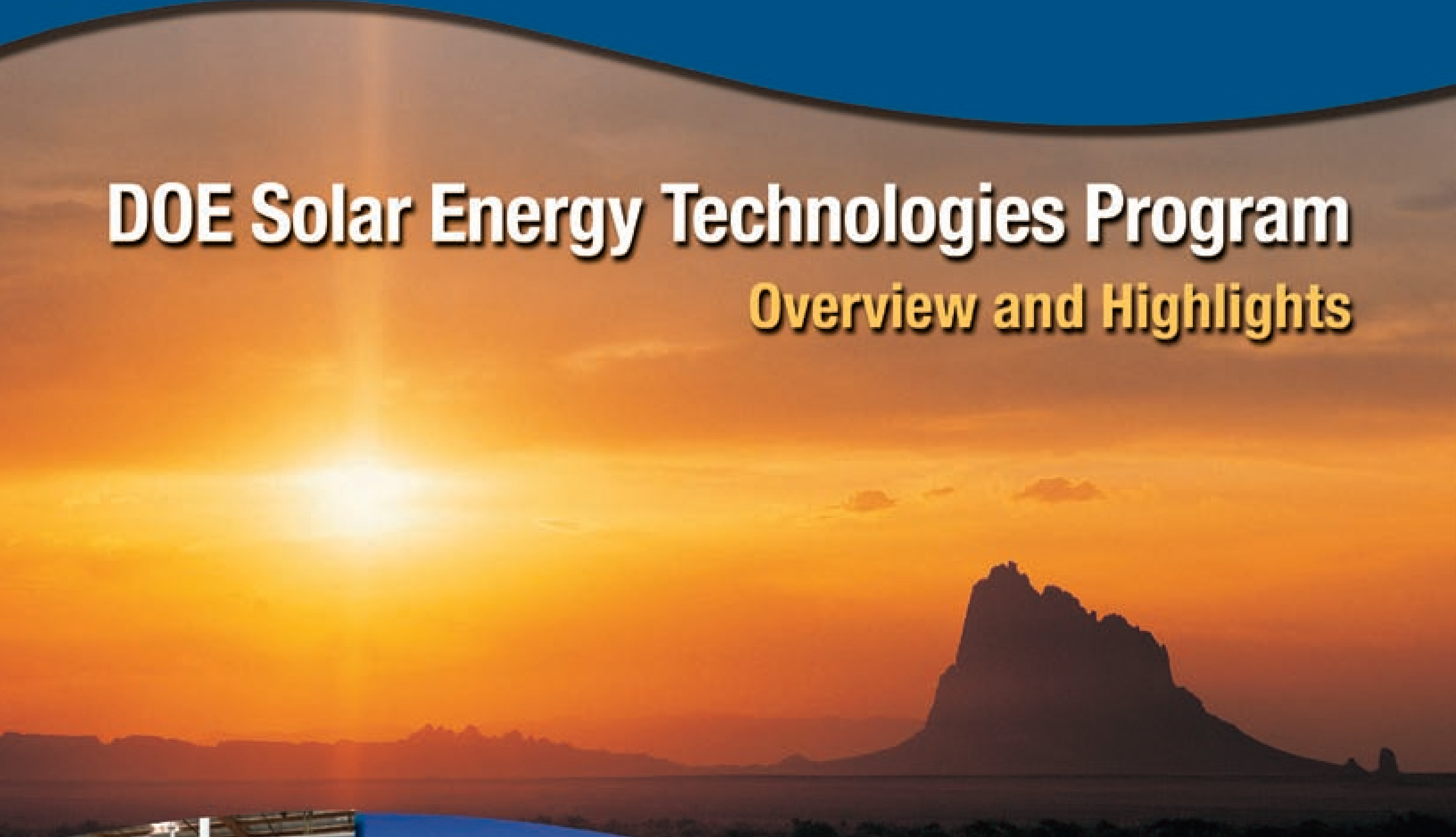
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

DOE Solar Energy Technologies Program

Overview and Highlights

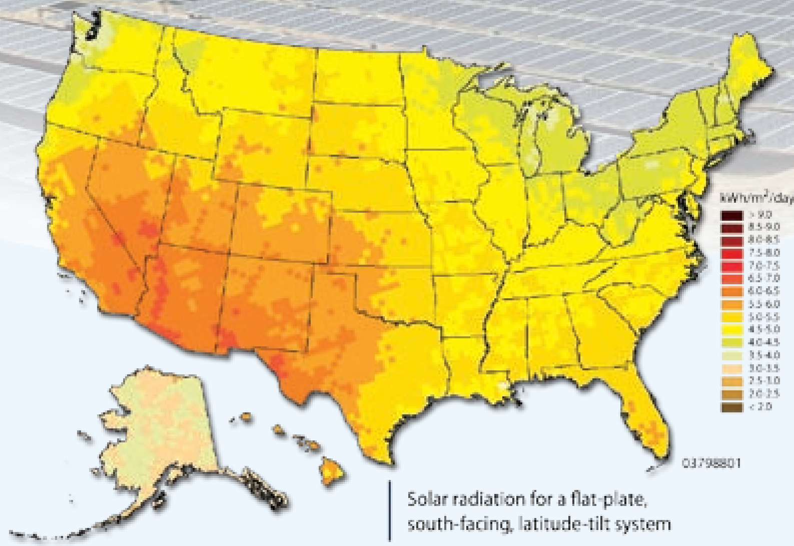


PowerLight Corp./PIX14597

The Solar Energy Technologies Program

Energy moves the modern world. Available, reliable, affordable energy. Since the Industrial Revolution, fossil fuels—coal, oil, and natural gas—have powered immense technological progress. But supplies of fossil fuels are limited, and continued reliance on them may have significant environmental consequences. Fortunately, there are alternatives. The most powerful one is right over our heads.

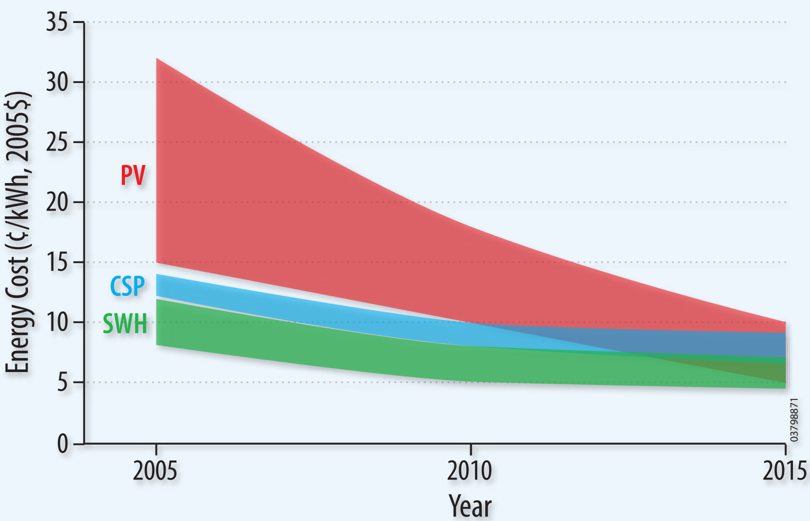
We are bathed in the clean, virtually inexhaustible energy of the sun. Each hour, enough sunlight reaches Earth to meet the world's energy needs for a year. To harvest this bounty, we need technology that efficiently converts the sun's energy into forms we can use. Developing this technology is the purpose of the U.S. Department of Energy (DOE) Solar Energy Technologies Program.



The United States has abundant solar resources. The sunlight falling on less than 0.5% of the mainland could satisfy all the nation's electricity needs.

Powerful Goals, Powerful Technologies

The Solar Energy Technologies Program is part of the DOE Office of Energy Efficiency and Renewable Energy. The Program's mission is to improve U.S. security, environmental quality, and economic prosperity through public-private partnerships that bring reliable and affordable solar energy technologies to the marketplace. It supports research and development on a wide range of photovoltaic (PV) and solar thermal technologies that convert sunlight into useful energy.



The goals of the Solar Energy Technologies Program are to reduce the cost of solar energy to be competitive with conventional energy sources in relevant energy markets and to bring solar technology to a level of market penetration that enables a sustainable solar industry. The Program's market-specific goals for 2015 (in 2005$) are 8–10 ¢/kWh in the residential sector, 6–8 ¢/kWh in the commercial sector, and 5–7 ¢/kWh in the utility sector. PV—photovoltaics; CSP—concentrating solar power; SWH—solar water heating.

Photovoltaic Technologies

The majority of the Program's budget is allocated to PV research and development (R&D). All PV devices convert sunlight directly into electricity. However, there is a variety of materials and processes for creating PV devices, each with its own benefits and drawbacks. The major trade-off is between cost and sunlight-to-electricity conversion efficiency—higher efficiency typically translates into higher cost. Program participants consistently achieve world-record efficiencies for different types of PV, but each effort has the same ultimate goal: optimizing cost and efficiency to produce the least expensive end-use electricity.

Solar Thermal Technologies

The sun's energy can be put to work in numerous additional ways. Solar thermal technologies provide electricity, hot water, space heating, and lighting. They can be very cost effective—solar water heating is the least expensive form of solar energy—and can even work in tandem with conventional energy sources to improve the flexibility and reliability of the electricity they produce.

A Systems-Driven Approach

The Program uses a "systems-driven approach" to guide and assess its activities. This approach emphasizes the importance of how the many aspects of a technology are related. For example, it considers how changes in a component—such as low-cost polymer frames for solar water heaters—affect an application or market. It also examines how changes in markets modify the

Contents

Stirling Energy Systems/PIX08728

Background photo: Arizona Public Service/PIX13739

requirements for component cost and performance, such as the impact of interconnection standards on the design of power inverters. The systems-driven approach enables the Program to do the following:

- Determine priorities within the Program.
- Identify key market sectors in which solar technologies can have significant impacts.
- Determine critical R&D to address technology barriers related to those markets.
- Develop standardized analyses to ensure that technologies meet cost, performance, and reliability targets.

Working Together

The Solar Energy Technologies Program draws on the capabilities of numerous public- and private-sector partners. DOE national laboratories—the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL), Oak Ridge National Laboratory, and Brookhaven National Laboratory—perform R&D and support program management. To use resources most effectively, cross-cutting teams from these laboratories are organized into *virtual laboratories*: the National Center for Photovoltaics (NCPV) for PV and Sun♦Lab for concentrating solar power. U.S. universities perform cutting-edge R&D and nurture the next generation of solar scientists and technologists.

