

SUNSHOT INITIATIVE

Solar Energy Technologies Office

U.S. Department of Energy



TACKLING CHALLENGES IN SOLAR:
2014 PORTFOLIO

Message from the Director



In 2010, a small team at the U.S. Department of Energy (DOE) posed a basic question: What would it take for solar to become a significant fraction of the nation's electricity generation capacity? The team started from the premise that solar energy must become an economically attractive option in order to grow beyond early adopters and early markets. We anchored our effort in the notion that consumers and businesses would choose solar energy not only because it is the environmentally sustainable choice, but because it will be the economic choice.

After extensive analysis to evaluate what it would take for solar energy to reach cost parity without subsidies, DOE developed a plan and launched the SunShot Initiative in early 2011. The initial analysis in the SunShot Vision Study set aggressive cost and performance targets, which at the time seemed distant and unrealistic. But such goals served a very important purpose; they created a framework to assess and address the grand challenges to achieve the ambitious SunShot goal by the end of the decade.

The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark.

- Michelangelo

Fast forward only a few years, and solar deployment is up. Way up. The amount of solar power installed in the United States reached an estimated 13 gigawatts at the end of 2013—an 11 fold increase since 2008. This dramatic growth in deployment has led to impressive job growth in the sector. By nearly all measures, the solar energy industry has been one of the fastest growing industries in the U.S. over the last five years. There are now more than 143,000 jobs in the solar sector, and these jobs are growing at almost 10 times the rate of the United States economy. Every four minutes, another American home or business goes solar, supporting workers whose jobs can't be outsourced.

This growth in deployment is supported by rapidly declining costs. The targets set for 2020 are now within reach. Just three years into a decade-long initiative, the industry has progressed 60% of the way toward the 2020 SunShot goal.

Message from the Director

Yet, solar still only accounts for approximately 1% of the nation's electricity generation capacity. There is plenty of room to grow, but many challenges and opportunities remain. Concentrating solar power holds the promise of integrated and dispatchable storage, but must overcome high capital costs for large-scale deployment. Low-cost photovoltaic modules can enable significant solar deployment, but face the challenge of a weakened U.S. manufacturing industry. Non-hardware soft costs, which now account for 64% of the total cost of small residential systems, create opportunities for innovative solutions to streamline processes and drive down the costs of permitting, interconnection, finance, and customer acquisition. And, as deployment reaches even higher levels of grid penetration, grid integration will become a more significant challenge—creating opportunities for storage-based solutions and building energy management integration.

As daunting as all those hurdles and roadblocks appear, I am continually reminded of the tremendous amount of innovation and ingenuity flowing from our national laboratories, businesses, and communities across the country. There are several large-scale concentrating solar power plants now online using technologies originally developed by DOE. SunShot awardees have broken more than a dozen world record solar cell efficiencies in the past few years. We now have photovoltaic inverters with advanced functionality that can help support the electrical grid. Communities are using innovative group purchase programs to reduce the cost of residential solar by more than 20%, and some cities now conduct permitting entirely online, cutting down the time to go solar from weeks to minutes. We have achieved much, but there is more to do.

We are at the dawn of the age of solar energy, and the future is bright.

Thank you,



Minh Le

Director

Solar Energy Technologies Office, SunShot Initiative
U.S. Department of Energy

Message from the Director	3
Tackling Challenges in Solar Energy	6
Photovoltaics	11
Next Generation Photovoltaics	14
Training Next Generation Researchers	20
Advancing Photovoltaic Efficiency	24
Cross-Cutting Photovoltaics Efforts	30
Concentrating Solar Power	34
Collecting the Sun	37
Receivers and Heat Transfer Fluids	40
Power Conversion and Systems	45
Thermal Energy Storage	49
Systems Integration	53
Grid Performance and Reliability	56
Dispatchability	64
Power Electronics	66
Communications	69
Plant Performance and Reliability	70
Technology to Market	74
Technology Commercialization and Business Innovation	76
Manufacturing: Innovation and Scale-Up	86
Cost Analysis: Technology, Competitiveness, Market Uncertainty	94
Soft Costs of Solar Deployment	95
Empowering State and Local Leaders	99
Harnessing Big Data Analysis and Technical Solutions	106
Training a Strong Solar Workforce	111
Developing Solar Finance and Business Solutions	117
Appendix: SunShot Funding Programs	120

Tackling Challenges in Solar Energy

The U.S. Department of Energy (DOE) Solar Energy Technologies Office works to accelerate the market competitiveness of solar energy by targeting cost reductions and supporting increased solar deployment. In 2011, DOE announced the department-wide SunShot Initiative—a collaborative national effort that aggressively drives innovation to make solar energy fully cost competitive (subsidy-free) with traditional energy sources before the end of the decade. In support of this crucial goal, the Solar Energy Technologies Office pivoted its focus to fulfilling the SunShot vision and continuously evaluates areas of opportunity to further support cost reductions. Through SunShot, DOE supports efforts by private companies, universities, and national laboratories to drive down the cost of utility-scale solar electricity to about \$0.06 per kilowatt-hour (kWh), and distributed solar electricity to at or below retail rates.

ENERGY INNOVATION: THE STATE OF SOLAR TODAY

Widespread solar energy deployment can strengthen U.S. economic competitiveness in the global clean energy race, help cut carbon pollution to combat climate change, and secure America's energy future. The United States has enormous potential to get its energy from the sun: photovoltaic (PV) panels on just 0.6% of the nation's total land area could supply enough electricity to power the entire United States.¹ PV can also be installed on rooftops with essentially no land use impacts. Seven southwestern states have the technical potential and identified land area to site enough concentrating solar power (CSP) to supply more than four times the current U.S. annual demand.¹ And as a domestic energy source, solar supports broader national priorities, including national security, economic growth, and job creation.

Energy captured from the sun is more affordable, accessible, and prevalent in the United States than ever before. In 2012, rooftop solar PV panels cost about 1% of what they did 35 years ago. Since the beginning of 2010, the average cost of solar PV panels has dropped more than 60% and the cost of a solar electric system has dropped by about 50%.

U.S. installations have grown eleven-fold from 1.2 gigawatts (GW) in 2008 to an estimated 13 GW. This is enough capacity to power the equivalent of 2.2 million average American homes² or supply the combined electricity needs of Austin, Texas, and Seattle, Washington, for one year.³

Markets for solar energy are maturing rapidly around the country, and solar electricity is now economically competitive with traditional energy sources in several states, including California, Hawaii, and Minnesota. Moreover, the solar industry is a proven incubator for job growth throughout the nation. Solar jobs have increased by nearly 20% since the fall of 2012, which is 10 times the national average job growth rate. There are more than 142,000 solar workers in the United States, and each day the solar industry creates 56 new jobs across America.⁴

1. National Renewable Energy Lab and U.S. Department of Energy. SunShot Vision Study. Feb. 2012. pp.4-5. See: <http://energy.gov/eere/sunshot/sunshot-vision-study>.

2. See: <http://www.seia.org/blog/seia-turns-40-shout-out-solar>

3. Based on electricity consumption data for 2012.

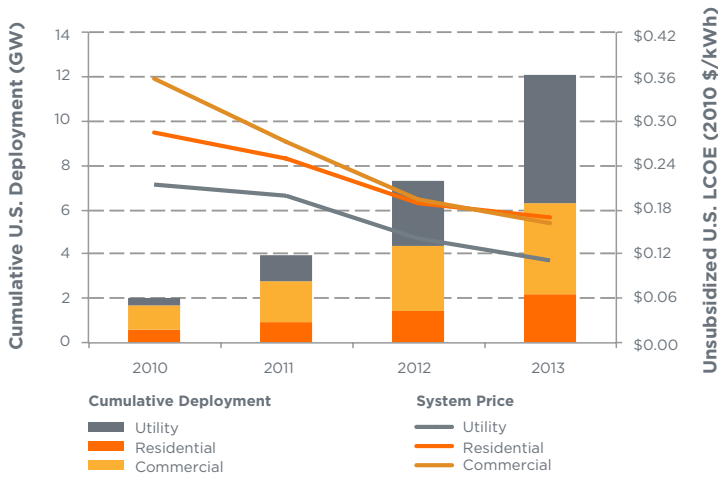


Figure 1. Average U.S. system price and cumulative deployment, by sector 2010-2013.

In 2013, solar energy reached a significant milestone: more than 1% (13 gigawatts) of the nation’s electricity generating capacity is now powered from the sun. This is a vast increase from 2008, when solar generation was less than 0.1% of the nation’s electricity capacity.² Yet significant work remains before solar achieves grid parity and realizes its full potential throughout the country. Solar hardware costs have fallen dramatically, but market barriers and grid integration challenges continue to hinder greater deployment. Non-hardware solar “soft costs”—such as permitting, financing, and customer acquisition—are becoming an increasingly larger fraction of the total cost of solar and now constitute up to 64% of the cost of a residential system.⁵ Technological advances and innovative solutions are needed to increase module and process efficiencies, drive down costs, and enable utilities to rely on solar for baseload power.

The SunShot Initiative is designed to establish American technological and market leadership in solar energy, diversify the nation’s electricity supply, reduce the environmental impacts of electricity generation, strengthen manufacturing competitiveness in the United States, train the next generation of the solar workforce, and catalyze domestic economic growth. The *SunShot Vision Study*, a guiding document

for the Initiative’s work, estimates that meeting SunShot cost reduction goals would allow solar to scale rapidly and potentially generate up to 14% of the nation’s total electricity demand by 2030 and 27% by 2050.⁶

THE SUNSHOT APPROACH

Modeled after President John F. Kennedy’s Moonshot goal to place a man on the moon in the space of a decade, SunShot is an aggressive, goal-driven national initiative. SunShot targets call for solar cost reductions of 75% relative to 2010 baseline levels. As such, the SunShot approach targets significant technological and market advancements that are needed to achieve grid parity by 2020. SunShot promotes market competitiveness with cost-based metrics, aiding the spread of technology and process innovations and enabling rapid growth in solar energy deployment.

Within SunShot, dedicated teams work on each of the Initiative’s five focus areas: PV, CSP, systems integration, technology to market, and soft costs.

- **PV and CSP:** SunShot funding supports transformative PV and CSP technology research and development (R&D) with the potential to yield significant cost reductions, efficiency improvements, and improved reliability standards. SunShot also supports the development of next generation PV technologies to carry innovation in solar energy beyond 2020 as well as CSP thermal energy storage technologies that can provide dispatchable power generation and enable greater deployment of other renewable energy sources.
- **Systems Integration:** Systems integration funding supports strategies to dramatically increase solar penetration in the nation’s electrical grid and enable safe, reliable, cost-effective, and widespread solar deployment.
- **Technology to market:** Technology to market funding supports commercialization, market readiness, and

4. The Solar Foundation. National Solar Jobs Census 2013. Feb. 2014. See: <http://thesolarfoundation.org/research/national-solar-jobs-census-2013>.

5. National Renewable Energy Laboratory. Dec. 2013. See: <http://www.nrel.gov/news/press/2013/5306.html>.

6. National Renewable Energy Laboratory and U.S. Department of Energy. SunShot Vision Study. Feb. 2012. p.7. See: <http://energy.gov/eere/sunshot/sunshot-vision-study>.

Tackling Challenges in Solar Energy

domestic manufacturing supply chains. Small solar businesses selected to participate in SunShot's competitive Incubator program have earned more than \$18 in follow-on funding for every \$1 in government investment. The success of this program has spurred similar efforts throughout the DOE Office of Energy Efficiency and Renewable Energy (EERE).

- **Soft Costs:** And while recent technological advances have drastically reduced the cost of solar hardware, making soft costs a greater share of the overall cost of solar, SunShot soft costs funding supports market transparency, workforce training, local solutions, and process improvements to make solar deployment faster, easier, and cheaper.

Since 1978, the Energy Department has supported the research, development, and deployment of a diverse array of energy technologies. These efforts have reduced the cost of these technologies and helped to improve the safety and reliability of the electrical grid. Within the Department, SunShot's work supports applied projects that target cost effective solutions to technological and market barriers, filling an important niche. SunShot coordinates its activities with the DOE Office of Science and the Advanced Research Projects Agency-Energy (ARPA-E) to prevent duplication of efforts while maximizing department-wide impact on solar energy. SunShot supports the Department's broader Clean Energy Manufacturing Initiative to increase the efficiency of the U.S. manufacturing sector and ensure that clean energy technologies continue to be made in America. SunShot also supports foundational research that is crucial to the advancement of solar energy technologies at the national laboratories and at user facilities that provide critical capabilities to the American solar industry.

FY13 funding distribution

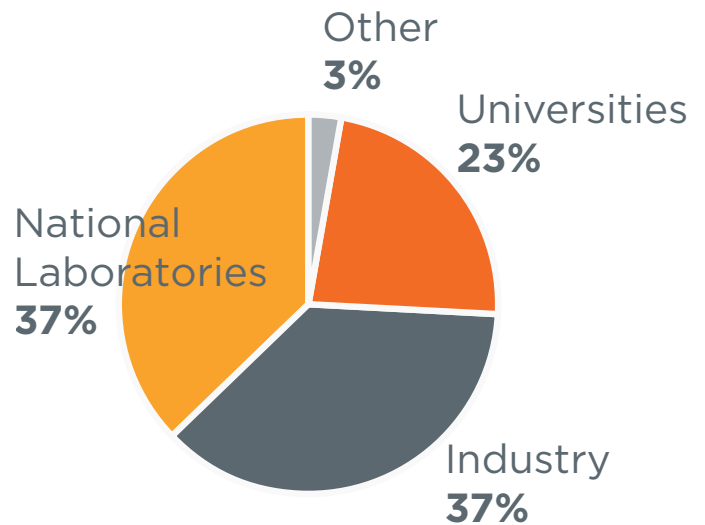


Figure 2. SunShot Initiative FY13 funding distribution.

A SUNSHOT FUNDING OPPORTUNITY: FROM CONCEPT DEVELOPMENT TO MANAGEMENT

SunShot funding programs target technical and market barriers for solar energy. To develop new funding programs, SunShot holds idea development sessions across teams to ensure cross-pollination between program focus areas and support the development of holistic approaches to tackling major challenges. The most promising topics are identified through internal debate and rigorous review by all SunShot program managers. SunShot also gathers industry experts at technical workshops to provide feedback on targeted barriers and potential solution pathways, and solicits broad input from stakeholders. Some of the ideas discussed at stakeholder workshops may eventually be incorporated

Core considerations for Office of Energy Efficiency and Renewable Energy programs

The proposed funding is...

Impactful	Targets a high-impact problem.
Additive	Will make a significant difference relative to private sector and other funding entity efforts.
Inclusive	Focuses on the broad problem. Is open to new ideas, new approaches, and new performers.
A Return on Investment	Will result in enduring economic benefit to the United States.
Within DOE's Role	Fulfills a proper, high-impact role for government versus an issue that is best left to the private sector to address on its own.

into funding programs, while others may not, based on stakeholder feedback. As part of the rigorous review for new funding programs, SunShot staff debate and refine potential topics and justify new programs with a set of criteria issued by EERE (see table).

Once a funding program is created, a solicitation or Funding Opportunity Announcement (FOA) is publicly issued to the stakeholder community to solicit applications (See the Appendix for a list of all SunShot FOAs). Each application is subjected to a rigorous review process, including evaluation by an external peer review panel consisting of distinguished scientists, engineers, and practitioners from academia, industry and national laboratories across the nation. Based on the rigorous technical review process, the alignment of the

application to SunShot goals, and the availability of funding, awards are made to the top few applications in any given funding program.

Once funding awards are made, SunShot team members actively manage projects through the length of the award agreement to ensure awardees meet agreed-upon project objectives, deliver on milestones, and yield valuable results. Post-award workshops and other SunShot events, including the biennial SunShot Grand Challenge Summit and Peer Review, connect awardees and other leaders doing innovative work in solar energy, furthering the spread of ideas and best practices within the SunShot community.

SUNSHOT: A STRIKING RECORD OF SUCCESS

Through game-changing innovations, SunShot's nearly \$900 million in investments over the last three years are transforming how solar systems are conceived, designed, manufactured, and installed in order to make it faster, easier, and cheaper to deploy solar. SunShot has funded hundreds of projects that are making solar more affordable and accessible—from streamlining panel manufacturing processes to reducing the red tape involved with permitting a residential solar energy system.

Only three years into the Energy Department's decade-long SunShot Initiative, the solar industry is already more than 60% of the way to achieving SunShot's cost target of \$0.06 per kWh for utility-scale PV (based on 2010 baseline figures),⁷ and more than halfway to CSP cost targets.⁸ Since SunShot's inception, the average price per kWh of a utility-scale PV project has dropped from about \$0.21 to \$0.11, the levelized cost of electricity for CSP has decreased from about \$0.21 to \$0.13,⁷ and solar jobs have grown by 53%.³

SunShot's success is a shining example of how government and industry can partner to move markets and grow our economy. SunShot's investments are paying dividends for domestic clean energy, while helping to prevent carbon emissions. Today, as a result of DOE's SunShot Initiative investments and the industry's accelerated pace to meet SunShot goals, the cost of going solar continues to drop and more solar is being added to our nation's energy mix.

While the solar industry has made significant progress only three years into the SunShot Initiative, grand challenges remain. The final 40% cost reduction to achieve the SunShot goal will require the most game-changing ideas and cutting-edge technological developments, from harnessing the power of big data to developing innovative financing mechanisms and more streamlined and efficient manufacturing processes. As SunShot continues to support innovative technical and market solutions to reduce the costs of solar, the Initiative will help to enable a world where homes, workplaces, and communities are powered by clean, renewable energy; utilities can count on solar to provide baseload power; and ubiquitous and cost-effective solar energy helps cut carbon pollution and fight climate change.

7. U.S. Department of Energy. Feb. 2014. See: <http://www.energy.gov/articles/us-utility-scale-solar-60-percent-towards-cost-competition-goal>

8. National Renewable Energy Laboratory. Internal Cost Model. Nov. 2013.

Photovoltaics

The Photovoltaics (PV) subprogram funds R&D that is critical to continued advances in solar cell and module technology. These advances enable lower costs, increased efficiency and improved reliability to support the widespread deployment of electricity produced directly from sunlight (“photovoltaics”). The PV portfolio includes research directed toward the SunShot Initiative goals as well as critical challenges beyond SunShot.

To meet the SunShot Initiative goal of an unsubsidized utility-scale PV system cost of \$1/W and to attain a levelized cost of energy (LCOE) of \$0.06/kWh by 2020, the PV program has the following targets:

- Module cost of \$0.50/W (including margin)
- Module efficiency of 20%

While module costs have decreased dramatically since the start of the SunShot Initiative, an additional 1/3 cost reduction is necessary. Further, increases in module efficiency enable decreases in the balance of systems costs (Fig. 1).

As the goals of the SunShot Initiative come within sight, the PV subprogram aims to address the next generation of challenges to support increased PV deployment, including

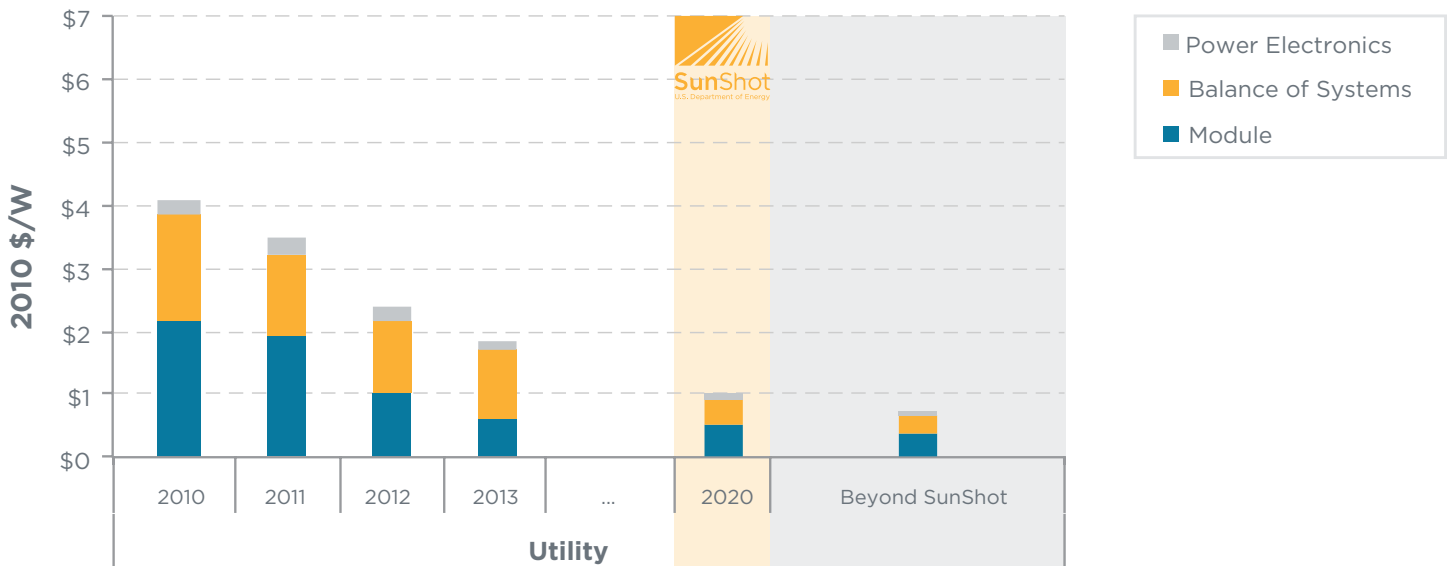


Figure 1. Evolution of the component costs of a PV system over time, also showing the SunShot targets and future reductions beyond SunShot. The PV subprogram work impacts the module and balance of systems costs.

Photovoltaics

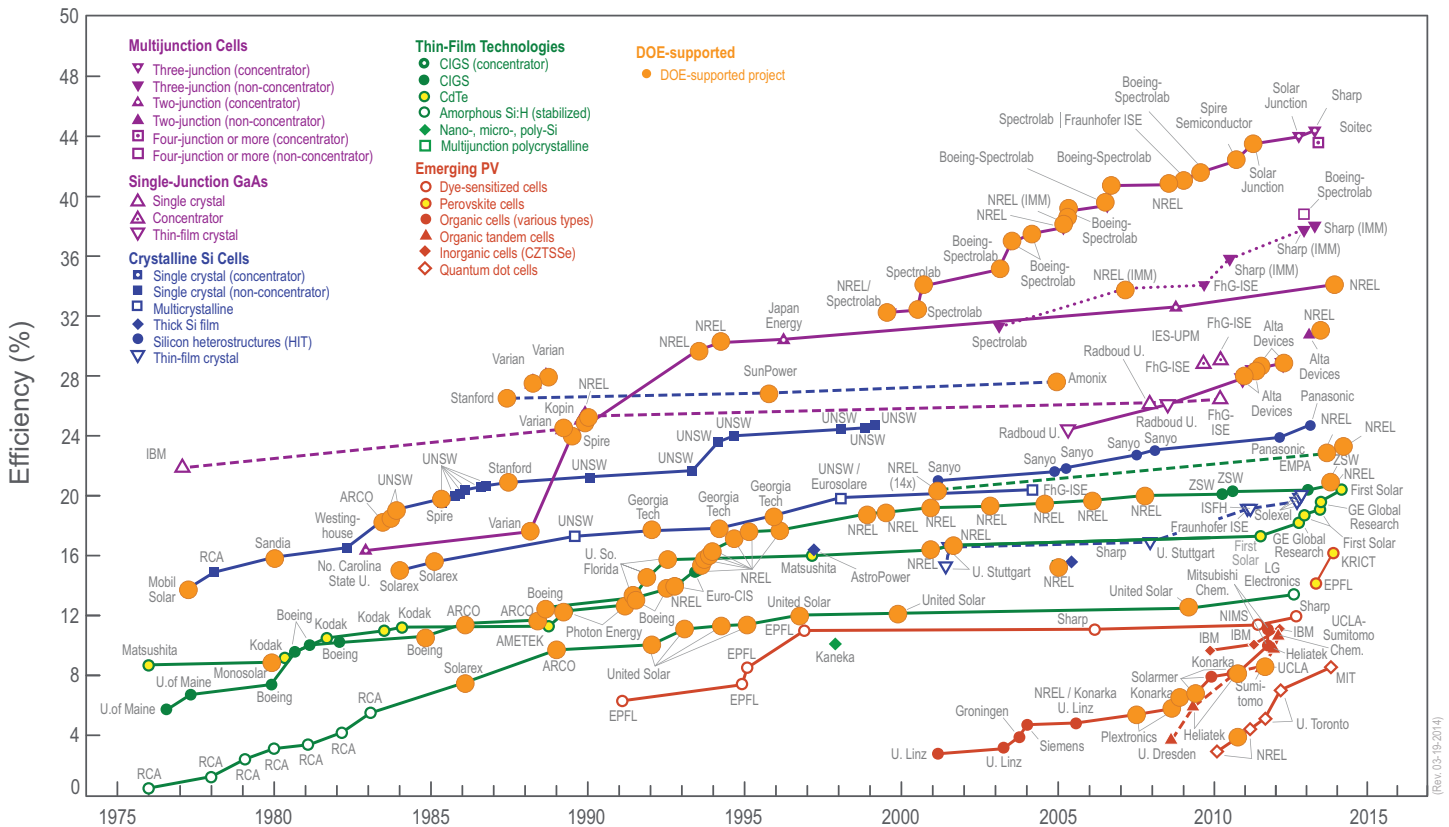


Figure 2. Record solar cell efficiencies of different technologies over the past several decades. Over one-half (orange dots) were funded by the PV subprogram and its predecessors. (Chart courtesy of NREL)

further reductions in the cost of PV electricity as well as reliability and life cycle sustainability. We also support the development of a skilled and diverse workforce of researchers prepared to address current and future challenges in the PV field. Accordingly, the PV portfolio spans from early-stage solar cell research until the point of commercialization. It includes work on materials, processes, and device structure and characterization techniques. Just a few examples of our projects include a combinatorial approach to find new earth abundant absorber materials, new silicon solar cell structures using organic and metal oxide heterojunctions, high efficiency III-V on Si multijunction solar cells, the development of a two-photon photoluminescence technique to separate bulk and surface lifetimes in thin films, and model systems for CdTe and CZTS solar cells to probe fundamental efficiency limits.

The PV subprogram helps to maintain U.S. leadership in PV R&D, with a strong record of impact over the past several decades. For example, over one half of the solar cell efficiency records on the National Renewable Energy Laboratory’s chart (Fig. 2) were supported by the PV subprogram and its predecessors.

The projects in the portfolio currently represent nearly \$200 million of investment (Fig. 3), made over periods from two to five years. About half of the funding is National Laboratory R&D through lab proposal development process agreements to the National Renewable Energy Laboratory (NREL). This funding to NREL represents a sustained commitment to high impact research and expertise across PV technologies, including thin films, silicon, III-V materials, performance testing, characterization, organic photovoltaics (OPVs), and new material development.

The remaining funding in the PV portfolio is primarily awarded through our competitive funding opportunity announcement (FOA) process to universities, national laboratories and industry. We currently have 10 active funding programs. Next Generation Photovoltaic Technologies (NextGen) 2 funds the development of early-stage, transformational PV technologies. The Foundational Program to Advance Cell Efficiency (F-PACE) 1 funds, in partnership with National Science Foundation (NSF), significant advancements in existing solar cell technologies. F-PACE 2 focuses on the development of model systems to understand and overcome barriers to increasing efficiency in Si and thin film solar cells. The Bridging Research Interactions through collaborative Development Grants in Energy (BRIDGE) program supports collaborative research teams using DOE Office of Science research facilities to reduce the cost of solar electricity. We help to build a diverse and talented workforce of solar researchers through the Minority University Research Associates (MURA) and Diversity in Science and Technology Advances National Clean Energy in Solar (DISTANCE) programs, which fund solar research at minority education institutions, and the SunShot Postdoctoral Research Awards, which fund recent Ph.D graduates across the country. The Physics of Reliability: Evaluating Design Insights for Component Technologies in Solar (PREDICTS) program works to improve reliability by funding the development of physics-based models for PV degradation mechanisms. In addition, we have a partnership with NSF to fund the Quantum Energy and Sustainable Solar Technologies (QESST) center at Arizona State University, and a partnership with DOE's Office of Science to fund Solar Energy Research for India and the U.S. (SERIIUS).

PV R&D portfolio funding distribution

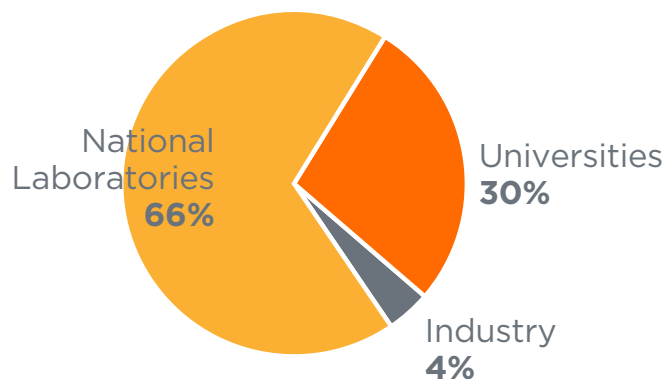


Figure 3. Distribution of funding in the PV portfolio by recipient type, including both FOAs and National Laboratory R&D.

The activity areas of our portfolio are Next Generation Photovoltaics, Training Next Generation Researchers, Advancing Photovoltaic Efficiency, and Cross-Cutting Photovoltaic Efforts, each of which are detailed herein.

Dr. Becca Jones-Albertus

Photovoltaics Program Manager
 Solar Energy Technologies Office
 U.S. Department of Energy

Next Generation Photovoltaics

This activity area encompasses research that has the potential to dramatically lower costs and/or increase efficiencies of PV module beyond the SunShot targets of \$0.50/W and 20%, respectively. It includes early-stage, applied research on new materials and device structures funded through the Next Generation Photovoltaics 2 (NextGen 2) and BRIDGE programs as well as National Laboratory R&D. The research supported by these programs will facilitate the entry of novel competitive technologies into the PV marketplace.

TRANSFORMING ORGANIC PHOTOVOLTAICS INTO A FULLY PRACTICAL ENERGY SOLUTION

University of Michigan | Ann Arbor, MI | \$1.5M | NextGen 2 | 09/2011-10/2015

This research effort addresses efficiency, reliability, cost and scalability issues that must be resolved to transform OPVs into a competitively viable product. Small molecular-weight, organic nanocrystalline cells are stacked to form a high-efficiency tandem architecture. The research team is using low-cost, light in-coupling schemes to enhance efficiency, exploring liquid phase and organic vapor phase deposition, and subjecting prototype devices to reliability testing.

SOLUTION PROCESSED PV ABSORBERS BASED ON COLLOIDAL NANOCRYSTALS LINKED WITH METAL CHALCOGENIDE LIGANDS

University of Chicago | Chicago, IL | \$1.5M | NextGen 2 | 09/2011-10/2015

Researchers on this project are developing solution-processed, all-inorganic PV absorber layers composed of colloidal nanocrystals. These are being electronically coupled through novel molecular metal chalcogenide ligands, which provide band-like carrier transport while preserving quantum confinement effects. At the end of the project, the research team plans to deliver a 20% efficient tandem cell composed of cadmium telluride (CdTe) nanocrystals for the top junction and lead sulfide (PbS) for bottom junction.

HOLE-BLOCKING LAYERS FOR SILICON/ORGANIC HETEROJUNCTIONS: A NEW CLASS OF HIGH-EFFICIENCY LOW-COST PV

Princeton University | Princeton, NJ | \$1.4M | NextGen 2 | 10/2011-10/2015

The aim of this project is to develop silicon/organic and silicon/metal oxide heterojunctions as a new class of high-efficiency, low-cost PV technology. Instead of a conventional p-n junction, a silicon/organic heterojunction is used to separate carriers, and a silicon/metal oxide interface provides a hole-blocking layer. These devices are fabricated by spin-coating or spraying a thin layer of an organic semiconductor on silicon. This low-cost, room-temperature process eliminates the need for the high-temperature diffusion steps typically used to fabricate p-n junctions.

SINGLE-CRYSTALLINE InGaAs/InP DENSE MICRO-PILLAR FOREST ON POLY-SILICON SUBSTRATES FOR LOW-COST HIGH-EFFICIENCY SOLAR CELLS

University of California | Berkeley, CA | \$1.5M | NextGen 2 | 09/2011-12/2015

Researchers on this project are developing a unique method to grow defect-free, III-V micro-pillar structures on single- and poly-crystalline silicon substrates. This approach combines the high-conversion efficiencies of compound semiconductor materials with the low costs and scalability of silicon-based materials. The dense forest of micron-sized indium gallium arsenide/ indium phosphide (InGaAs/InP) pillars provides omnidirectional, broadband light trapping and reduces the amount of rare earth materials required.

NEW MATERIALS FOR IMPLEMENTING TANDEM CIGS

University of Minnesota | Minneapolis, MN | \$1.5M | NextGen 2 | 09/2011-12/2015

Researchers on this project are aiming to demonstrate the first functional copper indium aluminum gallium diselenide / copper indium gallium diselenide (CIAGS/CIGS) tandem solar cell. The researchers are combining aluminum with both gallium and indium to form a wide band gap absorber and developing a novel tunnel junction using thermal and air-stable oxides. Finally, they are introducing a graded $Cd_xZn_{1-x}S$ layer using a novel continuous flow chemical bath deposition system which can better control process conditions and reduce particle loading.

COMBINATORIAL PLATFORM FOR DISCOVERY OF NANOCRYSTAL-INK BASED EARTH ABUNDANT ELEMENT PV WITH EFFICIENCY GREATER THAN 20%

University of Washington | Seattle, WA | \$0.49M | NextGen 2 | 09/2011-12/2015

The University of Washington research team is employing solution-phase chemistry methods used for CZTSSe device fabrication to conduct high-throughput experiments with a novel combinatorial deposition platform. This approach allows for the discovery of alloying and doping strategies that produce a back surface field and defect passivation strategies that can dramatically decrease recombination and increase the minority carrier lifetime. By using photoluminescence, current-voltage, capacitance-voltage, and external quantum efficiency analysis, the researchers hope to rapidly converge on practical routes to high-efficiency CZTSSe-based solar cells.

PYRITE IRON SULFIDE SOLAR CELLS MADE FROM SOLUTION

University of California | Irvine, CA | \$1.2M | NextGen 2 | 09/2011-12/2015

The goal of this project is to build a prototype solar cell made from nontoxic, inexpensive, and earth-abundant iron pyrite (FeS_2), also known as Fool's Gold, with an efficiency of 10% or greater. The research team is developing a stable p-n heterojunction using innovative solution-phase pyrite growth and defect passivation techniques. A pyrite-based device offers a pathway to meeting SunShot cost targets, 20% module efficiency, and terawatt scalability using a proven, manufacturable geometry that is suitable for rapid scale-up by a U.S. thin film PV industrial partner.

DEVELOPMENT OF III-Sb QUANTUM DOT SYSTEMS FOR HIGH EFFICIENCY INTERMEDIATE BAND SOLAR CELLS

University of California | Los Angeles, CA | \$0.9M | NextGen 2 | 09/2011-12/2015

The primary objective of this project is to identify and develop a III-Sb quantum dot absorbing medium for intermediate band solar cells (IBSC) via thorough experimental analysis supported by sophisticated band structure modeling. This is of interest because the theoretical efficiency limit of IBSCs is on par with triple junction solar cells. The team is working on band structure calculations, quantum dot solar cell device design, materials development, and in-depth experimental analysis of the quantum dot superlattice properties using TEM, QE and 2 photon absorption experiments. The team will be targeting the demonstration of a 20% IBSC with no open circuit voltage loss.

HOT CARRIER COLLECTION IN THIN FILM SILICON WITH TAILORED NANOCRYSTALLINE/AMORPHOUS STRUCTURE

Colorado School of Mines | Golden, CO | \$1.4M | NextGen 2 | 09/2011-12/2015

Researchers on this project are developing a new approach to the synthesis of hydrogenated nanocrystalline silicon (nc-Si:H), which exploits hot carrier collection as a way of boosting conversion. By using a novel gas phase plasma process, the research team is creating engineered films that incorporate quantum-confined Si nanocrystals with tailored surface termination. These engineered composites of amorphous and nanocrystalline Si have the potential to dramatically increase the efficiency of single junction and multijunction thin film Si solar cells by mitigating photo-induced degradation, increasing absorption, and offering the possibility of hot carrier devices.

BEYOND THE LAMBERTIAN LIMIT—NOVEL LOW-SYMMETRY GRATINGS FOR ULTIMATE LIGHT TRAPPING ENHANCEMENT IN NEXT-GENERATION PHOTOVOLTAICS

University of Delaware | Newark, DE | \$1.2M | NextGen 2 | 09/2011-12/2015

This project is addressing the efficiency limit and high fabrication cost of current light-trapping methods by developing novel low-symmetry gratings (LSG) for next-generation thin crystalline silicon and copper indium gallium selenide (CIGS) PV solar cells. The LSG design achieves light-trapping enhancement exceeding the $4n^2$ Lambertian limit within a specified range of photon wavelengths and can be fabricated using a low-cost, single-step nano-imprint/molding technique.

NEXT-GENERATION SULFIDE MATERIALS: OPTIMIZING CZTS AND DEVELOPING SnS BY SYSTEMATIC DEFECT ENGINEERING

Massachusetts Institute of Technology | Cambridge, MA | \$1.5M | NextGen 2 | 09/2011-12/2015

MIT is using systematic defect engineering to advance thin film PV cells based on tin sulfide (SnS), which offers high optical absorption and high carrier mobilities. Because tin and sulfur are earth-abundant materials and require processing temperatures below 400°C, use of these materials in thin film PV cells has the potential to lead to low-cost fabrication. A rapid ramp-up of efficiency is also possible by leveraging the decades of development of similar thin film materials.

SOLAR UPCONVERSION WITH METAL-ENHANCED BIMOLECULAR COMPLEXES

Leland Stanford Junior University | Stanford, CA | \$1.3M | NextGen 2 | 09/2011-12/2015

This effort aims to develop an efficient medium capable of using plasmonic materials and processes to convert low-energy transmitted photons to higher-energy photons, which can then be absorbed by any type of commercial solar cell. The research team is using electrodynamic simulations and *ab-initio* quantum computations to optimize existing upconversion processes and design new molecular complexes for high-efficiency PV upconversion in a solution-processable, scalable platform.

