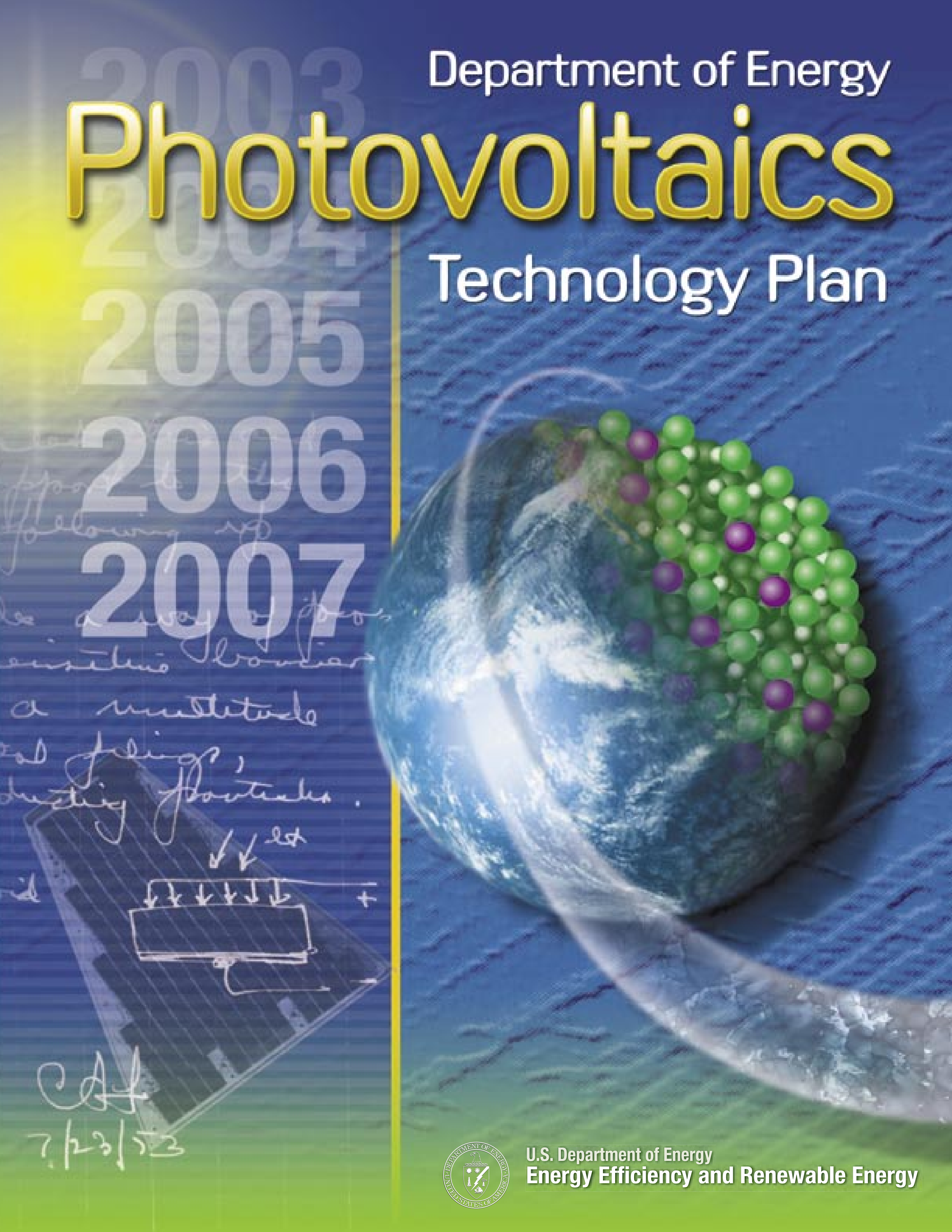


Department of Energy

# Photovoltaics

## Technology Plan

2003
2004
2005
2006
2007

U.S. Department of Energy
Energy Efficiency and Renewable Energy

# Great Ideas Changing the World

**1953** was a seminal year for science and technology, for how we view and un-derstand the world, and for how we shall live in it. That year, two great ideas were born—one on each side of the Atlantic.