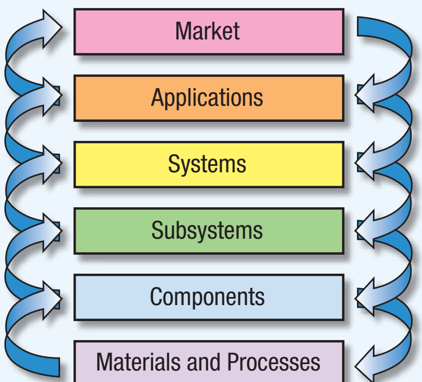
Solar industry partners not only produce innovations, but also ensure that the innovations are transferred to the marketplace.

Looking to the Future

This is an exciting time for solar energy. PV systems are being installed in unprecedented numbers in the United States and worldwide. The first new U.S. concentrating solar power plant in nearly 15 years was completed in 2005, and more plants are planned for the coming years. Other solar thermal technologies continue to make inroads as well.

In 2006, President George W. Bush proposed the Solar America Initiative to accelerate widespread commercialization of solar energy technologies. The goal is to achieve market competitiveness for PV electricity by 2015. It is estimated that, by 2015, the Initiative will result in deploying 5–10 gigawatts of PV (enough to power 1–2 million homes), avoiding 10 million metric tons of annual CO_2 emissions, and employing 30,000 new workers in the PV industry.

Solar energy is on the verge of becoming a viable part of our nation's energy supply, but challenges must still be overcome before it is competitive with conventional energy sources. The Solar Energy Technologies Program is committed to meeting these challenges and providing secure, clean energy for the future.



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The systems-driven approach helps identify common R&D concerns, avoid duplication of effort, and explore how advances in one area, such as subsystems, might change the assumptions or requirements for other areas, such as systems, applications, and markets.

For More Information

This *Overview* provides brief descriptions of Solar Energy Technologies Program activities. More detailed information, including contact information, is available from the following sources:

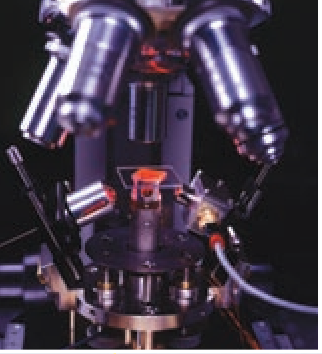
Web Sites

Solar Energy Technologies Program	www.eere.energy.gov/solar
National Renewable Energy Laboratory	www.nrel.gov/solar
Sandia National Laboratories	www.sandia.gov/Renewable_Energy/renewable.htm
Oak Ridge National Laboratory	www.ornl.gov/sci/solar
Brookhaven National Laboratory	www.pv.bnl.gov

Program Documents

DOE Solar Energy Technologies Program FY 2005 Annual Report (DOE/GO-102006-2246), www.nrel.gov/docs/fy06osti/38743.pdf

Search for additional program documents at www.osti.gov/bridge.



Warren Gretz/PIX04542

Measurements and Characterization

Energizing PV research through world-class analytical support

Measurements and characterization (M&C) are vital to PV technology development. To verify progress, you need a way to measure it. To fix something, you need to know what's broken. The NREL-led M&C project helps researchers measure progress and better understand the behavior of materials and devices—from single atoms to PV modules.

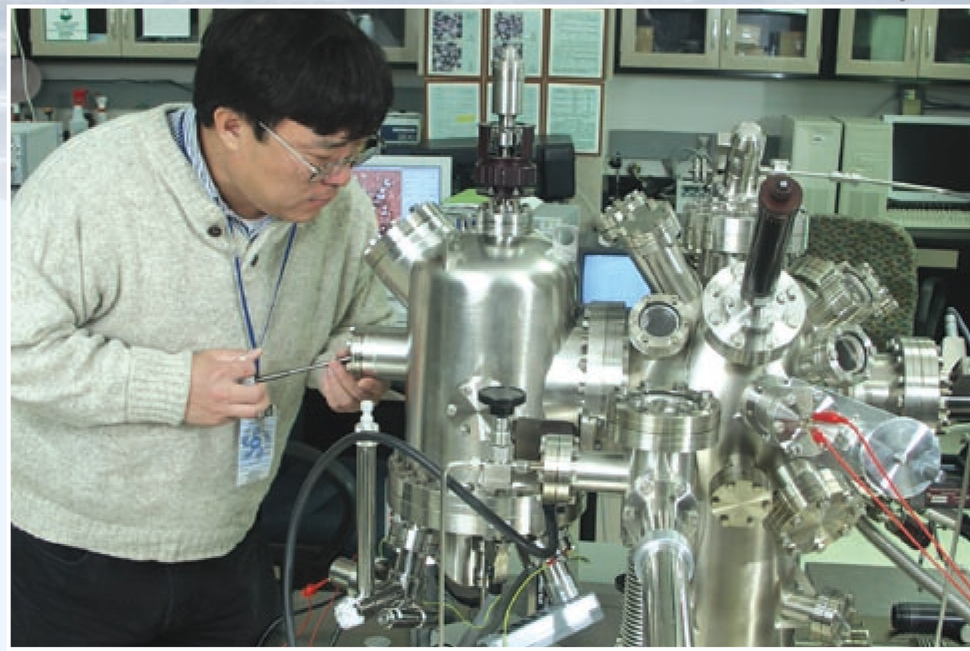
Industry, university, and government partners collaborate with the M&C project to gain access to its unique tools and expertise in analytical microscopy, cell and module measurements, electro-optical characterization, and surface analysis—sophisticated capabilities that would otherwise be out of reach for most partners. New M&C tools and techniques are being developed continually to keep pace with rapidly evolving PV technologies.

In the past year, the M&C project collaborated with more than 70 research groups, testing and analyzing thousands of material and device samples. Following are recent M&C highlights.

Goals

- Provide advanced measurement, evaluation, and analysis support and research for all PV materials and devices.
- Collaborate with national laboratory research groups, partners in university and industry laboratories, and PV manufacturers to solve research and manufacturing problems.
- Help clients understand and direct work on their research and develop commercial products.

Mike Linenberger/PIX14497

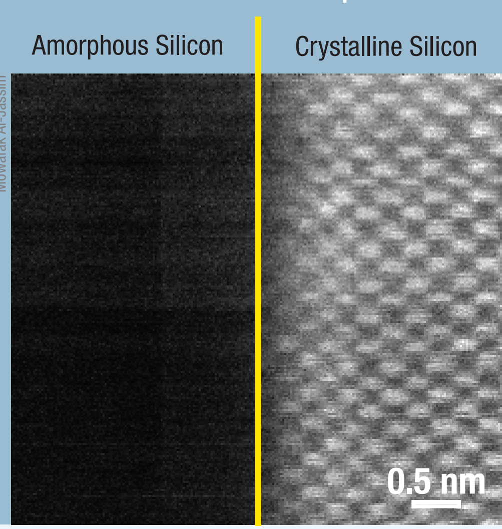


NREL scientists use scanning tunneling microscopy to study the atomic structure of solar cell materials.

Analytical Microscopy

Microscopy magnifies features that cannot be seen with the naked eye. It becomes analytical by applying tools or methods that provide information on a wide range of material properties. The M&C project recently used its analytical microscopy expertise to characterize silicon heterojunction PV cells. These cells consist of layers of amorphous silicon deposited on a crystalline silicon wafer. For a cell to be efficient, there must be a sharp, flat interface between highly ordered crystalline silicon and highly disordered amorphous silicon. The analytical microscopy results showed these conditions were present in cells created at relatively low substrate temperatures by a process called hot-wire chemical vapor deposition. A silicon heterojunction cell analyzed by the M&C project recently demonstrated a world-record 17% sunlight-to-electricity conversion efficiency.

Mowafak Al-Jassim



This atomic-resolution image of the front interface in a silicon heterojunction PV cell shows a sharp, flat interface between the highly disordered amorphous silicon and the highly ordered crystalline silicon.

Cell and Module Measurements

An important aspect of the M&C project's cell and module measurement work is calibration—measuring the amount of electricity produced by a PV device under standard conditions. Quality calibration is critical for manufacturing PV products. Many PV industry partners rely on NREL to calibrate reference cells and modules used in measuring their products. NREL recently marked a major achievement by expanding its ISO 17025 accreditation to include primary reference cell and secondary module calibration under industry standards. This accreditation bolsters client confidence that reported product performance can be verified and is accepted internationally. In addition, certified module qualification facilities require that their reference cell calibrations be traced to a certified laboratory—which is now possible through NREL—and NREL is one of four laboratories in the world certified to perform World PV Scale primary reference cell calibrations.

Jim Yost/PIX14093

In calibrating reference cells, NREL scientists concurrently measure spectral irradiance, total irradiance, and the cell's short-circuit current under outdoor conditions.

Electro-Optical Characterization

Electrical and optical techniques are used to examine many fundamental properties of materials. Recently, the M&C project designed, built, and tested an automated system to map the minority-carrier lifetime of silicon samples with diameters up to 6 inches. Movement of minority carriers creates the electric current in a PV cell, and a longer minority-carrier lifetime translates to better PV cell performance. The special system is being transferred to the PV industry for use in researching areas such as the performance of multicrystalline PV cells. PV cells made of multicrystalline silicon cost less to manufacture than those made of single-crystal silicon. However, the nonuniformity and numerous crystal boundaries in multicrystalline silicon degrade PV cell performance. Industry can use the system to map minority-carrier lifetimes across a multicrystalline silicon sample, leading to better understanding—and ultimately, improvement—of the areas that degrade performance.

Jim Yost/PIX09872

An NREL researcher loads a silicon wafer into the resonance-coupled photoconductive decay system to measure minority-carrier lifetime.

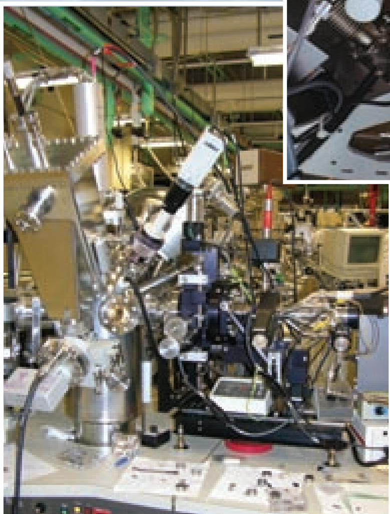
Surface Analysis

Surface analysis determines the chemical, elemental, and molecular composition of material surfaces and interfaces. The M&C project employed surface analysis to help the PV industry use polymers in PV modules. The industry would like to use the flexible polymers to replace glass in thin-film modules, but the polymers' permeability causes problems. One solution is depositing a thin moisture barrier on the polymer surface. The barrier's effectiveness can be measured by its ability to stop moisture and adhere to the polymer. The M&C project used analytical results to correlate the chemistry of the surface to the adhesion of the polymer. To facilitate 25-year module warranties, the study considered normal and damp/hot conditions.