AN INTEGRATED APPROACH TO ORGANIC PHOTOVOLTAICS

National Renewable Energy Laboratory | Golden, CO | \$4.4M | National Laboratory R&D | 10/2012-09/2015

OPVs could become a low-cost technology amenable to high-throughput fabrication techniques. However, OPVs need to overcome short device lifetimes and low efficiencies. This project integrates theory, computation, and characterization to discover and develop new materials for OPV that advance efficiency and improve lifetime. There are three integrated research tasks: **1)** the design and development of new absorber materials through combinatorial computational methods coupled to their direct synthesis, characterization, and device optimization; **2)** the development of charge-selective hole and electron contacts that optimize interface properties, performance, and stability for new active layer materials; and **3)** the investigation of device and materials degradation mechanisms and mitigation strategies to extend device lifetime.

MULTIFUNCTIONAL TRANSPARENT CONDUCTING OXIDES

National Renewable Energy Laboratory | Golden, CO | \$1.5M | National Laboratory R&D | 10/2012-09/2015

This agreement pursues the development of promising transparent conducting oxides (TCO) for use in PV cells. The first goal is to demonstrate earth-abundant TCOs using industrially-compatible processing conditions with material parameters comparable to TCOs commonly used today. The second goal is to model and demonstrate deposition of amorphous TCOs with tunable material properties that are flexible and/or cost effective. By furthering basic theory, demonstrating new materials, and optimizing processing, improved contacts can be created for multiple PV technologies.

RAPID DEVELOPMENT OF EARTH-ABUNDANT THIN-FILM SOLAR CELLS

National Renewable Energy Laboratory | Golden, CO | \$1.5M | National Laboratory R&D | 10/2012-09/2015

In order to diversify the materials base for inorganic thin film solar cells, which may allow for new technologies with reduced costs, an accelerated development technique is being pursued. The approach initially focuses on ternary copper sulfides and iteratively combines predictive first-principles theory and high-throughput experiments. Both individual materials and PV device prototypes will be developed using the high-throughput technique to accelerate the development process. The results of this project have the potential to drastically expand the materials options for PVs and produce new earth abundant thin film solar cells that are competitive with incumbent technologies.

LOW-COST, HIGH-EFFICIENCY, ONE-SUN HYDRIDE VAPOR PHASE EPITAXY III-V SOLAR CELLS

National Renewable Energy Laboratory | Golden, CO | \$1.5M | National Laboratory R&D | 10/2012–09/2015

This project aims to develop a new III-V, one-sun solar cell concept that has the potential to outperform silicon modules in both efficiency and cost. This will be achieved by growth of III-V materials by HVPE in a revolutionary, in-line reactor, rather than by expensive metallorganic vapor phase epitaxy (MOVPE) in a traditional batch reactor. The many advantages of HVPE include much lower precursor costs (pure metals rather than organometallic engineered molecules, representing a 5–10x savings), higher deposition rates (1–5 $\mu\text{m}/\text{min}$ or 10–50x faster), significantly increased material utilization (much lower arsine overpressure), and inherent cost savings due to atmospheric-pressure, in-line growth. This technology is expected to reach grid parity cost points, along with favorable balance-of-system (BOS) efficiencies, by significantly lowering the cost of III-V material growth and by applying a simple, fast layer-transfer process to reuse an epitaxial template wafer.

RATIONAL DESIGN OF WIDE BANDGAP BUFFER LAYERS FOR HIGH-EFFICIENCY THIN-FILM PV

Lawrence Livermore National Laboratory | Livermore, CA | \$0.31M | BRIDGE | 11/2012–11/2015

LLNL is working in collaboration with the University of Illinois at Urbana-Champaign and industry partners to provide critical understanding of the role of bulk and interface defects in limiting the performance of buffer layer materials necessary for the fabrication of stable, high efficiency thin film PV devices. This project is innovative in its application of first-principles atomic scale modeling to the design of buffer layer materials for thin film PV, as well as in coordinating complimentary state-of-the-art computational and experimental efforts to accelerate progress, expanding the breadth of expertise and resources being applied to PV system design.

DEVELOPING A TRANSPARENT EMITTER LAYER FOR CIGS SOLAR CELLS THROUGH SYNCHROTRON INVESTIGATIONS

National Renewable Energy Laboratory | Golden, CO | \$0.3M | BRIDGE | 11/2012–11/2015

Spectroscopic and diffraction measurements are being used in multiple energy ranges to probe different parts of transparent emitter layers (surface, near surface and bulk) and interfaces in CIGS thin-film PV devices. NREL is working in collaboration with Stanford Synchrotron Radiation Lightsource to apply synchrotron radiation methods and other tools to support the development of a transparent emitter layer.

VAPOR TRANSPORT DEPOSITION FOR III-V THIN FILM PHOTOVOLTAICS

University of Oregon | Eugene, OR | \$0.45M | BRIDGE | 11/2012–11/2015

Scientists at the University of Oregon are researching vapor transport (VT) deposition technology for III-V solar materials. Using photoelectrochemical (PEC) test cells, they have shown that n-doped Gallium Arsenide (n-GaAs) deposited in a simple close-space VT reactor has diffusion lengths of 1.5 μm even when deposited at rates of $\sim 0.5 \mu\text{m min}^{-1}$. Device physics simulations show that by controlling doping and forming solid-state junctions, AM1.5G (air mass global) efficiencies greater than 24% should be attainable.

COLLABORATIVE ATOMIC-SCALE DESIGN, ANALYSIS, AND NANO-FABRICATION FOR RECORD BREAKING, SINGLE CRYSTAL $Zn_xCd_{1-x}Te$ SOLAR CELL ARRAYS

University of Texas | El Paso, TX | \$0.9M | BRIDGE | 11/2012-11/2015

The goal of this project is to create a new collaborative capability to work around fundamental barriers to achieving high open-circuit voltages ($VOC \geq 1.0$ V) in CdTe/CdS solar cells. The project will create a patterned thin film design, deposition and analysis capability to create uniform $Zn_xCd_{1-x}Te$ /CdS solar cell arrays that will reduce the defect-density from 10^{14} to 10^{12} cm^{-3} and increase the V_{oc} from 0.85 V to 1.0 V.

***IN-SITU* ROLL-TO-ROLL PRINTING OF HIGHLY EFFICIENT ORGANIC SOLAR CELLS**

SLAC National Accelerator Laboratory | Menlo Park, CA | \$0.88M | BRIDGE | 11/2012-11/2015

The objective of this project is to develop a roll-to-roll printing setup for organic solar cells that will capture important aspects of existing industrial printing methods and will allow the printing process to be studied *in-situ* with both small and wide angle X-ray scattering. This novel ability will enable a more rapid rate of improvement in solar cell performance by allowing the team to directly tune the printing conditions and the ink formulations based on the feedback from the scattering experiments.

Training Next Generation Researchers

This activity area funds solar energy research to produce a talented and diverse workforce of scientists and engineers prepared to address future challenges in solar energy R&D. This area includes the MURA and DISTANCE programs and the SunShot Postdoctoral Research Awards.

COST EFFECTIVE POLYMER SOLAR CELLS RESEARCH AND EDUCATION

Norfolk State University | Norfolk, VA | \$0.3M | MURA | 09/2010–08/2014

The research objective is to investigate and develop polymer-based solar cells for potential cost-competitive, durable, lightweight, flexible, and high efficiency solar energy conversion applications. A donor/acceptor bicontinuously ordered nano structure type solid state morphology is targeted. The educational objectives of this project include training a next generation of young scholars, scientists and/or technical workforce to work on solar energy technology.

PRODUCTION AND CHARACTERIZATION OF NOVEL PHOTOVOLTAIC MATERIALS

North Carolina Central University | Durham, NC | \$0.3M | MURA | 09/2010–09/2014

This project enhances PV research and training efforts at NCCU focused on the development of novel nanoscale materials for PV applications. A unique ultrafast pulsed laser deposition and pulsed electron deposition facility is used to systematically study complex ternary and quaternary III-V and chalcopyrite semiconductor quantum dots (QDs) and nanowires (NWs) that are anticipated to play an important role in the development of advanced PV cells. Theoretical modeling of the electronic structure and carrier dynamics of QDs and NWs will complement the experimental research.

CREATING GREEN TALENT IN THE SOUTHWEST: A COMPREHENSIVE RESEARCH AND EDUCATION PROGRAM IN SOLAR CELL TECHNOLOGY AT THE UNIVERSITY OF NEW MEXICO FOR HISPANIC AND NATIVE-AMERICAN BACCALAUREATE STUDENTS

University of New Mexico | Albuquerque, NM | \$0.3M | MURA | 09/2010–09/2014

This project establishes a third generation PV laboratory at the Center for High Technology Materials where undergraduates will be exposed to research in nanotechnology-based PVs and ultra-high concentration solar cells, as well as a research effort in the Electrical and Computer Engineering (ECE) department on smart grids for future power distribution. Additionally, new core ECE courses are being developed that will be taken by all undergraduates, which will introduce them to PVs from both a device and a power systems perspective.

NEW NANOSTRUCTURED MATERIALS FOR EFFICIENT PHOTON UPCONVERSION

University of Delaware | Newark, DE | \$0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

In this research effort, new designs are being developed for nanostructured materials that maximize upconversion efficiency and can be easily integrated with existing PV devices. The three objectives for this project are: **1)** use well-controlled model systems to develop a fundamental understanding of the photophysical processes impacting upconversion efficiency, **2)** develop new nanostructured devices with high upconversion efficiency and minimal energy sacrifice and **3)** develop implementations of this design that can be produced and processed at commercially-relevant scales.

STOICHIOMETRY, INTERFACES, AND DEFECTS IN Cu_2S PHOTOVOLTAICS: A MODEL SYSTEM FOR ATTAINING STABILITY

Argonne National Laboratory | Lemont, IL | \$0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

This research aims to synthesize Cu_2S PV “model systems” by atomic layer deposition (ALD). Precisely defined ALD model systems will enable a fundamental understanding of the optoelectronic stability in Cu_2S -based devices. An in-depth look into the photophysical properties of such devices will further shed light on the importance of interfaces in thin film PV devices. The potential impact of these studies will provide the grounds to understand why theoretical device efficiencies are rarely obtained in large-scale fabrication.

IN-SITU, NON-DESTRUCTIVE OPTOELECTRONIC CHARACTERIZATION OF BURIED INTERFACES IN SOLAR MATERIALS USING TWO-PHOTON TOMOGRAPHY

The Molecular Foundry, Lawrence Berkeley National Laboratory | Berkeley, CA | \$0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

Developing new characterization tools that can non-destructively probe within PV materials *in-situ* enables researchers to zero in on limiting factors of their devices and provide insight into potential improvements. To meet this need, this project develops a two-photon microscopy technique that allows for 3D imaging of grains and grain boundaries in CdSe and CdTe polycrystalline materials. This microscopy technique operates on the principle that semiconductors are generally transparent to sub-bandgap light, thus using a pulsed infrared laser source to probe through the material.

MAGNETICALLY GUIDED NANO-MICRO SHAPING AND SLICING OF SILICON

University of California | La Jolla, CA | \$0.2M | SunShot Postdoctoral Research Awards | 10/2012–09/2014

This research effort has enabled the first successful direction-guided, nano/microshaping of silicon. The technique, utilizing a narrow array of Au/Fe/Au trilayer etch lines, is particularly effective in producing only micrometer-thick Si sheets by rapid and inexpensive means with 20 μm level slicing loss of Si material, thus greatly reducing the waste of Si material compared to the ~200 μm kerf loss per slicing in the typical saw-cut Si solar cell preparation. Such nano/ microshaping may enable a whole new family of novel Si geometries and exciting applications. Micrometer thin, massively parallel silicon sheets, very tall Si microneedles, zigzag bent Si nanowires, and tunnel drilling into Si substrates have already been demonstrated.

BOOSTING SOLAR VOLTAGE OUTPUT BY EFFICIENT EXTRACTION OF AUGER ELECTRONS

University of Washington | Seattle, WA | \$0.2M | SunShot Postdoctoral Research Awards | 10/2012-09/2014

A concept for increasing voltage in solar cell devices is proposed using non-radiative (Auger) de-excitation of metastable excited states of dopant ions. This hot carrier capture via interfacial electron transfer could be used to augment both PV and photoelectrochemical devices. The test case uses photoexcitation of CdS nanocrystals followed by efficient picosecond energy transfer to Mn^{2+} , with a long-lived (ms) excited state lifetime. Electrons injected into the CdS then capture this energy via Auger de-excitation, generating hot electrons to be extracted at a higher potential.

HIGH-EFFICIENCY THIN-FILM Fe_2SiS_4 AND Fe_2GeS_4 -BASED SOLAR CELLS PREPARED FROM LOW-COST SOLUTION PRECURSORS

Delaware State University | Dover, DE | \$0.33M | DISTANCE | 09/2013-09/2016

The objectives of this project are to introduce a solar course at Delaware State University and initiate a solar research program debuting with the development of a novel thin film PV technology using solution nano-precursors to Fe_2SiS_4 and Fe_2GeS_4 -based absorber layers in solar devices. This technology aims to create low cost solar cells by using solution processing of sustainable, inexpensive materials, coupled with reduced installation costs by enabling use of lightweight, flexible substrates. The solar cell devices target an efficiency of at least 5%.

COMPLETE ELECTROCHEMICAL ACCESSIBILITY OF METAL-ORGANIC FRAMEWORK FILMS DEPOSITED IN A LAYER-BY-LAYER FASHION

Northwestern University | Evanston, IL | \$0.2M | SunShot Postdoctoral Research Awards | 10/2013-09/2015

Metal-organic frameworks (MOFs) have been shown to possess interesting properties that may prove beneficial for efficient solar energy conversion schemes. For example, light harvesting MOF crystals have been prepared which exhibit ultrafast energy migration. This fast energy migration is hypothesized to be facilitated by the spatial separation of chromophores and the anisotropy of the crystals. The main objective of this project is to prepare oriented and well-characterized MOF films through the liquid phase layer-by-layer method, where individual components of the MOF are introduced to the substrate one at a time, and study them for their potential application in PVs.

EARTH-ABUNDANT MATERIALS FOR TERAWATT SOLAR ENERGY

Massachusetts Institute of Technology | Cambridge, MA | \$0.2M | SunShot Postdoctoral Research Awards | 10/2013-09/2015

This research effort is split into two distinct but related research directions on SnS and Cu_2ZnSnS_4 (CZTS). Because SnS evaporates congruently, akin to CdTe, this presents the possibility of developing a closed space sublimation growth process for SnS similar to that developed by First Solar for CdTe. The second half of the project focuses on studying the beneficial effects of chemical and structural disorder in CZTS thin films. The team will study intentionally disordered CZTS (d-CZTS) that may provide the benefits of crystalline CZTS while not suffering from the effects of phase disorder.

TRANSITION METAL CHALCOGENIDES FOR SOLAR FLOW BATTERIES

Cornell University | Ithaca, NY | \$0.2M | SunShot Postdoctoral Research Awards | 10/2013–09/2015

This work attempts to demonstrate the feasibility of a Solar Flow Battery (SFB), a photoelectrochemical device for simultaneous solar energy capture and storage using semiconductor photoelectrodes and flow battery redox couples. A model has been built to estimate limiting and achievable efficiencies for semiconductor photoelectrochemical cells driving energy storage reactions using arbitrary redox couples. Transition metal chalcogenides and relatively narrow-bandgap metal oxides appear to be promising semiconductor candidates for SFB systems. Promising electrolytes have also emerged from these modeling studies, including hydrohalic acids, metal-halogenide couples, vanadium couples, and cerium couples.

Advancing Photovoltaic Efficiency

Projects in this activity area focus on improving the power conversion efficiency of established solar cell materials, including Si, CdTe, CIGS and III-Vs, as well as addressing technological barriers to further advancement. This work enables progress towards and beyond the SunShot targets. Programs in this area include F-PACE 1 and 2 as well as National Renewable Energy Laboratory R&D. A goal of this area is to sponsor at least three new world records for PV efficiency each year.

ACCELERATING CPV SYSTEM EFFICIENCIES TO CREATE A SUSTAINABLE TERAWATT PLATFORM

National Renewable Energy Laboratory | Golden, CO | \$3.5M | F-PACE 1 | 09/2011-09/2014

A partnership between NREL, Spectrolab, and the University of California–Berkeley is working to reduce the cost of concentrating photovoltaics (CPV) modules by increasing the CPV cell efficiency. This project team aims to increase cell efficiencies to 48% by inserting selective reflectors between the junctions of the multijunction solar cells, thereby increasing the photovoltage. The work will strive to define the fundamental physics in parallel with implementing the concept.

III-V/ACTIVE-SI INTEGRATION FOR LOW-COST HIGH-PERFORMANCE CONCENTRATOR PHOTOVOLTAICS

Ohio State University | Columbus, OH | \$1.2M | F-PACE 1 | 09/2011-11/2014

This project works toward a paradigm shift for CPV technology, which is currently constrained by germanium Ge and GaAs substrates in terms of cost and efficiency barriers. The project integrates GaAsP and Ga-rich GaInP based subcells with a Si substrate to achieve high efficiencies with a roughly 100-time reduction in substrate cost per area. This yields a path to achieve panels at \$0.50/W and provides access to the economies of scale afforded by a Si wafer based manufacturing infrastructure.

TECHNOLOGY ENABLING ULTRA-HIGH CONCENTRATION MULTI-JUNCTION SOLAR CELL

North Carolina State University | Raleigh, North Carolina | \$1.0M | F-PACE 1 | 09/2011-11/2014

A major opportunity for improving cost efficiency in CPV systems lies in operating at higher solar energy concentrations. In collaboration with Spectrolab, this project is designing a tunnel junction between the top and middle cells of an indium gallium phosphide/gallium arsenide/germanium (InGaP/GaAs/Ge) triple junction structure that is functional at a concentration of 2,000 suns. The researchers are growing the tunnel junction from aluminum gallium arsenide (AlGaAs) and InGaP while using very thin aluminum gallium arsenide (AlGaAs) layers to inhibit diffusion.

REDUCED $\text{Cu}(\text{InGa})\text{Se}_2$ THICKNESS IN SOLAR CELLS USING A SUPERSTRATE CONFIGURATION

University of Delaware | Newark, DE | \$1.1M | F-PACE 1 | 09/2011-11/2014

To reduce the cost of $\text{Cu}(\text{InGa})\text{Se}_2$ manufacturing, the research team is halving the thickness of the absorber layer. Project efforts include developing the technology and underlying science for using a superstrate cell configuration, which is essentially an upside-down version of the conventional $\text{Cu}(\text{InGa})\text{Se}_2$ configuration. The anticipated outcome of the project is a CIGS solar cell with 0.7 μm thickness and 17% efficiency.

HIGH-EFFICIENCY, COMMERCIAL-READY CdTe SOLAR CELLS

Colorado State University | Fort Collins, CO | \$1.5M | F-PACE 1 | 09/2011-12/2014

The goal of this research is to improve the relative efficiency of cadmium telluride (CdTe) solar cells used in commercial modules by about 30% without increasing manufacturing costs. This is being accomplished by modifying the basic cell structure for higher voltage and fill factor and incorporating plasma processes for final substrate cleaning and modification of the CdS window for increased band gap (higher current). Combined with modest decreases in production costs and anticipated advances elsewhere, this effort contributes to a reduction of the reported \$0.75/W module cost to the \$0.50/W target.

HIGH-THROUGHPUT CIGS SOLAR CELL FABRICATION VIA ULTRA-THIN ABSORBER LAYER WITH OPTICAL CONFINEMENT AND (Cd, CBD)-FREE HETEROJUNCTION PARTNER

Old Dominion University | Norfolk, VA | \$1.1M | F-PACE 1 | 09/2011-03/2015

Old Dominion University, in collaboration with The University of Toledo and the University of Illinois at Urbana-Champaign, is developing a high-throughput and high-efficiency CIGS solar cell fabrication process via the use of an ultra-thin absorber layer, optical confinement and a heterojunction partner without cadmium (Cd) or use of chemical bath deposition (CBD). These new designs and processes aim to reduce CIGS material costs by a factor of ten, multiply throughput production by at least a factor of five, and achieve module costs of less than \$0.44/W with efficiencies higher than 20%.

DEVELOPMENT OF HIGH ELECTRONIC QUALITY CdTe FILMS REQUIRED FOR 1 V V_{oc} CdTe CELLS

University of South Florida | Tampa, FL | \$0.99M | F-PACE 1 | 09/2011-01/2015

Thin film CdTe is today's lowest cost PV technology, but the open-circuit voltage of these solar cells has stayed at 0.85 volts (V) for nearly 20 years. In order to reach the practical potential of thin film CdTe cells, the open-circuit voltage of the cell must increase to about 1 V. The main goal of this project is to demonstrate that CdTe films with doping concentrations greater than 10^{16} cm^{-3} and lifetimes in the range of 1-10 ns can be prepared, which is consistent with a V_{oc} of 1 V. Increasing the V_{oc} to this level paves the way toward reaching 20% cell and 17% module efficiencies.

UNDERSTANDING THE EFFECT OF Na IN IMPROVING THE PERFORMANCE OF CuInSe_2 -BASED PV

University of Delaware | Newark, DE | \$0.96M | F-PACE 1 | 09/2011-11/2014

Together with the University of Illinois at Urbana-Champaign, this project strives to find the pathways through which sodium (Na) improves the performance of CIGS-based PV devices. The researchers are growing CIGS films with different amounts of Na for full characterization. They are also fabricating devices to highlight correlations of operation, Na dosage, and the method of incorporation. This investigation helps provide a basic scientific and engineering understanding of the role of Na in CIGS PV that is needed for advancement toward the \$0.50/W module manufacturing goal.

NOVEL CONTACT MATERIALS FOR IMPROVED PERFORMANCE CdTe SOLAR CELLS

University of Illinois | Urbana Champaign, IL | \$1.1M | F-PACE 1 | 09/2011-11/2014

This project is developing new materials for front and back contacts used in CdTe PV cells. The new materials will reduce the back-contact barrier to zero and produce an ohmic contact, which increases the current flow and thus the efficiency of the PV cell. These advances are expected to increase device performance and process flexibility, providing lowered costs and greater yields.

ADVANCED PRECURSOR REACTION PROCESSING FOR Cu(InGa)(SeS)_2 SOLAR CELLS

University of Delaware | Newark, DE | \$1.2M | F-PACE 1 | 09/2011-11/2014

This project seeks to improve the manufacturability of CIGS-based PV modules by advancing the precursor reaction approach currently employed by a number of commercial entities. In partnership with the University of Florida, the researchers are investigating pathways to improved module performance and yield by modifying the interface between the CIGS absorber layer and molybdenum (Mo) back contact, and to increased throughput by studying precursor structures for rapid (<5 minute) processing. This approach can also allow for the omission of toxic hydrogen selenide (H_2Se) gas from the manufacturing process.

IMPROVING V_{oc} OF CdTe THIN FILM SOLAR CELLS: UNDERSTANDING AND TAMING THE GRAIN BOUNDARIES

Oak Ridge National Laboratory | Oak Ridge, TN | \$1.0M | F-PACE 1 | 09/2011-11/2014

This effort aims to develop technologies that can overcome the open circuit voltage (V_{oc}) limitations in cadmium telluride solar cells by understanding and controlling the grain boundaries (i.e., the bounding surface between crystals). The research team is working to improve minority carrier lifetimes from less than a few nanoseconds (ns) to more than 10 ns, which would lead the enhancement of V_{oc} from 840 mV to more than 1 V.

HIGH TEMPERATURE ROLL-TO-ROLL CdTe ON FLEXIBLE GLASS

National Renewable Energy Laboratory | Golden, CO | \$1.5M | F-PACE 1 | 09/2011-11/2014

NREL, Corning, Inc., and the Colorado School of Mines are developing highly efficient CdTe devices on flexible glass superstrates using high-temperature roll-to-roll processing. This approach combines the high deposition rates available in the existing CdTe manufacturing technologies with the throughput and capital equipment cost reductions offered by roll-to-roll processing and the balance-of-system savings enabled by flexible PV. The processing techniques explored here have the potential for efficiencies up to 18% and module costs below \$0.50/W.

ENABLING THE CIGS THIN-FILM PV TECHNOLOGY TO MEET THE DOE GOAL OF \$0.50/W MODULE PRICE

National Renewable Energy Laboratory | Golden, CO | \$6.2M | F-PACE 1 | 09/2011-11/2014

This effort is providing near- and mid-term research to advance thin film competitiveness via improved module performance and reliability of thin film PV technologies. The project is enhancing the buffer and transparent conducting oxide layers and broadening the approach to processing copper indium gallium diselenide (CIGS) cells. Successful completion of this project would include demonstration by the industry partners of a greater than 16% efficient commercial module and a \$0.23/W reduction in cost of module manufacturing through the efficiency improvements.

LOW COST BACK CONTACT HETEROJUNCTION SOLAR CELLS ON THIN CRYSTALLINE SILICON WAFERS: INTEGRATING LASER AND THIN FILM PROCESSING FOR IMPROVED MANUFACTURABILITY

University of Delaware | Newark, DE | \$3.8M | F-PACE 1 | 09/2011-12/2014

This project aims to provide a pathway to \$0.50/Wp modules using thin, kerfless, back-contacted, heterojunction silicon solar cells (IBC-SHJ). The proposed IBC-SHJ approach offers advantages over other high-efficiency silicon cell architectures, including compatibility with thin silicon wafers (<50 μm), by using low-temperature fabrication processes and a simplified laser-based manufacturing process that reduces the number of processing steps. By collaborating with IPG Photonics for laser processing and MIT for defect impact minimization, this award aims to fabricate a >20% efficient IBC-SHJ cell.

DEVELOPMENT OF LOW-COST, HIGH-EFFICIENCY, COMMERCIAL-READY, ADVANCED SILICON SOLAR CELLS

Georgia Institute of Technology | Atlanta, GA | \$1.5M | F-PACE 1 | 09/2011-12/2014

The objective of this project is to raise the efficiency of three promising silicon technologies beyond 20%: conventional p-type crystalline Si (Czochralski and monocrystalline), n-type Cz, and ~50 μm thick epitaxial Si. Efficiency gains will happen through four technology innovations: **1)** fine-line printing to reduce shadow losses; **2)** reduced contact losses to increase fill factor; **3)** improved surface passivation to lower surface recombination velocity; and **4)** improved back surface reflectance. These innovations will be addressed with industrially-relevant technologies, reducing time between bench-top validation and factory implementation.

CVD-BASED VALENCE-MENDING PASSIVATION FOR CRYSTALLINE SILICON SOLAR CELLS

Arizona State University | Tempe, AZ | \$1.5M | F-PACE 1 | 09/2011-12/2014

This project combines innovative silicon surface passivation and all aluminum contacts to create a new processing path towards cost-effective >20% efficient crystalline silicon solar cells. The surface passivation enables lower contact resistance between the metal/silicon, allowing less metal to be used. Cost would be further reduced by replacing silver with aluminum. Silver is the typical contact material in silicon solar cells and it is the second most expensive input material in the cell. In addition, the surface passivation of grains in multi-crystalline silicon will be explored in hopes of increasing the efficiency of cells made on this substrate.

HIGH-EFFICIENCY III-V MULTI-JUNCTION SOLAR CELLS

National Renewable Energy Laboratory | Golden, CO | \$6.9M | National Laboratory R&D | 10/2012-09/2015

This agreement integrates three parallel thrusts to create a 48% efficient four junction solar cell. First, process optimization will reduce electrically-active defects in and create a conductive buffer to the fourth junction. Second, degradation rates and the radiative interaction between junctions will be analyzed and quantified. Third, the fourth junction will be optimized for efficiency.

NEXT GENERATION SILICON PHOTOVOLTAICS

National Renewable Energy Laboratory | Golden, CO | \$8.6M | National Laboratory R&D | 10/2012-09/2015

This project is geared towards producing high efficiency tandem solar cells based on silicon (Si) technology. There are two areas of focus: **1)** developing techniques to achieve high efficient single junction Si solar cells through contact passivation; and **2)** modeling and realization of novel III-V materials and processes for producing a 30% efficient silicon tandem solar cell. The production of a tandem Si solar cell has the possibility of moving towards two junction efficiencies with lowered costs.

CdTe TECHNOLOGY: UNDERSTANDING HOW DEFECTS IN CdTe LIMIT THE PERFORMANCE OF SOLAR CELLS

National Renewable Energy Laboratory | Golden, CO | \$10.0M | National Laboratory R&D | 10/2012-09/2015

This project works to increase the open-circuit voltage and fill factor of CdTe solar cells. The approach is to examine single crystals grown by molecular beam epitaxy and polycrystalline CdTe films with different grain sizes to understand and increase carrier concentration and lifetime. Stoichiometry and doping are varied to influence lifetime and recombination by grain boundary type is studied.

CIGS TECHNOLOGY: OVERCOMING BARRIERS TO INCREASE EFFICIENCIES AND REDUCE COST

National Renewable Energy Laboratory | Golden, CO | \$9.0M | National Laboratory R&D | 10/2012–09/2015

Research in this project addresses the scientific issues that need to be overcome for CIGS solar cells to be successful in volume manufacturing. To increase cell voltage and efficiency, work is being done on higher bandgap devices (1.15 eV to 1.4 eV) than typically used. To increase current without compromising junction quality or incurring metastable behavior, CdS is being replaced by more transparent ZnOS. In addition, absorber processing is being simplified by using a two-step approach where metal precursors are prepared by evaporation and selenized rapidly in selenium vapor at high temperature.

NEXT-GENERATION EARTH-ABUNDANT THIN FILM CZTS PHOTOVOLTAICS

National Renewable Energy Laboratory | Golden, CO | \$6.9M | National Laboratory R&D | 10/2012–09/2015

Kesterites (i.e., “CZTS,” $\text{Cu}_2\text{ZnSnSxSe}_{4-x}$, and related alloys) can contribute to SunShot goals by providing an earth-abundant, thin film alternative to CIGS and CdTe. However, a substantial increase in kesterite performance is needed, requiring a greater fundamental understanding of kesterite materials. CZTS work at NREL is aimed toward developing this basic understanding of defects and interfaces in the kesterite materials system and how to control them during film processing. Defects and interfaces are studied in a variety of systems, ranging from theoretical models to simplified experimental samples and geometries, and to the best device quality polycrystalline thin films.

THIN SILICON SOLAR CELLS: A PATH TO 35% SQ LIMITS

Arizona State University | Tempe, AZ | \$3.4M | F-PACE 2 | 09/2013–09/2016

Arizona State University is leading a collaborative effort with the Massachusetts Institute of Technology, the California Institute of Technology, the University of New South Wales, and the Swiss Federal Institute of Technology to fabricate a novel device structure for ultra-thin crystalline silicon (c-Si) solar cells based on carrier selective contacts. A series of optical and material innovations will be developed that result in novel ultra-thin silicon solar cells with targeted efficiencies of 29%. If successful, such a cell using carrier selective contacts could approach the Shockley–Queisser (SQ) limit for silicon using a potentially commercializable device structure.

OVERCOMING THE FUNDAMENTAL BOTTLENECKS TO A NEW WORLD SILICON SOLAR CELL

Georgia Institute of Technology | Atlanta, GA | \$3.5M | F-PACE 2 | 09/2013–09/2016

The Georgia Institute of Technology has partnered with the National Renewable Energy Laboratory and Fraunhofer ISE to drive crystalline silicon (c-Si) solar cell efficiency past 26.5% through a fundamental and applied research program. The team's approach includes strategies of passivated contacts via tunnel dielectrics, emitter optimization, and enhanced light trapping through the development of photonic crystals and a plasmonic backside reflector. These improvements will help realize efficiency improvements that could be incorporated into the existing silicon PV technologies that represent the majority of the current PV market.

DRIVING CZTS TO THE SQ LIMIT: SOLVING THE OPEN CIRCUIT VOLTAGE PROBLEM

IBM Thomas J. Watson Research Center | Yorktown Heights, NY | \$4.4M | F-PACE 2 | 09/2013-09/2016

IBM is collaborating with the University of Delaware, the University of California in Santa Barbara, and Harvard University to address the open-circuit voltage deficit of copper zinc tin selenide (CZTS) technology through a model single crystal-based approach. This work will drive voltage and efficiency improvements toward the Shockley-Queisser (SQ) limit with targeted device efficiencies exceeding 18%. Achievement of the goals of this project would enable a system that uses relatively abundant material inputs with high performance and potentially low cost.

APPROACHING THE SHOCKLEY-QUEISSER LIMIT WITH EPITAXIAL CdTe

National Renewable Energy Laboratory | Golden, CO | \$4.5M | F-PACE 2 | 09/2013-09/2016

NREL, in collaboration with First Solar, Texas State University, Colorado State University, the Colorado School of Mines, and Washington State University, is using epitaxial cadmium telluride (CdTe) films grown by molecular beam epitaxy (MBE) to reach power conversion efficiencies greater than 24%. While traditional CdTe cells use a polycrystalline CdTe layer, this project will probe the limits for CdTe PV using epitaxial materials on single-crystal substrates to develop a model CdTe cell. The insight provided in these investigations has the potential to advance the polycrystalline CdTe industry through a better understanding of interfaces, critical defects, surface passivation, and doping strategies for CdTe devices.

Cross-Cutting Photovoltaics Efforts

This activity area includes projects that focus on characterization and/or testing of PV cells and modules through National Renewable Energy Laboratory R&D and the BRIDGE program, as well as reliability through the PREDICTS program. In addition, it includes core funding at NREL to support facilities, external partnerships and other cross-cutting needs. The QESST center, which houses a wide range of research from early-stage PV through manufacturing, and the SERIIUS partnership are also in this area.

QUANTUM ENERGY AND SUSTAINABLE SOLAR TECHNOLOGIES ENGINEERING RESEARCH CENTER (QESST ERC)

Arizona State University and Partners | \$6.0M | 05/2011–05/2016

A joint research center of the DOE and National Science Foundation (NSF), QESST is committed to research that spans the three leading commercial PV technologies: silicon, thin films, and tandem devices, while blurring the traditional lines between technologies by recognizing and exploiting their commonalities. This research is organized into three complementary thrusts—Terawatt Manufacturing, Moore’s Law Devices, and Advanced Enablers—and two demonstrative testbeds—Student-Led Pilot Line and Integration, Modules and Power Management. In addition, two themes—Sustainability and Education Research—permeate all areas of QESST research. QESST has 10 academic partners in the U.S. and around the world, and 48 industrial partners that span manufacturing, materials, production and installation of solar technologies.

SOLAR ENERGY RESEARCH INSTITUTE FOR INDIA AND THE UNITED STATES (SERIIUS)

National Renewable Energy Laboratory | Golden, CO | \$6.7M | 10/2011–09/2016

The Solar Energy Research Institute for India and the United States (SERIIUS) creates a bi-national network for fostering new ideas and collaborations to expedite a sustainable industry. SERIIUS is a joint effort between NREL and the Indian Institute of Science in Bangalore to address critical barriers for solar energy development in India that intersect the grand challenges for solar energy in the U.S. SERIIUS has three research thrusts: **1)** Sustainable Photovoltaics, which aims to develop next-generation materials, devices, and advanced manufacturing processes tailored to the needs, environment, and resource availability of India and the U.S.; **2)** Multiscale Concentrated Solar Power, which aims to overcome critical science and engineering challenges for reliable multiscale (including small 25–500 kW) CSP systems; and **3)** Solar Energy Integration, which aims to identify and assess key technical, economic, environmental, and policy barriers, enabling a research agenda for technical readiness in India and to benefit the United States.

PV PARTNERING AND BUSINESS DEVELOPMENT AGREEMENT

National Renewable Energy Laboratory | Golden, CO | \$12.0M | National Laboratory R&D | 10/2012–09/2015

The primary goal for this agreement is to expand NREL’s high-impact, collaborative partnerships with industry and academia in activities that exploit complementary capabilities and support the SunShot goals. There are two distinct partnering modes: non-proprietary partnering opportunities, which aim to publish the research outcomes in prominent journals, and proprietary

partnering opportunities, which aim to develop intellectual property that will increase the speed of product commercialization and expand the scale of PV deployment. Additional outreach activities focus on workforce development opportunities for graduate students and postdocs.

NATIONAL CENTER FOR PHOTOVOLTAICS CORE (NCPV) R&D SUPPORT

National Renewable Energy Laboratory | Golden, CO | \$14.2M | National Laboratory R&D | 10/2012–09/2015

This agreement provides cross-cutting support required by the core R&D agreements that make up the other PV laboratory agreements. Specifically, this agreement funds infrastructure support teams (Engineering & Informatics) and basic maintenance and limited enhancement of cross-cutting capabilities (Measurement & Characterization and Device Processing). The direct funding of these cross-cutting activities through this agreement allows for more efficient management, increased flexibility in response to changes in program needs, and aids in ensuring that these crucial activities and capabilities are sustainably maintained as core competencies within the National Center for Photovoltaics.

NCPV DIRECTOR'S INITIATIVE AND CAP-EX

National Renewable Energy Laboratory | Golden, CO | \$5.2M | National Laboratory R&D | 10/2012–09/2015

The National Center for Photovoltaics (NCPV) Director's Initiative was established in fiscal year 2011 as a vehicle for funding small R&D projects, unplanned laboratory equipment purchases, and other PV-related initiatives at the discretion of the NCPV Director. The funds have been used to catalyze high-risk research by making modest enhancements to R&D capabilities through equipment purchases as well as providing seed money for strategic hires. The Cap-Ex funds (\$4.5 million) are also allocated by the NCPV Director to support the greatest needs of NCPV.

CELL AND MODULE PERFORMANCE

National Renewable Energy Laboratory | Golden, CO | \$8.1M | National Laboratory R&D | 10/2012–09/2015

This agreement supports the independent evaluation of cell and module contract deliverables, providing the U.S. PV industry with accurate and independent efficiency measurements and calibrations for all PV technologies and material systems. This partnership allows the DOE Solar Program to fairly evaluate atypical cells in cases when the data are impacted by artifacts such as metastability, spurious photocurrents, bias rate, nonlinearity, and other issues such as contacting and area definitions. The NREL team supports commercial testing and module qualification labs by providing required ISO 17025-accredited calibrations. The team also supports domestic and international PV cell and module standards development.