*Gerald Pearson, Daryl Chapin, and Calvin Fuller (L to R) present to the public the first material to directly convert enough sunlight into electricity to generate useful amounts of power. (Courtesy of Bell Labs)*

In the Cavendish Laboratories of Cambridge, England, James Watson and Francis Crick unveiled their double helix model of DNA, or deoxyribonucleic acid. Today, 50 years later, this model has become the basis for our understanding of chromosomes, cell machinery, protein and enzyme synthesis, genetics, and evolution. It is leading to spectacular advances in medicine, genome and cancer research, genetic engineering, embryology, and cloning—and may one day even have a hand in energy production.

That same year, a second revolution was being initiated at Bell Laboratories in Murray Hill, New Jersey. There, Daryl Chapin, Calvin Fuller, and Gerald Pearson were developing the first practical solar cell—a 2.5-cm$^2$ cell made of crystalline silicon doped with phosphorous and boron to form the p-n junction, and with a conversion efficiency of about 6%. This small beginning would spur the growth of new industries, have a major impact on materials science, be fundamental in transforming communications, present an important new way to provide electricity for the nation and the world—and may one day even be used to power miniature medical probes.

Looking back on these 50 years of PV, we may be surprised at just how much progress the technology has made since that first silicon cell:

- Yearly production has soared from that single diminutive cell to more than 5 billion cm$^2$ of solar cells in 2002 (560 million watts)—an increase of 10 orders of magnitude.
- Module costs have plummeted, from about $1,500 per watt in 1955 (in 1955 dollars) to $3–$4 per watt (in 2003 dollars).
- We have grown from a market that was limited to powering a few satellites in the 1960s and 1970s to one that is worth $4 to $5 billion in PV modules and systems. And PV applications now embrace the whole spectrum of human electrical needs, including power for portable electronics, irrigation and farming, cabins and houses, buildings and manufacturing facilities, communities and villages, the grid and for remote use, satellites and repeating stations at the heart of telecommunications, and power that can be built into the structure and skin of buildings.
- From that first 2.5-cm$^2$ cell that produced only a few milliwatts of power under unconcentrated light, we are now able to make 1-cm$^2$ cells that produce 350 watts under 1200-suns concentration and nearly 90 kWh of electrical energy per year.
- Cells used to be made from only one material system—crystalline silicon—and one homojunction structure. Now, we make cells and modules using a variety of material systems (a-Si, CIGS, CdTe, and III-Vs) and device structures (single, double, and triple junctions; and homo- and heterojunctions).
- We have grown from a terrestrial market that was nonexistent in the 1950s and 1960s, and was still very small in the early 1980s, to today's market of more than 2.2 billion watts of PV installed worldwide, thanks to phenomenal growth rates of 24% per year during the last 15 years and 35% during the last 7 years.

Yes, PV technology has progressed greatly these last 50 years. Yet, from our vantage point, we can be

1953

**Jan/Feb 1953** — Daryl Chapin begins testing selenium solar cells in his studies of stand-alone power systems.

**March 1953** — Gerald Pearson detects a strong photovoltaic effect in a rectifier built according to Calvin Fuller's method of producing p-n junctions in silicon by lithium diffusion.

**March 1953** — Pearson provides Daryl Chapin with the device. Chapin reports obtaining 5 times more power from Pearson's sample cell than the commercial selenium cells Chapin had tested. ↓

**May/June 1953** — Chapin chooses to concentrate on silicon in his photoelectric studies. ↑

**Sept/Oct 1953** — Chapin reports that a phosphorus-diffused silicon solar cell outperforms Pearson's original cell by a factor of 2, reaching an efficiency of 4%.