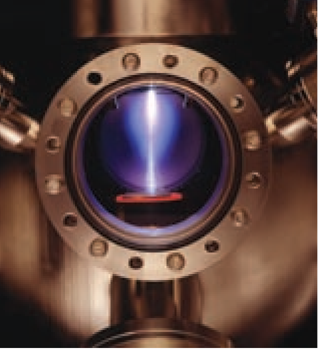
In another study, M&C researchers used a specially developed tool to study surface chemistry and electronic structure during chemical-bath deposition of cadmium sulfide. The results led to a modified method for depositing cadmium sulfide in a chemical bath that substantially improves the performance of copper indium gallium diselenide (CIGS) PV cells.

Jim Yost/PIX01437

Sally Asher



The M&C project's surface analysis cluster tool is used for studies of surface chemistry and physics using techniques such as Auger electron, X-ray photoelectron, and ultraviolet photoelectron spectroscopies, and thermal desorption mass spectrometry.


Jim Yost/PIX01506

Electronic Materials and Devices

Laying the groundwork for PV breakthroughs

The Electronic Materials and Devices (EM&D) project tackles the technological challenges of critical importance to today's PV industry and the PV industry of the future. The project's high-risk, high-reward R&D is led by NREL.

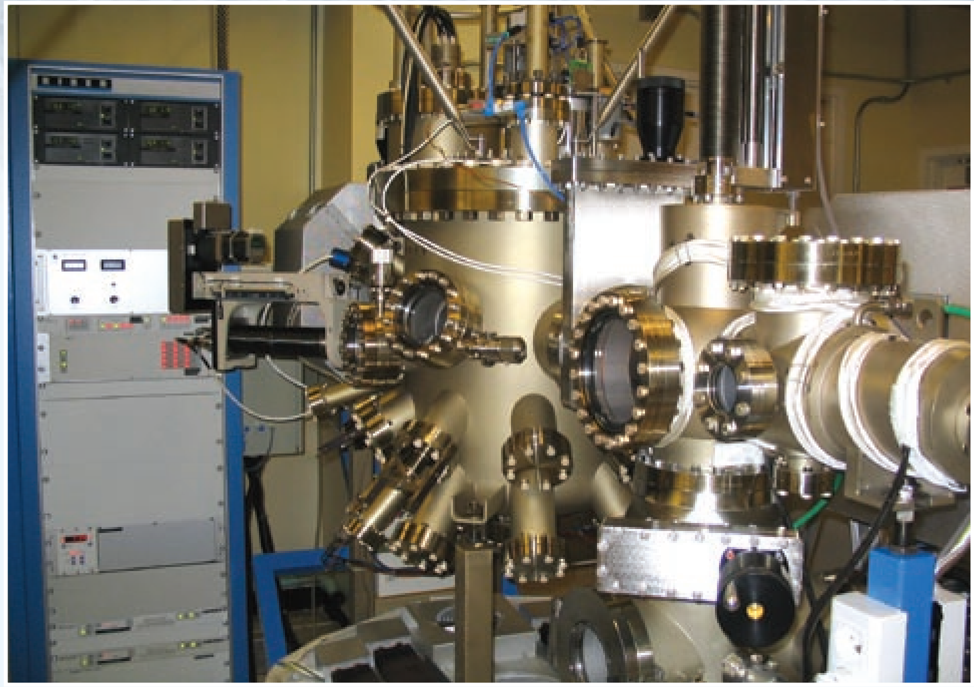
The United States has several unique opportunities to capitalize on PV technologies. First, the U.S. PV industry leads the world in developing thin films, the fastest growing segment of the PV market. Second, U.S. solar resources are well suited to use of PV concentrator systems for large-scale power generation. Finally, the relatively low cost of U.S. electricity will require PV to be less expensive here than in most of the world—necessitating new production methods that avoid costly vacuum processing, minimize mechanical stress, and increase throughput dramatically.

Exploring and developing technologies to exploit these three opportunities is the primary task of the EM&D project. The project performs research in semiconductor materials, device properties, and fabrication processes to improve the efficiency, stability, and cost of PV. It is a key contributor to the Thin Film PV Partnership, Crystalline Silicon Research project, and High-Performance PV project described elsewhere in this *Solar Energy Technologies Program Overview*. Following are descriptions of major EM&D activities and recent highlights.

Goals

- Assist industry and national research teams in addressing current PV material and device problems.
- Explore specific techniques and processes to develop and transfer PV technology improvements needed by industry in the near term.
- Create new technologies and lead the development of the knowledge base and tools for the future of PV.

John Benner/PIX14610


NREL's molecular beam epitaxy system is used to make advanced PV devices.

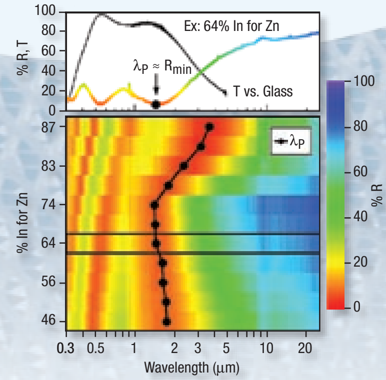
David Parsons/PIX07031

NREL fabricates record-efficiency CIGS cells using a physical vapor deposition system.

Processes and Advanced Concepts

One major focus is developing technology that enables combinatorial materials science. Conventional materials science operates in a linear fashion: perform an experiment, analyze the results, and use the results to decide on the next experiment. Today's advanced computing technology enables combinatorial materials science, in which many experiments are performed and analyzed nearly simultaneously at each step, to greatly accelerate the rate at which knowledge is acquired. However, the resulting flood of data can be overwhelming without new tools to interpret and communicate it. The EM&D project develops custom software tools to extract useful information from combinatorial experiments.

John Benner/PIX14611



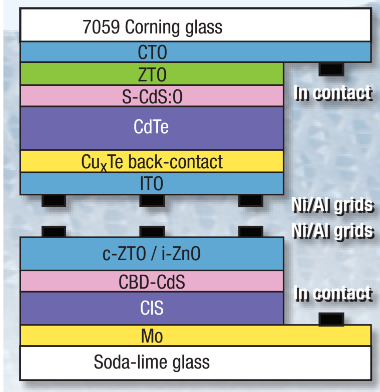
A custom software tool developed under the EM&D project facilitates the display and analysis of optical data for transparent conducting oxides, which are important components of many PV devices.

Thin Films

Thin-film PV uses an extremely thin layer of active semiconductor—the material that actually converts sunlight into electricity—which can be made from a variety of compounds. The EM&D project consistently fabricates thin films of cadmium telluride (CdTe) and copper indium diselenide (CIS, which is called CIGS when the element gallium is added) with world-record sunlight-to-electricity conversion efficiencies. To wring even more electricity out of a PV cell, thin films can be layered in a "multijunction" configuration, with each layer producing electricity from a different region of the solar spectrum.

Warren Gretz/PIX10119

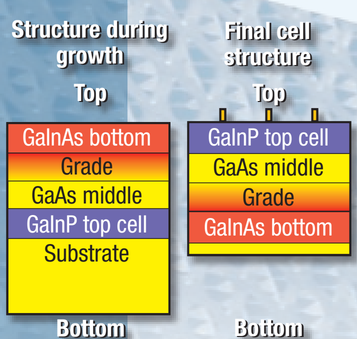
An NREL researcher applies a thin film of CdTe to a sample.



This CdTe-CIS multijunction cell developed under the EM&D project demonstrated a record 15.3% sunlight-to-electricity conversion efficiency.

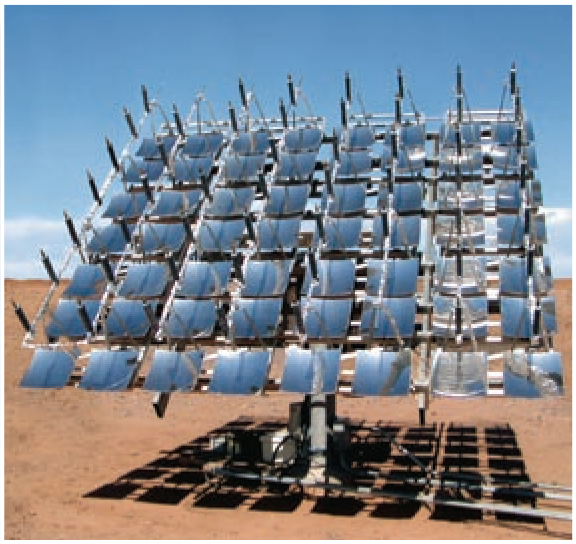
Concentrator PV Cells

PV concentrators use relatively inexpensive optics to concentrate sunlight onto a small area of high-efficiency, multijunction cells. In an ideal multijunction cell, the top layer produces most of the total power, so the top layer should be of the highest quality. However, in conventional designs grown from the bottom layer to the top, the structure of the top cell is degraded. The EM&D project is developing a novel approach to overcome this problem: growing the multijunction layers upside down. These "inverted" cells have many advantages and the potential to exceed 40%-efficient concentrator conversion. A world-record 37.9%-efficient concentrator cell has already been demonstrated using this approach. Additional strategies for lower-cost, high-performance concentrator cells being pursued by the EM&D project include growing multijunction cells on silicon substrates.

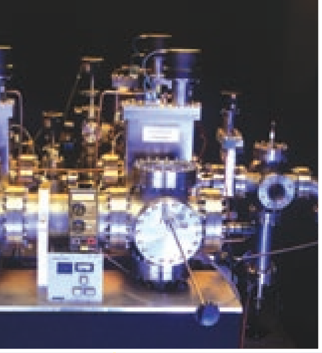


In the inverted cell configuration, the top layer is grown on a substrate at the bottom of a stack of additional layers (left). After growth, the original substrate is removed, the layers are turned upside down, and the electrical contacts are applied to what is now the top layer (right).

Arizona Public Service/PIX13740



Concentrators such as this one focus sunlight onto high-efficiency multijunction PV cells.