OVERCOMING SPATIAL, ENERGY, AND TEMPORAL LIMITS IN CHARACTERIZATION OF THE ELECTRONIC, OPTICAL, AND STRUCTURAL PROPERTIES OF PV MATERIALS

National Renewable Energy Laboratory | Golden, CO | \$3.5M | National Laboratory R&D | 10/2012–09/2015

This agreement pushes the limits of measurement techniques useful for PV materials. The focus is on two electrical techniques, admittance spectroscopy / deep-level transient spectroscopy (AS/DLTS) and scanning capacitance microscopy, as well as two optical techniques, two-photon time resolved photoluminescence and tip-enhanced Raman scattering. Developing these advanced measurement techniques and capabilities will further knowledge of how material structure impacts PV device performance.

DEVELOPING SPECTROSCOPIC PHOTOEMISSION ELECTRON MICROSCOPY (PEEM) FOR IMAGING NANOSCALE VARIATIONS IN THE CHEMICAL AND ELECTRONIC STRUCTURE OF THIN FILM MATERIALS

Sandia National Laboratories | Albuquerque, NM | \$0.3M | BRIDGE | 11/2012-11/2015

Spectroscopic photoemission electron microscopy (spec-PEEM) enables real-time imaging of PV materials and devices with unprecedented nanoscale (5-10 nm) sensitivity to chemical and electronic properties. Current microscopes do not have sufficient or concurrent spatial, spectral, temporal or contrast capabilities to image these nanoscale properties.

IN-SITU X-RAY ANALYSIS OF RAPID THERMAL PROCESSING FOR THIN-FILM SOLAR CELLS: CLOSING THE GAP BETWEEN PRODUCTION AND LABORATORY EFFICIENCY

SLAC National Accelerator Laboratory | Menlo Park, CA | \$0.9M | BRIDGE | 11/2012-11/2015

This project seeks to develop a rapid-thermal-processing / X-ray-diffraction and fluorescence facility (RTP/XRD-F) for *in-situ*, real-time investigations of the structural and chemical evolution of PV materials from the initial precursors to final products. It will enable better processing steps to yield higher efficiency, less expensive devices and will be used for Cu(InGa)Se₂ (CIGS), Cu₂ZnSnS₄ (CZTS), In-free transparent conducting oxides, and metal contacts to Si cells.

THREE-DIMENSIONAL MINORITY CARRIER LIFETIME MAPPING OF THIN FILM SEMICONDUCTORS FOR SOLAR CELL APPLICATIONS

Plant PV, Inc. | Berkeley, CA | \$0.45M | BRIDGE | 11/2012-11/2015

This project seeks to address the difficulty of accurately measuring bulk minority carrier lifetimes in novel semiconductor materials for thin film PV cells. Plant PV is developing a two-photon lifetime tomography technique to separate bulk minority carrier lifetime from surface recombination effects. This technique will enable rapid screening of PV materials by avoiding the need to construct full devices. This project will also develop three-dimensional minority carrier lifetime and charge collection efficiency maps that will be useful in identifying efficiency bottlenecks for new and conventional (e.g., CdTe, CIGS) thin film PV materials.

HOW GRAIN BOUNDARIES AFFECT THE EFFICIENCY OF POLY-CdTe SOLAR CELLS: A FUNDAMENTAL ATOMIC-SCALE STUDY OF GRAIN BOUNDARY DISLOCATION CORES USING CdTe BI-CRYSTAL THIN FILMS

University of Illinois | Chicago, IL | \$0.90M | BRIDGE | 11/2012-11/2015

This team is developing a fundamental understanding of the role of grain boundaries on the minority carrier lifetime and V_{oc} in CdTe thin films by **1)** fabricating epitaxial CdTe thin films on b-crystal substrates with well-defined grain boundary structures; **2)** studying the atomic and electronic structures of the grain boundary dislocation cores and interfacial transport properties; and **3)** performing first-principles calculations to determine the density of mid-gap states and find potential passivants.

NOVEL PHOTON MANAGEMENT FOR THIN-FILM PV

University of Utah | Salt Lake City, UT | \$0.45M | BRIDGE | 11/2012-11/2015

The objective of this project is to enable commercially viable thin film PVs with efficiencies greater than 20% using a novel optical spectral-separation technique at costs below current technologies. The team is developing processes for cost-effective manufacturing of integrated arrays of PV cells, for manufacturing polychromats in glass and for packaging the entire device.

IN-SITU X-RAY NANOCHARACTERIZATION OF DEFECT KINETICS IN SOLAR CELL MATERIALS

Arizona State University | Tempe, AZ | \$0.85M | BRIDGE | 12/2012-12/2015

This collaborative research team is addressing the non-radiative recombination that limits the open circuit voltage of Cu(In,Ga)Se_2 . The team is utilizing *in-situ* synchrotron-based nano-X-ray fluorescence microscopy (nano-XRF), and x-ray absorption nanospectroscopy (nano-XAS) coupled with nano-x-ray beam induced current (nano-XBIC) to understand the mechanisms that govern the electronic activity at grain boundaries and dislocations in CIGS absorber layers under operating, processing and growth conditions.

UNIFIED NUMERICAL SOLVER FOR DEVICE METASTABILITIES IN CdTe THIN-FILM PV

Arizona State University | Tempe, AZ | \$1.4M | PREDICTS | 09/2013-09/2016

ASU, in collaboration with First Solar, Colorado State University, and NREL, is developing a tool to study the fundamentals behind the performance and metastabilities of CdTe thin film PVs. The core of the solution will be a multi-level solver that combines macroscopic diffusion-reaction equations describing subsystems of point defects combined with the global Poisson equation. This will form a closed system that can be solved in time domain and quasi-3D space utilizing cylindrical grains.

COUPLED THERMO-MECHANICAL AND PHOTO-CHEMICAL DEGRADATION MECHANISMS THAT DETERMINE RELIABILITY AND OPERATIONAL LIFETIMES FOR CPV TECHNOLOGIES

Stanford University | Stanford, CA | \$1.1M | PREDICTS | 09/2013-09/2016

Stanford, in collaboration with NREL and Spectrolab, is investigating coupled intrinsic thermo-mechanical and photo-chemical degradation mechanisms that determine the reliability and operational lifetimes for concentrated photovoltaic (CPV) technologies. The research approach will result in quantitative metrologies to characterize degradation processes during PV operation, detailed kinetic models of degradation mechanisms, and reliability benchmarking of materials and interfaces in CPV devices and modules. The approach is based on fundamental materials science and reliability physics and development of accelerated testing protocols for more accurate lifetime predictions.

Concentrating Solar Power

Concentrating solar power (CSP) technologies use mirrors to focus and concentrate sunlight onto a receiver, from which a heat transfer fluid carries the intense thermal energy to a power block to generate electricity. A distinguishing feature of CSP is its ability to incorporate simple, efficient, and cost-effective thermal energy storage by virtue of converting sunlight to heat as an intermediate step to generating electricity. In addition to providing dispatchable power generation, CSP with thermal energy storage can also enable greater incorporation of other variable generation sources such as PV and wind on the grid. Furthermore, CSP systems can synergistically integrate with fossil-fueled power plants to offset fuel use and reduce carbon footprints. CSP, therefore, presents unique opportunities for the renewable energy space, and is a key enabling technology in the nation's all-of-the-above energy strategy.

The Falling Cost of Concentrating Solar Power

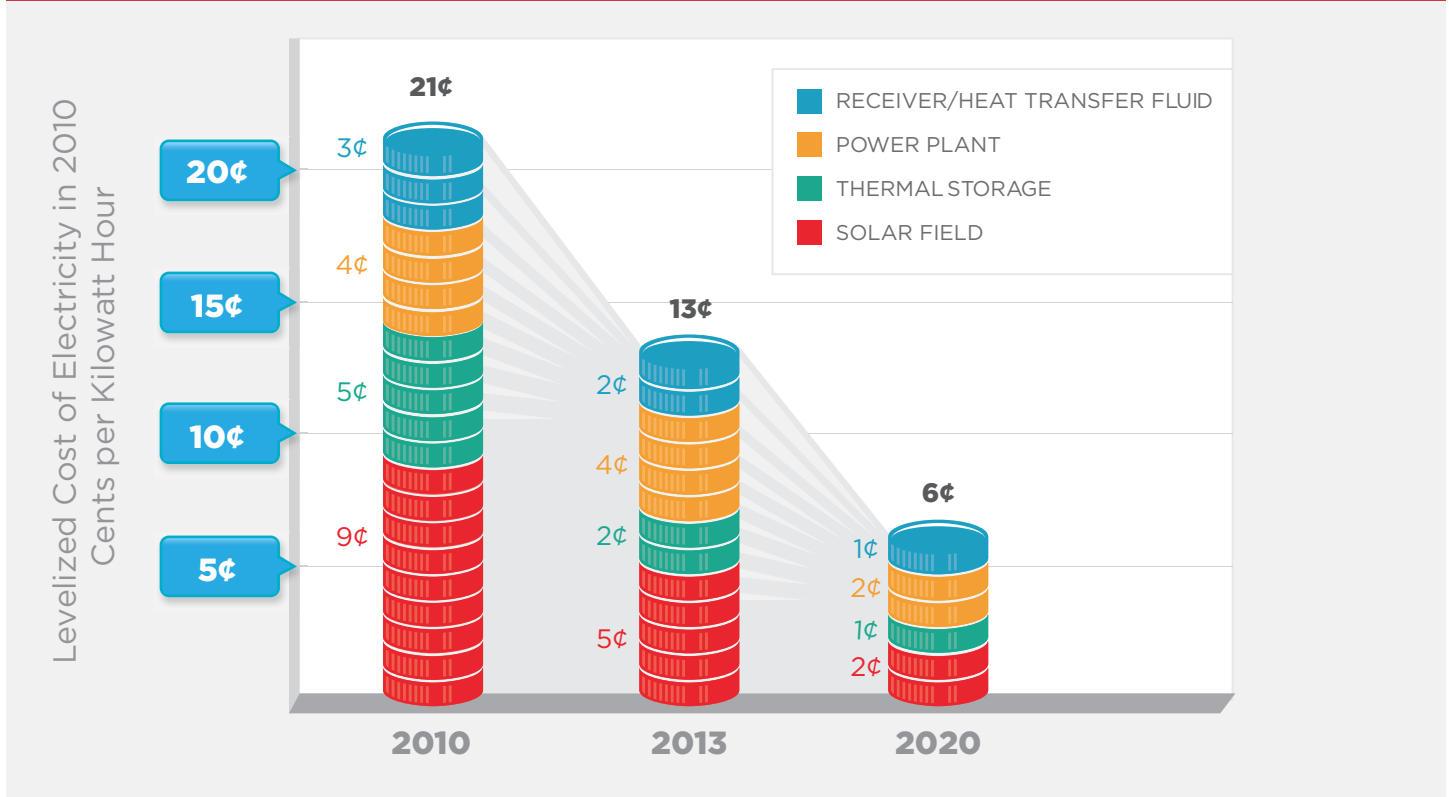
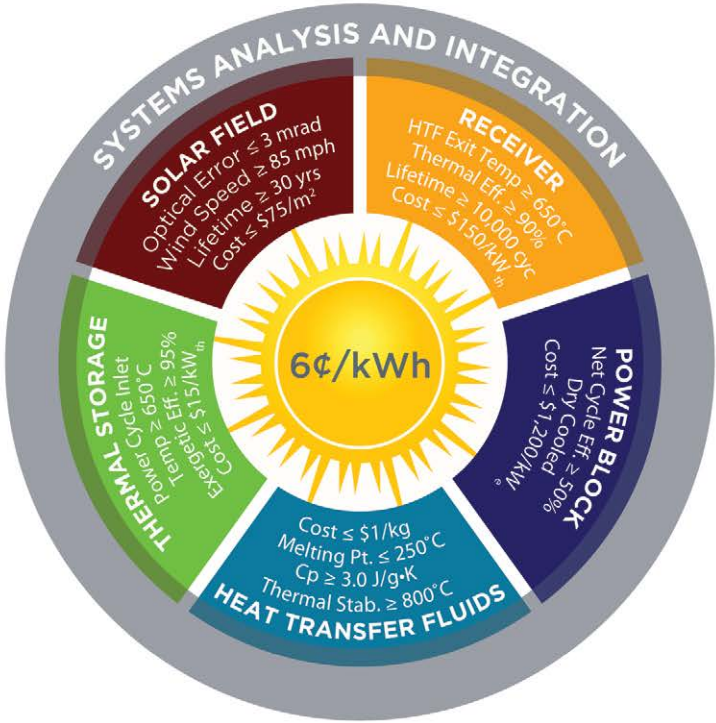


Figure 1. SunShot Initiative 2020 goal for concentrating solar power and the cost reductions achieved from 2010–2013.

Deconstructing 6¢/kWh



Competitive Programs

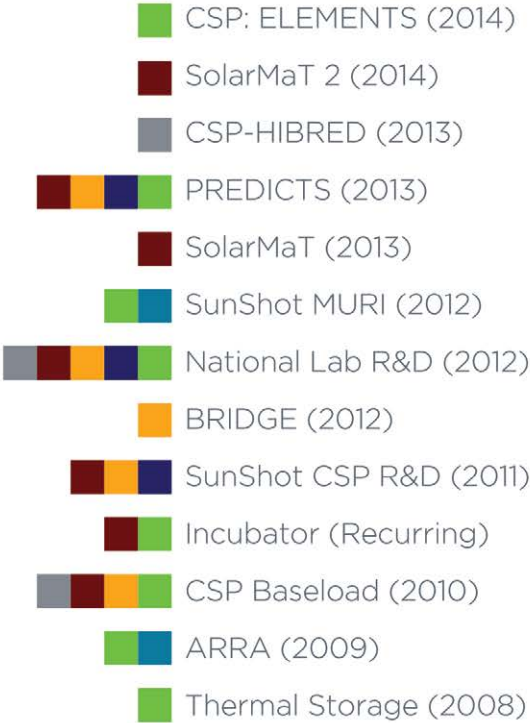


Figure 2. Technical metrics and cost targets for CSP subsystems to achieve an LCOE of \$0.06/kWh, and the subsystems addressed by the funding opportunity announcements released.

CSP technologies are deployed primarily in four system configurations: parabolic trough, linear Fresnel, dish engine, and power tower. Parabolic trough and linear Fresnel systems focus sunlight onto a linear receiver whereas dish engine and power towers focus sunlight onto a single central receiver. These system configurations include collectors (solar field), receivers, power block (power plant) and thermal energy storage subsystems. The SunShot Initiative goal for CSP translates to achieving a subsidy-free levelized cost of energy (LCOE) of \$0.06/kWh or less by the end of the decade. Toward this objective, Fig. 1 shows the cost reductions that are targeted in the various subsystems relative to their costs at the beginning of the decade. It is evident that these reductions represent an aggressive challenge that calls for significant technical advancements in performance and efficiency.

The LCOE target of \$0.06/kWh may be mapped using a techno-economic analysis to the performance and cost targets for each of the subsystems, as depicted in Fig. 2. In general, the targets require higher temperature operation at higher efficiency, longer lifetime, and lower cost. These target metrics are the basis for the competitive funding opportunity announcements of the SunShot CSP subprogram. The program provides funding—all through competitive awards—to industry, national laboratories and universities (Fig. 3) to develop component technologies and systems solutions to achieve the techno-economic goals of the SunShot Initiative. Since the launch of the Initiative in 2011, about \$145M has been committed for developing CSP technologies to meet SunShot goals.

Concentrating Solar Power

CSP R&D portfolio funding distribution

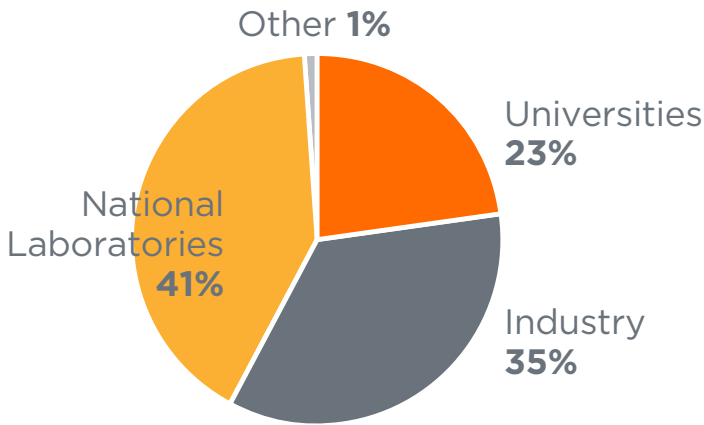


Figure 3. CSP R&D portfolio funding distribution among industry, national laboratories and universities in FY13.

Awarded projects are selected through a rigorous peer review process, and are actively managed with defined quantitative and measurable milestones, deliverables, and periodic stage gates with go/no-go criteria. Much emphasis is placed on understanding the fundamentals to drive innovation and technological advances at the component and system levels, with a steadfast focus on driving down costs.

The current portfolio of projects includes investments with near-term to long-term horizons that span all of the various CSP technologies. Ongoing R&D efforts aim to deliver transformative technologies within the next three to five years. These include highly efficient reflector materials integrated with low-cost collector structures, lean solar field manufacturing and assembly approaches, self-aligning and tracking controls, self-cleaning mirrors, novel receiver designs, solar selective

coatings for enhanced collection efficiency, corrosion-resistant materials and coatings, viable heat transfer fluids to carry the heat from the receivers for high temperature operation, and cost-effective thermal energy and thermochemical energy storage technologies. High-temperature, higher-efficiency power cycles such as the supercritical carbon dioxide Brayton cycle demonstrated at the 1–10 MW scales, and the solar-integrated air Brayton cycle, will also be very significant. These next-generation power cycle technologies have broader relevance beyond the solar industry to the nuclear, fossil and geothermal industries, among others. In addition, an award as part of the CSP-HIBRED (Heat Integration for Baseload Renewable Energy Development) funding opportunity seeks to catalyze near-term demonstration of hybrid power systems that integrate CSP with fossil-powered plants.

Just two years into the SunShot Initiative, DOE’s investments at the national laboratories, industry, and universities are beginning to pay off. Based on 2013 figures, the LCOE for CSP is \$0.08/kWh less than what it was in 2010 (Fig. 1)—that’s over the halfway mark in the reductions needed toward the SunShot target. While the initial reduction is impressive, much remains to be done as we continue to work towards the goal of subsidy-free cost parity of CSP-generated electricity on the grid.

Dr. Ranga Pitchumani

Chief Scientist and Concentrating Solar Power Program Manager

Solar Energy Technologies Office

U.S. Department of Energy

Collecting the Sun

The solar field comprises up to 40% of the total system costs for CSP technologies. The SunShot CSP subprogram seeks to dramatically reduce the cost of the solar field while improving optical accuracy and ensuring durability. In order to accomplish these goals, SunShot supports R&D efforts to develop high optical accuracy reflectors, reduce collector structure weight and material, develop lean and rapid methods for manufacturing, assembly and installation, develop highly efficient tracking and control methods as well as accurate metrology tools, and reduce collector soiling and the water required for operations and maintenance.

SunShot technical targets for the solar field:

- Cost <\$75/m²
- Optical error <3 mrad
- Sustain wind speed >85 mph
- Lifetime >30 years

SELF-CLEANING CSP COLLECTORS

Boston University | Boston, MA | \$0.7M | SunShot CSP R&D | 08/2012-01/2015

Boston University is developing a new method to keep solar collectors dirt- and dust-free to help maintain high optical efficiency. This project aims to develop large-scale prototypes, cost-effective manufacturing processes, and commercialize the technology in large-scale CSP devices for applications in semi-arid and desert climates. Specific objectives include establishing proof-of-concept of the application of the electrodynamic screen (EDS) for self-cleaning solar concentrators, producing and evaluating laboratory-scale prototypes of self-cleaning solar collectors, including flat mirrors and curved mirrors, and testing the EDS-incorporated collectors for optical efficiency of sunlight, dust removal efficiency, power requirements, and durability.

FLEXIBLE ASSEMBLY SOLAR TECHNOLOGY

BrightSource Energy | Oakland, CA | \$4.8M | SunShot CSP R&D | 08/2012-04/2014

BrightSource Energy is designing and deploying an automated collector-assembly platform and a more efficient installation process that has the potential to drastically reduce construction time and cost for utility-scale CSP facilities. This Flexible Assembly Solar Technology (FAST) system accelerates the heliostat assembly and field installation processes by combining elements of both on a single platform with direct access to the solar collector field. The system incorporates preliminary, partial assembly of the mirror units at a centralized offsite facility capable of supplying multiple CSP projects, an automated, transportable FAST platform for assembly completion, and delivery of the fully completed assemblies into the solar field for final installation.

Concentrating Solar Power

LOW-COST, LIGHTWEIGHT SOLAR CONCENTRATORS

Jet Propulsion Laboratory | Pasadena, CA | \$2.3M | SunShot CSP R&D | 10/2012-09/2015

JPL is designing an optimized solar thermal collector structure using a lightweight collector capable of lowering structural costs and simplifying installation to reach mass manufacture. The specific project objectives are to design and develop a mirror module using an inexpensive reflective film bonded onto a lightweight structural rigid foam support; design and develop a low-cost, non-traditional mirror-module support structure; select low-cost drive components and associated control system; design, integrate, and test a low-cost concentrator; and analyze the system's cost to demonstrate achievement of the \$75/m² collector system target.

SCATTERING SOLAR THERMAL CONCENTRATORS

Pennsylvania State University | State College, PA | \$0.2M | SunShot CSP R&D | 08/2012-10/2014

Penn State is designing and testing a novel solar collector system that relies on stationary optics and avoids the need for mirror movement. The system is capable of achieving optical performance equal to state-of-the-art parabolic trough systems, but at a lower cost. The research team is working to demonstrate a scattering solar concentrator with optical performance equal to existing designs of state-of-the-art parabolic troughs, but with the added benefits of immunity to wind load tracking error, more efficient land use, and elimination of movable heat transfer elements. The goals of the project are to demonstrate a small-scale, fully functioning prototype and test its performance outdoors, attain break-even optical performance compared against existing parabolic troughs, and improve the overall performance and reliability of the collector field.

ADVANCED MANUFACTURE OF REFLECTORS

University of Arizona | Tucson, AZ | \$1.5M | SunShot CSP R&D | 08/2012-04/2014

UA is developing technology to improve the optical accuracy and reflectivity of the self-supporting glass mirrors used in CSP collectors. The research team is working to optimize and validate a novel glass-molding technique that creates very precise mirrors in a variety of shapes. The focus is on developing a novel hot glass molding process that could be used for high-speed production at low cost and be easily integrated into a production line. In parallel, the research team is developing a novel way to boost second-surface silver reflectivity and inhibit soiling. The goals of the project are to develop new methods for rapidly shaping glass mirrors and coating them for higher reflectivity and soil resistance, include both point-focus and line-focus mirror designs, improve mirror optical accuracy, and reduce the cost of the solar trough mirrors made in very high volume by about 40%.

LOW-COST HELIOSTAT FOR MODULAR SYSTEMS

National Renewable Energy Laboratory | Golden, CO | \$2.2M | National Laboratory R&D | 10/2012-06/2014

NREL seeks to develop a novel collector design and heliostat field technologies that reach the SunShot Initiative cost and performance targets. This includes optimization of an efficient low-profile rigid collector design, implementation of inexpensive wireless communication and control devices to reduce field wiring, and development of an automated optical tracking/calibration technique that enables the use of lower-cost motor and drive components through improved error correction. This design will be optimized, prototyped, tested, and transferred to industry during the three year period of performance.

LOW-COST SELF-CLEANING REFLECTOR COATINGS FOR CSP COLLECTORS

Oak Ridge National Laboratory | Oak Ridge, TN | \$2.3M | National Laboratory R&D | 10/2012–09/2014

ORNL is developing self-cleaning, optically transparent coatings that can be applied to the surfaces of heliostats and collector mirrors in CSP systems. The goal is to reduce the time and costs associated with cleaning collector and heliostat mirror surfaces and increase the reliability and efficiency of CSP systems. The research team has developed optically transparent superhydrophobic (SH) materials and coatings based on nanostructured silica surfaces that can address soiling and maintenance issues associated with CSP systems. The team is investigating and optimizing the adhesion, transmittance, and water- and dirt-repellent properties of these multifunctional, nanostructured surface coatings, and using a suspension of SH silica nanoparticles, polymeric binders, and solvents that can be applied to large area surfaces using simple, low-cost spray coating techniques developed by the commercial paint industry.

PREDICTIVE PHYSICO-CHEMICAL MODELING OF INTRINSIC DEGRADATION MECHANISMS FOR ADVANCED REFLECTOR MATERIALS

National Renewable Energy Laboratory | Golden, CO | \$2.1M | PREDICTS | 01/2014–12/2016

NREL seeks to develop the capability to predict measurable characteristics from models of fundamental physico-chemical processes driving intrinsic degradation and failure mechanisms of advanced materials and coatings targeted for use in CSP systems. The team will use novel physics- and chemistry-based modeling techniques to predict the time evolution of reflector properties under both controlled and real world conditions. This prediction will be possible through the creation and application of validated, predictive models that use the measured behavior of individual materials to provide predictions for lifetimes of complete multi-layer reflectors.

Receivers and Heat Transfer Fluids

The SunShot CSP subprogram aims to significantly increase the operating temperatures, efficiency, and lifetime of solar receivers while lowering costs. The SunShot Initiative funds R&D on receiver systems, heat transfer fluids (HTFs), and related aspects within the industry, national laboratories and universities. This funding is intended to support the development of fundamentally new receiver designs and novel solar selective coatings, and to explore high temperature receiver corrosion and heat transfer fluid stability.

SunShot technical targets for receiver subsystems:

- Heat transfer fluid exit temperature from the receiver $>650^{\circ}\text{C}$
- Thermal efficiency $>90\%$
- Lifetime $>10,000$ cycles
- Cost $<\$150/\text{kW}_t$

HIGH-EFFICIENCY RECEIVERS FOR SUPERCRITICAL CARBON DIOXIDE CYCLES

Brayton Energy | Hampton, NH | \$1.6M | SunShot CSP R&D | 09/2012–08/2015

Brayton is building and testing a new solar receiver that uses supercritical carbon dioxide (s-CO_2) as the heat transfer fluid. The research team is designing the receiver to withstand higher operating temperatures and pressures than state-of-the-art technology so that the device can enable higher efficiency systems. The primary objectives of this project include achieving an outlet temperature for the receiver working fluid (s-CO_2) that is greater than or equal to 750°C , maintaining high receiver efficiency, retaining durability over the lifetime of the CSP plant, and significantly reducing the cost as compared to baseline receivers. To satisfy these objectives, the team is performing a combination of analytical modeling and hardware testing. The use of s-CO_2 in the power cycle is also being explored.

ADVANCED LOW-COST RECEIVERS FOR PARABOLIC TROUGHS

Norwich Technologies | White River Junction, VT | \$0.3M | SunShot CSP R&D | 08/2012–09/2013

Norwich has developed and validated optical and thermal models and completed optimization analysis to identify key performance characteristics for a first-generation laboratory prototype design of a unique vacuum-free receiver for parabolic troughs. The team built fully functioning optical and thermal laboratory prototypes using accurate, validated models that captured important underlying physical mechanisms. The test results from these prototypes establish performance exceeding the FOA requirement of thermal efficiency $>90\%$ for a CSP receiver while delivering an exit fluid temperature of $>650^{\circ}\text{C}$ and a cost $<\$150/\text{kW}_t$. The team's vacuum-free SunTrap receiver design promises improvements over conventional vacuum-tube collectors, allowing dramatic reductions in thermal losses at high operating temperatures.

NEAR-BLACKBODY, ENCLOSED PARTICLE RECEIVER INTEGRATED WITH FLUIDIZED-BED HEAT EXCHANGER

National Renewable Energy Laboratory | Golden, CO | \$3.7M | SunShot CSP R&D | 10/2012-08/2015

NREL will design, develop, and test a prototype high-temperature particle receiver and heat exchanger system. Many existing receiver designs are limited by an upper operating temperature of 650°C due to the use of nitrate salt as the heat transfer fluid and the limitation of available high-temperature coatings for high receiver efficiency. To overcome these limitations, NREL will develop an innovative receiver design with near-blackbody (NBB) absorptive performance, and select materials that can withstand temperatures of >1000°C. The concept uses low-cost stable materials, a ceramic solar receiver, and storage containers with refractory liners. These liners can accommodate temperatures much higher than oil/salt and ordinary metals or metal alloys at a fraction of the cost, thereby resulting in a low-cost, high-performance CSP system with TES capability for baseload solar power.

USING SOLID PARTICLES AS HEAT TRANSFER FLUID FOR USE IN CSP PLANTS

University of Colorado | Boulder, CO | \$0.5M | BRIDGE | 02/2013-01/2016

As part of an ultimate goal of developing a commercially-viable, transformative method for the design of next generation of CSP plants based on granular media as the heat transfer fluid, the objective of this project is to develop, verify and validate a first-principles modeling tool for use in the optimization, scale-up, and design of a near-blackbody (NBB) receiver. The continuum model will be implemented into the Multiphase Flow with Interphase eXchanges software framework, which is an open-source, cost-free computational fluid dynamics solver for multiphase systems. It will be validated using existing experimental data and discrete-element-method simulations carried out as part of the current effort. Once validated, the model will be used to assist in designing the NBB receiver to achieve the SunShot goal of \$0.06/kWh.

HIGH FLUX MICROCHANNEL RECEIVER DEVELOPMENT WITH ADAPTIVE FLOW CONTROL

Oregon State University | Corvallis, OR | \$0.8M | SunShot CSP R&D | 08/2012-02/2015

OSU seeks to reduce the size, weight and thermal losses from high temperature solar receivers by applying microchannel heat transfer technology to solar receiver design. Their objective is to design a supercritical CO₂ microchannel receiver operating at a fluid exit temperature of 650°C and absorbing an average flux of 100 W/cm² with a receiver efficiency of 90% or greater. OSU plans to develop two microchannel solar receiver designs, one for liquid cooled microchannel receivers and one for gas cooling. Metrics were determined using one-dimensional heat transfer calculations to estimate the maximum flux that could be absorbed on a microchannel solar receiver as a function of channel characteristics. Metrics for the supercritical CO₂ receiver will be based on “on sun” experimental results. Metrics for the other design will be based on laboratory test results, modeling, and simulation.

A SMALL PARTICLE SOLAR RECEIVER FOR HIGH TEMPERATURE BRAYTON POWER CYCLES

San Diego State University | San Diego, CA | \$3.1M | SunShot CSP R&D | 09/2012-08/2016

The objective of this project is to design, construct, and test a revolutionary high-temperature solar receiver in the multi-megawatt range that can be used to drive a gas turbine to generate low-cost electricity. A secondary goal is demonstrating, for the first time, a pressurized solar receiver with a window greater than 1 m in diameter. The proposed use for the receiver is to drive a gas turbine, but such a receiver can also be used for process heat applications and solar processing of fuels

Concentrating Solar Power

and chemicals. The capability of the receiver to generate pressurized (0.5 MPa) and high temperature (~1000 C) air at high efficiency (~90%) will be demonstrated at the multi-megawatt level via prototype testing at the National Solar Thermal Test Facility at Sandia National Laboratories.

HIGH TEMPERATURE FALLING PARTICLE RECEIVER

Sandia National Laboratories | Albuquerque, NM | \$4.5M | SunShot CSP R&D | 10/2012-09/2015

The objective of this project is to make revolutionary advancements in falling particle receivers for CSP applications that will enable higher temperatures and greater efficiencies at lower cost. Technical innovations will be pursued through a combination of modeling, systems analysis, design, testing, and optimization. These include: **1)** advances in receiver design with consideration of particle recirculation, air recirculation, and interconnected porous structures; **2)** advances in particle materials to increase solar absorptivity, energy storage, and durability; and **3)** advances in other areas, such as thermal storage, heat exchange, and particle conveyance.

LOW COST HIGH PERFORMANCE NANOSTRUCTURED SPECTRALLY SELECTIVE COATING

University of California | La Jolla, CA | \$0.9M | SunShot CSP R&D | 08/2012-03/2015

UCSD will employ a highly scalable process to fabricate and coat nanoparticles onto solar absorber surfaces to achieve ultra-high spectral selectivity. Refractory protected and unprotected semiconductor nanoparticles will be fabricated by spark erosion and coated onto absorber metal surfaces by spray coating. The material composition, size distribution, and morphology of the nanoparticles will be guided by numeric modeling as well as optimized by design of experiment tests. Optical and thermal properties, such as solar absorptance and infrared emittance will be modeled and measured. High temperature durability will be achieved by using modified semiconductors, refractory nanoparticles, ceramic matrix nanocomposites, and high temperature annealing. The proposed SSCs will achieve solar absorptance of greater than 94% and infrared emittance of lower than 7% at 750°C. This will enable higher thermal conversion efficiency ($\geq 90\%$) and operating temperature of heat transfer fluids ($\geq 650^\circ\text{C}$) in order to achieve lower operations and maintenance costs.

HIGH-TEMPERATURE THERMAL ARRAY FOR NEXT-GENERATION SOLAR THERMAL POWER PRODUCTION

Los Alamos National Laboratory | Los Alamos, NM | \$2.0M | National Laboratory R&D | 12/2012-11/2015

LANL is developing a MW-scale heat pipe-based technology designed to bridge the heliostat reflector field and the power cycle by replacing both the solar receiver and the heat transfer fluid system used in existing CSP systems. Major technical aspects of this work are focused on cost-effective wick composition, thermal array fabrication methods, countergravity physics, heat pipe start-up and thermal cycling protocols, and system testing and scaling for large-scale deployment.

DEGRADATION MECHANISMS AND DEVELOPMENT OF PROTECTIVE COATINGS FOR TES AND HTF CONTAINMENT MATERIALS

National Renewable Energy Laboratory | Golden, CO | \$3.2M | National Laboratory R&D | 10/2012-12/2015

NREL is working to extend the lifetime of containment materials and reduce the capital and maintenance costs of future solar power plants. Advanced protective coatings and surface modification techniques will be developed and evaluated to yield degradation rates lower than 30 microns/year. The objective is to develop and validate material systems and protective

conditions that increase the lifetime of HTF and TES containing materials at temperatures of 600 to 900°C. For molten salts, electrochemical techniques will be employed to understand and control the corrosion mechanisms; while for liquid metal alloys, immersion degradation will be evaluated. For supercritical CO₂ attack, autoclave and flow tests will be used. Coatings containing nanomaterials like graphite and alumina will be evaluated for this purpose.

DIRECT S-CO₂ RECEIVER DEVELOPMENT

National Renewable Energy Laboratory | Golden, CO | \$2.6M | National Laboratory R&D | 10/2012-8/2015

NREL seeks to develop, characterize, and experimentally demonstrate a novel high-temperature receiver technology using supercritical CO₂ (s-CO₂) directly as the heat transfer fluid. To be considered successful, the commercial technology must achieve the SunShot receiver targets of greater than 90% thermal efficiency while heating the CO₂ to 650°C. The commercial receiver will also be able to withstand 10,000 thermal cycles before mean-time-to-failure and have an expected commercial cost of less than \$150/kWt. A prototype receiver system will be constructed and tested to validate the performance model that will be used to develop the commercial receiver design. They will also characterize multiple direct receiver concepts, disseminate the results to industry, and produce a set of modeling tools and methodologies that can be used by other parties to deploy direct receiver technologies for s-CO₂ systems.

HIGH-TEMPERATURE SOLAR SELECTIVE COATING DEVELOPMENT FOR POWER TOWER RECEIVERS

Sandia National Laboratories | Albuquerque, NM | \$2.6M | National Laboratory R&D | 10/2012-11/2015

Sandia will develop solar selective coatings for next-generation power tower applications that exhibit high absorptance with low thermal emittance, surpassing the performance of the current benchmark material, Pyromark. These materials will be stable at high temperature ($\geq 700^\circ\text{C}$) in air, have high thermal conductivity, and be nonvolatile. The team will develop deposition methods that can be scaled up to practical sizes. The team will also conduct durability testing of promising materials deposited on receiver metal substrates in conventional thermal furnaces, solar simulators, and on-sun to understand the degradation mechanisms and improve stability under realistic simulated environments.

FUNDAMENTAL CORROSION STUDIES IN HIGH-TEMPERATURE MOLTEN SALT SYSTEMS FOR NEXT GENERATION CSP SYSTEMS

Savannah River National Laboratory | Aiken, SC | \$3.8M | National Laboratory R&D | 10/2012-09/2015

SRNL seeks to improve materials durability in CSP systems in the presence of high operating temperature (HOT) heat transfer fluids (HTFs) for use in advanced power production processes. Improvements in materials durability will be achieved via an integrated experimental and numerical approach that will identify optimal combinations of HOT HTFs with materials of construction and corrosion protection schemes that maintain the HTFs good heat transfer properties, achieve low corrosion rates, and indicate good performance in CSP system simulations. This objective will be achieved by combining: **1)** experimental determination of corrosion rates in model HOT HTF systems and identification of critical parameters of corrosion mechanisms, **2)** thermodynamic property modeling for HOT HTFs, **3)** risk mitigation methods for the identified corrosion mechanisms, **4)** demonstration of the effectiveness of corrosion mitigation methods and **5)** modeling of corrosion in heat transfer systems.

HALIDE AND OXY-HALIDE EUTECTIC SYSTEMS FOR HIGH PERFORMANCE HIGH TEMPERATURE HEAT TRANSFER FLUIDS

University of Arizona | Tucson, AZ | \$5.5M | MURI | 10/2012-09/2017

This project seeks to optimize the ternary and quaternary compositions of alkali halides (ionic salts) and metal halides (covalent salts) in a eutectic system in order to develop a high temperature heat transfer fluid that has low melting point (250°C), high temperature (800°C) thermal stability, as well as favorable thermal and transport properties. Oxy-Lewis acid/base and network-forming additives will be added into the system to reduce the vapor pressure and corrosion, and also to fine tune the thermal and transport properties.

HIGH-OPERATING TEMPERATURE HEAT TRANSFER FLUIDS FOR SOLAR THERMAL POWER GENERATION

University of California | Los Angeles, CA | \$5.0M | MURI | 10/2012-12/2017

The goal of this project is to develop liquid metals with thermophysical and corrosion properties suitable for use as heat transfer fluids at temperatures above 800°C. The team will employ combinatorial material synthesis and high-throughput characterization techniques together with advanced thermochemical modeling to efficiently identify compositions that are intrinsically less corrosive or where corrosion can be mitigated through the formation of passivation layers. Scaled flow loop tests will be performed to confirm the effective prevention or mitigation of corrosion. Heat transfer experiments will also be conducted to directly determine the convective heat transfer coefficients as a function of flow parameters and develop engineering models to facilitate optimal design of compact heat exchangers.

