, pending
- "Method of Manufacturing Large Dish Reflectors for a Solar Concentrator Apparatus," U.S. patent application 12/463,026, pending.

5. Major FY 2009 Publications

NMSU (nine published or submitted, including the following):

- M. Vasiliev, M. Lopez del Puerto, A. Jain, Lugo-Solis, and J. R. Chelikowsky, "Application of Time-Dependent Density-Functional Theory to Molecules and Nanostructures," *J. Mol. Struct.*: THEOCHEM, **914**,115-129 (2009).
- N. Al-Aqtash and I. Vasiliev, "Ab Initio Study of Carboxylated Graphene," *J. Phys. Chem. C,* **113,** 12970-12975 (2009).
- K-S. Liao et al., "Use of Microbiologically Formed Nanorods Composed of Elemental Tellurium in Polymer Composites for Strong Optical Limiting Responses," *Chem. Phys. Lett.,* (12/09).

University of Arkansas (15 published or submitted, including the following):

- Z. Li, E. Dervishi, V. Saini, V.P. Kunets, Y. Xu, A.R. Biris, G.J. Salamo, and A.S. Biris, "Polymer Functionalized n-Type Single Wall

Carbon Nanotube Photovoltaic Devices," *Appl. Phys. Lett.* (2010, in press).

- Z. Li, V.P. Kunets, V. Saini, Y. Xu, E. Dervishi, G.J. Salamo, A.R. Biris, and A.S. Biris, "Light-Harvesting Using High Density p-Type Single Wall Carbon Nanotube/n-Type Silicon Heterojunctions," *ACS Nano* **3**, 1407-1414 (2009).
- Z. Li, E. Dervishi, Y. Xu, V. Saini, M. Mahmood, O.D. Oshin, A.R. Biris, and A.S. Biris, "Carbon Nanotube Growth on Calcium Carbonate Supported Molybdenum-Transition Bimetal Catalysts," *Catalysis Lett.* **131**(3), 356-363 (2009).

NIREC

- M. Mascal and E.B. Nikitin (University of California Davis), "Towards the Efficient, Total Glycan Utilization of Biomass," *ChemSusChem* **2**(5), 423 (2009).
- M. Mascal and E.B. Nikitin (University of California Davis), "Dramatic Advancements in the Saccharide to 5-(Chloromethyl)furfural Conversion Reaction," *ChemSusChem* **9**, 859 (2009).

NDSU

- J. Hoey, D. Thompson, M. Robinson, Z. Mahmud, O.F. Swenson, I.S. Akhatov, and D.L. Schulz. "CAB-DW for 5 µm Trace-Width Deposition of Solar Cell Metallization Top-Contacts," *Proc. 34th IEEE Photovoltaics Specialist Conference*, June 8-12, 2009, 1857-1861.
- K. Pokhodnya, J. Sandstrom, X. Dai, P. Boudjouk, and D.L. Schulz. "Comparative Study of Low-Temperature PECVD of Amorphous Silicon using Mono-, Di-, Trisilane and Cyclohexasilane." *Proc. 34th IEEE Photovoltaics Specialist Conference*, June 8-12, 2009, 1758-1760.

TSEC

- J.E. Garland, D.J. Crain and D. Roy, "Examination of Resistive Power Losses in a Single Crystal Silicon Solar Cell," poster presented at the *Center for Advanced Materials Processing Fall 2009 Symposium*, Oct. 15, 2009.
- J.E. Garland, "Measurement and Analysis of Solar Cell Parameters," talk presented at the *Physics Department Colloquium, Clarkson University*, Jan. 15, 2010.

University of Nebraska at Kearney

- A. Kamler, et al. "Thin Films Formed by Selenization of $CuIn_xB_{1-x}$ Precursors in Selenium Vapor," *Sol. Energy Mater. Sol. Cells*, **93**(1), 45-50 (2009).
- J. Olejníček, et al. "Problems with Synthesis of Chalcopyrite $CuIn_{1-x}B_xSe_2$," *Mater. Sci. Forum*, **609,** 33-36 (2009).
- C.L. Exstrom, et al. "Solvothermal Preparation, Processing and Characterization of Nanocrystalline $CuIn_{1-x}Al_xSe_2$ *Materials," Proc. Mater. Res. Soc. Symp.*, **1165,** M05-03 (2009).
- J. Olejníček, et al. "A Non-Vacuum Process for Preparing Nanocrystalline $CuIn_{1-x}Ga_xSe$ Materials Involving an Open-air Solvothermal Reaction," *Sol. Energy Mater. Sol. Cells*, accepted for publication.

6. University and Industry Partners

Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)
Eikos, Inc., NREL	Golden, CO	Expertise, device fabrication, characterization, and materials	492
NIREC:			
Desert Research Institute H. Kuhns	Reno, NV	Developing Utility Accountant, a tool to help manage utility costs	90
University of Nevada, Reno A.M.Trzynadlowski	Reno, NV	Power electronic converter-controller for off-grid wind turbine systems	97
UC Davis, M. 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	Riverside, CA	Evaluate novel electrocatalytic materials for fuel cells	533

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Organization/ Principal Investigator	Location	Description/Title of Research Activity	FY 2008 ($K)
R. Haddon University of Toledo Dr. Marsillac	Toledo, OH	Liquid silane-derived films	200
RPI/Harvard CVM D. Schneider Sr.	Cambridge, NY	Value engineering/optimization of system components	50
Syracuse University J. Zhang	Syracuse, NY	System testing	0
Island Bay Window and Curtain Wall	Long Island, NY	Curtain wall panel fabrication	0

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