Jim Yost/PIX01812

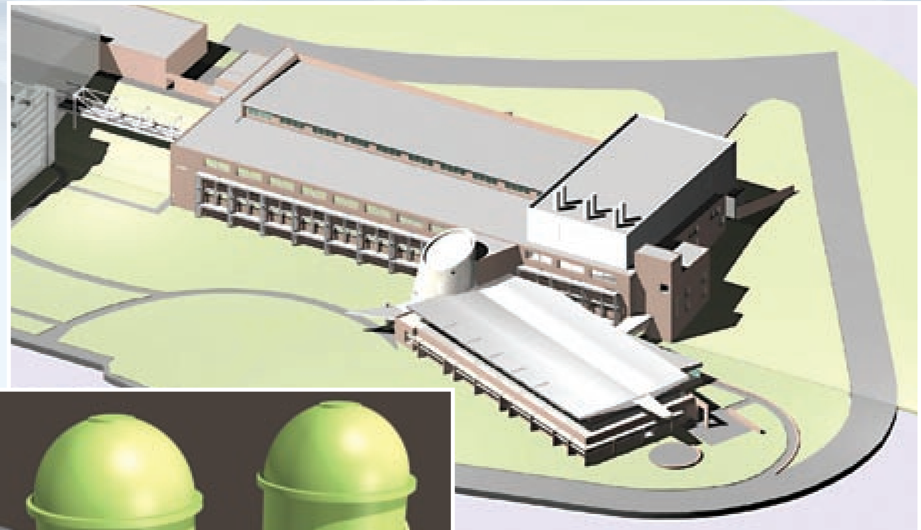
Crystalline Silicon Research

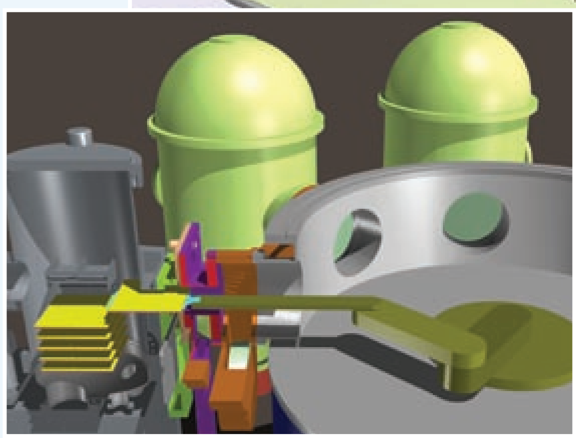
Bringing a proven technology to new heights

Crystalline silicon was the first material used in commercial PV devices and continues to make up more than 90% of today's new PV systems. Despite its long history, there is still much to learn about the fundamentals of solar-grade crystalline silicon—and considerable room to improve silicon PV technology. The NREL-led Crystalline Silicon Research project is at the forefront of these efforts.

The project comprises a group of institutions performing a wide range of R&D, from fundamental and exploratory studies to applied manufacturing research. It draws on the resources of these institutions to maximize their combined impact on crystalline silicon PV technologies and enhance the U.S. PV industry's competitiveness in the world market.

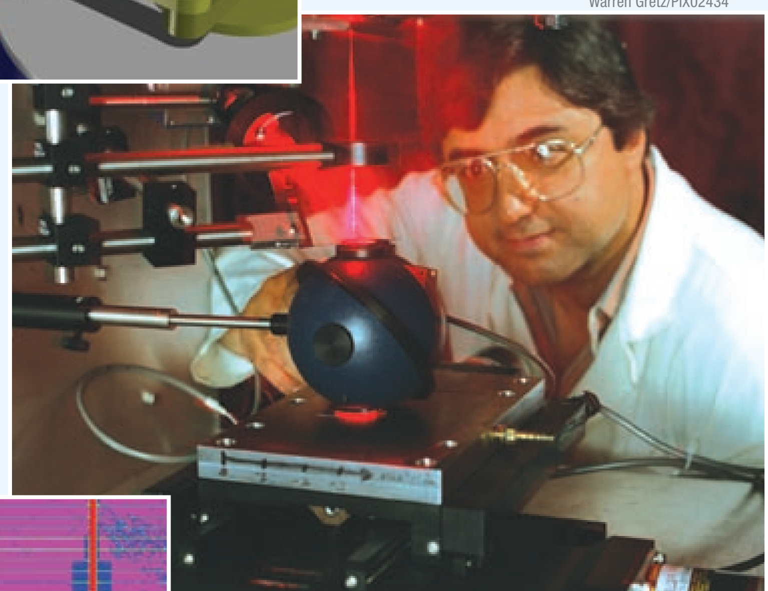
The new Science and Technology Facility (S&TF) at NREL exemplifies this cooperative approach. The S&TF will be a focal point for integrated material and device research and manufacturing R&D, with crystalline silicon being the initial emphasis. Members of the U.S. PV research community will collaborate through the S&TF with the goal of accelerating the progress of new technologies from the lab to the marketplace. Following is a brief overview including recent highlights from Crystalline Silicon Research project participants.



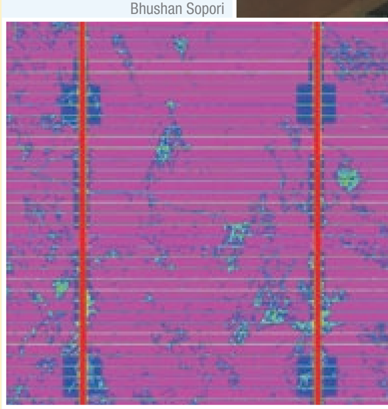


A silicon cluster tool (rendering at left) at the new Science and Technology Facility (rendering above) will use robotics to move samples from one stage of production or analysis to another in a controlled environment.

Warren Gretz/PIX02434



Bhushan Sopori



NREL invented a technology that "maps" defects in silicon, which is now used by many companies. The inset map of a 4.5 x 4.5-inch PV cell shows variations in levels of performance caused by the defects. This technology, along with related R&D described on the next page, is key to permitting the commercial use of solar-grade silicon, which is much less expensive than the purified silicon currently used in PV cells and lends itself to rapid large-scale production.

Goals

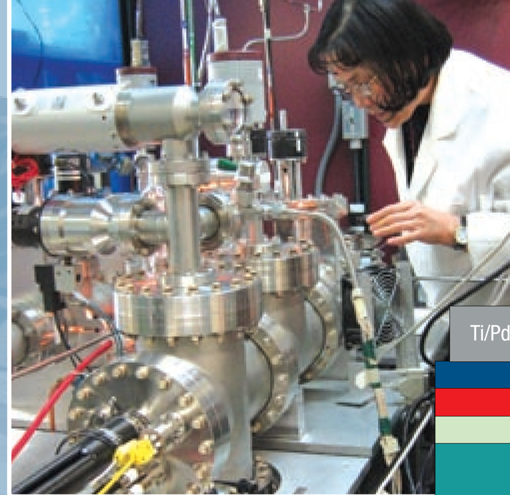
- Improve performance, reduce manufacturing cost, and ensure reliability of crystalline silicon PV technologies.
- Provide the experimental and theoretical foundations for innovative crystalline silicon concepts.
- Develop in-line diagnostic tools to increase manufacturing yield.
- Advance the understanding and performance of heterojunction silicon devices.
- Explore new concepts for preparing crystalline silicon thin films on glass as a less expensive, sturdier substrate.

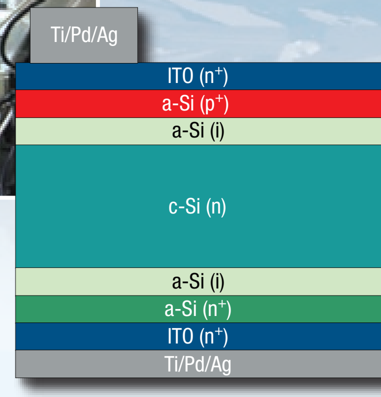
National Renewable Energy Laboratory

NREL develops advanced crystalline silicon PV concepts using its expertise in defect and device physics and thin-film deposition techniques. A major thrust of NREL's work is reducing the amount of silicon required in a PV device—essential for cutting the cost of silicon-based PV and ensuring future silicon supply. Using thinner layers of silicon presents challenges, such as bowing of the silicon wafers at high (greater than 250ºC) deposition temperatures. NREL pioneered the use of a technique called hot-wire chemical vapor deposition in high-efficiency solar cells, recently using it to fabricate a 17.8%-efficient silicon heterojunction cell at temperatures below 200°C.

Another way to reduce cost and silicon use is to deposit high-purity silicon thin films on glass or other inexpensive materials. NREL has dramatically improved the growth rate and quality of silicon thin films grown in this way. If successful, the approach could revolutionize thin-film silicon PV cells.

Rick Matson/PIX14601



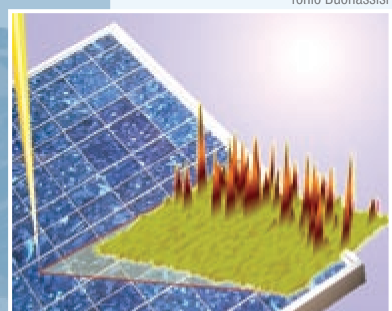


NREL used hot-wire chemical vapor deposition (above) to produce a 17.8%-efficient silicon heterojunction PV cell (right). A heterojunction is a region of electrical contact between two different materials, such as crystalline silicon (c-Si) and amorphous silicon (a-Si).

Universities

Integral to the Crystalline Silicon Research project is an effort involving fundamental and applied research by six universities. This work addresses the most pressing technical issues facing the U.S. PV industry. The research topics are determined largely via consensus among NREL, universities, and industry. There are a variety of alternative approaches to fabricating less-expensive silicon, most of which require overcoming performance-limiting material defects. Detailed study and passivation of such defects are reflected in some current university research projects. Equally important is the universities' role in developing the next generation of crystalline silicon PV technologists. Collaborations between universities and industry set the stage for incorporating graduates into the PV community.

Tonio Buonassisi



A research team led by the University of California, Berkeley, developed a technique for imaging and mitigating the debilitating effects of metal impurities in silicon PV cells, which may enable the PV industry to use impurity-laden, lower-grade silicon. This artist's conception shows X-ray radiation (upper left) striking a point on a PV cell and imaging the distribution of iron impurities.

Recent University Crystalline Silicon Research Projects

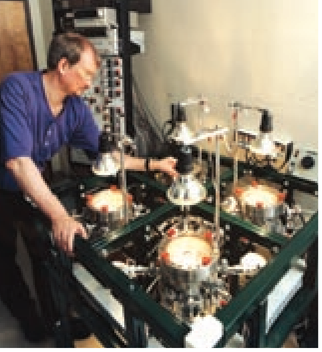
University Partner	Research Activity
California Institute of Technology	Chemical vapor deposition of silicon nitride for passivation and antireflection coating
Georgia Institute of Technology Manufacturing Research Center	Fundamental R&D for improved crystalline silicon solar cells, including in-situ wafer-crack detection; Manufacturing Research Initiative
Massachusetts Institute of Technology	Super prism reflector for high-efficiency thin-film crystalline silicon solar cells
North Carolina State University	Crystal growth and wafer processing for high-yield PV
Texas Tech University/Lehigh University	Hydrogen passivation of silicon solar cells: theory and experiment
University of California, Berkeley	Synchrotron-based analysis of the role of metal contaminants in solar-grade silicon

Georgia Tech

Georgia Institute of Technology, designated a DOE Center of Excellence in 1992, is charged with advancing the competitiveness of PV through applied device research. Georgia Tech consistently produces world-record-efficiency PV cells using a simple cell structure, conventional cell processing with screen-printed contacts, a single-layer antireflection coating, and rapid thermal processing. In a recent effort, Georgia Tech scaled up the size of their laboratory test samples from 4 square centimeters to the industrial size of 149 square centimeters. With this achievement, Georgia Tech is closing in on the goal of achieving 20% efficiency in readily manufacturable PV cells. Georgia Tech also collaborates directly with PV companies to improve device designs and manufacturing technologies.