EXAMINATION OF CERIUM OXIDE DOPANTS FOR THE SOLAR-DRIVEN THERMOCHEMICAL GENERATION OF HYDROGEN

California Institute of Technology | Pasadena, CA | \$0.2M | SunShot Postdoctoral Research Awards | 10/2013-09/2015

This project concerns the conversion of solar energy to chemical fuels with the recently demonstrated CSP-driven thermochemical generation of fuels from CeO_2 . The goal of this project is to assess the effect of modification of CeO_2 with the targeted dopants Pr, Tb, Nb, Ta, and Sn on hydrogen production efficiency at reduced operating temperatures. Based on the material properties of CeO_2 , a thermodynamic efficiency of up to 16% may be attainable even without sensible heat recovery, making CSP-driven thermochemical generation of fuels a promising CSP system for economical CSP energy storage.

Power Conversion and Systems

Power plant components and systems for CSP benefit from mature and well-understood technology found elsewhere in the power generation industry. The most common cycles employed by conventional CSP plants include subcritical Rankine and Stirling. Gross thermal-to-electric conversion efficiencies are typically 35%–45%, and working fluids include steam, hydrogen, and helium. The primary driver for improving CSP power cycles is to increase solar-to-electricity conversion efficiency. Because CSP facilities are typically located in desert areas where water is a scarce resource, high efficiency cycles utilizing dry cooling are needed, which may include systems that use topping and bottoming cycles, augmentation, or other hybrid options. The SunShot Initiative funds R&D on the power block and related aspects of power conversion within the industry, national laboratories and universities. This funding is intended to support the development of high temperature power cycles, such as supercritical-CO₂ (s-CO₂) and solar integration to Brayton cycles, solid state power conversion techniques as topping cycles, and to investigate hybrid power systems.

SunShot technical targets for power block subsystems:

- High temperature power cycles
- Net cycle efficiency >50%
- Dry cooled
- Cost <1,200/kW_e

CONCENTRATED SOLAR THERMOELECTRIC POWER

Massachusetts Institute of Technology | Cambridge, MA | \$1.0M | SunShot CSP R&D | 09/2012–02/2015

The objectives of this project are to demonstrate concentrating solar thermoelectric generators (CSTEGs) with >10% solar-to-electrical energy conversion efficiency that are capable of 24-hour operation. These objectives will be achieved through developing and demonstrating key components of the envisioned system, including **1)** achieving a >10% solar-to-electricity energy conversion efficiency, **2)** limiting optical concentration to <10x and potentially <4x, and **3)** demonstrating 24-hour potential through use of phase-change materials. This project builds on existing thermoelectric materials, leverages work conducted through an Advanced Research Projects Agency-Energy (ARPA-E) program on thermal storage materials, and focuses on system demonstration.

INTEGRATED SOLAR THERMOCHEMICAL REACTION SYSTEM FOR THE HIGH EFFICIENCY PRODUCTION OF ELECTRICITY

Pacific Northwest National Laboratory | Golden, CO | \$3.5M | SunShot CSP R&D | 10/2012–09/2015

PNNL seeks to advance the technology of solar thermochemical reaction systems from Technology Readiness Level (TRL) 3 to TRL 6. To accomplish this, we will improve the performance of the system and establish the design and manufacturing methods

Concentrating Solar Power

that enable solar power generation at a Levelized Cost of Energy (LCOE) of no more than \$0.06/kWh by 2020. Specific project goals include improving the performance of the solar thermochemical reaction system, improving the solar-to-chemical energy conversion efficiency from 63% to about 75%, increasing the solar thermochemical augment from about 20% to as much as 28%, reducing the manufacturing costs, and establishing a validated baseline for capital costs of solar thermochemical systems.

Nx-TEC: NEXT-GENERATION THERMIONIC SOLAR ENERGY CONVERSION

SLAC National Accelerator Laboratory | Stanford, CA | \$0.8M | SunShot CSP R&D | 10/2012-12/2014

This research will create a new solid state energy conversion technology based on microfabricated and photon-enhanced thermionic energy converters (PTECs) which, when used as a topping cycle in CSP systems, will enable system efficiencies in excess of 50%. Using device and system modeling, the team will design thermally-isolated, thermionic arrays and microelectromechanical-based wafer-stack technologies for their fabrication, culminating in the demonstration of devices with >5% power conversion efficiency. In parallel, the team will fabricate heterostructure semiconductor cathodes based on active layer absorbers such as GaAs and similar materials with the addition of band engineered passivating layers such as GaN to demonstrate high quantum efficiency Photon Enhanced Thermionic Emitters. The resulting Nx-TEC device will achieve a stand-alone laboratory efficiency of >15%; a significant intermediate step towards a stand-alone goal of >30%, which is needed to achieve the >50% system efficiency target.

DEVELOPMENT OF A HIGH EFFICIENCY HOT GAS TURBO-EXPANDER AND LOW COST HEAT EXCHANGERS FOR OPTIMIZED CSP SUPERCRITICAL CO₂ OPERATION

Southwest Research Institute | San Antonio, TX | \$6.8M | SunShot CSP R&D | 09/2012-07/2015

SwRI aims to develop a novel, high-efficiency supercritical CO₂ (s-CO₂) hot gas turbo-expander optimized for CSP applications, which have highly transient duty cycles. A secondary objective is to optimize novel printed circuit heat exchangers for s-CO₂ applications to drastically reduce their manufacturing costs. The s-CO₂ turboexpander and novel s-CO₂ heat exchanger will be tested in a 1-MWe s-CO₂ test loop and fabricated to demonstrate performance of the components and the optimized s-CO₂ Brayton cycle over a wide range of part load conditions and during representative transient operations. The scalable s-CO₂ expander design and improved heat exchanger address and close two critical technology gaps required for an optimized CSP s-CO₂ power plant.

OPTIMIZING THE CSP TOWER AIR BRAYTON CYCLE SYSTEM

Southwest Research Institute | San Antonio, TX | \$3.1M | SunShot CSP R&D | 09/2012-01/2015

The objective of the project is to increase the CSP tower air receiver and gas turbine temperature capabilities to 1,000°C by the development of a novel combustor, which can eventually be integrated into a commonly used gas turbine. The 1,000°C temperature target significantly exceeds the 650°C combustor inlet temperatures demonstrated in current Air Brayton CSP projects. The team proposes to achieve this at a reduced scale with emphasis on effects of thermal cycling on hardware and with extremely low emissions.

PHYSICS-BASED RELIABILITY MODELS FOR SUPERCRITICAL CO₂ TURBOMACHINERY COMPONENTS

GE Global Research | Niskayuna, NY | \$1.9M | PREDICTS | 10/2013-09/2016

GE seeks to develop a physics-based life prediction and reliability model for hybrid gas bearing (HGB) and dry gas seal (DGS) components. Coupled multi-physics models for performance prediction of these components during a typical supercritical CO₂ (s-CO₂) cycle will be developed in order to generate a loading history that serves as an input to the physics-based lifing model. The coupon level fatigue and corrosion experiments under a controlled CO₂ environment will be carried out and will provide critical validation of the performance prediction models and provide data that serves as input to the life prediction model. DGS test in a 1 MWe s-CO₂ loop will validate the performance prediction models and provide key data that serves as input to the life prediction model. A probabilistic framework will be developed to quantify statistical uncertainty and to calibrate and validate the physics-based life model.

ADVANCED NITRATE SALT CENTRAL RECEIVER POWER PLANT

Abengoa Solar | Lakewood, CO | \$4.5M | CSP Baseload | 09/2010-06/2014

Abengoa will demonstrate a 100 MW central receiver plant using nitrate salt as the receiver coolant, thermal storage medium, and heat transport fluid in the steam generator. The plan is to operate the plant at full load for 6,400 hours each year using only solar energy. Key components include a new high-temperature molten salt receiver based on a fossil boiler and heat exchanger design that will be more robust and more manufacturable; a cermet, high-temperature, low-emissivity selective coating for central receivers that is stable when exposed to air; an optimized surround heliostat field; and an optimized thermal storage, steam generator, and power cycle configuration based on dry cooling.

SAM ENHANCEMENTS FOR CSP

National Renewable Energy Laboratory | Richland, WA | \$0.6M | SunShot CSP R&D | 10/2012-09/2015

This project will leverage recent System Advisor Model (SAM) kernel improvements by developing a robust tool specifically designed for CSP systems. This work will enable simulations of more complex plant control algorithms and receiver, field, and storage models optimization codes while providing a standardized interface to streamline modeling efforts. The team will also develop and validate detailed high-temporal-resolution models. These models will support CSP grid integration simulation and analysis efforts performed by other centers at NREL. They will also help inform optimal plant-operation strategies and aid in the analysis of material thermal cycling. Finally, the team will develop models for advanced power cycles and hybrid plant designs that have been proposed for CSP systems. These innovative power cycles are potentially higher efficiency and lower cost alternatives to current CSP cycles.

THE DOE NATIONAL SOLAR THERMAL TEST FACILITY (NSTTF)

Sandia National Laboratories | Albuquerque, NM | \$2.5M | National Laboratory R&D | 10/2012-09/2015

This funding ensures that capabilities at the NSTTF are maintained, operational, and safe for researchers and industrial partners to utilize to achieve their scientific and business goals. The facility enables researchers in their study and benchmarking of subsystem performance on-sun at high flux, power, and thermal levels in the pursuit of DOE SunShot goals. Activities at the

Concentrating Solar Power

NSTTF includes the testing of novel, high-temperature solar receivers up to 6 MWth using the newly refurbished heliostat field; testing of prototype solar central receivers and associated components such as heat shields; evaluation of individual heliostat reflected beams with a Beam Characterization System (BCS); and evaluation of low-flux beams from customer provided heliostats, which will help reduce the cost of the heliostats, the most expensive part of a CSP plant.

SMUD CSP HIBRED PROJECT

Sacramento Municipal Utility District | Sacramento, CA | \$10.0M | HIBRED | 10/2012-12/2014

SMUD will design, develop, and demonstrate through commercial operation an advanced hybrid CSP technology that will be integrated at an existing natural gas-fueled combined cycle power plant at SMUD. The CSP system will provide 45 MW_t peak solar collection and 32 MW_t extended on-peak delivery to the power plant using stored energy for a net minimum reliable capacity increase of >10 MW_e solar generating capacity. The thermal energy input temperature to the thermal-to-electric conversion system's working fluid will be at or above 500°C. The CSP system will include high temperature thermal energy storage that will optimize reliable hybrid plant production during the summer afternoon peak and super peak dispatch hours.

Thermal Energy Storage

A distinguishing feature of CSP among other renewable technologies is its ability to include thermal energy storage at the point of power generation to handle the intermittencies of solar availability. The SunShot Initiative funds R&D on sensible, latent, and thermochemical energy storage and related aspects within the industry, national laboratories and universities. This funding is intended to help engineer heat transfer fluids for high temperature stability and thermophysical properties and develop novel thermal energy storage methods to meet technical and cost targets. The CSP subprogram is funding the following projects to achieve these DOE Sunshot goals. The first two projects involve Sensible Heat, the second two Phase Change Materials (PCMs), and the final eight Thermochemical.

SunShot technical targets for thermal energy storage subsystems:

- Improve heat transfer and thermal energy storage media
- Thermal energy storage cost $< \$15/\text{kWh}_{\text{th}}$ (kilowatt hours thermal)
- Exergetic efficiency $> 95\%$
- Material degradation due to corrosion $< 15 \mu\text{m}/\text{year}$.

HIGH EFFICIENCY THERMAL ENERGY STORAGE SYSTEM FOR CSP

Argonne National Laboratory | Argonne, IL | \$2.2M | National Laboratory R&D | 10/2012-09/2015

The goal of this proof-of-concept project is to develop an efficient high-temperature, lab-scale TES prototype by utilizing advanced phase change materials (PCMs) in combination with new, high-conductivity, graphite foams. The laboratory scale prototype TES system will be built and tested with the purpose of gathering performance data (e.g., transport properties, system durability, and thermal cycling) regarding a combination of PCM mixtures and foam types and densities. In addition, associated technologies needed for scale-up and practical implementation will also be developed. These include the process to infiltrate the foams, coating the foams for strength and environmental (oxidation/corrosion) durability enhancements, and joining techniques for system integration.

DISH STIRLING HIGH PERFORMANCE THERMAL STORAGE

Sandia National Laboratories | Albuquerque, NM | \$2.4M | National Laboratory R&D | 10/2012-09/2015

This objective of this project is to demonstrate the key components of a thermal storage system for dish Stirling power generation. The thermal storage system features latent heat transport and latent heat storage which is an optimal combination with the isothermal input of Stirling engines. This combination minimizes thermodynamic energy and exergy losses. The resulting subscale demonstration should be sufficient to interest partners in the manufacture of dish Stirling systems with storage. This system will provide up to six hours of storage on a 25 kWe Stirling system. The storage and the engine are both moved to the rear of the

Concentrating Solar Power

dish. This placement provides an optimum balance of the dish system, reduces cantilevered weight, and allows closing of the “pedestal gap,” leading to efficient structural designs. The size and duration of the proposed embodiment will enable sufficient storage on utility-scale dish Stirling deployments.

SULFUR BASED THERMOCHEMICAL HEAT STORAGE FOR BASED LOAD CONCENTRATED SOLAR POWER GENERATION

General Atomics | San Diego, CA | \$2.0M | Baseload | 09/2010-11/2014

The goal of the project is to demonstrate the engineering feasibility of using a sulfur-based thermochemical cycle to store heat from a CSP plant and support baseload power generation. The team will study the sulfur-generating disproportionation reaction and develop it into a practical engineering process step. The team will also carry out preliminary process components design and experimental validation. The engineering data will be used for process integration between the CSP plant, the sulfur processing and storage plant and the electricity generation unit. Through this project, the team will demonstrate the economics and safety of a CSP plant integrated with sulfur storage.

LOW-COST METAL HYDRIDE THERMAL ENERGY STORAGE SYSTEM FOR CSP SYSTEMS

Savannah River National Laboratory | Aiken, SC | \$2.5M | National Laboratory R&D | 10/2012-09/2015

The objective of this research is to evaluate and demonstrate a metal hydride-based TES system for use with a CSP system. The team's unique approach makes use of a hierarchical modeling methodology that combines modeling experience and material knowledge to screen several promising metal hydride candidate materials and select the best candidates for more thorough evaluation through experiments and more detailed models. During the second year, material optimization, bench-scale testing and more detailed component and system models will lead to a proof-of-concept demonstration and a preliminary system design. The culmination of this proposed research will be the design, fabrication and evaluation of a prototype metal hydride energy storage system that aims to meet SunShot cost and performance targets for thermal energy storage systems.

HIGH-TEMPERATURE THERMOCHEMICAL STORAGE WITH REDOX-STABLE PEROVSKITES

Colorado School of Mines | Golden, CO | \$1.0M | ELEMENTS | 05/2014-04/2017

This project will explore the techno-economic feasibility of redox cycles with low-cost, perovskite oxides for high-temperature thermochemical energy storage (TCES) in a concentrating solar plant. Perovskites (chemical structure $ABO_3-\delta$) can undergo endothermic reduction to store energy at temperatures as high as 900°C. The stored energy can be released by exothermic re-oxidation to provide high-temperature heat exchange to drive high-efficiency power cycles, such as supercritical CO_2 . Combined thermochemical and sensible energy in the partially reduced perovskites already identified can provide storage of 750 kJ/kg or more (with 60% coming from TCES) such that less than 1.5 m³ of particles can be re-oxidized to produce a MWh of electricity for a 50% power cycle.

ENGINEERING A NOVEL HIGH TEMPERATURE METAL HYDRIDE THERMOCHEMICAL STORAGE

Pacific Northwest National Laboratory | Richland, WA | \$3.5M | ELEMENTS | 05/2014-04/2017

The team will develop a concept for high-energy density thermochemical energy storage for CSP which is projected to meet SunShot energy and exergy efficiency targets. The full system will be designed, fabricated, and evaluated, to culminate in on-

sun testing with a solar dish to validate the projected efficiencies and full-scale performance. The technical concept is based on a system that consists of a high-temperature metal hydride bed for heat storage operating at $\geq 650^{\circ}\text{C}$ and 2.4 bar pressure connected to a second metal hydride bed operating at low temperature which is used to store H_2 near ambient temperature.

HIGH PERFORMANCE REDUCTION/OXIDATION METAL OXIDES FOR THERMOCHEMICAL ENERGY STORAGE

Sandia National Laboratories | Albuquerque, NM | \$3.0M | ELEMENTS | 05/2014–04/2017

Sandia will systematically design, develop, characterize, and demonstrate a robust and innovative storage cycle based on novel metal oxides with mixed ionic-electronic conductivity (MIEC). Thermal energy is stored as chemical potential in these materials through a reversible reduction-oxidation reaction; thermal energy from concentrated sunlight drives a highly endothermic reduction reaction that liberates lattice oxygen from the oxide to form O_2 gas, leaving an energy-rich oxygen-depleted solid. When desired, the heat is recovered as the MIEC is re-oxidized in an exothermic reaction upon exposure to air. The system is highly integrated with an air Brayton power cycle. The compressor of the Brayton engine delivers the heated, compressed air to the re-oxidizer reactor, which then drives the turbine of the Brayton engine; expansion of the air turns the turbine and generator thus efficiently producing electric power.

REGENERATIVE CARBONATE- AND SILICATE-BASED THERMOCHEMICAL ENERGY STORAGE SYSTEM FOR CSP

Southern Research Institute | Birmingham, AL | \$0.9M | ELEMENTS | 05/2014–04/2017

This project seeks to develop thermochemical energy storage (TCES) systems for CSP based on endothermic-exothermic gas-solid reaction cycles at temperatures $>650^{\circ}\text{C}$. The 24-month project will develop and demonstrate regenerative carbonate and silicate sorbent-based process in a simulated TCES system at bench scale. The project will advance the proposed TCES system from technology readiness level (TRL) 2 to 4 by demonstrating the system's key advantages, its high exergetic and energetic efficiencies, and its potential to meet a cost target of \$15/kWhth.

CARBON DIOXIDE SHUTTLING THERMOCHEMICAL STORAGE USING STRONTIUM CARBONATE

University of Florida | Gainesville, FL | \$1.0M | ELEMENTS | 05/2014–04/2017

The objective of this project is to find an economical thermochemical storage solution for CSP by means of inexpensive, safe, and non-corrosive chemicals. Using a previously unconsidered reaction, chemical bonds are broken using high temperature, concentrated sunlight. During off-sun periods, the reaction is reversed to release heat at temperatures previously unachievable in other thermochemical, latent, or sensible energy storage schemes. The energy is absorbed by a working fluid such as air and sent to a combine cycle power plant. The laws of thermodynamics dictate that the greater the temperature of a working fluid in a power block, the greater the efficiency of the cycle, making this technology a prime candidate for transformative change.

THERMOCHEMICAL STORAGE WITH ANHYDROUS AMMONIA: OPTIMIZING THE SYNTHESIS REACTOR FOR DIRECT PRODUCTION OF SUPERCRITICAL STEAM

University of California | Los Angeles, CA | TBD | ELEMENTS | 05/2014–04/2017

The team will design and build an ammonia synthesis reactor that is optimized for the direct production of supercritical steam and perform analysis that shows that storage of the energy rich gas mixture in adapted gas well systems can deliver the target cost of \$15/kWhth. The proposed research will make significant contributions toward the viability of the ammonia TCES storage

Concentrating Solar Power

concept and solar thermochemical storage more broadly. By careful optimization of the synthesis reactor and associated heat exchanger, it will demonstrate supercritical steam production at 650°C, a feat which has not yet been achieved for ammonia synthesis. In addition, a cost-effective storage solution for gaseous components will be investigated that could have far reaching impact for other candidate reactions given the importance of gas storage for a multitude of applications.

COMPUTATIONAL ANALYSIS OF NANOPARTICLES-MOLTEN SALT THERMAL ENERGY STORAGE FOR CONCENTRATED SOLAR POWER SYSTEMS

University of Texas | El Paso, TX | \$0.27M | MURA | 09/2010-09/2014

The research goal of this project is to perform computational analysis for designing an efficient and cost-effective thermal energy storage (TES) system for CSP using nano-fluidized molten salt as the storage medium. An efficient TES system contributes to reaching the SunShot goal of making solar electricity cost competitive with conventional sources. The educational efforts include an interdisciplinary course designed specifically for students with different backgrounds who share a common interest in renewable energy, a targeted solar energy workshop at the University of Texas at El Paso, and student and faculty visits and summer research at the National Renewable Energy Laboratory and Sandia National Laboratories.

Systems Integration

The SunShot Initiative Systems Integration subprogram aims to dramatically increase the penetration level and enable widespread deployment of solar in the nation’s electrical power system by addressing the associated technical and regulatory challenges. Considering a penetration scenario of 100 GW of solar interconnected on the nation’s grid, the challenges are quantified and addressed in the activity areas of Grid Performance and Reliability, Dispatchability, Power Electronics, Communications, and Plant Performance and Reliability. The program funds projects at the national laboratories, industry, and universities (Fig 2.) through competitive funding solicitations that map to the five activity areas and targets, as depicted in Fig. 1.

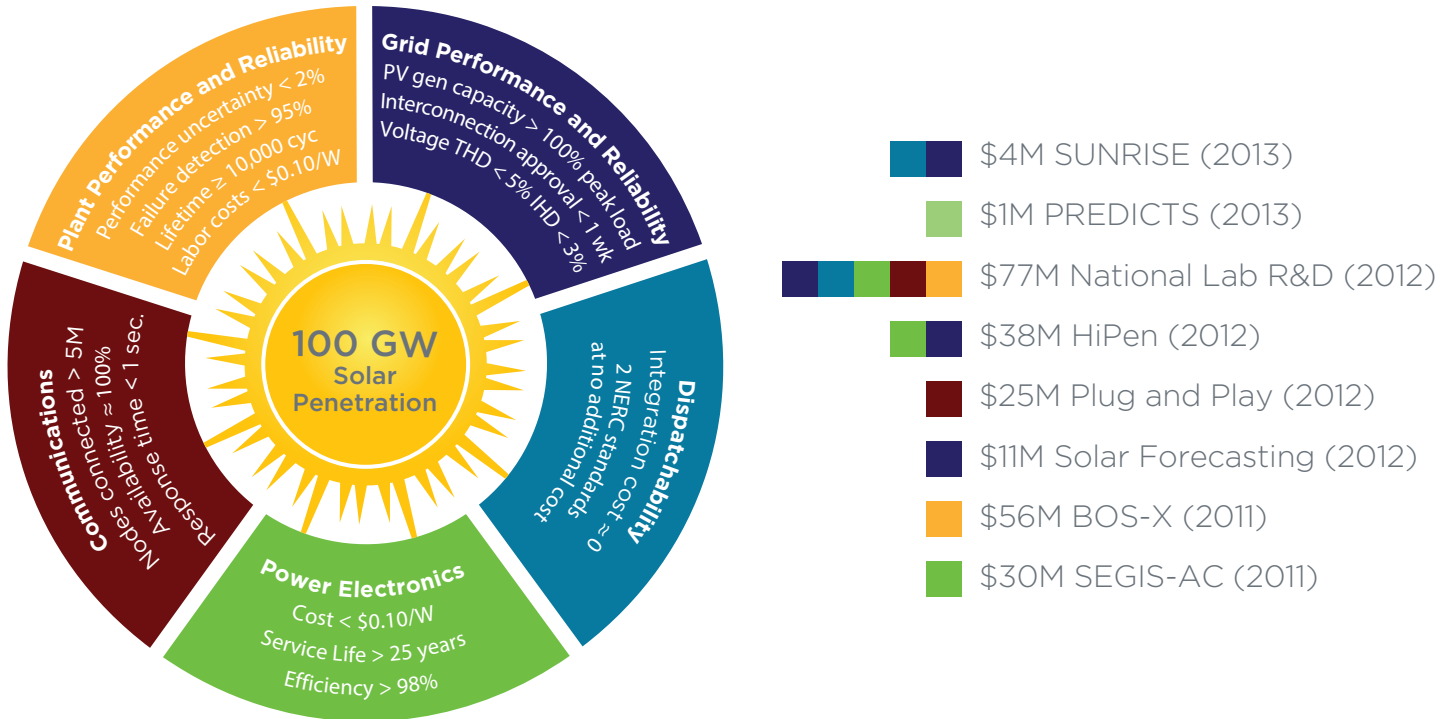


Figure 1. Systems Integration activity areas mapped to funding opportunities.

Grid Performance and Reliability: The current projects in the Grid Performance and Reliability activity area focus on achieving high penetration at the distribution level (<69 kV) and on the transmission grid in a safe, reliable and cost-effective approach. In order to accomplish these goals, SunShot supports: developing state-of-the-art utility modeling, simulation, and

analysis tools to address technical issues surrounding grid planning, operations, and reliability; developing advanced grid-friendly PV interconnection technologies; accelerating cost-effective deployment of PV generation on the distribution and transmission grid; developing validated inverter, solar system planning, operations and feeder models to enhance PV

Systems Integration

integration analysis techniques; demonstrating the feasibility of high-penetration PV scenarios under a wide range of system conditions through laboratory and field testing; advancing interconnection and performance standards and codes to enable high levels of PV integration for grid reliability; and engaging with industry and stakeholders to inform and receive feedback on PV integration.

Systems Integration portfolio funding distribution

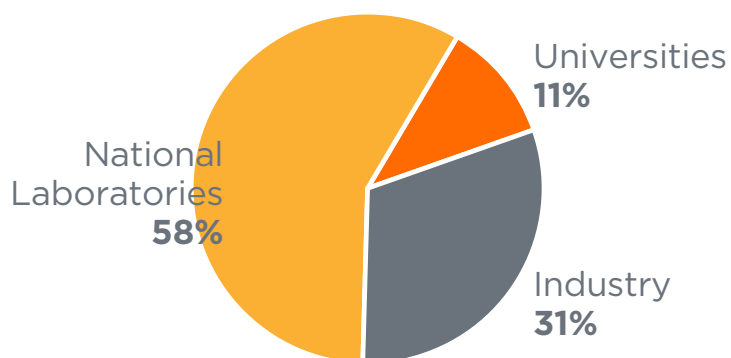


Figure 2. Systems Integration R&D portfolio funding distribution among national laboratories, industry and universities for FY13.

Dispatchability: The Dispatchability activity area of the portfolio aims to ensure that solar power plants based on PV and CSP technologies at utility and distributed scales are capable of being dispatched in a fashion that is comparable to or better than conventional power plants. SunShot addresses the issue of dispatchability with a two-pronged approach: **a)** extensive analyses to understand the impact of high penetration of solar power plants on the bulk power system and distribution system operations, and **b)** research on understanding and enhancing the dispatch capability of PV solar power plants, and investigating the value of varying energy storage capabilities for CSP plants. SunShot also supports the development of standardized methods for testing grid performance of PV solar power plants, and exploring and demonstrating the value of energy storage.

Power Electronics: Power Electronics are intelligent devices that can maximize the power output from the PV arrays on the one side and serve as the interfaces to the electric grid (or end use circuits) on the other, while ensuring overall system safety, reliability, and controllability. A technical challenge for power electronics is the optimal tradeoff between these three design drivers of performance, reliability, and cost. In order to accomplish these goals, SunShot supports cost reductions and efficiency improvements through: innovative circuit design, development of advanced components and optimal control; development of power electronics technologies to improve energy yield while reducing balance of system (BOS) hardware costs, process costs and installation time; development and field demonstration of smart inverter functionalities; and development of accelerated life testing methods and physics of failure models to predict faults and improve reliability.

Communications: To effectively inform grid operations with high-level integration of solar, visibility is required across multiple spatial scales (from the end user load through the distribution substation and beyond) and at multiple time scales (from microseconds to hours and days). Advances in information, Communications, and sensor technologies are needed to adequately monitor the behavior and manage the impact of the solar technologies integrating into the grid. Enterprise level integration of PV management systems, with grid management systems, is also critical to provide important information to grid operators. In order to achieve these goals, SunShot supports the development of open and interoperable communication and control architectures, communication requirements such as network latency, scalability, and availability, smart inverter communication standards such as IEC 61850, DNP3, and SEP 2, and enterprise integration standards based on common information model (CIM). SunShot also supports the implementation of standard communication protocols in inverter hardware and enterprise software and demonstration of end-to-end system integration and interoperability on actual distribution feeders with utilities.

Systems Integration activity areas funding distribution

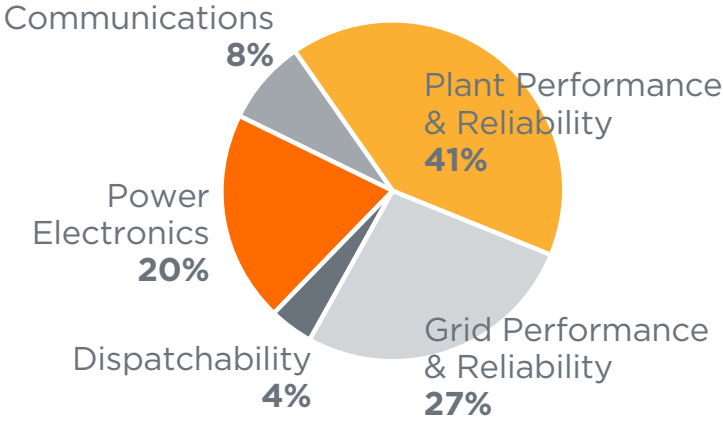


Figure 3. Distribution of funding for the ongoing awards for the Systems Integration activity areas.

Plant Performance and Reliability: As part of the Plant Performance and Reliability activity area, the program also funds R&D to provide the information and tools that solar module manufacturers, system integrators, project developers, and the financial community need to support their efforts to reduce installed system and operations and maintenance

(O&M) costs. SunShot funding aims to improve and reduce uncertainty in PV product and system performance, lifetime, durability, and availability; thereby reducing risk and associated costs such as the cost of and time to obtain financing, cost of warranties and service agreements. An allied objective is to reduce material costs and speed the installation time of the associated racking and wiring hardware. The subprogram also funds five regional test centers across the nation in support of this activity area.

The projects in the subprogram’s portfolio address the goals of the five activity areas (Fig. 3) toward the overall SunShot Systems Integration vision. The active projects in the five activity areas are briefly described in this volume. Building on the significant strides made so far, the program looks forward to continuing to advance the forefront of technologies toward the SunShot goal.

Dr. Ranga Pitchumani
Chief Scientist and Systems Integration Program Manager
Solar Energy Technologies Office
U.S. Department of Energy

Grid Performance and Reliability

SunShot funding is designed to accelerate cost-effective deployment of PV on the distribution and transmission grids, demonstrate the feasibility of high-penetration PV scenarios under a wide range of system conditions through laboratory and field testing, and advance interconnection and performance standards and codes to enable high levels of PV integration for grid reliability. SunShot supports the development of state-of-the-art utility modeling, simulation, and analysis tools to address technical issues surrounding grid planning, operations, and reliability; advanced grid-friendly PV interconnection technologies; and validated inverter, solar system planning, operations and feeder models to enhance PV integration analysis techniques. Through its funding programs, SunShot and its awardees engage with industry and stakeholders to inform and receive feedback on PV integration.

SunShot technical targets for grid performance and reliability:

- PV generation capacity >100% of peak load on the line segment of distribution feeder circuit
- Adverse effect of inverter conversion efficiency (associated with non-unity power factor) in the LCOE <3%
- Voltage THD (Total Harmonic Distortion) effect of PV <5% and individual harmonic <3%
- PV short circuit current contribution <1 P.U.
- Interconnection study approval time based on advance screening methodology <1 week
- Interconnection study cost to customer <\$1000
- Availability of quasi-static-time-series analysis (QSTS) modeling and realtime data analytics tools
- Advanced multi-inverter anti-islanding schemes and certification tests validated and implemented for high penetration PV scenarios

IMPACTS OF HIGH PENETRATION OF PV WITH ENERGY STORAGE AT FLAGSTAFF ARIZONA

Arizona Public Service | Flagstaff, AZ | \$2.2M | Hi-Pen | 01/2010-09/2014

The project team will evaluate the impacts of high penetrations of distributed PV and energy storage on a dedicated feeder to identify the technical and operational modifications that could be deployed in future feeder designs. Models describing the interactions between operations and weather/PV/feeder equipment are being developed and validated with actual feeder data so that results will be broadly applicable to other utility projects.

MODELING AND ANALYSIS OF HIGH-PENETRATION PV IN FLORIDA

Florida State University | Tallahassee, FL | \$2.0M | Hi-Pen | 04/2010-10/2014

This project aims to leverage simulation-assisted R&D based on a wide variety of Florida feeders that already incorporate high levels of PV power. Working with utilities, the team will evaluate and model impacts of the effects of high-penetration PV on distribution and transmission. Validated models that include characterization of the Florida solar resource will be developed for the range of feeder designs, and power management solutions will be evaluated.

MODELING AND ANALYSIS OF HIGH-PENETRATION PV IN CALIFORNIA

National Renewable Energy Laboratory | Golden, CO | \$3.3M | Hi-Pen | 10/2009-09/2014

The project team will utilize field verification to improve the ability to model and understand the impacts of high-penetration PV on electric utility systems and develop solutions to ease high-penetration PV deployments. The team will develop and verify advanced modeling and simulation methods for distribution system planning and operations; define the impacts of high penetration levels of PV on the distribution and transmission grid with high-fidelity simulation tools; develop a handbook of validated models and solutions for the stakeholder community; and provide simulation-assisted evaluation/de-risking of technology solutions to enable successful integration of high levels of PV.

INCREASING DISTRIBUTED PV PENETRATION LEVELS

National Renewable Energy Laboratory | Golden, CO | \$3.7M | National Laboratory R&D | 10/2013-09/2015

This project will improve existing utility modeling tools and develop new conversion tools in an effort to improve interconnection screens and studies to assist utilities, PV developers, stakeholders and regulatory agencies. The team will develop Hardware in the Loop methods, create advanced visualization tools, lead the development of interconnection standards and codes, engage with key industry stakeholders, including the Federal Energy Regulatory Commission and state Public Utility Commissions, and develop educational materials for utility personnel.

ACCELERATING COST-EFFECTIVE DEPLOYMENT OF SOLAR GENERATION ON THE DISTRIBUTION GRID

Sandia National Laboratories | Albuquerque, NM | \$3.3M | National Laboratory R&D | 10/2013-09/2015

The goal of this project is to remove grid access barriers, reduce the cost for solar generation and produce the following outcomes: **1)** provide a full and complete data-driven technical foundation that supports revised SGIP (Small Generation Interconnection Procedure) screens, **2)** develop new ways to use feeder classifications to estimate possible impacts of high-penetration scenarios, **3)** develop a tool to create high-resolution solar data for any location on a feeder for use by utility planners and university students to conduct impact studies, and **4)** develop new screening procedures and implement new SGIP screens nationwide.

ACCELERATING DEVELOPMENT OF ADVANCED INVERTERS

Sandia National Laboratories | Albuquerque, NM | \$2.6M | National Laboratory R&D | 10/2013–09/2015

This project will enable the use of inverter grid-support and ride-through functions on distributed generation resources by addressing issues with islanding and implementation of inverter manufactures through development of: affordable communications-based anti-islanding scheme; collaborative controls that provide grid support and prevent islanding; and development of testing procedures that validate function performance.

TRANSMISSION & ALTERNATIVES ANALYSIS AND STRATEGIC STAKEHOLDER ENGAGEMENT

National Renewable Energy Laboratory | Golden, CO | \$2.1M | National Laboratory R&D | 10/2012–09/2014

During this project, NREL will examine the Western Interconnection large-scale stability and frequency response under high solar and wind penetration and identify means to mitigate adverse performance impacts via transmission reinforcements, storage, advanced control capabilities or other alternative means. The second activity is to improve the understanding and better utilization of advanced PV controls through field testing and demonstration on a real utility-scale PV plant via partnership with a collaborating energy industry member. To accomplish this goal, NREL will identify a potential partner(s), establish a technical review committee, and develop and implement a detailed scope of work and test plan for a field project to demonstrate the grid-friendly capabilities of utility-scale PV power plants. The third activity is to create a validated, flexible, 3-phase, cycle-by-cycle model of PV inverters and PV plants, and their associated controls in the Power System Computer Aided Design (PSCAD) program, which is both well established and fully supported. The proposed model is generic and open source in nature, easy to modify for different implementations by different manufacturers, and will accommodate future enhancements required by the regional reliability organization or local utilities as the solar PV penetration increases. NREL will communicate the tools, methods, and results from grid integration research to targeted stakeholders. The goal is to engage the utilities, regulators, policymakers, and organizations that establish reliability and operational rules to ensure that they have the tools and data needed to study high solar penetrations and understand the reliability and balancing impacts of solar. This effort involves a threefold strategy: **1)** participation in utility forums and the Utility Variable Generation Integration Group (UVIG), **2)** participation in technical committees, **3)** engagement with regulators, policymakers, and other key stakeholders, and **4)** provide specific technical support and input to the transmission planning process in the Western Interconnection.

OPERATIONAL SIMULATION TOOLS AND LONG TERM STRATEGIC PLANNING FOR HIGH PENETRATIONS OF PV IN THE SOUTHEASTERN U.S.

Electric Power Research Institute | Palo Alto, CA | \$0.87M | SUNRISE | 10/2013–09/2015

In collaboration with the Tennessee Valley Authority Southern Company, the Sacramento Municipal Utility District, the California Independent System Operator, and other partners, EPRI will develop: high-penetration solar future scenarios in the southeastern U.S., distribution grid-feeder clustering and characterization, models for solar generation hosting capacity, and power production simulation. These tools, processes, and studies will be used to assess the full breadth of operational and business impacts posed by high levels of solar generation and to formulate associated strategic plans for the southeastern U.S. that ensure both system reliability and utility financial health. This project will result in an end-to-end strategy and operations project that leverages prior efforts, including DOE-funded projects, and provides a pathway for successfully integrating large amounts of solar generation.

This project will further disseminate analytical results, operational tools, and strategic planning processes to allow for replication that advances PV integration beyond simply the traditional “sunny” regions.

COMPREHENSIVE SOLUTIONS FOR INTEGRATION OF SOLAR RESOURCES INTO GRID OPERATIONS

AWS Truepower | Albany, NY | \$0.39M | SUNRISE | 10/2013–09/2015

This project primarily looks at the benefits from more cost-effective unit commitment and dispatch, and reduction in balancing reserves due to reducing uncertainty in solar forecasting. This project will improve the Pacific Northwest National Laboratory’s ramp and uncertainty prediction tool by incorporating accurate forecasting of solar generation, and then integrate the tool with the Siemens market applications software currently used by the California Independent System Operator (CAISO) to perform unit commitment and dispatch. This project will utilize probabilistic forecast algorithms for solar energy production of large-scale PV plants and rooftop PV installations, to enable CAISO to incorporate solar generation forecasts directly into their tools that perform power system operations, thus reducing the uncertainty and hence the costs of system integration of solar generation into the bulk power system.