**Nov/Dec 1953** — No matter what he tries, Chapin cannot exceed 4% efficiency with phosphorus-diffused silicon.

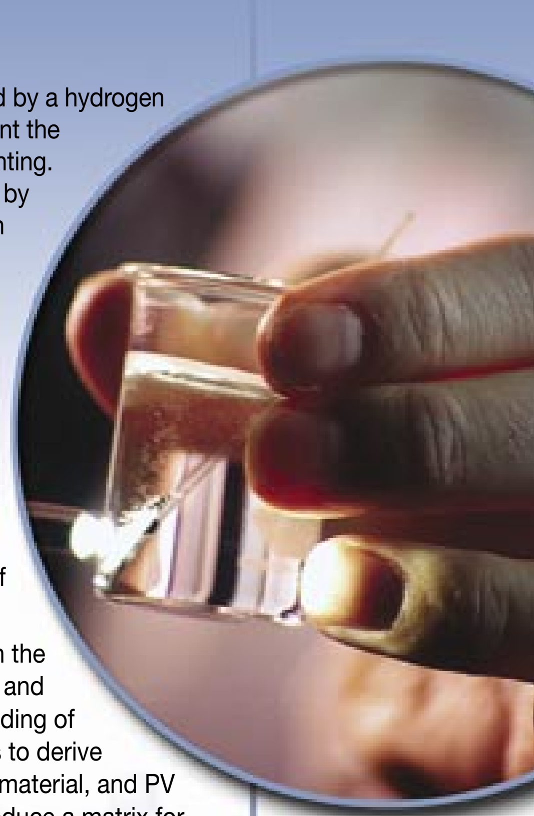
certain of far greater progress in the next 50 years. Consider:

- We are taking existing PV technologies to the next level of high efficiency and low cost, where multijunction thin-film modules will convert 20% of the sun's energy to electricity, and where high-bandgap, high-efficiency devices for use under concentrated sunshine will deliver power for under $1 per watt.
- Our advances in materials science are enabling us to engineer the bandgaps of materials, pointing the way toward multijunction cells that may soon be able to reach conversion efficiencies greater than 40%.
- Photovoltaics is integral to a trend toward the use of distributed generation technologies that can be employed on minigrids, used to boost electric power at a substation level, or used locally for electricity or for highly efficient combined heat and power.
- We are exploring a range of new and exciting ideas that may help "leapfrog" PV to a new level of versatility, low cost, and high efficiency:
    - Quantum dots and quantum rods, in which quantization effects allow us to "tune" bandgaps precisely, leading to efficient capture and conversion of the entire solar spectrum.
    - Conjugated polymer solar cells, which incorporate quantum dots, quantum rods, $C_{60}$ materials, and nanotubes to convert sunlight or transmit electrons; which may be flexible enough to conform to interesting surfaces; the polymer materials of which may be manipulated to tune bandgaps and thus capture and convert a wide portion of the solar spectrum; and which may one day be printed or even "painted" onto a surface.
    - Cells that can use the excess energy imparted to a generated charge carrier to produce more electricity or to generate another charge carrier, rather than be wasted as heat, and thus, greatly increase the conversion efficiency.

Through these and other innovations, we can imagine a future in which PV technology is part of a total domestic energy package…a future in which you may drive home from work and plug your car, powered by a hydrogen fuel cell, into your house to supplement the electricity needed for cooking and lighting. During the day, electricity—produced by the PV system integrated into the skin and structure of your house—will exceed the needs of the house and be used to split hydrogen from water. This hydrogen represents a means of storing solar energy in a form that can be used the next morning as fuel for your car. This whole-systems approach will allow houses, with their energy-efficient designs and renewable energy systems, to become net generators of energy, rather than net consumers.

And we can imagine a future in which the two great ideas of 1953 will intersect and unite. Where, for example, understanding of the double helix will enable scientists to derive conjugated polymers from cellulosic material, and PV scientists will use that material to produce a matrix for polymer solar cells. Or where biochemists and physicists work together to develop cellulosome proteins that can be coupled with quantum dots and used to maneuver the dots into ordered arrays, which can then be embedded into a conjugated polymer matrix. Or where advanced microsized thermophotovoltaic systems may use the heat of the human body to power microrobots that could be used to repair internal bodily parts and organs.