Ajeet Rohatgi/PIX08532

Georgia Tech's University Center of Excellence for Photovoltaics plays a major role in crystalline silicon research. Georgia Tech consistently produces world-record-efficiency PV cells and holds the current benchmark for six different silicon technologies.



Institute of Energy Conversion/PIX08521

High-Performance PV

Pushing the frontiers of PV performance

The High-Performance Photovoltaics (HiPer PV) project explores the ultimate performance limits of PV technologies. Led by NREL, the project's team of university, industry, and government partners aims to double the sunlight-to-electricity conversion efficiency of PV devices while dramatically cutting the cost of solar energy.

Overcoming the dominance of today's conventional energy sources won't be easy. To meet the challenge and become a mainstream energy option, PV must reach ever-higher levels of performance and cost effectiveness. The achievements can be steady and incremental—or revolutionary. The HiPer PV project seeks revolution, to take grand leaps beyond today's state-of-the-art PV technology.

The project's revolutionary ideas take many forms. Novel thin-film cells are layered to capture more of the sun's energy. Concentrator systems focus light onto ultra-high-efficiency cells. Emerging concepts—such as nano-sized "quantum dots"—promise breakthroughs in PV efficiency and affordability. And a new generation of revolutionary leaders is nurtured through support of PV research at U.S. universities. Following are recent HiPer PV project highlights.

Goals

- Develop thin-film multijunction devices with 25% (cell) and 20% (module) sunlight-to-electricity conversion efficiencies.
- Develop precommercial multijunction concentrator modules with greater than 33% sunlight-to-electricity conversion efficiencies.
- Advance high-risk/high-reward, "third-generation" PV technologies aimed at substantially surpassing the performance of existing technologies.
- Facilitate progress of high-efficiency technologies toward commercial-prototype products.
- Create solar energy research opportunities for minority college students.

Recent High-Performance PV Project Partners

Thin-Film Multijunction Cells
Georgia Institute of Technology
Oregon State University
University of Delaware
University of Florida
University of Oregon
University of Toledo

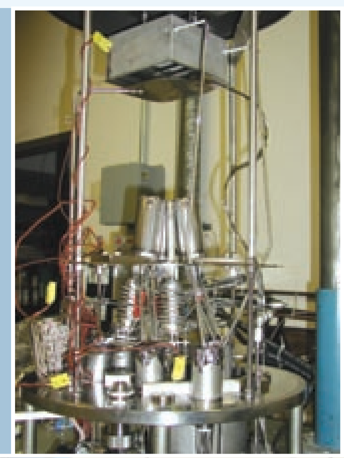
Multijunction Concentrators
Amonix, Inc.
Arizona State University
Boeing-Spectrolab
California Institute of Technology
Concentrating Technologies
JX Crystals
Ohio State University
University of Delaware

Future-Generation and Novel High-Efficiency Concepts
Princeton University
Northwestern University
University of Colorado, Boulder
University of Delaware

Minority University Research Associates Project
Central State University
Fisk University
Howard University
North Carolina A&T State University
North Carolina Central University
Southern University and A&M College
University of Texas, Brownsville
University of Texas, El Paso

Thin-Film Multijunction Cells

Thin-film PV uses an extremely thin layer of active semiconductor, the material that actually converts sunlight into electricity. Thin films can be layered to form a "multijunction" cell. Each layer produces electricity from a different wavelength of sunlight. NREL recently fabricated a world-record 15.3%-efficient thin-film multijunction cell as part of the HiPer PV project—see the Electronic Materials & Devices highlight on page 7. The University of Delaware's Institute of Energy Conversion developed a process to improve the CIGSS (copper indium gallium sulfur-selenide) layer of a multijunction cell, recently demonstrating 11.9% efficiency from that layer alone.



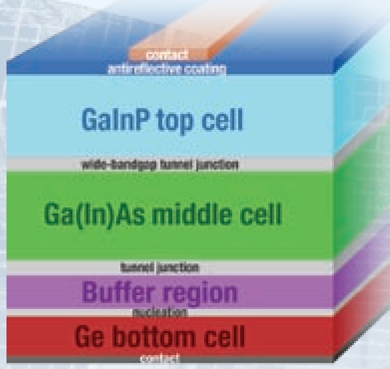
William Shafarman

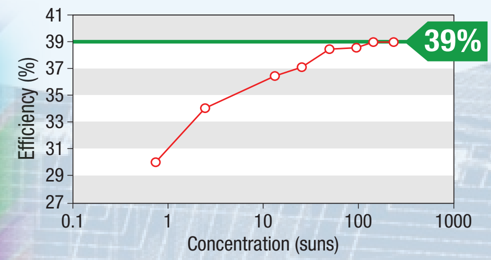
William Shafarman

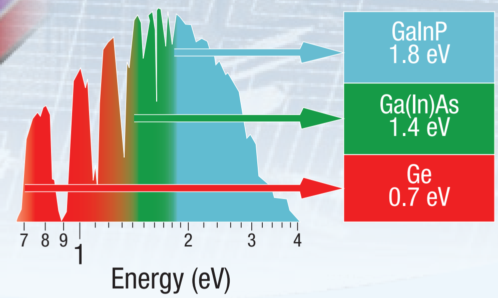
A team at the University of Delaware's Institute of Energy Conversion (right) developed a physical vapor deposition system (in background at right, detail at top right) for elemental evaporation of CIGSS thin films.

Multijunction Concentrators

PV concentrator systems use relatively inexpensive optics to concentrate sunlight onto a small area of high-efficiency multijunction cells. When sunlight is concentrated onto multijunction cells, they become even more efficient than under normal ("1-sun") conditions. As part of the HiPer PV project, NREL recently fabricated an "inverted" multijunction cell with a world-record efficiency of 37.9% at a concentration of 10.1 suns—see the Electronic Materials & Devices highlight on page 7. Boeing-Spectrolab achieved a world-record 39.3% efficiency for another type of multijunction cell—the highest NREL-confirmed efficiency ever measured for a PV device.





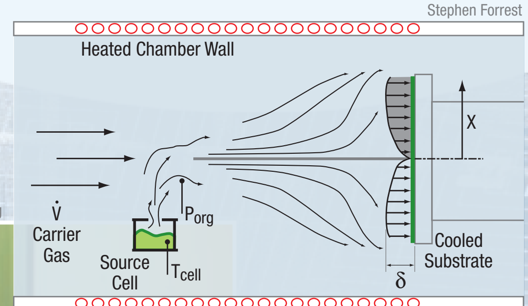


Boeing-Spectrolab's 39.3%-efficient multijunction cell: structure (top left), energies of sunlight converted to electricity by each of the cell's materials (bottom right), and graph of increasing efficiency with increasing concentration, showing highest efficiency achieved at 236 suns (top right).

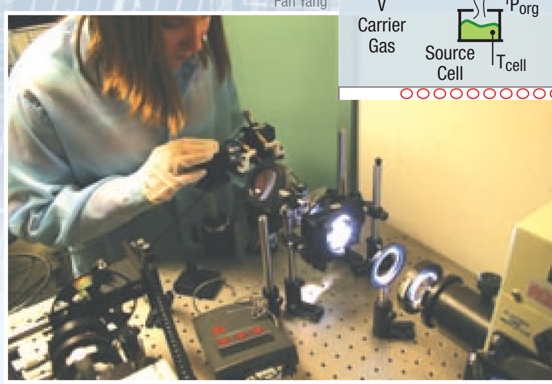
Future-Generation and Novel High-Efficiency Concepts

Fundamental research in advanced materials and processes is the first step toward tomorrow's PV innovations. NREL and numerous universities are investigating a wide range of novel approaches. Research on organic PV cells could result in ultra-low-cost plastic PV, or even PV "paint" that turns entire buildings into power plants. Nano-science is employing infinitesimal quantum dots to triple the electricity produced by each photon of sunlight. Other efforts include dye-cell research, solid-state spectroscopy and theory, and computational materials science. Perhaps most importantly, new potentially world-changing ideas are blossoming every day in the minds of some of the nation's top scientists.

Stephen Forrest



Fan Yang



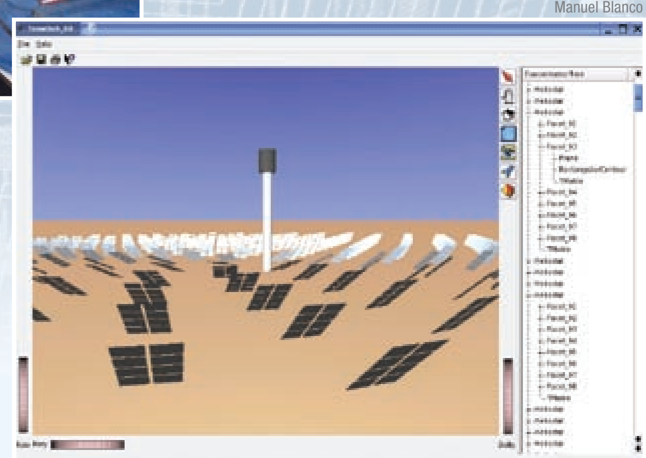
Researchers at Princeton University use their organic vapor-phase deposition system (schematic above) to boost the efficiency of organic PV cells (being measured at left).

Minority University Research Associates

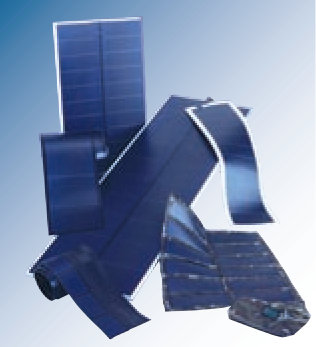
The Minority University Research Associates (MURA) project encourages minority college students to pursue careers in renewable energy science and technology. Undergraduates perform research at their universities during the academic year, then intern with industry or DOE national laboratories during the summer. The project has sponsored more than 100 students—some who have gone on to pursue graduate degrees and positions in government and industry solar research—and produced many solar energy research accomplishments.

Manuel Blanco

Manuel Blanco



MURA associates at the University of Texas at Brownsville—including undergraduates Juana Amieva and Azael Mancillas (above)—are developing Tonatiuh, a software tool for designing and analyzing concentrating solar power systems (right).