INTEGRATION OF BEHIND-THE-METER PV FLEET FORECASTS INTO UTILITY GRID SYSTEM OPERATIONS

Clean Power Research | Napa, CA | \$0.5M | SUNRISE | 10/2013–09/2015

This project looks at the improvement in accuracy of load forecasting in California that can be realized from forecasts of behind-the-meter distributed (rooftop) solar PV generation. The forecasts developed are provided to the California Independent System Operator for incorporation into the Automatic Load Forecasting System whose load forecasts will quantify the influence of the increasing penetration of customer-sited or behind-the-meter PV system power production. Also, this project will evaluate distributed solar generation forecast accuracy and apply further improvements in solar forecasting developed by the University of California at San Diego. Forecasting behind-the-meter distributed PV generation power production within a region will enable grid balancing authorities to dispatch generation resources more effectively, significantly lowering the need for additional spinning generation reserves and mitigating the impact on existing reserve capacity. This project is expected to reduce the costs of integrating higher penetrations of PV into the grid by incorporating distributed PV generation forecast into utility planning and operational tools in California, as a replicable and scalable approach that other areas of the country could follow.

DISTRIBUTED RESOURCE ENERGY ANALYSIS AND MANAGEMENT SYSTEM (DREAMS) DEVELOPMENT FOR REAL-TIME GRID OPERATIONS

Hawaiian Electric Power Company | Honolulu, HI | \$0.50M | SUNRISE | 10/2013–09/2015

Hawaii has two different Energy Management Systems (EMS) on the islands of Oahu and Maui, and already has very high solar penetration. This project will design new capabilities for these systems to enable visibility to thousands of uncontrolled, distributed rooftop PV resources and factor advanced 15-minute short term wind and solar forecasting capability for the region into the EMS decision-making process. This project is innovative in incorporating solar generation forecasts into the operational EMS and working with two major EMS vendors (Siemens & Alstom) to create advanced EMS software. The results of this project will motivate technology development to enable operational change under high renewables penetration, thereby reducing the cost and impact of integrating large amounts of solar.

INTEGRATED SIMULATION DEVELOPMENT AND DECISION SUPPORT TOOL SET FOR UTILITY MARKET AND DISTRIBUTED SOLAR POWER GENERATION

Electricore, Inc. | Valencia, CA | \$0.42M | SUNRISE | 10/2013-09/2015

This project will develop a simulation and decision support toolset that simulates the utility grid in real time and contains a decision support system for effective integration of centralized and distributed solar power generation. This toolset, designed for real-time operations personnel, will be integrated within existing utility procedures. The Distribution Management System will enable real-time simulation of distributed solar PV generation in the San Diego Gas & Electric territory. The methodology and enabling software will be available to utilities across the U.S. for widespread adoption and cost benefits for utilities and their ratepayers. This project will further result in improved day-ahead generation commitments and real time operations, and increased reliability and system balancing from improved visibility, enabling more efficient and innovative management of utility assets.

A PUBLIC-PRIVATE-ACADEMIC PARTNERSHIP TO ADVANCE SOLAR POWER FORECASTING

National Center for Atmospheric Research | Boulder, CO | \$4.1M | Solar Forecasting | 10/2012-09/2015

In this project, a solar power forecasting system will be configured to forecast across a range of temporal and spatial scales. The system technologies will employ solar radiation and cloud measurements, including images from total sky imagers; satellite observations; local meteorological observations; publicly-available numerical weather prediction (NWP) modeling results, including the high-resolution rapid refresh (HRRR); weather research and forecasting (WRF)-solar model tuned for cloud prediction and radiative transfer modeling; statistical blending of forecast technologies tuned to prediction times from 15 minutes to 36 hours; irradiance to power conversion models; displays tuned to the needs of the end user; and built-in assessment metrics. These technologies will be incorporated into a prototype solar power forecasting system that will be tested in collaboration with utilities and independent system operators (ISOs) in geographically diverse areas, including Long Island, Colorado, coastal California, and Hawaii. Each component will be verified and validated using specially designed evaluation techniques. The system will be deployed in operational environments of utility and ISO partners with engagement of commercial forecast providers, who will tailor the methods to the needs of the deployment. This iterative process will incorporate user feedback and assess the economic value of the forecasts. The results will be widely disseminated through publications, workshops, and software. The impact of this effort will be enhanced solar power forecasting that is integrated into utility operations, advancing the penetration of renewable energy.

WATT-SUN: A MULTI-SCALE, MULTI-MODEL, MACHINE-LEARNING SOLAR FORECASTING TECHNOLOGY

IBM | Yorktown Heights, NY | \$3.9M | Solar Forecasting | 10/2012-09/2015

This work aims to develop a novel approach to solar forecasting, which will not only combine and integrate different prediction models but also use state of the art machine learning technologies to drastically improve the accuracy of predictions. Similar to the recently demonstrated Watson computer system, the proposed technology will leverage deep machine learning and self-adjusting voting algorithms to decide between various forecasting models and expert systems. The approach will yield the best forecasts and more importantly, continuously improve and adjust as the system is operating and evolving. The solar forecasting framework is independent of proprietary weather or solar radiation models and enables the technology to scale and to be adopted by solar producers, electrical utilities, independent system operators (ISOs), and other stakeholders. The forecasting will also be validated at multiple sites with significantly different weather patterns. The team will work closely with utilities, solar power

producers, and ISOs to integrate the proposed technology and to determine the value of solar forecasting on daily operation, load modeling, optimizing spinning reserve, and day ahead planning.

SOLAR FORECAST IMPROVEMENT PROJECT

National Oceanic and Atmospheric Administration | Boulder, CO | \$2.0M | Solar Forecasting | 02/2014-01/2017

DOE will work with NOAA and the awardees of the Solar Forecasting funding opportunity, the National Center for Atmospheric Research (NCAR) and IBM, to provide a pathway for public dissemination of weather model improvements resulting from the research conducted by NCAR and IBM on solar forecasting. This activity falls under the Memorandum of Understanding signed by the two agencies in 2011, in which they agreed to collaborate to advance the science and services needed in support of weather-dependent and oceanic renewable energy. NOAA will consult with IBM and NCAR in areas of NOAA's expertise including numerical weather prediction (NWP), irradiance forecasting, cloud-tracking algorithms, ground-based measurements, model verification, and metrics. Further, NOAA will provide baseline global horizontal irradiance (and later, direct normal irradiance) forecasts from the 3 km High-Resolution Rapid Refresh (HRRR) and an advanced version of the 13 km Rapid Refresh (RAP) models. NOAA will provide these grids and all other needed model grids, as well as consult the NCAR and IBM teams, as needed, on use of the model fields. NOAA will also provide a clear pathway for HRRR, RAP, and NWP model assimilation from research into the NOAA operational model suite, thus realizing the goal of operational solar forecasts.

SOLAR VALUE ANALYSIS AND MARKET PENETRATION MODELING

National Renewable Energy Laboratory | Golden, CO | \$3.4M | National Laboratory R&D | 10/2012-09/2015

This project will help implement a comprehensive framework for characterizing solar technical and economic potential and representing solar technologies in capacity-expansion models by conducting foundational model development and analysis activities. The results from this project will improve upon existing modeling efforts in both utility-scale (wholesale) markets and distributed (retail) markets and continue to evaluate the interaction between these two market sectors. In the utility sector, the proposed research will further evaluate key drivers of economic competitiveness. These include solar prices, local solar resources, electric-sector market dynamics (e.g., load growth, regional renewable portfolio standards and other policies, the existing mix of conventional generation resources and transmission infrastructure, fuel prices, and retirements of conventional generators), the value of solar generation (e.g., solar capacity value, the impact of solar variability on the need for additional operating reserves, and the change in these factors with increasing solar deployment), project-level investor risk, and several other factors. In the distributed PV sector, the proposed research will continue ongoing analysis of the retail value of PV, including, for example, how customers weigh the costs and benefits of PV ownership. Filling this gap will help to inform the development of policies aimed at encouraging the type of solar market growth envisioned under the SunShot Initiative.

ADVANCING SOLAR INTEGRATION ON TRANSMISSION SYSTEMS

Sandia National Laboratories | Albuquerque, NM | \$3.1M | National Laboratory R&D | 10/2012-09/2015

Sandia's 3-year integrated program incorporates elements of each of the SunShot Transmission Grid Integration (TGI) research areas: System Integration Study Template, Models and Tools Improvement, and Transmission Analysis and Transmission Alternatives. Strategic stakeholder engagement and information dissemination are also an integral part of the proposed activities, to ensure the broadest possible impact. The work plan is organized into four tasks: **1)** Improve simulation models for solar generation

interconnection and grid planning, **2)** Improve methods and tools for the analysis of high penetration scenarios, **3)** Evaluate the technical feasibility of high penetration solar deployment, and **4)** Enhance critical stakeholder engagement to disseminate TGI information.

CORE COMPETENCIES FOR SOLAR RESOURCE ASSESSMENT

National Renewable Energy Laboratory | Golden, CO | \$3.3M | National Laboratory R&D | 10/2012-09/2015

The Core Competencies for Solar Resource Assessment project aims to improve the tools and methods to measure solar radiation and therefore reduce uncertainty in predicting solar output and improve the bankability of financing solar projects. This project has three tasks that conduct research on advancing solar resource measurements: Task 1-Broadband and Spectral Calibration and Measurement; Task 2-Continue developing the National Solar Radiation Data Base (NSRDB); and Task 3-Standards and Expert Committees. Task 1 is focused on reducing spectral and broadband solar measurement uncertainty through improvement in instrumentation, calibration and cross-comparison. NSRDB is the most widely used public solar radiation database in the U.S. In Task 2, the NSRDB will be updated with high-resolution, satellite-based solar radiation datasets created using a state of the art physical model thereby providing users with a lower uncertainty, higher-resolution dataset to use. Finally in Task 3, international consensus on standards in solar measurement and modeling is developed to represent the state of the art knowledge through continuous formal engagement of various stakeholders such as through participation in developing radiometric standards, through American Society for Testing Materials International.

SOLAR RESOURCE MODELING AND MEASUREMENT RESEARCH

National Renewable Energy Laboratory | Golden, CO | \$2.3M | National Laboratory R&D | 10/2012-09/2015

The Solar Resource Modeling and Measurement Research project aims to improve the tools and methods to measure solar radiation and therefore reduce uncertainty in predicting solar output and improve the bankability of financing solar projects. This project has two tasks that conduct research on advancing solar resource measurements: Task 1-Satellite Based Modeling and Validation, and Task 2-PV System Derived Data. In the first task, the advanced Geostationary Operational Environmental Satellite Solar Insolation Product Project seeks to advance the state of the art in satellite-based solar resource assessment and reduces the uncertainty of the solar resource data through improvements in the physics of the resource-assessment method. The cost associated with conventional measurements of solar radiation using thermopile instruments prevents wide scale measurement of the solar resource. Therefore, in the second task, the goal is to develop and validate cost-effective instruments and methods for gathering solar radiation data, which will facilitate improved ground-based solar resource data availability.

ADVANCED SOLAR RESOURCE MODELING AND ANALYSIS

Sandia National Laboratories | Albuquerque, NM | \$1.2M | National Laboratory R&D | 10/2012-09/2015

The dominant contribution to uncertainty in projected power and energy from solar arrays arises from uncertainty in the estimated solar resource. Uncertainty in estimated irradiance stems from uncertainty in the models that translate satellite measurements to estimated irradiance; portray the spatial and temporal variation in irradiance over a power plant's footprint or over a fleet of solar power systems; and separate global horizontal irradiance into its beam and diffuse components. This project performs R&D leading to improved models which can reduce these uncertainties and thus lead to reduced financial and technical risk to solar

power deployment. The key activities for this project are: improve irradiance estimated from satellite data through extensive validation of the emerging Global Solar Insolation Project's Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI) estimates, improve upon current methods to represent the geographic smoothing of irradiance over the spatial extent of utility-scale power plants, as well as over fleets of solar power systems, provide guidance for the number of sensors required for accurate spatial irradiance measurement, and improve models that estimate DNI and plane-of-array (POA) irradiance from GHI.

UTILIZATION OF RENEWABLE ENERGY TO MEET NEW NATIONAL CHALLENGES IN ENERGY AND CLIMATE CHANGE

Howard University | Washington, DC | \$0.3M | MURA | 09/2010-09/2014

This research project models integrated networks of renewable energy resources and loads and evaluates the generation balance through appropriate storage and control design. As part of the project, design of performance indices will be developed for achieving generation/load balance, frequency control, and power quality and reliability under different disturbances. Education and training in this project includes high school, undergraduate and graduate students in simulation and hands-on research development of the integrated scheme.

Dispatchability

The SunShot Initiative supports research to better understand the impact of high penetration of solar power plants on the transmission and distribution electricity grids. SunShot also supports the development of standardized methods for testing grid performance of PV solar power plants and exploring and demonstrating the value of energy storage.

SunShot targets for dispatchability of solar power plants:

- Meet or exceed generator performance standards specified by NERC and individual power grids that are applicable for conventional power plants.
- Satisfy the above metric without increase in cost.
- Ensure treatment of solar power plants in a manner similar to conventional generators without additional integration cost.

MODEL-BASED INTEGRATED HIGH-PENETRATION RENEWABLES PLANNING AND CONTROL ANALYSIS

PHI Holdings, Inc. (PEPCO) | Washington, DC | \$1.0M | SUNRISE | 10/2013-09/2015

This project will implement integrated transmission and distribution system high-penetration distributed energy resource (DER) interconnection, planning, monitoring and control analysis that will cover PEPCO's entire operating area. This project will quantify individual and combined effects of PV and DER, system configuration, equipment and control changes on renewable penetration levels, system efficiency and reliability, and ensure that the common model and model-based algorithms allow same data, data validation, and analysis to be used for all activities. This project is expected to result in significant increase in solar penetration capacity in the distribution system 10-15% beyond where it would be without the proposed project.

INTRA-HOUR DISPATCH AND AUTOMATIC GENERATOR CONTROL DEMONSTRATION WITH SOLAR FORECASTING

University of California | San Diego, CA | \$0.5M | SUNRISE | 10/2013-09/2015

This project will demonstrate an operational tool for reducing costs associated with real-time dispatch and automatic generation control for different solar penetration scenarios in the Sacramento region. Innovative features of this project include clustering analysis on the expected solar variability per region for the Sacramento Municipal Utility District system, day-ahead and real-time load forecasts for the whole service areas and within clusters, and uncertainty quantification for integrated solar-load for both distributed and central station PV generation. This project is expected to reduce power system operation costs by committing appropriate amounts of energy resources and reserves, as well as to provide operators a prediction of the generation fleet's behavior in real time for realistic PV penetration scenarios.

OPERATIONAL ANALYSES, MODELS AND TOOLS IMPROVEMENT

National Renewable Energy Laboratory | Golden, CO | \$3.5M | National Laboratory R&D | 10/2012-09/2015

This project consists of multiple activities conducted by NREL. The first activity is a study that analyzes the impact of large-scale deployment of wind and solar in the Eastern Interconnection of the U.S. The Eastern Renewable Generation Integration Study (ERGIS) analyzes two strategies for reaching 30% combined wind and solar targets and informs stakeholders about the operational impacts of these two strategies. The second activity analyzes the optimal method for operating reserve requirements with high solar penetrations. The first objective is to improve a software tool that models both the holding and deployment of reserve capacity to be used by a large system operator. The second objective is to understand the nontraditional factors that influence the need for operating reserve and compare how these should contribute to optimal operating reserve requirements for a balancing area. The third activity is to examine in detail the value proposition for CSP technology, focusing on the implementation and use of CSP with thermal energy storage. NREL will evaluate the ability of CSP to provide dispatchable energy, firm system capacity, and ancillary services. Further, the value of CSP will be compared to other sources of system flexibility, especially in enabling higher penetrations of variable generation resources such as PVs. The final activity in this project is to create a new national solar database with higher temporal and spatial resolution, and provide public access to this data to reduce the costs and risks of integrating solar power systems into the electric power grid.

Power Electronics

SunShot funding supports cost reductions and efficiency improvements through innovative circuit design, advanced components, and optimal control mechanisms. Specifically, research in this area supports the development of power electronics technologies to reduce balance of system (BOS) hardware costs, reduce installation time, and improve energy yield, as well as the development of plug-and-play technologies to reduce installation time and process costs. SunShot awardees are developing and demonstrating smart inverter functionalities and developing accelerated life testing methods and physics of failure models to predict faults and improve reliability.

SunShot technical targets for power electronics and related aspects:

- Conversion efficiency >98%
- Cost <\$0.10/W (for utility-scale inverter)
- Service life 25 years
- Include grid support functions (e.g., Volt/Var, voltage ride through)

TRANSFORMING PV INSTALLATIONS TOWARD DISPATCHABLE, SCHEDULABLE ENERGY SOLUTIONS

Advanced Energy | Fort Collins, CO | \$3.1M | SEGIS-AC | 09/2011-06/2015

Advanced Energy will address three important needs in the further deployment of PV systems: **1)** demonstrating and commercializing a new anti-islanding method utilizing Phasor Measurement Units (PMUs), **2)** demonstrating a set of advanced grid support functionalities of power electronics, and **3)** demonstrating a novel “ramp rate controller” to enable control of the downward ramp rate of a PV plant under transient cloud conditions.

EXTREME COST REDUCTIONS WITH MULTI-MEGAWATT CENTRALIZED INVERTER SYSTEMS

Alencon, LLC | Hatboro, PA | \$3.0M | SEGIS-AC | 09/2011-12/2014

Alencon will develop and commercialize a new type of transformational power electronic technology to utility-scale PV systems based on novel, patent-pending ideas. A 99.1% efficient, centralized inverter with a capacity of up to 100 megawatts lies at the heart of the Alencon system. Feeding this single inverter is an advanced harvesting network that utilizes string-wise maximum power point tracking and high DC voltage (2500 VDC) nodes that are easy to install and maintain.

SMART GRID READY PV INVERTERS WITH UTILITY COMMUNICATION

Electric Power Research Institute | Knoxville, TN | \$4.5M | SEGIS-AC | 09/2011-05/2015

EPRI will develop, implement, and demonstrate smart-grid ready inverters with grid support functionality and required utility communication and control links to capture the full value of distributed PV. The key elements are: **1)** head-end communications at the utility operations center through integration of distributed energy resource (DER) distribution management system (DMS),

2) back-end DER plant master controller, and 3) smart grid functionality built into inverters. PV inverter grid support functions will be put into practice using the distributed network communication protocol that enables utility operators to interact from central office-level DMS to the plant. Real world demonstrations will be carried out in three regions of the United States with four major utilities, each of which have different types of utility operating systems and implementations of utility-scale PV inverters.

MODULE EMBEDDED MICRO-INVERTER SMART GRID READY RESIDENTIAL SOLAR ELECTRIC SYSTEM

GE Global Research | Niskayuna, NY | \$1.5M | SEGIS-AC | 09/2011-04/2015

GE will develop and demonstrate a new microinverter that is functionally integrated with the AC module to reduce packaging and materials cost for both the microinverter and the module laminate, and a new intelligent circuit breaker that reduces microinverter cost by offloading duplicate safety and protection functions in an AC module system to a dedicated branch circuit.

INTEGRATED MICROINVERTERS FOR ENABLING TRUE ACPV MODULES

SolarBridge Technologies | Austin, TX | \$1.7M | SEGIS-AC | 09/2011-12/2014

SolarBridge will develop a novel residential PV system consisting of a PV module with an integrated “Universal PV-Dock” and a high-reliability, low-cost, high-efficiency microinverter. The collective system forms an ACPV module that simultaneously increases energy harvest and reduces balance of systems costs. The proposed system also addresses many practical aspects of the PV installation cost, such as supply chain and inventory management, late (or field) adaptation of products, and communications for data collection and performance monitoring, thereby yielding a substantially lower levelized cost of energy.

DEVELOPMENT AND DEMONSTRATION OF SMART GRID INVERTERS FOR HIGH-PENETRATION PV APPLICATIONS

University of Hawaii | Honolulu, HI | \$5.1M | SEGIS-AC | 09/2012-06/2015

The University of Hawaii will demonstrate the advanced residential PV solutions at two widely different utilities. On the island of Maui, smart PV inverters and control and management software will be combined with retrofits to existing PV inverters with the goal of evaluating the ability of the systems to mitigate voltage fluctuations caused by variability of PV systems, contribute to grid stability during frequency excursions and faults, and report real-time PV output to both the utility and customer. The project team will also install new PV inverters with the goal of enabling higher PV penetration on a secondary distribution network.

PV SYSTEM RELIABILITY

Sandia National Laboratories | Albuquerque, NM | \$4.6M | National Laboratory R&D | 10/2012-09/2015

Sandia will conduct research to address widespread reliability and safety issues in today's PV systems. Specifically, the team will investigate PV arc-fault and ground fault issues and inverter reliability. Arc fault R&D efforts will assist with the development of arc-fault detector/circuit interrupter certification standards through Underwriters Laboratories task groups and the International Electrotechnical Commission Technical Committee. Inverter reliability efforts will utilize the electro-thermal modeling tool, piecewise linear electrical circuit stimulation, and lab and field testing to evaluate and optimize inverter designs to achieve a 25-year inverter lifetime under realistic usage conditions (including advanced inverter functionality, such as Volt-Ampere Reactive support).

MODULE LEVEL POWER ELECTRONICS RELIABILITY AND ACCELERATED TESTING STANDARDS

Sandia National Laboratories | Albuquerque, NM | \$1.4M | PREDICTS | 10/2013-03/2016

Sandia leads the collaborative development and initial implementation of industry-standard tests for module level power electronics reliability in stand-alone and module-integrated configurations. Test development will utilize a sound physical understanding of failure mechanisms and degradation modes with extensive laboratory and field testing incorporated to validate the tests and test protocols that are developed and to ensure broad applicability across the industry.

HIGH-PENETRATION PV WITH ADVANCED POWER CONDITIONING SYSTEMS

Virginia Polytechnic Institute and State University | Blacksburg, VA | \$2.6M | Hi-Pen | 04/2011-12/2014

Virginia Tech will develop and commercialize three advanced power conditioning designs that enable high penetration PV systems without adversely impacting utility operation. The team is also establishing guidelines about the PV hosting capacity a feeder can accommodate depending upon feeder design, and will validate approaches to mitigate effects.

DISTINCT: DIVERSITY IN SOLAR TALENT THROUGH INNOVATIVE CURRICULUM AND TRAINING: AN INTEGRATED RESEARCH & EDUCATION APPROACH TOWARDS CREATING DIVERSITY AND ADVANCING UTILITY-SCALE SOLAR TECHNOLOGY

University of Texas | San Antonio, TX | \$0.75M | DISTANCE | 09/2013-09/2016

This research is focused on the concept design and development of an innovative N-port power electronic converter that is modular, compact and cost-effective. The converter will provide a distributed, high-voltage internal electrical architecture with an integrated high-frequency, high-voltage, solid-state transformer. An integral component of this effort is to significantly enhance the “smart” integration of functionalities that go well beyond conventional grid support functions and accommodate solar resource variability due to widespread deployment of solar.

Communications

SunShot supports the development of open and interoperable communication and control architectures, enterprise integration standards based on common information model (CIM), smart inverter communication standards, and communication requirements such as network latency, scalability, and availability. Project teams working in this area are implementing standard communication protocols in inverter hardware and enterprise software, and demonstrating end-to-end system integration and interoperability on actual distribution feeders with utilities.

SunShot technical targets for communications and related aspects:

- Open and interoperable communication and control architectures
- Hundreds of thousands of connected nodes
- Near 100% network availability
- Real-time or near real-time network response

DEVELOPMENT OF AN INNOVATIVE PLUG AND PLAY PHOTOVOLTAIC ELECTRIC SYSTEM

North Carolina State University | Raleigh, NC | \$2.2M | Plug and Play | 01/2013-04/2015

NCSU's Systems Engineering Center will develop a new plug-and-play PV technology to improve all aspects of residential solar PV systems through major innovation, refinement, and standardization. The key efforts are: **1)** reducing the costs of the structural elements, installation, and mounting components, **2)** reducing the cost and improving the performance and reliability of the electrical components, **3)** simplifying the integration of the panels into the electrical grid, including communications, control, and safety considerations, and **4)** designing for the market.

PLUG AND PLAY SOLAR PV FOR AMERICAN HOMES

Fraunhofer Center for Sustainable Energy Systems | Boston, MA | \$8.8M | Plug and Play | 01/2013-01/2016

The Fraunhofer CSE will develop a new plug-and-play PV system that self-checks for proper installation and safety and communicates with the local utility and local jurisdiction to request permission to feed power into its smart meter. The utility and locality will remotely grant permission to the system to connect, and the PV system will immediately start to produce power to either consume in-house or feed into the distribution grid. In addition, the team will work with the national codes and standards community to identify hurdles for such a system, propose code changes, and develop technologies that will enable the system to be listed by Underwriters' Laboratories and therefore not subject to local building inspections. Progress of the technology development will be demonstrated yearly with partnering utilities and localities.

Plant Performance and Reliability

To support solar plant performance and reliability, SunShot supports R&D of characterization and diagnostic tools, data, analysis, and models to quantify, predict, and improve performance, lifetime, durability, and availability at both the component and plant/system level. SunShot also supports the development of standards and codes to provide confidence in the safety, reliability, and performance of commercial components and systems, as well as products that integrate one or more components to include building-integrated photovoltaics (BIPV), integrated grounding, and module-integrated racking. Program goals in this area include drastically reducing the part counts of associated balance of plant hardware, incorporating lean processes in hardware installation, and using alternative/innovative materials for racking, module backsheets, and module frames.

SunShot technical targets for plant performance and reliability as well as balance of plant hardware costs include:

- Provide the sufficient research data to support the approved publication of consensus standards for comparative lifetime testing of PV modules.
- Enable the creation of a consensus standard for PV system energy performance evaluation that reduces the level of uncertainty by >2% and reduces the business process time associated with negotiating performance guarantees to 3 days or less.
- BIPV systems that enable residential solar at <\$2.00/W
- Materials costs for polymer and steel systems at <\$0.15/W and <\$0.20/W respectively
- System weight of <2lbs/sqft
- Hardware and electrical labor costs <\$0.10/W
- Publication of a validated set of protocols enabling commercial testing laboratories to produce Sandia Array Performance Model coefficients with 90% of predicted model performance values agree within 2% of the results from Sandia National Laboratories
- Automated detection of >95% of PV string failures and system faults with next-generation PV monitoring analysis methods

ADVANCED MEASUREMENT AND ANALYSIS OF PV DERATE FACTORS

Sandia National Laboratories | Albuquerque, NM | \$2.6M | National Laboratory R&D | 10/2013–09/2015

This project focuses on improving the accuracy and reducing the uncertainty of PV performance model predictions by addressing several common elements of all PV performance models referred to as “derates.” Derates are represented by simple empirical factors that are not tied to underlying physical loss mechanisms. There is significant uncertainty regarding appropriate values for these factors.

CHARACTERIZING EMERGING PHOTOVOLTAIC TECHNOLOGIES

Sandia National Laboratories | Albuquerque, NM | \$5.1M | National Laboratory R&D | 10/2013–09/2015

The Sandia team will focus on developing, improving and validating characterization methods for PV modules, inverters and embedded power electronics. Characterization methods are at the heart of technology assessments and provide the basis for accurate modeling of components and systems. Outputs of the project include measurement and analysis procedures that industry can use to better distinguish and understand the performance differences between competing module and inverter products, new component designs and new technologies such as new PV cell designs, inverter topologies and more.

INCREASING PREDICTION ACCURACY

National Renewable Energy Laboratory | Golden, CO | \$4.2M | National Laboratory R&D | 10/2009–09/2014

The goal of this project is to quantify and reduce uncertainties in PV system performance models by systematically analyzing, quantifying, and propagating uncertainty using research-quality PV monitoring data in various climates, leading the international PV Performance Monitoring Collaborative (PVPMC) to standardize and document existing and emerging modeling algorithms, making targeted model improvements for concentrating PV technologies and systems, and developing new methods for extracting more information from PV monitoring systems and data streams.

IMPROVEMENT AND VALIDATION OF SOLAR SYSTEMS MODELING ALGORITHMS AND TOOLS

National Renewable Energy Laboratory | Golden, CO | \$3.1M | National Laboratory R&D | 10/2013–09/2015

The project team aims to improve system modeling accuracy and risk assessment via research into improved data and algorithms, make robust models available to the PV industry, and improve the characterization of risk and bankability across all markets (residential, commercial and utility). The project’s ongoing value to the community is to enable and accelerate research and analysis of solar technologies through the development and dissemination of cutting-edge solar and finance modeling through desktop tool, software engine, and web services such as the System Advisory Model (SAM) and PVWatts.

PREDICTING SERVICE LIFE FOR PV MODULES

National Renewable Energy Laboratory | Golden, CO | \$9.9M | National Laboratory R&D | 10/2013–09/2015

NREL is developing a set of accelerated stress tests that can provide quantitative predictions of module service life in a variety of climates for different PV technologies and applications. The developed accelerated stress tests will be incorporated into a set of standards.

QUANTIFYING RISK THROUGH BANKABILITY REPORTS AND STANDARDS

National Renewable Energy Laboratory | Golden, CO | \$2.8M | National Laboratory R&D | 10/2013–09/2015

NREL is focusing on the technical details of assessing PV performance risk with the goal of reducing risk (both actual and predicted) and decreasing the time and cost needed to assess this risk. To this end, NREL is developing standards to quantify PV performance, documenting actual PV performance versus predicted performance across large data sets (50,000+), and documenting and standardizing the quantification of degradation rates.

EMERGING TECHNOLOGY CHARACTERIZATION

National Renewable Energy Laboratory | Golden, CO | \$3.0M | National Laboratory R&D | 10/2013–09/2015

NREL will conduct research to remove barriers due to uncertainties associated with the performance of emerging technologies. The emerging technologies addressed are thin film and concentrating PV (CPV) modules. The team will develop procedures to stabilize the performance of thin film PV modules (CIGS and CdTe) for measurement of performance at Standard Rating Conditions. The team will also develop and validate testing methods to determine outdoor power ratings of CPV modules and reduce uncertainty from $\pm 10\%$ to $\pm 5\%$.

IEC AND NEC PV STANDARDS

National Renewable Energy Laboratory | Golden, CO | \$2.0M | National Laboratory R&D | 10/2013–09/2015

NREL aims to provide technical validation to reduce uncertainty in predictions of PV performance, quality, safety, and product lifetimes in order to differentiate technologies and products and set baselines for product improvement and investment. This is accomplished by continuing DOE representation and participation in several standards and codes activities to ensure that the best technical work available in the areas of PV measurements and testing are turned into standards and codes. Particular attention is paid to the International Electrotechnical Commission (IEC), the National Electric Code (NEC), and various building codes to support codes that facilitate the growth of PV and avoid codification of requirements that unfairly or inaccurately limit implementation of PV.

INNOVATIVE BALLASTED FLAT ROOF SOLAR PV RACKING SYSTEM

Cascade Engineering | Grand Rapids, MI | \$0.60M | BOS-X | 12/2012–07/2014

Cascade Engineering is incorporating a number of material and labor savings opportunities into a lightweight, low-cost, injection-molded plastic solar PV racking system. The goal is to reduce total balance of system costs by 25%.

REGIONAL TEST CENTERS

National Renewable Energy Laboratory and Sandia National Laboratories | Golden, CO and Albuquerque, NM | \$12.0M | National Laboratory R&D | 10/2011–Ongoing

SunShot established the Regional Test Centers to further develop standards, establish a technical basis for PV bankability/economic viability, provide geographically diverse test beds for large-scale system demonstrations, and to offer technical assistance and independent validation of PV performance and reliability.

SOLAR INSTALL, MOUNT, PRODUCTION, LABOR, EQUIPMENT (SIMPLE) BALANCE OF SYSTEMS

Georgia Tech Applied Research Corporation | Atlanta, GA | \$2.8M | BOS-X | 09/2011-01/2015

Georgia Tech is developing residential, commercial, and utility solar PV racking and mounting systems that reduce hardware and labor costs by 50% over current industry best practices. Design innovations are being pursued across multiple pathways, including: reduced part count, standardization, factory assembly, wire management, reduced roof penetrations, tool-less systems, integrating assembly line processes, pre-panel assembly, significant material reduction, self-squaring, prefabrication, factory assembly, structural/material efficiencies, and self-stability/ballasting.

DEPLOYABLE COMMERCIAL ROOFTOP SOLAR ELECTRIC SYSTEM

GE Global Research | Niskayuna, NY | \$1.5M | BOS-X | 12/2011-12/2014

GE is developing a lightweight, mechanically-interconnected, multi-module solar electric array that can enable total installed costs of less than \$2.50 per watt. Key innovations include: assembly weight of less than 2 lbs/ft²; significant reductions in racking weight, material handling costs, and install time; an integrated busway; and optimization for project net present value based on higher energy production revenues on size-constrained commercial rooftops.

DEVELOPMENT AND PRODUCTIZATION OF HIGH-EFFICIENCY, LOW- COST BUILDING-INTEGRATED PHOTOVOLTAIC SHINGLES USING MONOCRYSTALLINE SILICON THIN FILM SOLAR CELLS

Solexel | Milpitas, CA | \$7.2M | BOS-X | 09/2011-07/2014

Solexel is developing a building-integrated photovoltaic (BIPV) solar shingle product that demonstrates a business case for achieving a \$2 per watt or less total installed cost residential BIPV system at large scale by 2017. The design is incorporating high-efficiency (>21%), flexible, thin monocrystalline silicon cells, very low-cost distributed power electronics circuitry at the cell level, and integrated microinverters.

Technology to Market

Dramatic reductions in the cost of solar will enable the high penetration deployment of solar energy technologies. It is essential then, but insufficient, to discover new materials, build first-of-a-kind devices, or identify that we must simplify PV interconnection backlogs: to have real impact, we must also transition all of these solutions to the marketplace. As a taxpayer-funded program, the SunShot Initiative also aims to create domestic jobs through commercial activity in the solar sector. The Technology to Market subprogram builds on SunShot's record of enabling groundbreaking devices and concepts in earlier stage programs with follow-on funding. Technology to Market targets two known funding gaps in bringing new technologies to market: the ones that occur at the prototype commercialization and commercial scale-up stages, as illustrated in Figure 1.

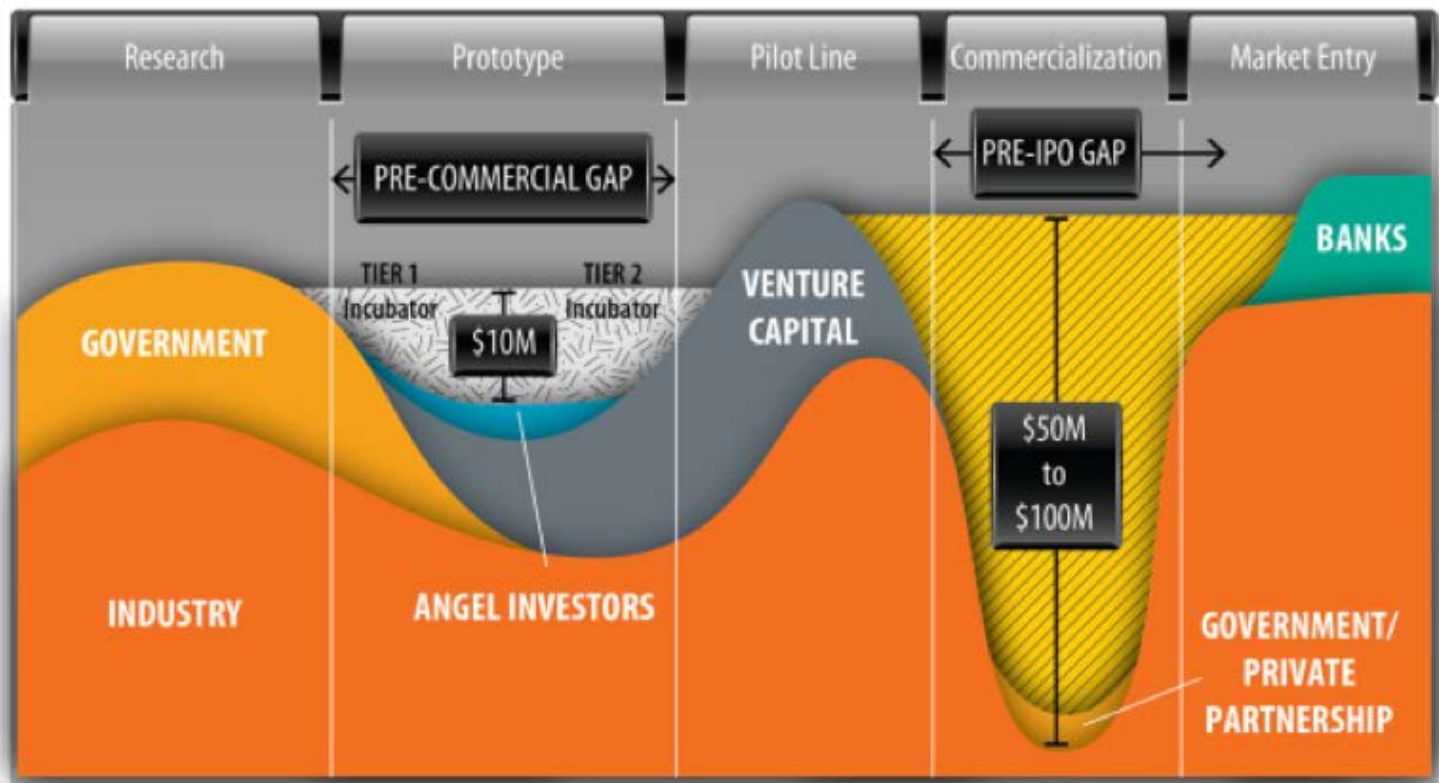


Figure 1. Commercialization and scale-up funding gaps addressed by SunShot's Technology to Market Program.