United Solar Ovonic/PIX13567

Thin Film PV Partnership

Fulfilling the promise of thin-film photovoltaics

The Thin Film PV Partnership spearheads R&D on emerging thin-film PV technologies. Led by the National Center for Photovoltaics and NREL, the Partnership leverages the combined efforts of the thin-film PV industry, universities, and government research institutes.

The idea of thin films is simple: truly cost-competitive PV devices can be produced by using an extremely thin layer of active semiconductor, the material that actually converts sunlight into electricity. The semiconductor layers on thin-film PV cells are only a few millionths of a meter thick and deposited on inexpensive materials such as glass.

The Thin Film PV Partnership has helped reduce costs and improve performance of thin-film devices over the past decade, and thin films have recently burst into the marketplace. By 2010, U.S. production of thin-film modules is expected to exceed that of crystalline silicon modules. The United States continues to be a world leader in thin-film module manufacturing as well. A recent survey by the Partnership indicates the United States will account for almost half of the projected 500 megawatts (MW) of global thin-film production capacity in 2008. World thin-film production was 85 MW in 2005.

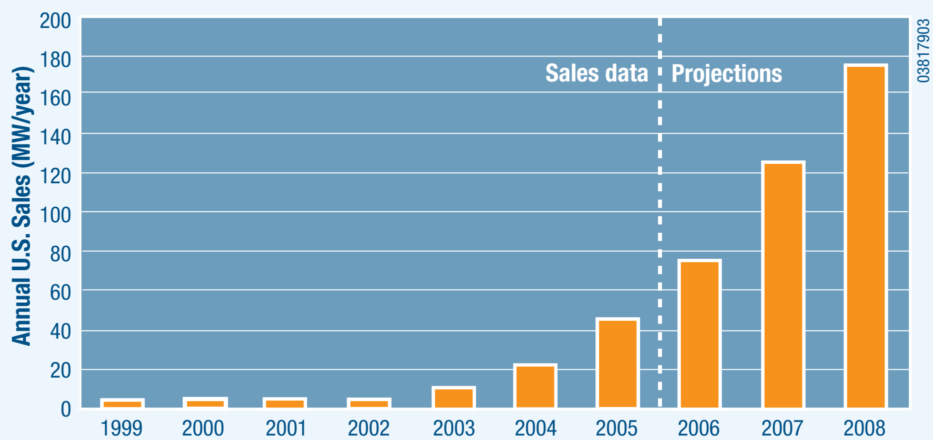
Goals

- Support the near-term transition to first-time manufacturing and commercial introduction of reliable thin-film PV modules.
- Build a technology base on which thin films can continue to improve in terms of manufacturing, performance, reliability, and reduced cost for products competitive in the PV marketplace.
- Sustain innovation to support progress toward ambitious long-term PV cost and performance goals leading to cost-competitive PV electricity.

Recent Thin Film PV Partnership Participants

- Brookhaven National Laboratory
- Case Western University
- Colorado School of Mines
- Colorado State University
- Energy Conversion Devices
- Energy Photovoltaics
- First Solar
- Florida Solar Energy Center
- Global Solar Energy
- International Solar Electric Technologies
- Iowa State University
- ITN Energy Systems
- NanoSolar
- National Institute of Standards and Technology
- National Renewable Energy Laboratory
- Pacific Northwest National Laboratory
- Pennsylvania State University
- Shell Solar Industries
- Syracuse University
- Texas A&M University
- United Solar Ovonic
- University of Delaware, Institute of Energy Conversion
- University of Florida
- University of Illinois
- University of Nevada
- University of North Carolina, Chapel Hill
- University of Oregon
- University of South Florida
- University of Toledo
- University of Utah

Despite the success so far, much R&D remains to be done to make thin films competitive with conventional energy sources. Research areas include improving the fundamental understanding of materials and devices, increasing device efficiency and reliability, and developing manufacturing capabilities for large-scale production. The Thin Film PV Partnership supports these efforts with a focus on amorphous silicon, cadmium telluride, and copper indium diselenide thin films. Following are highlights of several partners working on these technologies.



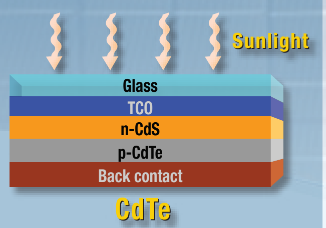
Historical (through 2005) and projected (2006–2008) U.S. sales of thin-film PV modules made in the United States. Source: NREL.

Amorphous Silicon

United Solar Ovonic (Uni-Solar) manufactures a 136-watt (W) "peel-and-stick," flexible, multijunction amorphous silicon (a-Si) thin-film module for commercial rooftop applications. Its sales in 2005 were about 22 MW. Uni-Solar has also reported achieving a record 15.1%-efficient (active area, initial efficiency) tandem a-Si/nanocrystalline-Si cell. Improving this technology to the point of commercial production is a major focus of Uni-Solar's continuing R&D efforts.

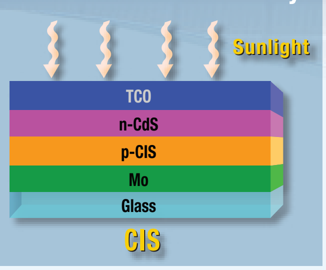
Cadmium Telluride

First Solar, LLC, is the major Thin Film PV Partnership industry partner focusing on cadmium telluride (CdTe) thin films. The company sold about 20 MW of CdTe PV in 2005 and is planning to increase its production capacity to 100 MW in 2007. In 2003, First Solar and NREL shared an R&D 100 Award for developing an innovative CdTe module manufacturing process.



Copper Indium Diselenide

Shell Solar Industries manufactures thin-film modules based on copper indium diselenide (CIS, which is called CIGSS when the elements gallium and sulfur are added). The company has fabricated an 11.7%-efficient, 86-W thin-film CIGSS module, which is entering the European market in 2006. Shell Solar collaborates extensively with NREL and the Partnership's National CIS R&D Team. Among other accomplishments, NREL researchers have fabricated a thin-film CIGS solar cell with a record total-area efficiency of 19.5% using an NREL-patented three-stage process.



United Solar Ovonic

Uni-Solar "peel-and-stick" a-Si thin-film modules in a 300-kW array, Beijing Capital Museum, China.

United Solar Ovonic

President George W. Bush tours Uni-Solar's manufacturing plant in Michigan to highlight his 2006 Solar America Initiative.

First Solar

First Solar CdTe thin-film modules in a 1.3-MW solar field, Germany.

Harin Ullal

Shell Solar 1.5-kW array composed of 80-W CIS modules undergoing long-term reliability testing at NREL's Outdoor Test Facility.

Evergreen Solar

PV Manufacturing R&D

Teaming with industry to accelerate production, slash costs

The PV Manufacturing R&D (PVMR&D) project unites the resources of government and industry to boost PV manufacturing productivity and cut costs. Under the project, NREL subcontracts with members of the U.S. PV industry to perform cost-shared R&D aimed at enhancing existing PV manufacturing technologies and facilitating adoption of new PV technologies into the marketplace.

Since its inception in 1991, the project has issued more than 70 subcontracts with more than 40 companies. These partnerships have resulted in increased PV production capacity, decreased PV manufacturing costs, and a substantial return on the public-private investment in the project.

The research addressed by PVMR&D subcontracts is guided by U.S. PV industry participants. Crystalline silicon, thin-film, and concentrator technologies are included. Projects are chosen primarily by external evaluators based on which activities are most likely to advance PVMR&D goals.

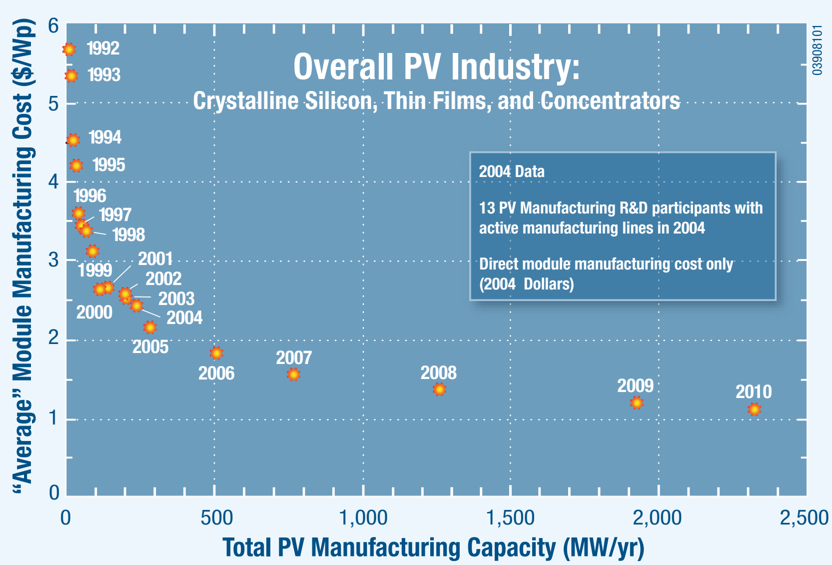
Most subcontracts have addressed process-specific improvements, module manufacturing, or balance-of-systems work. Recent work has focused specifically on integrating state-of-the-art process controls with current production technology, improving manufacturing yield, and enhancing module field reliability and durability. Following is a sample of project participants and recent accomplishments.

Goals

- Improve PV manufacturing processes and products.
- Accelerate PV manufacturing cost reductions.
- Increase commercial PV product performance and reliability.
- Establish a technological foundation supporting significant U.S. PV manufacturing scale-up.
- Position the U.S. PV industry to meet rapidly emerging large-scale deployment opportunities.
- Achieve these goals in an environmentally safe manner.

PV Manufacturing R&D Project Industry Participants since 2001

Company	Technology/Process
AstroPower, Inc./GE Energy (USA), LLC, Delaware	Silicon Film™ PV
BP Solar International, LLC, Maryland	Cast silicon PV
Dow Corning Corporation, Michigan	PV module packaging
Energy Conversion Devices, Inc., Michigan	Amorphous silicon thin-film PV
Energy Photovoltaics, Inc., New Jersey	Amorphous silicon thin-film PV
Evergreen Solar, Inc., Massachusetts	String Ribbon™ silicon PV
First Solar, LLC, Ohio	Cadmium telluride thin-film PV
ITN Energy Systems, Inc., Colorado	CIGS thin-film PV manufacturing processes
PowerLight Corporation, California	PV systems integration
RWE SCHOTT Solar/SCHOTT Solar, Inc., Massachusetts	EFG ribbon silicon PV
Shell Solar Industries, California	Single-crystal Cz silicon PV
Sinton Consulting, Inc., Colorado	Silicon characterization instruments
Specialized Technology Resources, Inc., Connecticut	PV module packaging
Spire Corporation, Massachusetts	PV module manufacturing processes
SunPower Corporation, California	Single-crystal float-zone silicon PV
Xantrex Technology, Inc., California	Inverters

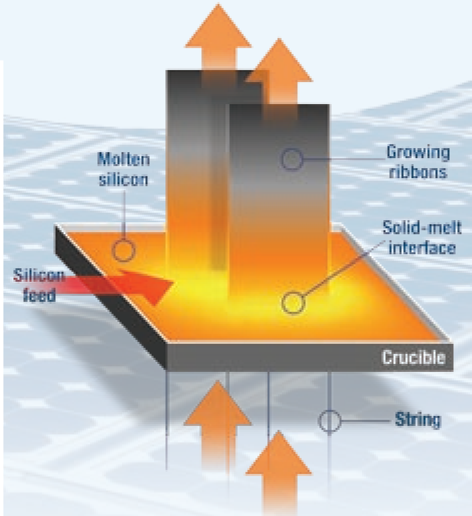


U.S. PV module manufacturing cost vs. capacity, 2004. Since 1992, production capacity of PVMR&D participants grew from 14 to 240 megawatts at the close of 2004—a 16-fold increase. At the same time, direct manufacturing costs (in 2004 dollars) declined from $5.70 to $2.44 per peak watt, a 57% decrease. Year 2005–2010 projections shown on the graph are PVMR&D goals.

Evergreen Solar
Marlboro, Massachusetts

Evergreen Solar manufactures PV modules using its unique String Ribbon technique. Under a PVMR&D subcontract, Evergreen Solar developed the technology to grow two String Ribbons from a single crucible, doubling ribbon growth capacity within the same manufacturing space.

Evergreen Solar



PowerLight Corporation
Berkeley, California

PowerLight Corporation's PowerGuard® tiles are used to mount large PV systems directly to roofs without mechanical fastening—the easy installation reduces PV system cost. PowerLight has made many improvements to the tiles as part of the PVMR&D project, including manufacturing yield increases, cost reductions, and implementation of quality-assurance systems. The company recently designed a prototype foamless tile and began applying PVMR&D improvements to its new sloped PowerGuard tiles.

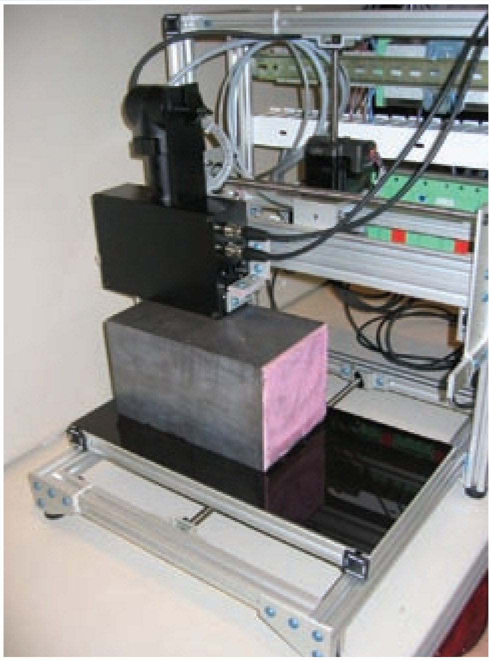
PowerLight Corp./PIX13454

PowerLight Corp./PIX14594

Sinton Consulting
Boulder, Colorado

Under a PVMR&D subcontract, Sinton Consulting developed an instrument that measures silicon at an early stage in the PV manufacturing process, providing information that helps companies ensure quality, reduce waste, and monitor solar cell costs. This "Quasi-Steady-State Silicon Evaluation System" received a prestigious R&D 100 Award in 2005, which recognized it as one of the year's most technologically significant new products.

Sinton Consulting



R&D 100

Additional PV R&D

Sandia National Laboratories/PIX08978

This solar carport at the Indian Pueblo Cultural Center in Albuquerque, New Mexico, is part of the Million Solar Roofs/ Solar Powers America initiative.

Warren Gretz/PIX03877

PV modules of all types are analyzed at NREL's Outdoor Test Facility.

Neelkanth Dhere

The Florida Solar Energy Center tests PV systems under hot and humid conditions.

The efforts detailed in the previous sections are complemented by additional R&D projects that, though smaller, are vital to the success of solar technologies. Following are brief descriptions of these projects and key players involved.

Million Solar Roofs/Solar Powers America

DOE Headquarters and Regional Offices, NREL, SNL, Interstate Renewable Energy Council, National Energy Technology Laboratory

Facilitates installation of solar energy systems on U.S. buildings.

Domestic PV Applications

NREL, SNL

Provides a focal point for DOE activities through developing projects, disseminating information, promoting public awareness, managing subcontracts, and providing technical assistance.

PV Module Reliability R&D

NREL, SNL

Develops and applies advanced module measurement techniques, diagnostic methods, and instrumentation to mitigate degradation, reduce costs, and improve performance.

PV Systems Analysis

NREL, SNL

Performs systems performance and cost modeling, market/value/policy analysis, and benchmarking projects.

Solar Resource Characterization

NREL

Addresses solar resource assessment including access to data and characterization of the solar resource.

Regional Experiment Stations

SNL, DOE Golden Field Office (DOE/GO), University of Central Florida/Florida Solar Energy Center, New Mexico State University

Provides technical support to the Solar Energy Technologies Program, including reducing systems costs, improving systems reliability, improving system performance, and removing barriers to deployment.

Building-Integrated PV

NREL, DOE/GO

Fosters widespread acceptance of PV-integrated buildings by overcoming technical and commercial barriers and facilitating the integration of PV into the built environment through technology development, applications, and key partnerships. See the Solar Decathlon feature on the following page.

Warren Gretz/PIX10222

A researcher at NREL's Solar Radiation Research Laboratory inspects a radiometer, one of the tools the lab uses to collect solar resource information.

PV Systems Engineering

NREL, SNL, DOE/GO

Characterizes performance and reliability of emerging PV technologies, assists with development and implementation of codes and standards, and provides world-class solar irradiance capabilities, measurements, and standards.

System Evaluation and Optimization

SNL

Provides laboratory and field-test information to establish the performance and reliability of current PV systems and identifies opportunities for improved system design and component integration in next-generation systems.

Sandia National Laboratories/PIX07115

Research at SNL improves the integration of PV with U.S. electrical systems.

Inverter & BOS Development

SNL

Supports engineering advancements through characterization feedback of newly developed power electronics and balance-of-systems (BOS) hardware and establishes suitability for incorporation of new inverters and BOS into integrated systems.

Environmental Health and Safety

Brookhaven National Laboratory

Minimizes potential environmental health and safety impacts associated with current and future PV energy systems and applications.

In Focus

The Solar Decathlon

Challenging students to build the solar future

When students compete in the Solar Decathlon, they make a bold statement about the value of solar energy—to themselves, their communities, and the entire world. In this international collegiate competition, student teams design, build, and operate attractive, highly energy-efficient, completely solar-powered houses. The students and houses compete in ten contests that reflect all the ways people use energy in their homes.

During two years of planning, building, and unceasing productivity leading up to the active competition, a remarkable transformation occurs. The student architects and engineers come to embrace the possibilities of energy efficiency and solar energy. Their myriad innovations stimulate R&D and advance solar technologies. The students go on to share their passion with leaders and building professionals in their communities—and with the media and public who see their masterpieces on display. Perhaps most importantly, they bring their unique knowledge of solar energy into their future careers as architects and engineers.

For more information, visit the Solar Decathlon Web site: www.solardecathlon.org.

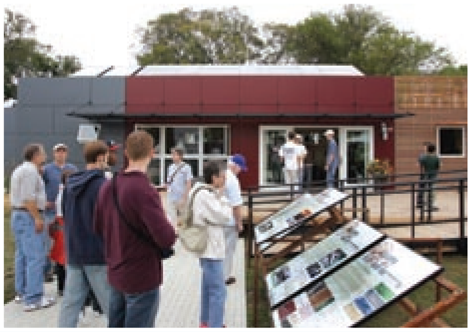
Crowds of visitors make it clear that the American public is hungry to learn about clean, renewable energy. Combined, the Solar Decathlons in 2002 and 2005 drew more than 250,000 to the National Mall in Washington, D.C.

PIX14606

In 2005, as in 2002, the University of Colorado team brought home the top trophy by achieving the highest combined score for all ten Solar Decathlon contests. Second-place Cornell, third-place Cal Poly, and fourth-place Virginia Tech each won two individual contests in 2005.

PIX14604

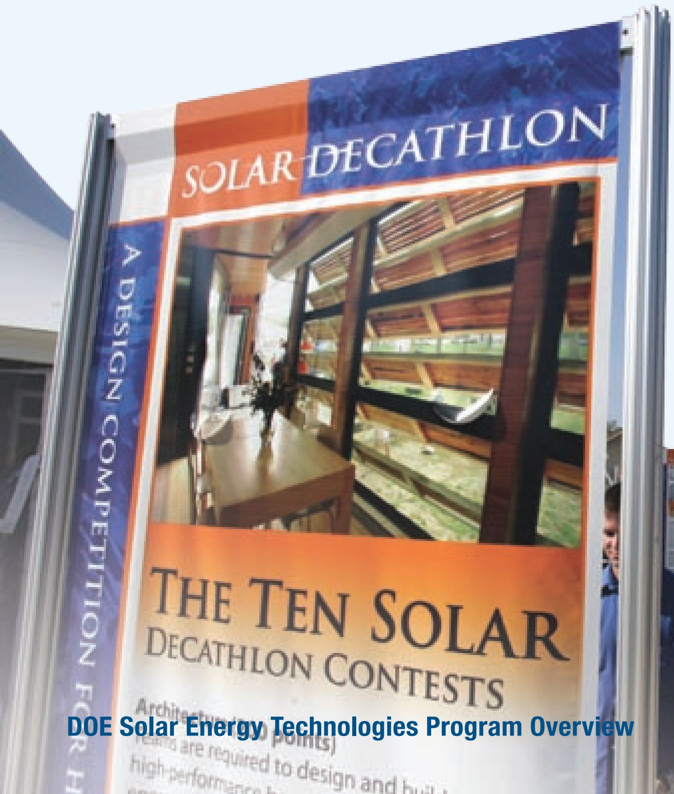
The 2005 Solar Decathlon Architecture Jury confers on the merits of the New York Institute of Technology's house. The jury was especially impressed by the students' use of solar panels to generate hydrogen for a fuel cell. Eight separate judging panels weighed in during the competition, all comprising experts in their respective fields (e.g., engineering, lighting, and communications).