Commercially-focused technologies and business solutions in the SunShot portfolio are nurtured across varying stages in both the Incubator program and in the ongoing Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) programs. Businesses with later-stage technologies can apply for manufacturing programs such

as Solar Manufacturing Technology (SolarMaT) and Scaling Up Nascent PV at Home (SUNPATH), both of which support cost-effective, domestic, manufacturing processes. If topically suitable, manufacturers and component suppliers can also join the consortia funded under the Photovoltaic Manufacturing Initiative (PVMI). All Technology to Market programs are tightly

structured to ensure that recipients commercialize the funded technology and achieve technical milestones. Through various other activities, SunShot's Technology to Market program also creates venues for helping the recipients find non-DOE follow-on funding and form strategic partnerships.

The flagship program in the Technology to Market portfolio is the SunShot Incubator program, currently in its ninth round.

Past recipients have attracted more than \$18 in follow-on funding for every \$1 in federal investment. The Incubator program supports small businesses seeking to commercialize innovative PV and CSP device concepts and manufacturing pilot lines, as well as innovations in hardware installation, grid conversion technologies, and novel business models and software platforms for reducing soft costs.



Figure 2. Incubator awardee QBotix has developed a robotic tracking system that increases solar PV power plant production by up to 45% and delivers cost savings up to 20%.

In addition to funding commercialization-stage activities and beyond, Technology to Market tends to the internal compass of the SunShot Initiative by supporting market and cost analysis. This analysis informs SunShot's strategic direction and reveals the market barriers that can be addressed through solicitations. On an ongoing basis, SunShot closely scrutinizes the progress of its projects and programs and evaluates internal decision-making with reference to bottom-up cost analyses. These analyses, crucial to a rapidly-evolving industry, address conversion technologies and systems as well as supply chain- and location-specific competitive advantages.

The programs described below fall into three thematic areas across the Technology to Market portfolio: Technology Commercialization and Business Innovation, Manufacturing Innovation and Scale-Up, and Cost Analysis.

Dr. Lidija Sekaric

Technology to Market Program Manager

Solar Energy Technologies Office

U.S. Department of Energy

Technology Commercialization and Business Innovation

The SunShot Incubator program, which began in 2007, is now in its ninth round. Recipients, who graduate from the program within 12-18 months, have attracted outstanding levels of private follow-on funding relative to federal investment. Tightly formulated commercial and technical deliverables are the cornerstone of the program. The program also boasts breadth and permanence: the solicitation is open to a wide range of topics and recurs annually, subject to appropriations. The Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) are congressionally-mandated programs that, although not entirely managed from within SunShot, serve the purpose of piloting topics and concepts that complement the rest of the SunShot portfolio. SunShot aims to select and support Incubator and SBIR/STTR recipients whose innovative ideas will continue to benefit the solar market: the program goal is to have at least 50% of recipients and/or their business solutions survive and have impact in the marketplace beyond 2020.

SunShot Incubator Program

The SunShot Incubator Program provides early-stage assistance to help small businesses cross technological barriers and de-risk their products and services, while encouraging private sector investment to maximize impact. The program is focused on rapidly commercializing products and services with the potential to make solar more affordable. The SunShot Incubator Program partners with U.S. industry to accelerate innovation and meet aggressive cost and market penetration goals.

MOSAIC

Berkeley, CA | \$2.0M | Incubator 6 | 06/2012-09/2014

Solar Mosaic is bringing much-needed capital to the solar industry by building a web platform for everyday Americans to create and fund solar projects. Mosaic's unique online crowdfunding platform will help reduce the soft costs of solar financing and customer acquisition while enabling thousands of Americans to own a piece of the growing clean energy economy.

ENKI TECHNOLOGY

San Jose, CA | \$1.5M | Incubator 7 | 10/2012-09/2014

Enki Technology is working to improve PV module efficiencies and reduce the levelized cost of energy (LCOE) through development of low-cost high-performance functionalized anti-reflective coatings for PV cover glass. Enki's unique platform of products offer high-durability coatings for desert environments, anti-soiling coatings for arid and dusty environments and coatings optimized for world class optical performance. Enki offers coating processes on industry standard equipment with products that can be cured at low or high temperatures for compatibility with existing infrastructure. Enki is continuing to expand its product offerings to provide tailored anti-reflection coatings that solve customer problems.

Project Highlight: Solar Census

Awardee	Solar Census
Location	Walnut Creek, CA
Award Amount	\$0.73M
Period of Performance	10/2013–11/2014
Primary Industry Area	Online Shade Tool

Solar Census will leverage its patented algorithms to produce the first commercial-grade online shade tool that enables salespeople and system designers to customize PV systems in 3D and create highly accurate quotes in minutes (Fig. 3). The software will streamline the sales and design process, reduce change orders and soft costs, and increase close rates and homeowner satisfaction.

How this Technology is Transformational

Solar Census Surveyor is the first commercial-grade online rooftop shade analysis tool. This fully automated software draws from 3D spatial databases and applies patented algorithms to model the shading effects on a particular roof on a 24/7/365 basis to determine exact solar access values. This software can be used by solar installers, financiers, and other solar sales companies to qualify a house for solar in seconds and design a solar system to ensure optimal return on investment without leaving their desks.

This software truly revolutionizes the solar sales cycle. The National Renewable Energy Laboratory evaluated the accuracy of the online tool's shade values and determined that performing a virtual survey with Solar Census Surveyor is "scientifically equivalent" to using a handheld Solmetric SunEye. In addition to the instant shade analysis, the software provides an instant financial proposal and 3D CAD model. The need for a site visit is entirely eliminated with this software and companies can go directly from lead to install.

Why this Innovation is Important for the United States

This software connects solar to the web and can help to increase adoption of solar energy. By making buying and selling solar much simpler, Solar Census' online analyses can drastically reduce costs. This software eliminates the need for a physical site survey, reducing the cost of installers' workers compensation insurance, radically shortening the sales cycle, increasing close rates, dramatically reducing change orders, ensuring optimal system placement and reducing installation labor. Further, enabling remote surveys allows companies, funds, governments and individual Americans to guarantee the security of their investments, helping to continue stability and confidence in the solar industry.

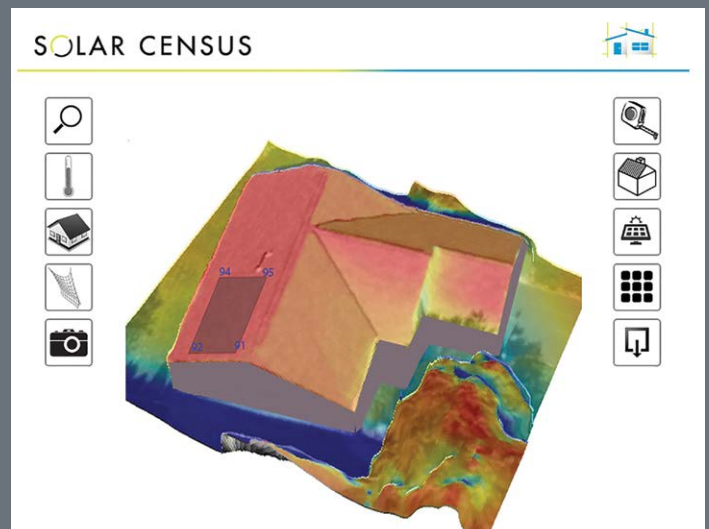


Figure 3. Incubator awardee Solar Census is producing the first commercial-grade online shade tool that enables salespeople and system designers to customize PV systems in 3D and create highly accurate quotes in minutes.

REhnu

Tuscon, AZ | \$1.0M | Incubator 7 | 10/2012-05/2014

REhnu is transitioning a new concentrating photovoltaic (CPV) technology, already proven in a University of Arizona prototype, to a low-cost form ready for commercial production. The technology uses large glass dish reflectors, each with a compact array of CPV cells at its focus. This makes it economical to build systems with an extended 40-year lifetime and maintain high power output by swapping in new cells as multijunction technology improves.

SOLAFLECT

Norwich, VT | \$1.0M | Incubator 7 | 02/2013-04/2015

Solaflect Energy has developed a low-cost Suspension Heliostat™ that dramatically reduces steel usage by utilizing steel cables instead of steel truss structures to stabilize mirror panels. The SunShot project will focus on continued development of the heliostat design, design for robotic manufacture, reduction of manufacturing and installation labor requirements, and the transition to high volume commercialization.

STION

San Jose, CA | \$2.0M | Incubator 7 | 12/2012-06/2014

Stion has developed a disruptive technology based on a tandem copper indium gallium diselenide (CIGS) module that uses a revolutionary thin film design to enable broader and more effective harvesting of available light. The tandem module, which utilizes mechanically stacked top and bottom modules to avoid the design and manufacturing challenges associated with multijunction monolithic integration, enables 18% efficiency on full-size CIGS modules.

APPLIED NOVEL DEVICES, INC.

Austin, TX | \$0.50M | Incubator 8 | 10/2013-09/2014

Applied Novel Devices is developing a low-cost, high-efficiency inter-digitated back contact (IBC) solar cell technology using a novel self-aligned direct patterned deposition system. The process for forming the cells eliminates the expensive multi-level patterning and alignment needed for conventional IBC cells. This technology is applicable to both implanted and heterojunction based IBC cells.

BRITTMORE GROUP, LLC

San Jose, CA | \$0.68M | Incubator 8 | 10/2013-09/2014

The Brittmore Group will develop and demonstrate an automated system for pre-assembling frameless PV modules into larger panels using construction adhesives. This system will deploy panels across large-scale PV arrays by industrial robots that traverse the mounting rack. This technique promises a significant reduction in construction duration and cost. It is also expected to accelerate market acceptance of frameless PV modules, which further reduces structural materials and electrical installation costs.

CELLINK CORPORATION

Belmont, CA | \$0.70M | Incubator 8 | 03/2014-03/2015

Cellink Corporation is creating an interconnect circuit that will be used to interconnect back-contact solar cells. The circuit is a standalone, simplified flex circuit that will be used in place of the back encapsulant in a back-contacted solar module. This product will reduce the costs of manufacturing silicon modules by 10%.

CLEAN POWER RESEARCH

Napa, CA | \$0.94M | Incubator 8 | 10/2013-03/2015

Clean Power Research is developing the next PowerClerk® platform to significantly reduce soft costs associated with interconnecting distributed solar to the utility grid. By taking the interconnection process online and automating communications, application submission and review will be streamlined, and sophisticated solar retailers will be able to apply for interconnection directly from their proposal tools. Additionally, the platform leverages information collected in PowerClerk in a solar engagement tool that utilities can use to engage their customers early in the solar sales process. This interactive online tool will allow utility customers to see how many of their neighbors have gone solar, explore personalized economics of solar, and connect with installers and financing.

DEMETER POWER GROUP

West Palm Beach, FL | \$0.50M | Incubator 8 | 10/2013-09/2014

Demeter will offer solar lease or services agreement financing collected as an assessment on the property tax bill via its web-based platform: PACE3P. By securing payments to the property, instead of the offtaker, PACE3P lowers the levelized cost of energy by 20%, makes more deals “bankable” without a corporate guarantee, and enables the first uniform, scalable financing for commercial solar.

ENERGYSAGE

Cambridge, MA | \$1.2M | Incubator 8 | 10/2013-03/2015

The EnergySage Marketplace transforms the complex solar PV shopping process into a simple, online comparison-shopping experience. The unique, innovative platform provides unprecedented levels of choice, transparency, and information at no cost to consumers. Consumers can compare quotes from multiple, pre-screened installers in a consistent matrix format across all financing options. EnergySage reduces time and effort for both consumers and installers, significantly reducing customer acquisition costs, boosting consumer confidence, and accelerating mass market solar adoption.

FOLSOM LABS

San Francisco, CA | \$0.35M | Incubator 8 | 01/2014-12/2014

Folsom Labs makes solar array design software that combines advanced performance modeling with cloud-based design tools. Under the SunShot award, Folsom Labs will extend its core HelioScope product to provide automatic evaluation of various system designs and component choices to quickly find the lowest LCOE approach for a given site.

GENABILITY

San Francisco, CA | \$1.0M | Incubator 8 | 03/2014-09/2015

Genability is implementing an independent analysis of projected and actual solar savings and a monthly savings statement that automatically tracks actual savings, compares actual with projected savings, and determines the optimum rate plan for customers. The “Verified by Genability” mark will help to lower bid preparation costs and time and increase lead to customer conversions.

GEOSTELLAR

Martinsburg, WV | \$0.75M | Incubator 8 | 10/2013-03/2015

Geostellar will streamline the procurement, financing, installation, and maintenance of solar arrays with the creation of a Solar Project Record. The Solar Record provides application developers with important data, including the estimated cost of solar energy production on a particular rooftop, utility rates, load profiles, incentives, property ownership, equipment configuration, installation, and permitting requirements for individual properties across the United States. This tool will be available to homeowners, installers, government agencies, and financing companies through Web and mobile applications.

INFINITE INVENTION, LLC

Philadelphia, PA | \$0.50M | Incubator 8 | 10/2013-03/2015

Infinite Invention is developing the Solar Socket, a device for plugging in solar PV between the electric meter and meter case. It streamlines the installation process by reducing wiring costs, scheduling requirements, and site inspection time and allows for swapping in new technologies as they emerge. In addition, a version with onboard metering and communications lets power flow directly into the utility grid.

KWH ANALYTICS

Oakland, CA | \$0.45M | Incubator 8 | 10/2013-09/2014

kWh Analytics aggregates historical data on PV system performance and financial credit. Combined with a cloud based storage system, parallel computing architecture and Bayesian statistics, kWh Analytics reduces third-party financing costs by offering highly-scalable investment risk analytics.

RENEWABLE POWER CONVERSION

San Luis Obispo, CA | \$1.0M | Incubator 8 | 10/2013-03/2015

Renewable Power Conversion will produce an environmentally sealed inverter featuring plug-and-play installation/replacement and a maintenance-free lifetime equal to that of PV modules. The Macro-Micro is a modular 17 kW inverter enabling high system granularity and redundancy. Power is efficiently converted and collected with an inverter efficiency of 98.5% and system power collection at 600 Vac. This distributed multi-string inverter provides multi-megawatt PV projects with a low LCOE alternative to large central inverters.

SILICON SOLAR SOLUTIONS

Fayetteville, AR | \$0.50M | Incubator 8 | 10/2013-09/2014

Silicon Solar Solutions, in partnership with Georgia Tech and Roth & Rau, is developing a hydrogen treatment to optimize the emitter of n-type solar cells resulting in improved conversion efficiency and reduced silver gridlines. The technology has shown 15% relative efficiency improvements while using 1/3 less silver grid lines in the lab. The goal of this project is to demonstrate the technology on commercial solar cells.

SIMPLY CIVIC

Parker, CO | \$0.40M | Incubator 8 | 10/2013–03/2015

Simply Civic is developing an online solar project application that will be available to jurisdictions nationwide. The tool will seamlessly enable jurisdictions and installers to track the status of solar projects while making it faster and simpler to complete required paperwork.

SINEWATTS

Palo Alto, CA | \$0.50M | Incubator 8 | 10/2013–09/2014

SineWatts is developing an inverter architecture that is 10X smaller, 100% siliconized and 70% lower in installed cost. The SineWatts Inverter Molecule™ is a single silicon IC based distributed inverter co-packaged with its PV panel and is of the footprint of an iPhone. SineWatts' patent pending architecture allows the molecules to utilize advanced silicon power switching technologies developed for mobile applications to be utilized for grid-supportive, highly reliable and dispatchable PV power plants.

SMASHSOLAR

El Cerrito, CA | \$0.50M | Incubator 8 | 10/2013–09/2014

SMASHsolar is developing a scalable PV mounting system that installs in half the time with half the parts and allows an array to easily expand over time. This project will develop and test an integrated mounting system that shifts field work to the factory, resulting in a simplified installation process that drives down balance of systems costs.

SOLARNEXUS, INC.

Berkeley, CA | \$0.50M | Incubator 8 | 03/2014–05/2015

SolarNexus and its partners will integrate a range of software used for customer acquisition, system design, permitting, and monitoring—resulting in the industry's first ecosystem of inter-operable software applications. The integration of key functionality from separate software vendors will significantly eliminate data re-entry and enhance the productivity of solar professionals with a simplified software experience. The ecosystem will leverage the Integrated Energy Project (IEP) Model (iepmode.net), an existing, publicly available data standard for the transfer of solar project information.

SUN NUMBER

Deephaven, MN | \$1.0M | Incubator 8 | 10/2013–03/2015

Sun Number is analyzing rooftops to determine the best roofs and the best locations of roofs for solar. This data is used to create Sun Number Scores – a tool to educate consumers about the solar potential of their homes. This data is combined with other information about the roof and the building to qualify properties and lower the cost of customer acquisition.

SUNRUN

San Francisco, CA | \$1.6M | Incubator 8 | 10/2013–03/2015

Sunrun is creating an integrated system for automatic design, costing, simulation, proposal generation, pricing, permitting, and field change management for a PV system. This end-to-end platform will optimize system performance and greatly reduce project cost and lead-to-cash process time.

Supporting Innovation Research and Technology Transfer at Small Businesses

The DOE Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) Programs aim to stimulate technological innovation, use small businesses to help meet federal R&D needs, foster and encourage participation by socially and economically disadvantaged entrepreneurs, and increase private sector commercialization of innovations derived from federal R&D. SunShot SBIR/STTR Programs provide seed capital for early stage R&D with high commercialization potential. Active projects in the SunShot SBIR/STTR portfolio span a wide range of R&D topics, including: PV device fabrication and optimization, manufacturing metrology, diagnostics, and process control, corrosion-resistant sensors for high-temperature applications, and automation systems for large-scale PV installations.

TRANSPARENT, FLEXIBLE CdTe MODULES FOR HIGH EFFICIENCY TANDEM PV

Lucintech, LLC | Toledo, OH | \$1.0M | STTR 2 | 08/2012-08/2014

Polycrystalline thin film cadmium telluride (CdTe) is a candidate material for a top cell in multijunction thin film solar cell structures, but its use is limited by the lack of high performance transparent back contacts to the CdTe. In this project Lucintech, LLC and its research partner, the University of Toledo, are adapting single-wall carbon nanotube structures for CdTe solar cell electrodes and scaling up toward the manufacturing of magnetron-sputtered CdS/CdTe devices with very thin and smooth CdTe layers ideal for applying transparent back contacts. The goal is to develop a top-cell structure for flexible tandem modules to match a low-bandgap bottom cell such as CIGS or Si, and to optimize a stand-alone, transparent top cell with less than 500 nm of CdTe for use in PV window applications.

REAL TIME PV MANUFACTURING DIAGNOSTIC SYSTEM

MicroXact, Inc. | Blacksburg, VA | \$1.0M | SBIR 2 | 08/2013-08/2015

The application of in-line diagnostics to PV cell manufacturing lines with high production capacity (>10 MW/year) has the potential to significantly increase productivity and reduce costs by improving yield. In this Phase 2 project, MicroXact, Inc. is developing and demonstrating a high-throughput, in-line PV manufacturing diagnostic system that provides data on the spatial uniformity of thickness and refractive indices of thin films as they are processed in a roll-to-roll configuration. The retrieved information will provide the opportunity to detect a wide variety of processing errors, including but not limited to thickness/composition inhomogeneity, non-uniform scribing, thin film stress, cracking, and layer separation.

UTILITY-SCALE PV COST REDUCTION BY AUTOMATED PANEL INSTALLATION SYSTEM

Brittmore Group, LLC | San Jose, CA | \$0.70M | SBIR 2 | 12/2013-12/2015

To reduce the costs of installing large-scale solar projects, Brittmore Group, LLC is developing and demonstrating a robotics-based automated installation system. The system consists of three key components: a mobile factory where individual modules are preassembled and wired into larger panels, a simplified, fixed-tilt, ground-mount support system that doubles as an above-ground transport track for panel installation, and an industrial robot that takes preassembled panels from a centralized logistics area and installs them at megawatts-per-day rates. In this SBIR Phase 2 project, Brittmore Group will fully productize their system by taking all three components from alpha-stage to full production. The anticipated public benefit of a fully productized Brittmore system is one of reduced large-scale PV installation costs and shorter time to power generation and revenue.

Project Highlight:

Apparatus for Optimizing Photovoltaic Solar Manufacturing Efficiency through Real-Time Process Feedback and Spectral Binning of Cells

Awardee	Tau Science Corporation
Location	Beaverton, OR
Award Amount	\$0.98M
Period of Performance	08/2013–08/2015
Primary Industry Area	Metrology for PV Manufacturing

Tau Science is developing in-line metrology techniques to improve the quality and performance of solar cells and reduce manufacturing costs.

How this Technology is Transformational

Solar cell manufacturers lack immediate feedback on key process steps such as junction formation and film deposition. This gap is particularly impactful when an offline sampling plan cannot be easily implemented. Furthermore, manufacturers measure cell performance inline under white light conditions, but are unable to obtain cell response as a function of wavelength without extensive offline testing. Tau Science Corporation is developing non-contact, electro-optic techniques to extract semiconductor bandgap and full spectrum photoresponse. Expected commercial applications include module scanning for failure analysis, cell spectral sorting, inline monitoring for absorber/emitter quality, and substrate contamination and surface preparation control.

Why this Innovation is Important for the United States

The U.S. maintains a key presence in test and measurement equipment for PV, and this project aids in pushing the state of the art in this area. This project helps to support the nation's long-term energy goal of building higher performance, consistently robust solar devices at a lower cost.

ADVANCED CERAMIC MATERIALS AND PACKAGING TECHNOLOGIES FOR REALIZING SENSORS FOR CONCENTRATING SOLAR POWER SYSTEMS

Sporian Microsystems, Inc. | Lafayette, CO | \$1.0M | SBIR 2 | 01/2014-01/2016

Advancements in current instrumentation technology are needed to improve and optimize the performance and reliability of existing and future CSP plants. A specific need has been identified for improved pressure, temperature, flow, and level sensors for emerging CSP heat transfer fluids and thermal energy storage fluids. Sporian Microsystems, Inc. is addressing this need by developing, testing, and demonstrating small, highly reliable, high-temperature-operable (600-1300°C), corrosion-resistant sensors. Sporian's sensor technology is based on the combination of advanced high temperature packaging, recently developed silicon carbide nitride (SiCN) based polymer derived ceramics, and advanced integrated electronics. The proposed sensors will improve the efficiency and economic viability of CSP systems, and may have a variety of additional applications for nuclear power generation, fossil fuel power generation, concentrating solar fuels, and transportation systems.

RELIABILITY IMPROVEMENT IN SOLUTION PROCESSABLE ROLL-TO-ROLL PHOTOVOLTAIC MODULES

Next Energy Technologies, Inc. | Santa Barbara, CA | \$1.0M | SBIR 2 | 05/2014-05/2016

Limitations of conventional solar technologies in their form factor, weight, flexibility, color-tunability, transparency have impeded growth in flexible PV and large, building-integrated photovoltaic (BIPV) markets. Addressing this opportunity, Next Energy Technologies, Inc. is developing soluble small molecule organic semiconducting inks that can be coated onto conventional plastic rolls in high yields using roll-to-roll technology. The goal of this project is to demonstrate that the lifetime of encapsulated organic PV devices made using organic soluble small molecules is long enough to meet the needs of the markets (20-30 years for rigid encapsulation; 3-5 years for flexible encapsulation). The development of the technology is anticipated to achieve a price point that will compete with non-renewable energy sources and help the U.S. transition to a clean energy future.

SOFTWARE TOOL FOR CODE-COMPLIANT ASSESSMENT OF WIND LOADS ON SOLAR PHOTOVOLTAIC PANELS

TIAX, LLC | Lexington, MA | \$0.22M | SBIR | 06/2013-03/2014

Presently, the proper installation of PV panels to withstand wind loads is conducted by licensed installers who use and individually interpret the relevant building codes and standards. These design calculations can be laborious requiring expertise in the applicable codes and looking up a multitude of parameters, an exercise that is subject to judgment and prone to human errors. TIAX is leveraging its expertise in structural analysis, software development, and building technologies, to develop an application that automates the calculation of wind loads and provides recommendations for the appropriate PV mounting systems. By creating a software tool, TIAX provides a way to standardize wind load calculation and minimize human errors in code-compliant installation.

DEVICE-PHYSICS-ACCURATE COST-EFFECTIVE CELL AND MODULE TEST INSTRUMENTS

Sinton Instruments | Boulder, CO | \$0.17M | SBIR | 06/2013-03/2014

Sinton Instruments is changing the way that cells and modules are tested, in order to be faster, cheaper, and better. Detailed device physics testing are being integrated into test sequences so that the cell characteristics at cell test can be related back to the incoming material, substrate doping, and carrier recombination measurements done during the cell manufacture, as well as forward to the module characterization and reliability testing. This will contribute to lowering the cost of PV by enabling an

unbroken chain of detailed process control and optimization throughout the entire cell and module manufacturing process. After module manufacture, detailed characterization will enable better reliability testing for modules by tracking fundamental semiconductor parameters within the module.

MODULAR DISTRIBUTED CSP WITH STORAGE SYSTEM USING WATER/STEAM PHASE CHANGE FOR ENERGY STORAGE AND GENERATION

Terrajoule Corporation | Redwood City, CA | \$0.22M | SBIR | 06/2013-03/2014

Core challenges for distributed CSP with storage include: the economic practicality of turbines at the sub-MW scale; the cost effectiveness of molten salt thermal electric storage; and poor turbine efficiency when engineered for variable power output. Terrajoule Corporation developed a proprietary solution to bypass these challenges, and is performing engineering designs and analyses for three closely-related system improvements that can be implemented in a demonstration of a modular distributed CSP with storage system at the 100 kW scale with 6 to 14 hours of thermal electric storage, using water/steam phase change for energy storage and generation.

NOVEL MODULE ARCHITECTURE DEVELOPMENT FOR INCREASED PV RELIABILITY AND REDUCED COSTS

Direct Solar, LLC | Fort Collins, CO | \$0.22M | STTR | 06/2013-03/2014

Module reliability has a direct impact on the levelized cost of energy (LCOE), or the cost of the energy produced by the PV system. To improve the reliability of thin film PV modules, Direct Solar, LLC is developing a new module architecture and encapsulation technology, utilizing a specialized, two-part edge seal incorporating high-strength, UV-tolerant silicone, and low-moisture, vapor-transmission polymers in conjunction with a separate desiccant material. This technology is particularly suited for addressing the durability, adhesion and moisture performance concerns of thin film PV modules.

REAL-TIME POD-CFD WIND-LOAD CALCULATOR FOR PV SYSTEMS

Central Technological Corporation | Altamonte Springs, FL | \$0.22M | SBIR | 06/2013-03/2014

Wind-loading calculations for structures do not necessarily take into account relevant characteristics, such as those from full 3D effects, end effects, turbulence generation and dissipation, as well as minor effects derived from shear forces on installation brackets and other accessories. Central Technological Corporation is developing a real-time response framework based on the Proper Orthogonal Decomposition method to calculate in real time the loads on PV modules that result from wind-induced drag and lift forces on rooftop-mounted PV systems.

Manufacturing: Innovation and Scale-Up

An integral part of EERE's Clean Energy Manufacturing Initiative, SunShot has supported manufacturing through programs that have adapted to the rapidly changing industry landscape. The Photovoltaic Manufacturing Initiative (PVMI), which started slightly before the SunShot Initiative was launched, supports consortia in university R&D with input from manufacturers, an industry supply chain consortium, and a unit-process service line. SunShot has also launched one round of a manufacturing scale-up program named SUNPATH. Another program that supports R&D and innovation in manufacturing, SolarMaT, recurs annually and funds PV and CSP supply chain improvements as well as innovation in system component manufacturing. Supply chain innovation, previously a stand-alone program, is now incorporated topically into SolarMaT. The Technology to Market subprogram supports innovation in manufacturing and aims to reverse the declining trend of U.S. market share in solar manufacturing before 2020 and enable the U.S. manufacturing industry to service the growing U.S. solar market.

Photovoltaic Manufacturing Initiative (PVMI)

The purpose of this funding is to support the development of the U.S. PV manufacturing industry. Two different approaches are taken: the first approach encourages universities to conduct industry-relevant R&D projects related to PV manufacturing. The second approach supports the industry in accelerating the development and implementation of PV manufacturing-related technologies through both collaborative and non-collaborative models, including the creation of manufacturing development centers.

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM

PVMC, Inc. | Albany, NY | \$62.5M | PVMI | 09/2011-12/2017

The U.S. Photovoltaic Manufacturing Consortium (PVMC) is coordinating an industry-driven initiative to accelerate the development, manufacturing, and commercialization of next-generation, copper indium gallium diselenide (CIGS) thin film, PV manufacturing technologies, tools, and materials. PVMC seeks to drive down the cost and risk of bringing CIGS technologies to the marketplace. In partnership with the PV industry, PVMC has developed a PV Technology Roadmap as a guide for assessing R&D needs and opportunities for innovation. In addition, PVMC will operate complementary programs to foster new PV technologies and firms and develop the U.S. PV workforce. PVMC is also working with the University of Central Florida to develop cost-effective, in-line measurement and inspection tools to enable increased c-Si PV manufacturing yield.

Project Highlight: Bay Area Photovoltaic Consortium

Awardee	Stanford University and University of California-Berkeley
Location	Palo Alto, CA
Award Amount	\$25.0M
Period of Performance	08/2011–06/2016
Primary Industry Area	PV Technology

The Bay Area PV Consortium (BAPVC) funds industry-relevant R&D to impact high-volume PV manufacturing using a competitive selection process open to all universities. This project, managed by Stanford University and the University of California–Berkeley, develops and tests innovative new materials, device structures, and fabrication processes necessary to produce cost-effective PV modules in high volumes. The research advances technologies that bring down manufacturing costs and improve device performance

characteristics to help achieve SunShot cost targets. Member companies determine the specific topics for R&D to ensure close alignment with industry and manufacturing needs and review individual project progress.

How This Activity is Transformational

Expertise and R&D tools available at universities can be critical for solving many of the difficult technical challenges of PV technology. However, it can be difficult for university researchers to directly connect their work to real world issues. Problems that need solutions are not well-articulated and opportunities that require solutions are missed.

The BAPVC forms direct connections between industry and universities by soliciting requests for proposals, its project review process, and its bi-annual meetings that link companies and leading university researchers.

Why This Innovation is Important for the United States

Universities are clearly one of the most important drivers of U.S. innovation. The BAPVC helps ensure that those assets are working on relevant problems and rapidly communicating their results to U.S. companies.

SOLAR ROCHESTER

College of NanoScale Science and Engineering, SUNY | Albany, NY | \$26.0M | PVMI | 07/2011–09/2016

CNSE is creating a fee-for-service, PV Manufacturing Development Facility (MDF) accessible to PV companies. The facility will be able to accommodate a range of services and equipment, including access to advanced tools, manufacturing expertise, secure fabrication space for users' proprietary tools, and pilot production services — all in a secure intellectual-property environment. The MDF is focusing on the commercialization of silicon PV manufacturing processes and technologies. It aims to reduce the costs and development time for participating PV industry leaders to deliver innovative, emerging technologies from the laboratory to commercial manufacturing lines. These capabilities enable start-ups, materials suppliers, and other PV innovators to eliminate a major portion of their upfront capital costs and initial operating costs during product development and pilot production.

Scaling Up Nascent PV AT Home (SUNPATH)

This program supports the initial ramp towards domestic high-volume manufacturing of globally cost-competitive PV technologies. SUNPATH helps strengthen domestic manufacturing and demonstrates that innovative PV technologies can be cost-effectively made in the U.S. Targeted SUNPATH funding is enabling three innovative, high-tech companies to accelerate cost reductions and commercialization of their solar PV technologies. At capacity, SUNPATH is expected to support approximately 600 direct American manufacturing jobs and thousands more throughout the solar industry.

PROJECT SILICON: RECLAIMING U.S. SILICON PV LEADERSHIP

1366 Technologies | Bedford, MA | \$7.0M | SUNPATH | 09/2012–09/2014

This award is assisting the industrial-scale demonstration of 1366's Direct Wafer process – an innovative, kerfless approach to forming multi-crystalline silicon wafers. Traditional silicon wafers are sawn from large silicon ingots, producing thousands of wafers per ingot. Sawing turns half of the ingot into sawdust, known as kerf-loss. Direct Wafers are made directly from molten silicon, circumventing the sawing process, which may reduce manufacturing costs by 50% compared to traditional processing. Furthermore, Direct Wafers have the same form factor as traditional wafers, allowing “drop in” compatibility with existing cell production lines. Approximately half of the current global PV shipments use multi-crystalline wafers, of which, the wafers themselves are a multi-billion dollar market. This project supports the design, build, and demonstration of 1366's industrial-scale Direct Wafer producing equipment; the layout, design and construction of a pilot-scale manufacturing facility; and commercial development activities.

LARGE-SCALE COMMERCIALIZATION OF DILUTE NITRIDE TRIPLE JUNCTION SOLAR CELLS

Solar Junction | San Jose, CA | \$4.8M | SUNPATH | 09/2012–04/2014

Solar Junction is expanding its manufacturing capacity and reducing the costs of its high-efficiency (>40%) triple junction solar cells. Solar Junction's cells are suited for high-concentration photovoltaic (HCPV) applications, where sunlight is tightly focused onto a small-area cell. Driving down the cost of manufacturing and increasing cell efficiency is important for making HCPV technology cost competitive. Under this award, Solar Junction will progress towards SunShot's cost targets by a three-pronged approach. First, Solar Junction will make technology improvements to increase cell efficiency, which increases the power output per cell area. Second, cell processing will migrate to a larger substrate size, which increases manufacturing capacity and reduces scrap. Third, an asset-light strategy for wafer fabrication will be employed, where Solar Junction outsources its high-volume wafer growth to IQE, an epitaxy toll manufacturer. By award end, Solar Junction aims for an annual capacity of 40 MW with more efficient cells that cost 20% less.

Project Highlight: Soitec Solar Industries

Awardee	Soitec Solar Industries
Location	San Diego, CA
Award Amount	\$25.0M
Period of Performance	09/2012–09/2014
Primary Industry Area	Concentrating PV modules

Soitec is an international industrial manufacturing company that develops and manufactures semiconductor materials and concentrating photovoltaic (CPV) power plant technology. SUNPATH is assisting with building a highly-automated 280 MWp factory in San Diego (a.k.a., SANFAB) for the production of its concentrating PV modules, which have efficiencies of approximately 30%, compared to the 15–20% efficiency of non-concentrating flat-plate PV modules.

How This Activity is Transformational

To drive down costs of the modules, the factory is highly automated and integrates vertically the value chain of several production steps under one roof. Equipment from electronic and printed circuit board manufacturing as well as technologies using robots and gantry systems similar to automotive manufactures are utilized. Lean manufacturing principles and a certified quality management system are deployed.

The San Diego factory will manufacture the new Soitec CX-M500, Soitec's fifth generation CPV modules that feature enhanced performance characteristics specifically designed to benefit large-scale utility power plants. The modules will be used in a 28 kWp CPV system with over 1150 square feet

of solar modules, a size that delivers high performance while significantly reducing the cost of installation and maintenance. This CPV system is designed to improve the levelized cost of electricity (LCOE) for very large solar power plants with a roadmap to SunShot's targeted LCOE.

Why This Innovation is Important for the United States

The CX-M500 modules will supply utility-scale CPV power plants throughout the U.S. Southwest and other sunny regions across the globe. The San Diego factory has already produced modules for the largest CPV power plant in the state of California (Newbery Solar 1) and has more than 300 MWp of project pipeline to fulfill. At full operational capacity, the factory is anticipated to create 450 direct jobs and more than 1,000 indirect jobs around San Diego.

Solar Manufacturing Technology (SolarMaT)

The Solar Manufacturing Technology program assists the development and demonstration of innovative manufacturing technologies in both the PV and CSP industries that will increase the U.S. share of the global solar market and create competitive advantage for domestic manufacturers. This program aims to create the next generation of solar industry-standard manufacturing technology.

IMPROVED LARGE APERTURE COLLECTOR MANUFACTURING

Abengoa Solar, LLC | Lakewood, CO | \$1.9M | SolarMaT | 09/2013–09/2015

Abengoa Solar will demonstrate new manufacturing and assembly technologies for use in CSP parabolic trough systems to achieve cost reduction and enable innovative technology to quickly enter the market. This project will focus on highly-automated manufacture of trough components, onsite assembly of the troughs at the solar field and improved quality control using automated inspection.

RAPID, COMPACT C-Si MODULE MANUFACTURING

PPG Industries, Inc. | Allison Park, PA | \$2.1M | SolarMaT | 09/2013–09/2016

PPG Industries, Inc. will partner with Flextronics International, Inc. to design and pilot a rapid PV module assembly process that replaces labor-intensive packaging steps with automation. The process uses an all-liquid encapsulation approach to completely eliminate lamination. The team will optimize encapsulation and backsheet formulations and develop the application processes required to rapidly and consistently dispense them, along with an automated system to place a 60- or 72-cell matrix into the encapsulant.

DEVELOPMENT OF MANUFACTURING TECHNOLOGY TO ACCELERATE COST REDUCTION OF LOW CONCENTRATION PV MODULES

Solaria Corporation | Fremont, CA | \$2.0M | SolarMaT | 09/2013–09/2015

Solaria will cut costs for its low-concentration silicon PV module by automating a number of manufacturing process steps including the stringing and tabbing step that is used to assemble and align the c-Si strips that are placed under a lensing glass top sheet. This removes a primary barrier to enable Solaria to undertake high-volume PV module manufacturing in the United States.

HIGHLY AUTOMATED MODULE PRODUCTION UTILIZING ADVANCED LIGHT MANAGEMENT

SolarWorld Industries America, Inc. | Hillsboro, OR | \$2.4M | SolarMaT | 09/2013–09/2015

SolarWorld will incorporate an advanced light management system into its PV modules that will achieve substantial efficiency improvements at little additional cost. The light management system reduces optical losses from tabbing ribbon and area between cells and represents a large, unrealized opportunity for module efficiency improvements. The proposed SolarWorld approach cost-effectively utilizes low-cost components implemented using highly automated robotic systems.

Project Highlight:**Road to Grid Parity through Deployment of Low-Cost 21.5% n-Type Si Solar Cells**

Awardee	Suniva, Inc.
Location	Norcross, GA
Award Amount	\$4.5M
Period of Performance	10/2014–09/2016
Primary Industry Area	PV Technology

Suniva, Inc., in partnership with the Georgia Institute of Technology, will develop a low-cost, highly-efficient silicon PV cell technology that will reach the marketplace within three years and meet the SunShot 2020 target of \leq \$0.50/W module cost. This effort will overcome cost and efficiency barriers through advances in PV science and technology innovation involving new process tools and result in pilot production of 21.5% efficient cells.