Student-led house tours are a major element of the Communications contest. Cal Poly students began the tour outside the house with signage describing design features and specific components.

PIX14605

Student team members from the University of Puerto Rico assemble their house before the start of the second Solar Decathlon in October 2005. The students dedicated two years of their lives to this project, beginning with college courses on energy efficiency and "Solar Energy 101."



All photos by Stefano Paltera/Solar Decathlon

Geri Kodey

Solar Thermal Technologies

Creating innovative avenues to competitive solar energy

Solar thermal technologies employ a variety of methods to convert sunlight into useful energy. The DOE Solar Thermal Subprogram leads the efforts of national laboratories, industry, and universities in making these technologies viable energy sources for today and tomorrow.

The Solar Thermal Subprogram comprises two key activities: concentrating solar power (CSP) and solar heating and lighting (SH&L). CSP technologies—which include parabolic trough and dish/engine power plants—concentrate sunlight up to 1,000 times to generate electricity. SH&L technologies harness the sun to provide hot water, space heating, and lighting for buildings. Following are recent CSP and SH&L highlights.

Goals

- Support development and expansion of near-term and next-generation parabolic trough technology for centralized power generation.
- Improve reliability, performance, and cost of dish/engine components and systems and support industry in commercializing the technology.
- Collaborate with U.S. industry to reduce the cost of energy from solar domestic water heaters by at least 50%.
- Design, fabricate, test, and disseminate information about high-performance hybrid solar lighting systems.

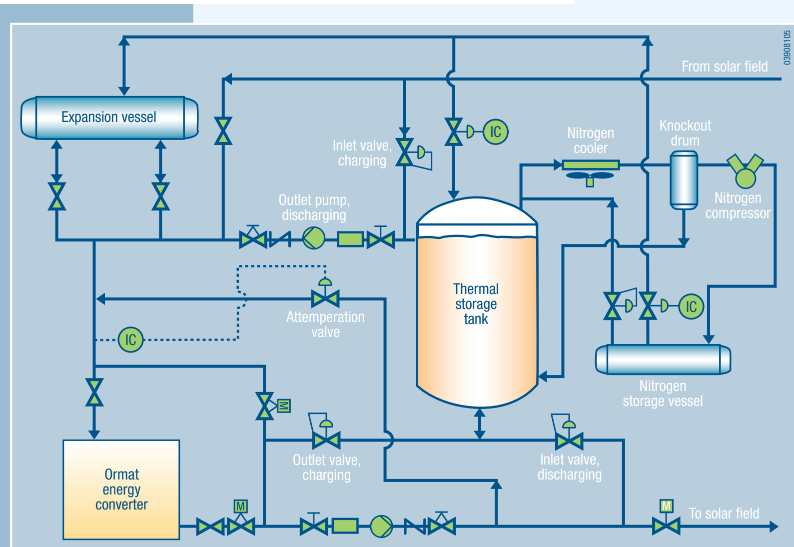
Geri Kodey

The first commercial parabolic trough plant in nearly 15 years was completed at the end of 2005. Owned by Arizona Public Service, the 1-MW plant features parabolic trough collector technology developed by Solargenix under a cost-shared R&D subcontract with NREL.

Parabolic Trough Systems

Parabolic trough systems use mirrors to focus sunlight onto an oil-filled receiver pipe. The heated oil is then used to generate electricity in a conventional steam turbine. Trough power plants are the lowest-cost centralized solar power option, with great potential to become directly competitive with conventional power sources. One objective of the NREL-led Parabolic Trough R&D project is to advance trough technologies that can be deployed in sunny areas such as the Southwest United States in the near term. The longer-term objective is to develop advanced technologies that make future trough plants competitive with conventional power plants.

To achieve these objectives, the project is helping to increase the availability of U.S. solar collector technology, improving parabolic trough receivers, and supporting development of advanced thermal storage technologies. The project is also improving tools and testing capabilities and improving the technological knowledge base necessary to support the needs of a growing U.S. trough industry.



Thermal energy storage (TES) technologies allow solar energy to be stored when the sun is shining and used when power is needed most. The Parabolic Trough R&D project is working to reduce the cost of TES through development of a single-tank thermocline TES system, which will reduce the cost of TES by more than 50% compared with a two-tank system.

Dish/Engine Systems

Dish/engine systems use dish-shaped arrays of mirrors to concentrate sunlight onto receivers. The heated receiver provides energy to an engine, which produces electricity. As part of the Dish/Engine System R&D project, Stirling Energy Systems (SES) and SNL are collaborating to improve dish/engine system performance, reliability, and cost and to deploy systems in the Southwest United States.

The SES dish/engine system is based on a McDonnell Douglas system with a record 29.4% sunlight-to-electricity efficiency. SES and its industry partners are redesigning the system for low-cost, high-volume production. The development hardware has been financed through private-sector sources, with DOE providing in-kind engineering support through SNL. This unique relationship has been highly effective in advancing the SES technology. Deployment opportunities are promising as well. To date, SES has announced power purchase agreements of 500–850 MW with Southern California Edison and 300–900 MW with San Diego Gas and Electric.

J. Lloyd

The six-dish Model Power Plant at SNL facilitates SES dish/engine R&D, including system development and reliability improvement.

Solar Water Heaters

Solar water heaters are the least expensive type of solar power and have a large potential for reducing conventional energy use—domestic hot water accounts for about 13% of U.S. residential energy use. Barriers to widespread use of solar water heaters include initial cost as well as unfamiliarity with the technology by builders, architects, plumbers, and roofers. DOE, NREL, and industry partners aim to reduce the cost of energy from mild-climate and cold-climate solar water heaters by at least 50% by using low-cost polymer materials and simplifying manufacturing, assembly, and installation.

Davis Energy Group

FAFCO

Two approaches to low-cost solar water heating: Davis Energy Group/SunEarth's glazed and unglazed polymer integral collector storage (above) and FAFCO's thermosiphon system (right).

Hybrid Solar Lighting

Artificial lighting is the largest component of electricity use in commercial U.S. buildings. Hybrid solar lighting can reduce electricity demand while improving light quality and reducing the waste heat produced by conventional electric bulbs. Hybrid solar lighting "routes" sunlight through optical fibers into buildings, where it is combined with electric light in hybrid light fixtures. Sensors keep room lighting steady by adjusting the electric lights based on the sunlight available. DOE, Oak Ridge National Laboratory, and industry partners are collaborating to design, fabricate, and test high-performance hybrid solar lighting systems.

Melissa Lapsa

Phil Toledano

Oak Ridge National Laboratory installed a hybrid solar lighting system at Sacramento Municipal Utility District's Customer Service Center (left). Sunlight collected by such a system is routed through optical fibers to provide interior lighting (right).

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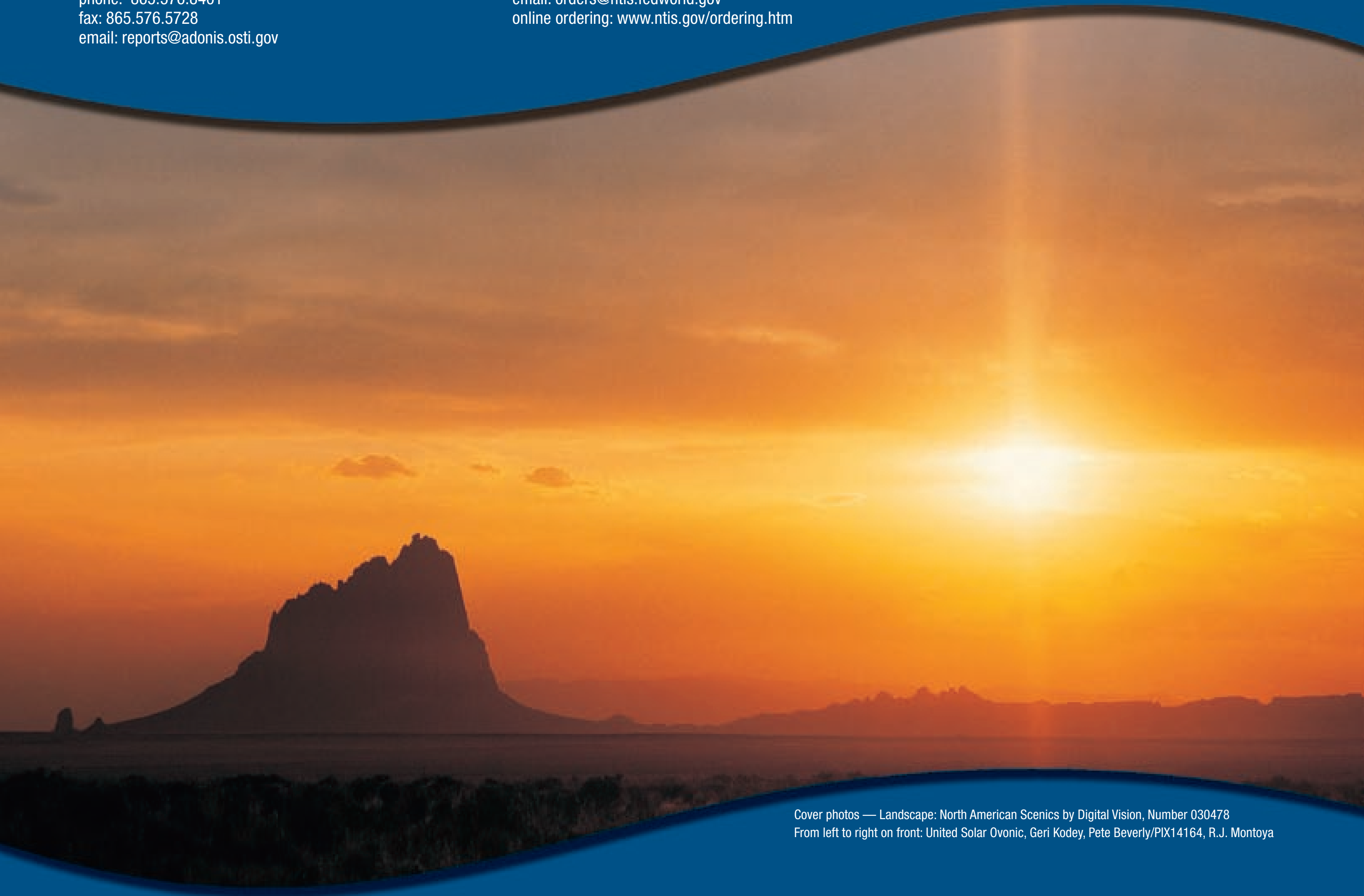

Cover photos — Landscape: North American Scenics by Digital Vision, Number 030478
From left to right on front: United Solar Ovonic, Geri Kodey, Pete Beverly/PIX14164, R.J. Montoya

U.S. Department of Energy
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