How This Activity is Transformational

The majority of present c-Si PV cells are fabricated on p-type c-Si substrates that have limited minority carrier lifetime and therefore limited efficiencies. Moving to n-type silicon allows for longer lifetimes and more efficient cells. However, the movement toward n-type substrate material has been slow as changes in process and equipment require significant development. This is an important step on the ever moving PV roadmap.

Why This Innovation is Important for the United States

While differentiating technology is often proposed and demonstrated at companies in the U.S., the subsequent difficult and time-consuming manufacturing development has taken place at offshore manufacturing sites. Suniva's cell manufacturing is in the U.S. and the company has relied on innovation to keep its performance and cost profile competitive. This innovation will allow Suniva to continue on its current advantaged trajectory.

High Impact Supply Chain R&D for PV Technologies and Systems

The purpose of this funding opportunity is to identify and accelerate the development of cross-cutting and unique products or processes that are expected to have a disruptive impact on the PV industry.

ULTRA BARRIER TOP SHEET FOR FLEXIBLE PV

3M Company | St. Paul, MN | \$4.3M | Supply Chain 2 | 04/2011-06/2014

3M's objective is to develop and commercialize a flexible, highly-transparent ultra-barrier top-sheet (UBT) that enables successful commercialization and growth of flexible solar modules manufactured from second- and third-generation PV technologies. This UBT is being manufactured with a proprietary high volume, low cost roll-to-roll process that has the potential to meet or exceed the technical requirements for these solar technologies. Successful commercialization of the UBT could have a dramatic impact on the solar industry by reducing total costs for installation in current markets such as commercial rooftop and residential building-integrated PVs.

GLASS INNOVATIONS FOR IMPROVED EFFICIENCY THIN FILM PV

PPG Industries, Inc. | Cheswick, PA | \$2.8M | Supply Chain 2 | 04/2011-12/2014

The goal of this project is to develop the materials, coating designs, and manufacturing processes necessary to commercialize a new glass article for the cadmium telluride (CdTe) module manufacturing industry. This new glass article combines an improved transparent conductive oxide plus buffer layer, a high transmission glass substrate, and a low-soiling anti-reflective coating into one product offering. The combination of these various technologies into a single product results in performance gains and improvements in module cost. The cost reductions stem from the choice of deposition technology, scaling to high volume manufacturing, and systems integration of multiple coating operations.

Project Highlight:Reduced Cost and Manufacturing Complexity of High Efficiency IBC Solar Cells using Ion Implantation and *in-situ* Patterning

Awardee	Applied Materials, Inc.
Location	Gloucester, MA
Award Amount	\$4.8M
Period of Performance	04/2011-06/2014
Primary Industry Area	PV Manufacturing Equipment

Applied Materials is developing a patterning capability for a solar ion implant tool that enables the creation of patterned doped regions on an interdigitated back contact (IBC) solar cell in a single process.

How this Technology is Transformational

The majority of present c-Si PV cells are fabricated by diffusing an emitter junction into a doped wafer, with the emitter electrical contact formed by a metal grid screen printed on the front side of the cell. One established path toward increasing cell efficiency is to place both the emitter and base contacts on the back side of the PV cell, thereby increasing absorbed light by eliminating the front contact grid. Process steps to create this back contact structure are presently more expensive per wafer than the standard cell. A high throughput ion implantation tool that can pattern while implanting can reduce cost by creating emitter and base regions in a single process step while achieving higher efficiency.

Why this Innovation is Important for the United States

Manufacturing tools are an important component of the PV manufacturing supply chain. Developing and manufacturing advanced tools helps U.S. companies stay at the forefront of technology and allows companies to define the technology roadmap.

Cost Analysis: Technology, Competitiveness, Market Uncertainty

As a basis for strategic planning, competitiveness analysis, funding metrics and targets, SunShot supports analysis teams at national laboratories to assess technology costs, location-specific competitive advantages, and policy impacts on system financing, and to perform detailed levelized cost of energy (LCOE) analyses.

Project Highlight: NREL Cost Analysis

Awardee	National Renewable Energy Laboratory
Location	Golden, Colorado
Award Amount	\$1.0M per year
Period of Performance	Ongoing
Primary Industry Area	Cost Analysis

How This Analysis is Transformational

NREL researchers and analysts collect bottom-up data on a wide range of technologies: bulk and thin film crystalline silicon, CdTe/CIGS, multijunction, concentrating PV technologies, CSP heliostats, trackers, and overall PV system costs. This work helps the SunShot Initiative stay informed on current areas of focus, bottlenecks, and the opportunities for major innovation. The data also creates a sensitivity analysis of a variety of cost contributors to better understand decision-making in manufacturing competitiveness space. Most of the commercially-available data outside this program is not sufficiently backed up by diligence of the actual cost of solar technology manufacturing nor does it thoroughly analyze sustainable business models. Thus the internal analysis, vetted through peer-reviewed publications, when appropriate, is strategically important for SunShot Initiative and the U.S. solar industry in general.

Why This Innovation is Important for the United States

As the solar market grows, the importance of reclaiming parts of the manufacturing supply chain in the United States grows every day. In order for the SunShot Initiative to support manufacturing strategically with limited funds, the program needs to stay informed to decide how taxpayer investments can best translate into businesses taking root in the United States. In-house analysis capability allows for the flexibility in obtaining the needed data and the cost breakdown, helping the SunShot Initiative serve the community in a timely manner and support U.S. industry where it needs it most. In addition, this analysis work helps identify existing U.S. strengths in talent, innovation, and access to investment in a variety of sectors to help retain and regain U.S. competitiveness.

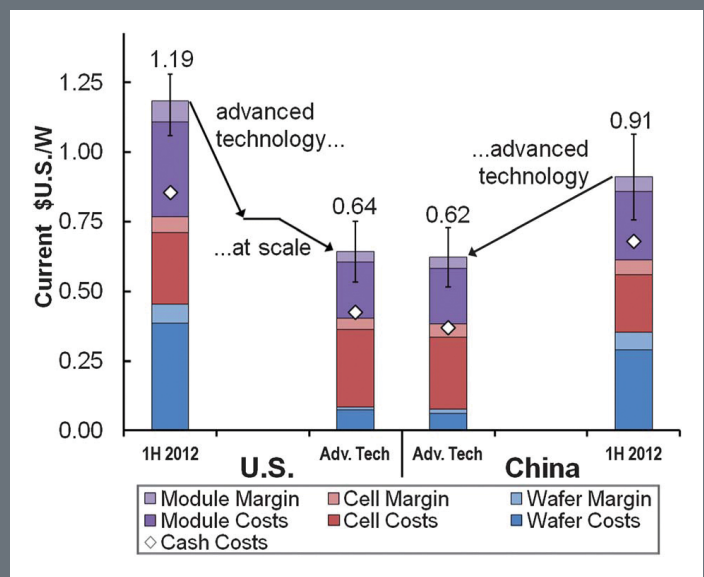


Figure 4. Cost-equalizing pathways for regional PV manufacturing.⁹

9. Goodrich et al. Assessing the Drivers of Regional Trends in Solar Photovoltaic Manufacturing. Energy and Environmental Sci. 6(10), 2811 (2013).

Soft Costs of Solar Deployment

As overall solar prices have dropped, the U.S. has enjoyed unprecedented growth in both solar installations and jobs through the development of successful business and deployment models across the country. Between 2008 and 2012, the U.S. doubled renewable energy generation from wind, solar and geothermal sources. Technology development, commercialization and manufacturing scaling have contributed significantly to rapid reductions in hardware costs since the inception of the SunShot Initiative. Now, however, addressing solar “Balance of System-Soft Costs” present the most substantial opportunities to spur strong U.S. growth in solar deployment in the coming years.

Total PV System Price, by Sector and System Size (first half of 2012)

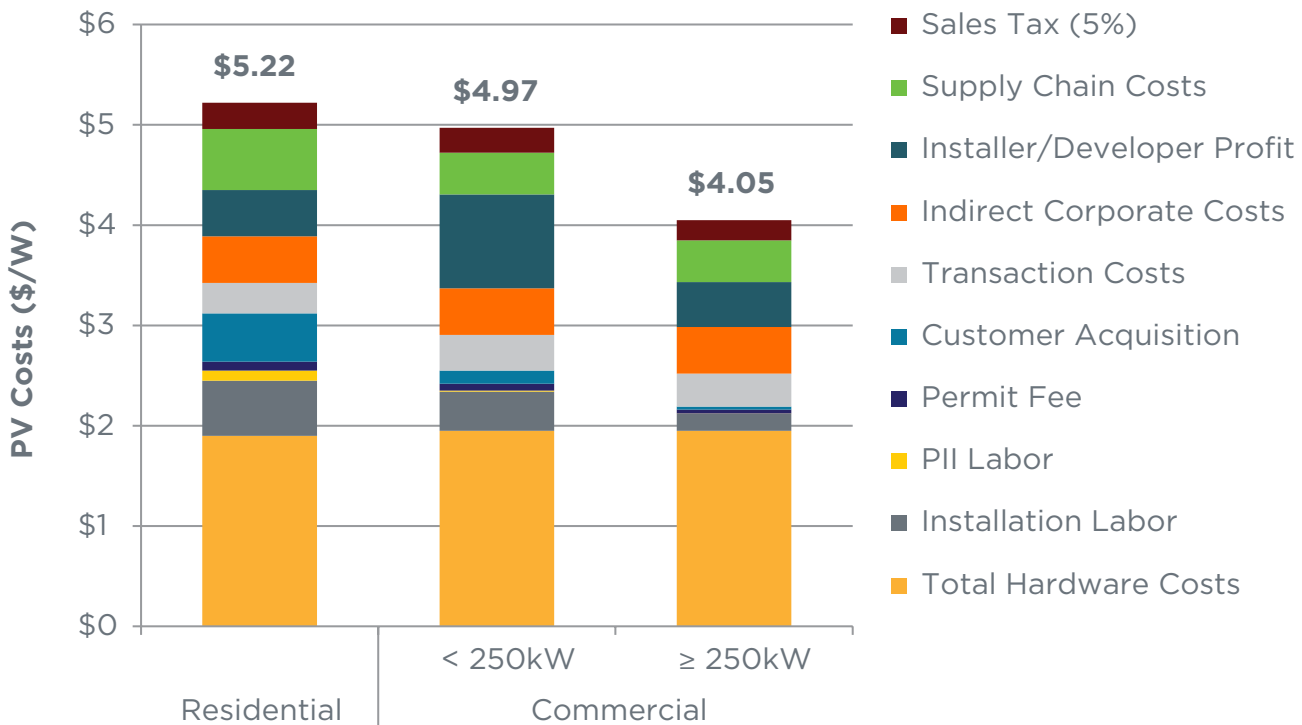


Figure 1. Total PV system price, by sector and system size (first half of 2012).¹⁰

These soft costs include financing, customer acquisition, permitting, installation, labor, inspection, and other non-hardware costs. Taken together, soft costs and barriers to solar deployment now make up over half the cost of total

system prices for residential, small and large commercial PV systems. In order to achieve the goals of the SunShot Initiative, average soft costs need to be reduced to approximately \$0.65/W for residential systems and \$0.44/W for commercial systems by 2020 (Fig. 1).

10. Friedman et al 2013 <http://www.nrel.gov/docs/fy14osti/60412.pdf>

Soft Costs of Solar Deployment

Moreover, soft costs can vary significantly as a result of a fragmented energy market system that presents a highly variable landscape for those looking to deploy solar. The same solar equipment may vary widely in its final installation price due to process and market variations across jurisdictions. This creates barriers to even more rapid industry growth. Development and adoption of standards at the local level and applying regional approaches can create a more uniform and accessible business environment. Through SunShot, DOE supports the development of innovative and scalable solutions, enabling communities and leaders to build their local economies and establish clean energy initiatives that meet their needs, while creating sustainable market conditions.

The SunShot Initiative has built a diverse portfolio of soft cost activities. We are working with a broad range of stakeholders to expand access to solar energy to every home, business and community. We are also supporting the development of an exciting new generation of powerful data, network, and IT-related tools that amplify the effectiveness of these local initiatives and help grow markets intelligently. These tools increase market transparency, improve consumer protection, and improve access to low-cost financing for a growing number of consumers. Together, these efforts will make it faster, easier and cheaper than ever before to deploy solar technology.

In order to support reductions in soft costs and promote uniform access to solar, the SunShot soft costs subprogram has focused its efforts into the following activity areas:

- Empowering state and local decision-makers through timely and actionable resources, peer networks, and technical assistance
- Harnessing big data analysis and technical solutions to support the many stakeholders involved in solar deployment

- Training an innovative solar workforce to enable the solar industry to meet growing demand
- Developing solar finance and business solutions to expand access to capital and accelerate market growth

Underlying these efforts are extensive analyses that characterize non-hardware costs and barriers. Work from the national laboratories including the National Renewable Energy Laboratory (NREL), Sandia National Laboratories, Lawrence Berkeley National Laboratory (LBNL) and Argonne National Laboratory (ANL), as well as insightful tools and analyses from project partners like the Rocky Mountain Institute and Optony, Inc., have helped shed light on these costs and the potential pathways to address them. These programs have developed datasets, standards and guides that can serve consumers across the country.

EMPOWERING STATE AND LOCAL LEADERS

SunShot works to support leaders that develop strategies and solutions to directly reduce the costs and barriers to solar access and that may slow deployment at the local level. Our programs are structured to measure the effectiveness of a variety of these local programs and strategies. Through the Rooftop Solar Challenge (RSC 1 and 2), SunShot has benchmarked hundreds of communities and empowered them to advance their solar market maturity through measures that have saved Americans nearly 800 years of “red tape” related roadblocks to date. These projects have shortened permitting and inspection times by 40% and reduced permitting fees by 12% for participants. Innovations developed through RSC 1 communities in 2013 are now being shared through training and technical assistance from SunShot’s Solar Outreach Partnership (SolarOPs) program.

In April 2014, SunShot launched a new program called Solar Market Pathways to support the development of sustainable, multi-year solar deployment plans. We anticipate that this program will enable new activity to support community efforts like shared solar, financing programs like commercial property-assessed clean energy (PACE), and the incorporation of solar into local emergency response plans. The goal of Solar Market Pathways is to help provide local business certainty, address regulatory challenges, disseminate best practices and lessons learned, and establish a clear path for the next five to ten years of solar deployment in the awarded region.

Building networks that can support the development and diffusion of proven and effective programs for solar deployment continues to be a core strategy we employ for expanding access to solar energy.

HARNESSING BIG DATA ANALYSIS AND TECHNICAL SOLUTIONS

At the most fundamental level, soft costs are the result of the time and effort people spend to accomplish tasks related to solar deployment. Automation, increased access to data and information, and software and information management tools can help reduce the time and effort needed to complete a solar installation. SunShot is supporting the creation, analysis and functionalization of data and information through a number of efforts.

By combining the power of big data with cutting-edge social science, projects funded under SunShot's Solar Energy Evolution and Diffusion Studies (SEEDS) program enable researchers to test, measure and validate local deployment program effectiveness, accelerating innovation in business and market development while advancing foundational knowledge of social science dynamics. In addition, soft costs-related Incubator awards support small businesses and startups that provide solutions to soft cost challenges for a variety

of stakeholders, including installers, finance providers, state and local jurisdictions, and the public. Through these efforts, along with a variety of solutions developed by our partners including national laboratories, non-profit organizations, and others, a wide range of tools are now available to support solar deployment.

TRAINING A STRONG SOLAR WORKFORCE

As the solar industry has grown, SunShot has focused its efforts on the creation of consistent, high-quality workforce training and skills-credentialing in the solar industry and beyond. The Solar Instructor Training Network (SITN) is a nationwide network of qualified solar instructors who train solar installers, technicians, designers, and sales professionals in every region of the U.S. through partnerships with nearly 400 community colleges. Building on this effort, SITN has also helped provide high-quality training resources to building code officials and local inspectors, helped ensure that consumers receive optimal production and safety from PV installations, and increased consumer confidence.

In addition, the Grid Engineering for Accelerated Renewable Energy Deployment (GEARED) program has created a network of four regional university training consortia that connect utilities and solar manufacturers with university power system engineering programs to train current and future engineers. These new engineers will be able to integrate renewable energy into the grid and transform the electric utility sector into a marketplace that supports innovation. Solar design and grid integration at the utility scale is getting a jumpstart through another award to the National Rural Electric Cooperative Association (NRECA). NRECA will help its coops build solar management expertise locally and create replicable models for deploying solar through its more than 900 member electric cooperatives.

Soft Costs of Solar Deployment

DEVELOPING SOLAR FINANCE AND BUSINESS SOLUTIONS

Solar installers and utility professionals aren't the only professionals who need solar skills. SunShot also supports work in finance, real estate, and community and shared solar development. Our national laboratories, universities, non-profits and talented startups have led exciting workshops, gathered stakeholders for work sessions, and built a suite of new tools to support solar growth. Our Solar Access to Public Capital (SAPC) group is working with financial institutions, project developers, and manufacturers to publicly release standardized contracts and methods for assessing risk portfolios in order to unlock new streams of capital to support solar project finance.

Finally, for those who like to both dream and "go" big – we have the SunShot Prize: \$10 million available for anyone who can pull together a team to install solar PV on at least 6,000 rooftops while meeting targeted SunShot goals.

Looking forward, the SunShot soft costs subprogram aims to expand the availability of high-quality data, information, tools and resources to support the solar industry. We continue to provide opportunities for state and local leaders to tap into networks that can help them deploy solar sustainably and economically. We are increasing support for the testing, measuring and analysis needed to ensure that communities (both local and professional) can design programs that work for them and the people they serve. We look forward to expanding access to solar energy and to helping to make it faster, cheaper and easier for all Americans to realize the many benefits of solar energy today and into the future.

Dr. Elaine Ulrich

Soft Costs Program Manager

Solar Energy Technologies Office

U.S. Department of Energy

Empowering State and Local Leaders

SunShot works to support leaders at the local level to develop strategies and solutions to directly reduce the costs and barriers to solar access and deployment. Current efforts are building networks that can support the development and diffusion of proven and effective programs and help leaders establish clear pathways for sustainable and economical solar deployment across the U.S.

Rooftop Solar Challenge 2

The SunShot Initiative's Rooftop Solar Challenge 2 (RSC2) empowers teams to address various and expensive permitting, zoning, metering, and connection processes that are currently required to install and finance residential and commercial solar systems. The RSC2 supports eight diverse teams from around the country that bring together city, county, and state officials, regulatory entities, private industry, universities, local utilities, and other regional stakeholders to reduce these soft costs, clear a path for rapid expansion of solar energy, and serve as models for other communities across the nation.

Teams will implement step-by-step actions with the goal of cutting red tape to make it faster, easier, and cheaper for Americans to go solar. Teams are streamlining permitting processes, updating planning and zoning codes, improving standards for connecting solar power to the electric grid, and increasing access to financing.

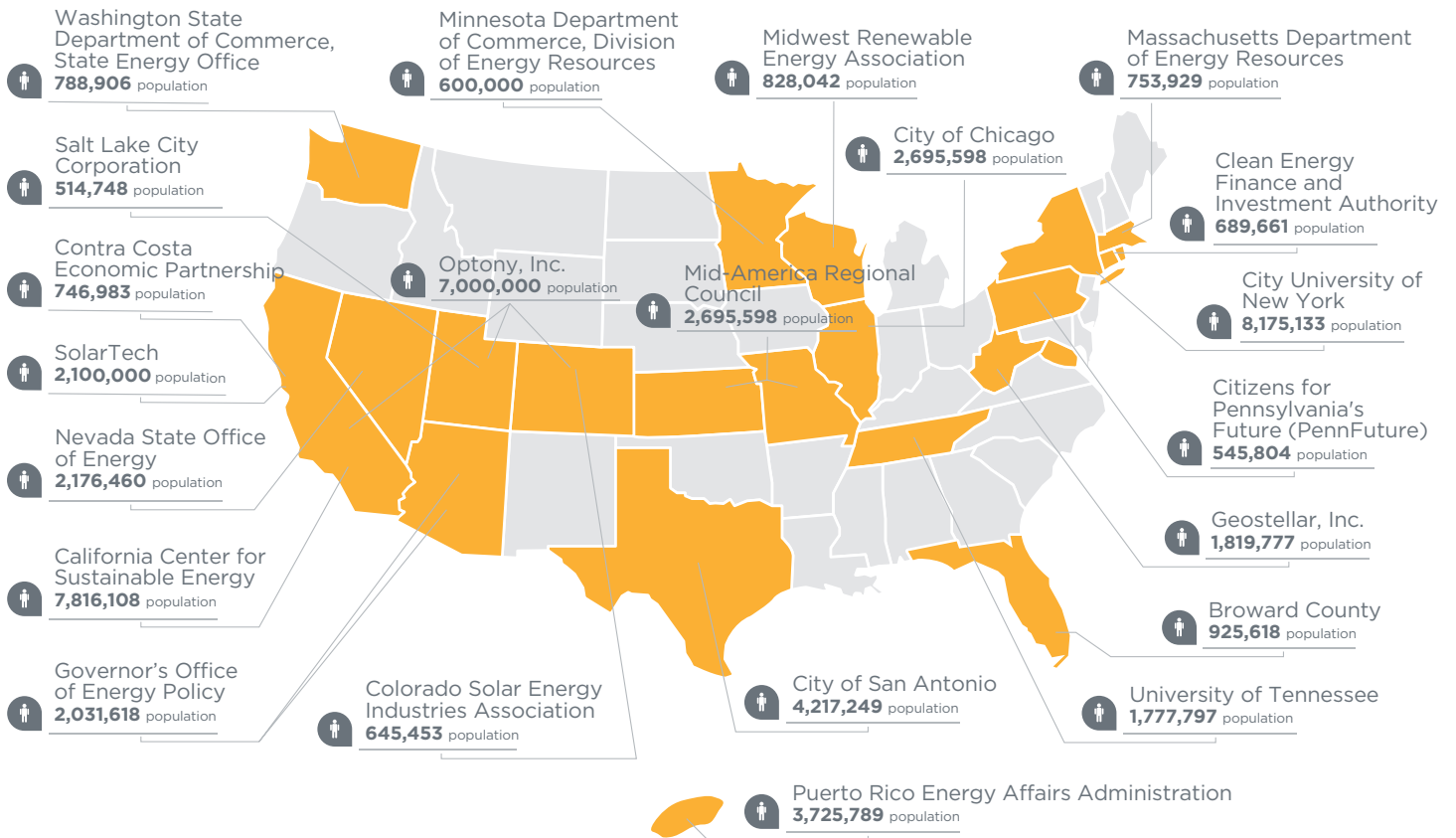
With support from SunShot, 22 teams from across the country participated in the first round of the Rooftop Solar Challenge, launched in 2011. These projects yielded innovative solutions and tools that made a significant impact across the country—making it cheaper and faster to go solar.

Some highlights of the RSC 1 projects (Fig.2)

- In Broward County, Florida, residents can now get a solar energy system permit and a preapproved set of design plans in just thirty minutes thanks to a new online permitting system. They are receiving follow-on funding to continue their work through the second round of our program.
- Utah Clean Energy and Salt Lake City partnered to create a one-stop online information portal that simplifies the process of going solar by providing online tools and resources for all stakeholders;
- In Chicago, solar permits cost 25% less and can now be obtained in a day instead of a month, while interconnection applications can now be submitted electronically to the local utility, saving time and money.

Soft Costs of Solar Deployment

Figure 2. Map of Round 1 Participants



47 Million Americans Impacted

Total award amount: **\$12.0M**

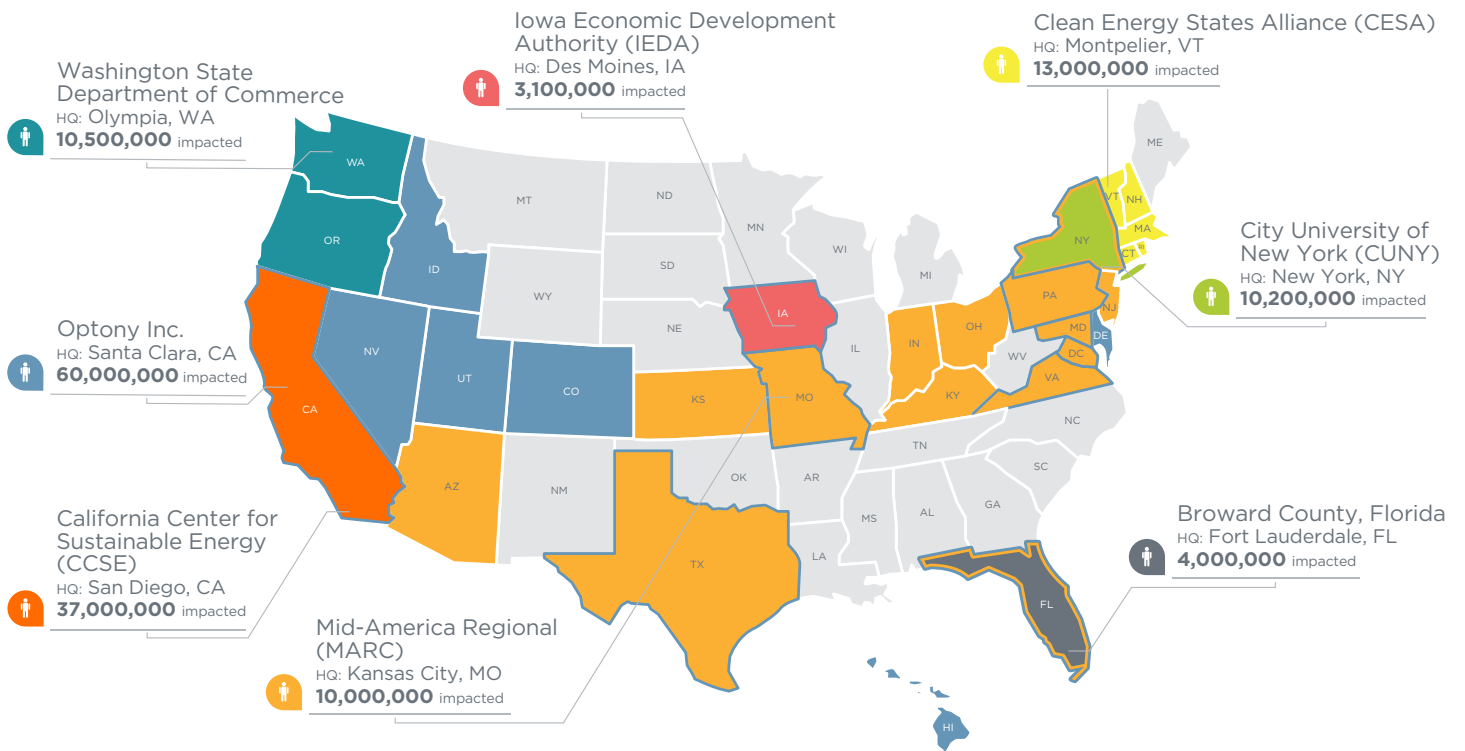
Award duration: **12 Months**

The results

- Saved Americans nearly 800 years of red tape-related roadblocks—or 10 lifetimes.
- Helped groups of neighbors go solar together by spurring group purchasing programs that drove down total system costs by up to 20%.
- Shortened permitting time by 40% and reduced permitting fees by 12%.
- Eliminated the paper chase and put the permitting and plug-in approval processes online for millions.
- Made it faster, easier, and cheaper for nearly 50 million Americans to go solar.

Building on the Challenge’s first round, the eight teams participating in the RSC2 will expand the reach of innovative strategies that are making it easier, faster and cheaper for more homeowners and businesses to finance and install solar systems. From November 2013 to May 2016, these awardees will develop and replicate creative solutions to help standardize complicated permitting and interconnection processes that often vary from jurisdiction to jurisdiction. The solutions will also facilitate easy, cheaper bulk purchasing and support user-friendly, fast online applications.

Figure 3. Map of Round 2 Participants



148 Million Americans Impacted

Total award amount: **\$12M**
Award duration: **30 Months**

Awardee	Locations	Population Impact	DOE Funding
Broward County	FL	4M	\$1.6M

Highlights: Go SOLAR–Florida will expand its market-leading online permitting solution to nine local municipalities and six additional Florida counties, and will continue to engage Florida stakeholders to expand financing options in the state as it unlocks its full potential as a leader in PV deployment.

Soft Costs of Solar Deployment

Awardee	Locations	Population Impact	DOE Funding
California Center for Sustainable Energy	CA	37M	\$1.3M
<p>Highlights: The Golden State Solar Impact Project will transform California’s solar market by making permitting and interconnection processes more uniform, rapid, and transparent across the state. The project will implement a standardized permitting process and develop tools such as a statewide interconnection and data portal to dramatically reduce soft costs in California.</p>			
City University of New York	NY	10.2M	\$1.4M
<p>Highlights: NYSolar Smart will create a toolkit of policies, programs, and resources to enable jurisdictions, utilities, industry, and end users to reduce the time and cost of installing solar PV. These include Web-accessible permitting, virtual net-metering guidelines for master-metered buildings, group purchasing programs, and updated model zoning ordinances. NYSolar Smart’s IT tools will include a customizable customer acquisition portal, solar maps, market analytics, and a one-stop PV market portal.</p>			
Clean Energy States Alliance	NH, MA, CT, RI, and VT	1.3M	\$1.5M
<p>Highlights: The New England Solar Cost-Reduction Partnership will build a thriving regional solar market by: increasing coordination across Connecticut, Massachusetts, New Hampshire, Rhode Island, and Vermont; refining and deploying innovations developed in Connecticut and Massachusetts during Rooftop Solar Challenge 1; and more widely implementing best practices across the region, including online permitting and group purchasing programs.</p>			
Iowa Economic Development Authority	IA	3.1M	\$1.0M
<p>Highlights: The Iowa Statewide Solar Readiness Initiative is a collaborative effort to promote solar energy adoption in Iowa. The Iowa Economic Development Authority and its partners will work with communities, utilities, and other solar stakeholders to develop educational materials, identify policy barriers and potential solutions, create an online solar toolbox, perform individual market barrier assessments for pilot communities, and create customized community action plans.</p>			

Soft Costs of Solar Deployment

Awardee	Locations	Population Impact	DOE Funding
Mid-America Regional Council	KS, MO, AZ, NY, PA, NJ, FL, TX, OH, KY, IN, MD, VA and DC	10M	\$2.6M
<p>Highlights: MARC and the National Association of Regional Councils will use established and trusted relationships among regional planning councils and local governments to spread solar-friendly best practices to nine diverse regions across the country, building upon successful efforts in the Kansas City region to create a strong solar market.</p>			
Optony, Inc.	CA, NV, UT, ID, CO, HI, TX, FL, IA, MO, DC, VA, MD, DE, PA, and NY	60M	\$2.6M
<p>Highlights: The American Solar Transformation Initiative will use an innovative online Solar Roadmap platform and hands-on engagement to assist over 400 jurisdictions where solar potential is abundant, but resources and information are scarce. The project will improve permitting processes, establish solar friendly planning and zoning guidelines, streamline the interconnection process, expand financing options, and ultimately develop strong solar markets across the country.</p>			
Washington State Department of Commerce	WA, OR	10.5M	\$1.7M
<p>Highlights: The Pacific Northwest Solar Partnership aims to double PV capacity in Washington and Oregon by creating a more uniform and vibrant regional solar market. The collaborative project will establish “solar ready” corridors and simple online permitting and common interconnection processes for 80% of residents. The effort will also continue to expand innovative, locally developed financing solutions such as community solar and Solarize group purchasing programs to provide access to financing options in every utility territory in the two-state region.</p>			

Soft Costs of Solar Deployment

SOLAR OUTREACH PARTNERSHIP

International City/County Management Association | Washington, DC | \$4.9M | SolarOPs | 08/2010-07/2015
ICLEI-Local Governments for Sustainability | Oakland, CA | \$5.1M | SolarOPs | 08/2010-07/2015

The SunShot Solar Outreach Partnership (SolarOPs) Program is empowering local governments to go solar. Comprised of experts in solar soft cost reduction strategies, the team collects, creates and delivers best practices to accelerate solar energy adoption by providing timely and actionable information to local governments across the country. Through regional workshops and e-learning activities, the SolarOPs team has reached more than 4,000 individuals in all 50 states, representing more than 1,500 local government entities.

One of the key features of SolarOPs is the delivery of targeted one-on-one technical assistance to local governments looking to make their community solar-ready. Technical assistance is being delivered to local governments in North Carolina, California, Delaware, and New Jersey, among others.

The SolarOPs team is developing factsheets, case studies, and technical reports based on cutting-edge research related to solar and economic development, solar and resiliency planning, innovative solar financing, solar jobs analysis, community solar and solar and firefighter safety. In addition, the SolarOPs team coordinates communications among the Rooftop Solar Challenge 2 teams whose work covers 28 states and the District of Columbia, representing nearly 150 million people. For more information visit solaroutreach.org.

PUBLIC AND PRIVATE SECTOR TECHNICAL ASSISTANCE

National Renewable Energy Laboratory | Golden, CO | \$3.0M | National Laboratory R&D | 10/2012-09/2015

This agreement helps provide broad introductory information to policymakers and implementers, as well as deep, specific policy development and impact information to directly facilitate market development and technology deployment within jurisdictions. This agreement provides the foundational, unbiased, and in-depth research from which technical assistance responses are tailored to produce decision support information for policymakers and implementers. The technical assistance performed by NREL (and the Lawrence Berkeley National Laboratory as a subawardee) is coordinated with other SunShot technical assistance efforts such as SolarOPs to ensure broad access to experts and critical information upon request to state and local decision-makers across the country who are addressing opportunities and challenges associated with an expanding solar market and increased deployment.

REGULATORY AND PERMITTING INFORMATION DESKTOP (RAPID) ROADMAP

National Renewable Energy Laboratory | Golden, CO | \$0.50M | National Laboratory R&D | 12/2013-09/2014

This agreement at NREL is helping to optimize and streamline the regulatory process for utility-scale solar projects. Through the process of developing roadmap content, the project brings together both state and federal agencies, engaging them in reviewing and coordinating the permitting process for large solar PV developments and helping them reduce developers' costs and time for solar deployment. The Solar Regulatory Roadmap will build off of the existing Geothermal Regulatory Roadmap for 10 western states, which was developed by NREL in support of EERE's Geothermal Technologies Office, and has received overwhelming positive response from industry and agencies.

Policy Stacking and Foundational Analysis

Achieving the cost reduction and deployment goals of the SunShot Initiative will require effective policy and informed policymakers at all levels of government. This project seeks to inform critical solar-relevant policy decisions at the state, local, and federal levels through strong analytic research that identifies and develops critical policy ordering for effective market development, tracks and evaluates policies and market mechanisms that impact solar costs and deployment, and identifies and evaluates the critical elements within solar policies and market mechanisms that influence their effectiveness.

Lawrence Berkeley National Laboratory | Berkeley, CA | \$1.2M | National Laboratory R&D | 10/2012–09/2015

LBNL researchers, in collaboration with the National Renewable Energy Laboratory, will analyze policy developments, compliance costs, and impacts as they relate to solar energy within state renewable portfolio standards, third party tax equity, third party ownership, and federal tax policies. In addition, this project will conduct analysis of key issues at the intersection of solar deployment, utility regulation, and retail rate design, to address the market drivers associated with customer electricity bill savings.

National Renewable Energy Laboratory | Golden, CO | \$4.7M | National Laboratory R&D | 10/2012–09/2015

NREL researchers, in collaboration with Lawrence Berkeley National Laboratory, will coordinate a Policy Activities Advisory Team to provide insights, feedback, and refinement to the research, and assist in communicating and disseminating research findings. NREL will also develop a variety of effective policy strategies, or “stacks,” in different jurisdictional governance and economic contexts and within different technology pricing scenarios and conduct analyses to identify and understand the impact and effectiveness of implementing policies that interact within the same markets. With respect to the regulatory environment, NREL will analyze the impact of utility rates on grid parity, explore options and considerations for equitably addressing utility system costs of solar, and address interactions between rate design, customer adoption, and the associated impact on utilities. NREL will also identify solar issues in utility supply procurement processes, explore a range of solutions that state and local policymakers could support, and create fair evaluation processes. Finally, NREL will conduct market-responsive analysis on topics such as: voluntary markets that provide technology access; utility community solar programs; providing regulators information needed to identify pathways forward for dealing with increasing levels of distributed solar that are appropriate for their state’s context; net metering policies and caps; and possible approaches to address the expected expiration of maintenance of the California Solar PV Database.

Harnessing Big Data Analysis and Technical Solutions

SunShot is supporting the creation, analysis and functionalization of data and information in order to reduce the time and effort needed to deploy solar. These programs have accelerated the development of a wide range of tools and solutions addressing soft cost challenges that face a variety of stakeholders, including installers, finance providers, state and local jurisdictions, and the public.

Understanding the Evolution and Diffusion of Solar Technologies

Through the Solar Energy Evolution and Diffusion Studies (SEEDS) program, seven research teams are harnessing real-world data to solve solar industry challenges. By charting market evolution and technology innovation, the projects are advancing and applying new branches of science to spur solar cost reduction. Big data, network science, behavioral economics, and social physics have emerged as powerful tools in the SunShot toolbox. For example, mapping out the dynamics of social learning within a community is revolutionizing the basic understanding of innovation diffusion and is also dramatically reducing the soft costs for customer acquisition. Also, decoding the structure and pace of past technological breakthroughs is aiding today's scientists and engineers in their pursuits to make solar hardware more efficient and less costly. Over the next three years, the SEEDS program is poised to make scientific leaps that transform cast-off data into practical strategies underlying the design and implementation of energy policies.

UNDERSTANDING THE EVOLUTION OF CUSTOMER MOTIVATIONS AND ADOPTION BARRIERS IN RESIDENTIAL PHOTOVOLTAIC MARKETS

National Renewable Energy Laboratory | Golden, CO | \$2.3M | SEEDS | 04/2013-06/2016

Decisions of whether to adopt rooftop solar are driven by many factors, including system price, access to information, and the experiences of peers within social networks. Analytical models for projecting market growth typically only account for the price variable, and not other important decision parameters. An agent-based model can elucidate the ways that PV markets will evolve by simulating the complex and interrelated decision dynamics of individuals in a social system. This project, led by NREL and in collaboration with researchers from Portland State University, the University of Arizona and other institutions, is collecting a rich dataset that is being used to train regionally-specific, agent-based models to simulate decision-making under different test scenarios, and to run real-world pilot tests that validate results with market partner Clean Power Finance.

DESIGN OF SOCIAL AND ECONOMIC INCENTIVES AND INFORMATION CAMPAIGNS TO PROMOTE SOLAR TECHNOLOGY DIFFUSION THROUGH DATA-DRIVEN BEHAVIOR MODELING

Sandia National Laboratories | Albuquerque, NM | \$2.3M | SEEDS | 04/2013-03/2016

The project team, including researchers from Sandia National Laboratories, the University of Pennsylvania Wharton School, the California Center for Sustainable Energy, Vanderbilt University, and NREL, is developing an approach for designing social and economic incentives to enhance solar diffusion. The team is integrating individual-level data about solar adoption patterns with

data generated from Lab and field experiments and surveys to construct an individual-level computational model to predict solar adoption. They are using the model to drive agent behavior in an agent-based simulation, with agents' interactions captured using social influence variables. The team will use the model to forecast adoption patterns in response to alternative policy interventions, and use computational optimization techniques to arrive at candidate policies.

TOWARDS AN EMERGENT MODEL OF TECHNOLOGY ADOPTION FOR ACCELERATING THE DIFFUSION OF RESIDENTIAL SOLAR PV

University of Texas | Austin, TX | \$0.50M | SEEDS | 04/2013-03/2016

The goal of energy market transformation is to identify and target existing market barriers. Comprehensive analysis is needed to quantify peer influences, information dissemination, and other factors that, in addition to technical and financial factors, are barriers to major adoption. For this project, university researchers are acting as visiting scholars, or scholars in residence, hosted by six Texas electric utilities. Researchers have access to rich datasets that are enabling them to analyze real-world market barriers. The results will inform a pilot project that the researchers will run with partner utilities.

THE INFLUENCE OF NOVEL BEHAVIORAL STRATEGIES IN PROMOTING THE DIFFUSION OF SOLAR ENERGY

Yale University | New Haven, CT | \$1.9M | SEEDS | 04/2013-03/2016

Communities across the U.S. are instituting Solarize programs in which homeowners band together to collectively purchase rooftop solar systems. This project is quantifying the effectiveness, cost-effectiveness, and scalability of this and other strategies that leverage social interactions to accelerate diffusion of solar technologies. Researchers from Yale University and New York University are designing and running a series of randomized field trials to study the new Solarize Connecticut program. The field tests are being implemented with partner SmartPower.

EVALUATING THE CAUSES OF PHOTOVOLTAICS COST REDUCTION: WHY IS PV DIFFERENT?

Massachusetts Institute of Technology | Cambridge, MA | \$0.49M | SEEDS | 04/2013-03/2016

For half of a century, PVs have experienced a 20% cost reduction every time cumulative production doubles. This rate of technological improvement is unmatched by other competing energy technologies. Yet, there exists no practical explanation for this empirically observed trend. This project is investigating a wide range of hypotheses for describing the technology evolution process to form an overarching theory that can be applied to accelerate cost reductions in solar.

HELIOS: UNDERSTANDING SOLAR EVOLUTION THROUGH TEXT ANALYTICS

SRI International | Arlington, VA | \$0.60M | SEEDS | 04/2013-06/2015

Machine learning is a powerful computational tool that underlies an array of complex tasks from weather prediction to email spam filtering. By reading and organizing a massive amount of data from disparate sources, the tool can uncover and exploit buried patterns in the data. For this project, SRI is developing the Helios platform to detect unseen technological breakthroughs and bottlenecks for solar technologies by analyzing decades' worth of scientific publications and patents.

Soft Costs of Solar Deployment

FORECASTING AND INFLUENCING TECHNOLOGICAL PROGRESS IN SOLAR ENERGY

University of North Carolina | Charlotte, NC | \$0.95M | SEEDS | 04/2013-03/2016

Researchers from University of North Carolina-Charlotte, Arizona State University, and University of Oxford aim to make better forecasts of future cost reductions for new energy technologies. By abstracting the process of technological progress as a time-varying network of interconnected components, the team is employing a new theory to help inform optimal investment strategies in the R&D pipeline. This will help the industry more quickly and cost-effectively achieve technical and deployment goals. By analyzing hundreds of years' worth of patent data and historical cost and production data, the team is constructing a network—called a “technology ecosystem”—to forecast and influence technological progress

NATIONAL UTILITY RATE DATABASE

Illinois State University | \$0.85M | Soft BOS | 09/2011-08/2014

The National Utility Rate Database was created by the National Renewable Energy Laboratory in 2010 as a free, web-based tool in which the energy analysis community could contribute, edit, and download utility rate data. Illinois State University was selected to populate, maintain, and improve the database.

PVMAPPER UTILITY SCALE SITING TOOL

Boise State University | \$2.8M | Soft BOS | 09/2011-08/2014

This project created an open source, project planning tool based on geographic information systems that optimizes siting for utility-scale solar developments. The tool enables users to assess sites based on quantifiable physical characteristics and constraints of the natural resource as well as military, land use, solar resource, water resource, and public acceptance factors.

NATIONAL SOLAR PERMITTING DATABASE

Clean Power Finance | \$3.0M | Soft BOS | 09/2011-08/2014

This database is designed to help streamline and reduce the time and costs attributed to the solar permitting process. The community-based online tool compiles the most complete and accurate permitting requirements from solar professionals and local authorities in one single online location.

REGULATORY AND UTILITY SOLUTIONS TO ADVANCE SUNSHOT INITIATIVE GOALS

Interstate Renewable Energy Council | \$3.0M | Soft BOS | 09/2011-08/2014

IREC and its sub-partners, Keyes, Fox & Wiedman, and others, will work to dramatically expand market opportunities for solar PV by pursuing fair and transparent solar pricing and interconnection policies (for all parties – utilities, solar developers and consumers) in the 20 states with the highest potential for significant solar PV market growth. IREC will work to analyze and suggest collaborative remedies (for debate by all stakeholders) to the technical and administrative barriers still impacting cost-effective interconnection and transmission in the 10 states poised to achieve the highest penetrations of solar PV. This award will support IREC in encouraging technical and policy studies that drive solutions to the incorporation of high-penetration solar PV scenarios into utility planning and operations management activities in the five states with the highest solar PV penetrations. IREC will also provide technical assistance to communities and states that wish to explore community and shared solar models.

INNOVATIVE SOLAR BUSINESS MODELING

Rocky Mountain Institute | \$0.68M | Soft BOS | 09/2011–08/2014

RMI is developing and pilot testing a new utility business modeling tool: EDGE—the Electricity Distribution Evaluator. EDGE is a MATLAB-based simulation tool designed to comprehensively assess the distributed energy resource value proposition in different regulatory and utility business model environments based on a detailed assessment of the technical and operational implications. With its SunShot funding, RMI has accelerated the creation and adoption of innovative approaches to utility regulation, rate design, and business models to enable high-penetration deployment of distributed solar PV. New approaches are necessary to avoid conflicts between the interests of solar customers, utility ratepayers, utilities, and other stakeholders as penetration of solar PV increases. RMI will convene leading experts, policymakers, and industry thought leaders to identify best practice solutions to potential barriers, taking into consideration new technologies and value-creation opportunities in grid integration. RMI will disseminate information about best practice solutions to regulators, utilities, and other stakeholders nationwide. Intensive engagements with regulators and utilities in targeted states will accelerate innovation, implementation, and learning in areas with high penetration of solar PV.

HAWAII'S CLEAN ENERGY TRANSFORMATION AND GRID CONNECTION

Hawaii Dept. of Business, Economic Development & Tourism | \$0.70M | Soft BOS | 09/2011–08/2014

The Hawaii State Energy Office, housed within the HDBEDT, will use SunShot funds initially to support a technical review committee (TRC) to provide technical assistance and advice to the Public Utility Commission on grid interconnection-related tasks, advised by the Reliability Standards Working Group. TRC staff will evaluate and further refine the findings of the reliability standards studies developed by Hawaiian utilities, and then establish technical reliability standards. To the extent that the existence of reliability and/or curtailment challenges of integrating more variable renewables—including feed-in tariff resources—on any of the islands served by the Hawaiian Electric Companies are validated, this award will support the HDBEDT in performing and managing state utility commission studies by qualified technical entities to identify near-term, mid-term and long-term solutions for each island, and work to implement those solutions as quickly as possible. The award will also support updates to Hawaii's state clean energy permitting tools.

LONG-TERM MONITORING OF UTILITY-SCALE SOLAR ENERGY DEVELOPMENT AND APPLICATION OF REMOTE SENSING TECHNOLOGIES

Argonne National Laboratory | Chicago, IL | \$0.38M | National Laboratory R&D | 11/2013–09/2014

To date, a comprehensive approach to long-term monitoring for utility-scale solar development in the desert southwest has not been established. Under this agreement, Argonne National Lab's researchers are developing appropriate, cost-effective approaches for long-term monitoring of potential environmental impacts, including the evaluation of **1)** actual direct, indirect, and cumulative impacts compared to predicted environmental impacts; **2)** the effectiveness and/or appropriateness of measures taken to avoid or minimize impacts at the project site; and **3)** the effectiveness of regional, compensatory mitigation investments. As part of this effort, Argonne is partnering closely with the U.S. Bureau of Land Management, which is actively engaged in developing such programs for solar development in designated solar energy zones on public lands. Ultimately, this agreement helps lay the foundation for rapid and streamlined installation of large-scale solar on public lands, lowering the costs and helping to double renewable energy generation again by 2020.

Soft Costs of Solar Deployment

WATER USE BY PV SUPPLY CHAIN

National Renewable Energy Laboratory | Golden, CO | \$0.35M | National Laboratory R&D | 10/2013-09/2014

NREL will build off the foundational work conducted in the *Sunshot Vision* Study to provide a more comprehensive assessment of the water use benefits and tradeoffs associated with high penetration of solar power technologies. NREL proposes to fill gaps in the analysis of use and trade-offs (economic and environmental) concerning PV water use relative to water use by other energy technologies. The results of this project will provide deliverables supporting the DOE SunShot Program as well as the United States' leadership of and contribution to the International Energy Agency (IEA) Implementing Agreement on Photovoltaic Power Systems Task 12 on Environmental Health and Safety.

REDUCING PROJECT RISK THROUGH ANALYSIS OF SOLAR PV RELIABILITY DATA

Sandia National Laboratories | Albuquerque, NM | \$1.3M | National Laboratory R&D | 10/2012-09/2015

This research builds a database of operational PV production in existing installations, eventually targeting 100 MW of long-term operating data. Through analysis of production and system maintenance, Sandia's research will help delineate the actual maintenance costs and optimal maintenance schedules for various sizes and configurations of PV equipment, helping to reduce uncertainty and risk in financing and insuring PV installations. The work refines the PV Reliability, Operations & Maintenance (PVROM) database and calculator, an open platform tool to track reliability.

SOLAR LOADS AND ROOFING STRUCTURES: WHEN IS ADDITIONAL ENGINEERING NEEDED?

Sandia National Laboratories | Albuquerque, NM | \$1.4M | National Laboratory R&D | 10/2012-09/2015

In many jurisdictions, building inspectors require a stamped engineer's review of blue prints to assure that solar rooftop installations will not require structural upgrades to comply with building codes. This can add hundreds, if not thousands of dollars to an individual installation's cost. Through this agreement, Sandia tested the most common residential roof structures in U.S. domestic housing to determine actual load bearing capacity based on applicable national structural regulations (i.e., ASCE 7-10) and developed mitigation designs as necessary to bring inadequate structures up to code. Sandia is now disseminating this information and educating solar professionals on structural aspects of rooftop installations through workshops, conferences, and publications in peer reviewed and trade journals. In early 2015, Sandia will issue a final nationally-applicable Solar Structural Guide.

SOLAR GLARE HAZARD ANALYSIS AND SITING TOOL

Sandia National Laboratories | Albuquerque, NM | \$1.1M | National Laboratory R&D | 10/2012-09/2015

With growing numbers of solar energy systems being proposed and installed throughout the United States, the potential impact of glint and glare from PV modules, concentrating solar collectors, receivers, and other components is receiving increased attention as a potential hazard or distraction for pilots, air-traffic control personnel, motorists, and residents. (Glint is defined as a momentary flash of light, while glare is defined as a more continuous source of excessive brightness relative to the ambient lighting.) Through this agreement, Sandia has developed a free, internet accessible tool (SGHAT) that allows participants to input simple installation assumptions and orientation, and receive within minutes a detailed analysis of potential glint and glare by time of day and seasonally across the year for that installation.

Training a Strong Solar Workforce

SunShot supports the creation of consistent, high-quality workforce training and skills credentialing in the solar industry and beyond. These programs ensure that consumers receive optimal production and safety from PV installations, and increase consumer confidence. In addition, SunShot also supports partners that are training current and future engineers to not only integrate renewable energy into the grid, but to transform the electric utility sector into a marketplace that supports innovation.

Integrated Skills for a Growing Clean Energy Workforce

SunShot created the Solar Instructor Training Network (SITN) to help establish a well-trained and highly-qualified solar energy workforce of sufficient size and diversity to meet the estimated needs of the United States for PV installation, based off of projections by the National Renewable Energy Laboratory and the Solar Foundation that the U.S. will require up to 250,000 workers by 2030. Through SITN, the number of qualified instructors in the U.S. for PV installation and skills training has grown from less than 60 in 2006 to nearly 1,000 today. These qualified, credentialed instructors are based in approximately 400 accredited community colleges, technical high schools and labor training centers. SITN is coordinated by a national administrator, which manages nine Regional Training Providers (RTPs) who partner with local institutions in each state the RTP serves. Through SITN, SunShot has supported the development of the Solar Career Map, best practice training manuals, open source curricula, specialty support for veterans and commercial installers, solar rooftop inspection training for municipal building inspectors, and more.

NATIONAL ADMINISTRATOR OF THE SITN

Interstate Renewable Energy Council | Latham, NY | \$4.9M | SITN | 10/2010-12/2015

IREC serves as the national point of contact for the network, conducting outreach to disseminate its products and best practices. IREC has led the development of a robust national infrastructure that can meet the employment needs of a rapidly growing domestic solar industry. The group manages the network's collaboration, coordinates joint activities, and works with a broad set of stakeholders to prioritize and address issues related to solar workforce training. IREC assesses instructional quality by credentialing programs and led the formation of the North America Board of Certified Energy Practitioners.

NORTHEAST SOLAR PHOTOVOLTAIC INSTRUCTOR TRAINING PROVIDER

Hudson Valley Community College | Malta, NY | \$0.96M | SITN | 01/2010-12/2014

States served: Maine, Vermont, New Hampshire, New York, Massachusetts, Rhode Island, Connecticut

Hudson Valley has worked with 25 partner institutions in the Northeast to establish a network of Institute of Sustainable Power Certified instructors across the seven northeastern states and develop a solar PV training facility (the Training and Education Center for Semiconductor Manufacturing and Alternative and Renewable Technologies, or TEC-SMART) that will support future instructor training in the region.

Soft Costs of Solar Deployment

NORTHEAST SOLAR INSTRUCTOR TRAINING PROVIDER-NORTH

Kennebec Valley Community College | Fairfield, ME | \$1.0M | SITN | 01/2010-06/2015

States Served: Maine, Vermont, New Hampshire, New York, Massachusetts, Rhode Island, Connecticut

Kennebec Valley Community College serves the same northeastern states as Hudson Valley, with a specialty in commercial PV installation training. SunShot previously supported KVCC as the National Solar Thermal Training Provider, and KVCC retains solar thermal training equipment and instruction expertise. KVCC partners with additional community colleges and International Brotherhood of Electrical Workers (IBEW) labor training centers in the Northeast.

NORTHERN MID-ATLANTIC STATES SOLAR INSTRUCTOR TRAINING PROVIDER

Pennsylvania State University | University Park, PA | \$1.1M | SITN | 01/2010-12/2014

States Served: Pennsylvania, New Jersey, West Virginia, Delaware

By engaging a broad spectrum of stakeholders, including roofing industry and organized labor partners, the Pennsylvania State University's Northern Mid-Atlantic Solar Regional Training Center will support a comprehensive training infrastructure for sales, design, installation, commissioning, and service of both solar PV and solar heating and cooling technologies.

SOUTHERN MID-ATLANTIC PROVIDER OF SOLAR INSTRUCTOR TRAINING

North Carolina State University/ NC Solar Center | Raleigh, NC | \$1.0M | SITN | 01/2010-12/ 2014

States Served: North Carolina, South Carolina, Maryland, District of Columbia, Virginia

SMAPSIT provides classroom and mobile training instruction in PV installation and technical sales, and training for building code officials throughout the five states it serves. By collaborating with a local energy industry leader, North Carolina State University will also provide additional professional development opportunities to the local workforce such as providing apprenticeships with companies.

SOUTHEASTERN SOLAR TRAINING NETWORK

Florida Solar Energy Center-University of Central Florida | Cocoa, FL | \$1.0M | SITN | 01/2010-12/2014

States/Territories Served: Florida, Georgia, Alabama, Mississippi, Tennessee, Kentucky, Arkansas, Puerto Rico and the U.S. Virgin Islands

SSTN has developed industry-recognized energy training centers throughout the southern U.S, building courses in Master of Science, Technical Sales and other related PV and electrical coursework. SSTN's programs will create a trained pipeline of workers to meet current and future employment demands needed by the solar industry.

MIDWEST PROVIDER OF SOLAR INSTRUCTOR TRAINING

Midwest Renewable Energy Association | Custer, WI | \$1.0M | SITN | 01/2010-12/2014

States Served: Wisconsin, Minnesota, Iowa, Illinois, Indiana, Ohio, Michigan

With leader campuses in each state served, annual conferences and robust web-based curricula sharing tools, the Midwest Provider of Solar Instructor Training has energized the heartland with instructor development opportunities and trainings for

local building inspectors. The program has used team learning methods and collaborative technologies to create instructional resources. It maintains a mobile training unit and offers a broad array of professional solar development courses.

SOUTH CENTRAL SOLAR INSTRUCTOR TRAINING PROVIDER

Energy Institute at Houston Community College | Houston, TX | \$0.75M | SITN | 01/2010-12/2014

States Served: Texas, New Mexico, Arizona, Louisiana, Missouri, Oklahoma

This partnership will establish a network of educational, industry, and state partners to ensure the availability and effectiveness of solar installation training throughout the region. This project will also provide professional development opportunities for educators at institutions that wish to start or improve training and education programs in solar installation.

ROCKY MOUNTAIN SOLAR TRAINING PARTNERSHIP

Salt Lake Community College, Solar Energy International, and the Utah Solar Energy Association | Salt Lake City, UT | \$1.3M | SITN | 01/2010-06/2015

States Served: Utah, Colorado, Wyoming, Nevada, Arizona, Alaska, Washington, Oregon, Montana, Idaho, North Dakota, South Dakota, Kansas, Nebraska

Rocky Mountain covers the vast Western Plains, providing PV training equipment and instruction to PV trainers at community, tribal and technical colleges. RMSTP also trains county and city building code officials in solar inspection techniques. Participating institutions from states within the region will be selected through a competitive process. RMSTP provides train-the-trainer courses via mobile training vehicles, the Internet and hands-on workshops, based on Solar Energy International's nationally recognized solar PV curricula.

CALIFORNIA-HAWAII SOLAR INSTRUCTOR TRAINING PARTNERSHIP

California Community College Chancellors Office and the University of Hawaii System | San Francisco, CA | \$1.0M | SITN | 01/2010-12/2014

States Served: California and Hawaii

Serving the more solar-developed markets of California and Hawaii, this partnership offers more advanced training, veteran-specific partner institutions, a Spanish-language PV training curricula, and certification program for solar PV instructors. CA-HI organizes building code official trainings, and provides professional development and curricular resources to California Community College faculty, Hawaiian university and community college faculty, regional occupational programs, and technical high schools.

ONLINE MULTIMEDIA VIDEO MODULES FOR TRAINING CODE INSPECTORS AND PV INSTALLERS

Sandia National Laboratories | Albuquerque, NM | \$0.14M | National Laboratory R&D | 10/2012-09/2014

Sandia and New Mexico State University have partnered to produce multimedia training tools and resources, and deliver trainings to solar installers, building and electrical inspectors and others regarding technical topics in PV installations (rooftop and ground mount, residential and commercial scale). Materials are available in print, video, flash memory, and through PDA devices and are Internet accessible, at no cost, to installers and inspectors in the field. NMSU and Sandia have produced more than 20 "special topics" in short video format, delivered through the web, on PV installation practices.

Human Talent for a New, Robust and Integrated Electrical Grid

Grid Engineering for Accelerated Renewable Energy Deployment (GEARED) is designed to help support increased power system research, development, and analytical capacity nationwide at the university and graduate level while simultaneously growing the expertise and preparedness of current and incoming electric utility sector professionals for high penetrations of solar and other distributed energy technologies.

NATIONAL NETWORK ADMINISTRATOR OF GEARED

Interstate Renewable Energy Council, Solar Energy Power Association | Latham, NY & Washington, DC | \$1.1M | 10/2013-09/2018

IREC and SEPA co-lead the GEARED network, presenting innovative approaches and networking strategies to grow the expertise and preparedness of current and future electric utility sector professionals for high penetrations of solar and other distributed technologies. This unique partnership of utility and workforce expertise will connect utilities, clean energy businesses, educational institutions, and credentialing organizations as integrated national stakeholders.

FEEDER: FOUNDATIONS FOR ENGINEERING EDUCATION FOR DISTRIBUTED ENERGY RESOURCES

University of Central Florida | Orlando, FL | \$3.2M | GEARED | 10/2013-09/2018

The FEEDER center will help establish cross-institutional smart grid curriculum, facilitating research collaborations among its academic, utility and industrial partners, and incorporating the latest and most relevant research findings into new educational materials and courseware. The new power systems engineers and engineering faculty emerging from FEEDER will accelerate the deployment of distributed renewable energy technologies onto the electric utility grid. FEEDER will also research technological components such as distributed control, optimization, advanced communication, renewable generation and smart grid integration.

Consortia: University of Central Florida, Auburn University, Florida State University, University of Arkansas, University of Florida, University of Kentucky, University of South Carolina, National Renewable Energy Laboratory, Los Alamos National Laboratory, Southern Company, Duke Energy, Florida Power & Light, Tennessee Valley Authority, Kentucky Power, Orlando Utilities Commission, Lakeland Electric, East Kentucky Power Cooperative, ABB, LEIDOS, L-3 Communications, Mitsubishi Power Systems Americas, Northern Plains Power Technologies, OSIssoft LLC, S&C Electric Company, SAIC, Schneider Electric, Siemens, United Technology Corp.

LEVERAGING INDUSTRY RESEARCH TO EDUCATE A FUTURE ELECTRIC GRID WORKFORCE

Electric Power Research Institute | Knoxville, TN | \$4.2M | GEARED | 10/2013-09/2018

EPRI will define and develop educational offerings for all levels: high school students, undergraduate and graduate students, practicing engineers pursuing a professional master's degree or graduate certificate, and mature and experienced engineers keen on understanding and developing skills to design, plan, operate, and protect the evolving energy systems which constitute the smart grid. To accomplish this task, EPRI will rely on previous and ongoing high-level research within the project team. The implementation phase will have undergraduate and graduate program components, as well as a variety of custom tailored short courses, tutorials, workshops, symposia, open access courses, and other methods of delivery in accordance with the program priorities set in consultation with our utility members for the benefit and development of all aspects of their diverse workforce.

Consortia: Georgia Institute of Technology, Clarkson University, University of North Carolina-Charlotte, University of Puerto Rico-Mayaguez; Central Hudson Gas and Electric, Consolidated Edison, Inc., CPS Energy, DTE Electric Company, Duke Energy, First Energy, Lincoln Electric System, LG&E and KU, National Grid, New York ISO, New York Power Authority, and Southern Company Services.

SOUTHWEST UNITED STATES OF AMERICA: DISTRIBUTED TECHNOLOGY TRAINING CONSORTIA (SWUSA)

Electricore | Valencia, CA | \$2.3M | GEARED | 10/2013-09/2018

SWUSA will create power and energy systems training, curricula, and workforce preparedness through the inclusion of data collection and analysis, power systems expertise, and application-specific training activities which build on fundamental principles, modeling and simulation tools, field-immersed training and methods of performance validation. The outcome of the program will result in better prepared and greater numbers of graduates ready to contribute to the field of power systems which depend upon the safe, reliable and efficient generation sources which make up an increasingly diverse mix of renewable power. Additionally, the program will deliver critical training modules which are intended to support mid-career professionals and be woven into utility training programs used all over the country.

Consortia: University California-San Diego, San Diego State University, Arizona State University, University of Hawaii-Manoa, San Diego Gas & Electric, Southern California Edison, Pacific Gas & Electric, Maui Electric Company, Lawrence Berkeley National Laboratory and California Independent System Operator Corporation.

MARMET: MIDAMERICA REGIONAL MICROGRID EDUCATION AND TRAINING CONSORTIUM

Missouri University of Science & Technology | Rolla, MO | \$4.3M | GEARED | 10/2013-09/2018

MARMET will integrate cutting-edge research and advanced instructional methods to create a flexible, evolving approach to microgrid training for all levels of students. Scalability, reliability, stability, controllability, and resiliency are just a few of the operational areas to be impacted, especially by electric utilities. Researchers globally are addressing these issues, but MARMET proposes to rapidly develop modular material to capture and reflect the newest trends in electric power engineering and to make it available in traditional and non-traditional settings.

Consortia Organizations: University of Illinois, Iowa State University, University of Wisconsin, Ameren Services, City Utilities, National Rural Electric Coop Association, and Perfect Power Institute.

Soft Costs of Solar Deployment

SOLAR UTILITY NETWORK DEPLOYMENT ACCELERATION (SUNDA)

National Rural Electric Cooperative Association | Arlington, VA | \$3.6M | SUNRISE | 10/2013-09/2017

The National Rural Electric Cooperative Association (NRECA) with its partners, the National Rural Utilities Cooperative Finance Corporation, the Federated Rural Electric Insurance Exchange, and Power Secure will work closely with a cohort of 15 rural electric cooperatives (coops) in 17 states to integrate more than 23 MW solar assets rapidly and cost-effectively. The team helps accelerate solar adoption at electric coops through standardized designs, streamlined financing, packaged insurance, group equipment purchasing, and extensive training and outreach. The number and diversity of cooperatives that are participating in this program is impressive. Not only are the coops geographically diverse, but they also differ in the number of customers they service, workforce and solar expertise. The team has an aggressive target of getting to a solar installed cost of \$1.6/W without subsidies by 2017. The project is designed to help lower the cost of solar deployment across rural America. The impact of NRECA's work will be felt beyond the over 900 cooperatives serving our rural communities in bringing de facto standards for integrating solar assets in rural communities.

Participating cooperatives include: Anza Electric Cooperative, Inc. (CA), Brunswick Electric Membership Corp. (NC), CoServ Electric (TX), Eau Claire Energy Cooperative (WI), Great River Energy (MN), Green Power EMC (GA), Maquoketa Valley Rural Electric Cooperative (IA), Oneida-Madison Electric Cooperative (NY), Owen Electric Cooperative (KY), Pedernales Electric Cooperative (TX), Plumas-Sierra Rural Electric Cooperative (CA), Sandhills Utility Services, LLC (NC), Sussex Cooperative (NJ), Tri-State Generation & Transmission Association (CO), Vermont Electric Cooperative (VT).

Developing Solar Finance and Business Solutions

SunShot supports work in finance, real estate, community and shared solar development by working with financial institutions, project developers, and manufacturers to unlock new streams of capital to support solar deployment.

SOFT COST MODELING AND ANALYSIS

Achieving the SunShot cost targets will require aggressive cost reductions in every aspect of the PV supply chain. In order to track progress and identify key pathways to reducing those costs, DOE and stakeholders need transparent and credible information and analysis to quantify soft and hard costs more accurately.

Lawrence Berkeley National Laboratory | Berkeley, CA | \$2.2M | National Laboratory R&D | 10/2012-09/2015

LBNL researchers, in partnership with the National Renewable Energy Laboratory, will collect, synthesize, analyze, and disseminate comprehensive data on the installed price of U.S. PV systems via its annual Tracking the Sun report series and derivative journal articles and outreach activities. LBNL researchers will also track and analyze the installed utility-scale solar cost, price, and performance data—a rapidly growing sector of solar deployment. Finally, LBNL and NREL will partner with academic researchers to pursue innovative, “deep dive” research projects, such as an analysis of the impact of city-level permitting processes on residential PV prices and development times, and conducting a comparative analysis of residential PV system prices in the United States and Germany.

National Renewable Energy Laboratory | Golden, CO | \$4.5M | National Laboratory R&D | 10/2012-09/2015

NREL researchers, in partnership with LBNL, will provide quarterly syntheses of industry trends and detailed breakdowns of total and soft costs using bottom-up PV cost modeling; conduct analyses that will facilitate industry benchmarking and the development of future cost roadmaps, projections, and cost models; provide up-to-date, accurate project-level installed price data to populate the OpenPV Project database; and conduct analysis to better understand how third-party PV products are fundamentally changing customer-adoption decisions and ownership preferences. Finally, to better understand the domestic and global solar market, NREL researchers will perform international comparative analysis to inform the development of predictive models for future cost trajectories in the United States.

ADVANCED FINANCING MECHANISMS TO ACHIEVE SUNSHOT

National Renewable Energy Laboratory | Golden, CO | \$4.0M | National Laboratory R&D | 10/2012-09/2015

The project is designed to expand the availability and lower the cost of capital to deploy solar installations in the United States. The project will standardize, inform, and provide data to investors, developers, lenders, regulators, rating agencies, and other stakeholders in the renewable energy community to enable wide-scale adoption of solar energy through low-cost, consistent, and ubiquitous financing opportunities. This effort will engage solar, legal, financial and advisory industries to standardize solar

Soft Costs of Solar Deployment

lease and PPA documents; educate various stakeholders on system and credit performance; develop best practices for system installation, operation and maintenance, and independent engineering in order to facilitate investor confidence systems; and comprehend rating agency and investor risk perspective by engaging rating agencies to provide “shadow ratings” on mock portfolios of residential and commercial assets. To help create these products, NREL organized the Solar Access to Public Capital Working Group, an assembly of over 150 leading organizations in the fields of solar deployment, finance, counsel, and analysis. Under this agreement, NREL also conducts thorough analysis of opportunities and barriers to capital market investment and bank lending for expanded solar deployment, and develops the datasets necessary to quantify the relevant risks enabling institutional investment in the asset class. Finally, NREL engages the banking industry to standardize solar loan documents, educate banks and their regulators on system and loan performance, and expand comprehension of best practices and activities in commercial PACE programs in order to materially expand lending activity for solar deployment.

RESIDENTIAL AND COMMERCIAL REAL ESTATE AND PV ENERGY SYSTEMS

When selling or purchasing a property with a solar installation attached, one might expect that installation to add value to the overall property. Prior to this agreement, however, property appraisers had no consistent valuation methodology and so often assigned a value of “zero” to the solar component of the home or building in question.

[Lawrence Berkeley National Laboratory | Berkeley, CA | \\$0.60M | National Laboratory R&D | 10/2012-09/2015](#)

LBL researchers (in collaboration with Sandia) are compiling data on residential and commercial solar installation pricing in a home sale transaction and developing an appropriate valuation tool (an algorithm and web tool) that calculates fair market value to solar installations that are part of a home/building. LBNL is pursuing a “cost” approach in developing a method for estimating historical average net-installed costs of PV systems, as well as labor and building costs, and correlating those net installed “cost” estimates of PV systems to actual PV property sales premiums to determine if, and to what degree, “cost” drives prices. This agreement addresses two SunShot objectives: decreasing costs by expanding access to low-cost financing options, and addressing policy and regulatory barriers to increase deployment.

[Sandia National Laboratories | Albuquerque, NM | \\$0.55M | National Laboratory R&D | 10/2012-09/2015](#)

Sandia researchers (in collaboration with Lawrence Berkeley National Laboratory) are compiling data on residential and commercial solar installation pricing in a home sale transaction and developing an appropriate valuation tool (an algorithm and web tool) that calculates fair market value to solar installations that are part of a home/building. Sandia is pursuing an “income” approach to improve this PV Value tool, in order to accommodate more complex utility rate structures, lease to purchase options, utility rate escalation, and tax and revenue considerations. Sandia will correlate the PV Value tool’s “income” value estimates with actual PV property sales premiums to determine if, and to what degree, “income” drives sales prices. The team also prepared and are disseminating training materials for property appraisers.

THE SUNSHOT PRIZE: RACE TO THE ROOFTOPS

Open for registrations and applications | \$10.0M | 09/2012-01/2015

In September 2012, the Energy Department launched an audacious new market stimulation prize in support of the goals of its SunShot Grand Challenge, which aims to make solar competitive with fossil fuels by the end of the decade. The \$10 million SunShot Prize challenges the ingenuity of America's businesses and communities to make it faster, easier, and cheaper to install rooftop solar energy systems. Successful competitors will deploy at least 6,000 new rooftop PV installations in the U.S. at an average pre-subsidy, non-hardware cost of \$1 per watt. Winners will break this significant price barrier, considered to be unachievable a decade ago, and prove that they can repeatedly achieve a \$1 per watt, non-hardware cost using innovative, verifiable processes and business practices. The winners of the first phase of the competition will be announced in Fiscal Year 2015 with cash awards likely to be made in 2016. The prize competition is still open for registration and applications until December 31, 2014.

Appendix: SunShot Funding Programs

The table below lists competitive funding opportunity announcements (FOAs) funded by the SunShot Initiative as of fiscal year 2011. Funding amounts and award numbers reflect awards made under competitive FOAs. Only active awards are described in this document. Funding amounts shown here and throughout the rest of this document reflect only the federal portion of each award.

Please note: Awards made to federally-funded research centers (i.e., national laboratories) through laboratory agreements are not included in this reference table.

Funding Opportunity Announcement (FOA)		Focus Area(s)	Funding (M)	Awards Made
Fiscal Year 2011				
BOS-X	Extreme Balance of System Hardware Cost Reductions	Systems Integration	\$37.7	9
F-PACE 1	Foundational Program to Advance Cell Efficiency	Photovoltaics	\$34.8	18
Incubator 6		Technology to Market	\$7.7	10
MURA	Minority University Research Associates	Photovoltaics	\$1.6*	6
NextGen 2	Next Generation Photovoltaics 2	Photovoltaics	\$22.7	23
PVMI	Photovoltaics Manufacturing Initiative	Technology to Market	\$114.8	3
RSC 1	Rooftop Solar Challenge	Soft Costs	\$12.0	22
SBIR/STTR	Small Business Innovation Research and Small Business Technology Transfer	Technology to Market	\$3.2	8
SEGIS-AC	Solar Energy Grid Integration Systems - Advanced Concepts	Systems Integration	\$22.5	8
SITN	Solar Instructor Training Network	Soft Costs	\$14.0	10
SUNPATH	Scaling Up Nascent Photovoltaics AT Home	Technology to Market	\$34.6	3
SunShot CSP R&D	Concentrating Solar Power Research and Development	Concentrating Solar Power	\$44.1	21
Supply Chain 2	High Impact Supply Chain R&D for PV Technologies and Systems 2	Technology to Market	\$14.9	4
Soft BOS	Reducing Market Barriers and Non-Hardware Balance of System Costs	Soft Costs	\$11.2	7
Fiscal Year 2012				
BRIDGE	Bridging Research Interactions through Collaborative Development Grants in Energy	Photovoltaics Concentrating Solar Power	\$7.9 \$0.48	11 1
HIBRED	Heat Integration for Baseload Renewable Energy Development	Concentrating Solar Power	\$10.0	1
Incubator 7		Technology to Market	\$10.5	11

Appendix: SunShot Funding Programs

Funding Opportunity Announcement (FOA)		Focus Area(s)	Funding (M)	Awards Made
MURI	Multidisciplinary University Research Initiative: High Operating Temperature Fluids	Concentrating Solar Power	\$10.5	2
Plug and Play	Plug-and-Play Photovoltaics	Systems Integration	\$20.9	2
RSC 2	Rooftop Solar Challenge 2	Soft Costs	\$12.2	8
SBIR/STTR	Small Business Innovation Research and Small Business Technology Transfer	Technology to Market	\$3.2	16
SEEDS	Solar Energy Evolution and Diffusion Studies	Soft Costs	\$4.4	5
Solar Forecasting	Improving the Accuracy of Solar Forecasting	Systems Integration	\$7.8	3
Fiscal Year 2013				
DISTANCE	Diversity in Science and Technology Advances National Clean Energy in Solar	Photovoltaics	\$1.1	2
F-PACE 2	Foundational Program to Advance Cell Efficiency 2	Photovoltaics	\$16.0	4
GEARED	Grid Engineering for Accelerated Renewable Energy Deployment	Soft Costs	\$15.1	5
Incubator 8		Technology to Market	\$14.4	20
PREDICTS	Physics of Reliability: Evaluating Design Innovations for Component Technologies in Solar	Photovoltaics Concentrating Solar Power Systems Integration	\$2.6 \$4.0 \$1.4	2 2 1
SBIR/STTR	Small Business Innovation Research and Small Business Technology Transfer	Technology to Market	\$3.3	8
SolarMaT	Solar Manufacturing Technology	Technology to Market	\$13.0	5
SUNRISE	Solar Utility Networks: Replicable Innovations in Solar Energy	Systems Integration Soft Costs	\$4.2 \$3.7	7 1
Fiscal Year 2014				
ELEMENTS	Efficiently Leveraging Equilibrium Mechanisms for Engineering New Thermochemical Storage	Concentrating Solar Power	TBD**	TBD**
Incubator 9		Technology to Market	TBD**	TBD**
NextGen 3	Next Generation Photovoltaics 3	Photovoltaics	TBD**	TBD**
SBIR/STTR	Small Business Innovation Research and Small Business Technology Transfer	Technology to Market	TBD**	TBD**
Solar Market Pathways		Soft Costs	TBD**	TBD**
SolarMaT 2	Solar Manufacturing Technology 2	Technology to Market	TBD**	TBD**

*Funding for MURA reflects FY'10-FY'14 dollars.

**Only FOAs that have been announced publicly as of May 2014 are listed in this table. No implication is made about future funding solicitations.

U.S. DEPARTMENT OF
ENERGY

Energy Efficiency &
Renewable Energy

For more information, visit:
energy.gov/sunshot

DOE/EE-1081 • May 2014

Printed with a renewable-source ink on paper
containing at least 50% wastepaper, including
10% post consumer waste.