The next 50 years offer great promise—of wondrous new technologies; of hundreds of billions of watts, or even terawatts, of installed PV systems; of truly inexpensive PV electricity; of a hydrogen, PV, and solar economy; and of PV and solar industries emerging among the most important industries of the world. And though some of the exciting and more "radical" ideas may fall by the wayside, PV markets, PV technologies, and PV progress will march on inexorably. This five-year plan represents some of the next important steps on that march toward such a future.



*Fifty years hence, we may witness the emergence of a solar-hydrogen future where solar electricity is used to generate hydrogen from water via electrolysis, presenting the nation and the world with a pristine way to produce energy—not only for electricity, but for heat and fuels.* *(Richard Peterson, PIX01443)*

**January 1954** — Fuller, starting with arsenic-doped silicon, diffuses boron to form a thin p-layer. ↓

**April 25, 1954** — At a press conference in New York, Daryl Chapin, Calvin Fuller, and Gerald Pearson present to the public the first material to directly convert enough sunlight into electricity to generate useful amounts of power. ↑

**1958** — First PV-powered satellite is launched. ↓

**1958** — RCA Labs investigates gallium arsenide, indium phosphide, and cadmium telluride cells.

**1960** — First solar-powered transcontinental radio broadcast is made between U.S. Signal Corps (NJ) and Hoffman Electronics (CA), USA.

1960

# Delivering the Promise

**Yes,** we can imagine the promise that PV holds 50 years hence. But delivering that promise entails having a technical plan that shepherds a wide portfolio of technologies through phases of R&D, from basic concepts to applications. It entails a cooperative national endeavor among America's scientific, engineering, and industrial talent—from industry, academia, and national laboratories—to accelerate the development of PV. And it entails guiding the effort from the federal level, through policies, organization, funding, and strategies.

## The Technical Plan

**Fundamental Research.** This part of the Plan covers basic research, material and device characterization, high-efficiency concepts, and most of the research on crystalline silicon.

*Basic & University Research* — Scientists explore new concepts that could leapfrog PV past its present state of the art, to result in far cheaper and more efficient devices. These include organic solar cells, quantum-dot solar cells, and quantum rods in polymer matrices. By the end of 2007, scientists expect to identify the most promising of the new concepts, provide a theoretical understanding of doping high-bandgap and organic materials, and assess the viability of radical ideas, such as cells in which a single photon could produce two charge carriers.

*Measurements & Characterization* — Researchers determine the electro-optical properties of semiconductor materials, analyze material surfaces and interfaces, investigate the structure and composition of materials, evaluate output performance of devices, create diagnostic tools for manufacturing processes, and develop novel characterization techniques. These activities are vital for the progress of PV technology, especially with the emergence of exotic materials, nanotechnologies, and the arising need for intelligent process control.

*High-Performance & Concentrator Research* — The goal is highly efficient cells for use with concentrators to produce low-cost power. To date, researchers have made a triple-junction cell (GaInP/GaAs/Ge) that is 32% efficient under 1-sun and greater than 36% under 600-suns concentration. By 2007, the Plan calls for increasing this efficiency to more than 39% under high concentration, demonstrating a 4-junction cell, and developing dish-concentrator systems for high-efficiency cells. It also calls for making prototype modules of multijunction polycrystalline thin films that can reach 20% efficiency under concentration.

*Crystalline Silicon* — Researchers are exploring novel ways to cut costs and increase performance for this mature PV technology. One approach

*The many advances made by the R&D program include breakthroughs that enable researchers to understand materials on the molecular level and to tune the bandgaps of PV materials.*

# Five-Year PV Technology Plan: Technical Areas and Targets

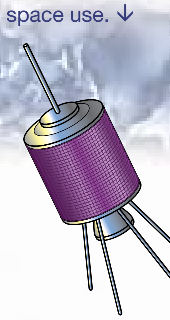
| | | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|
| Fundamental Research | **Basic and University Research** | • Initiate theoretical studies for doping of high-bandgap and organic materials.<br>• Renew most-promising "Future Generation PV" subcontracts and conduct peer review of "Beyond the Horizon PV" project.<br>• Initiate research on applications of combinatorial techniques for high-throughput studies of PV materials and devices. | • Determine operational characteristics of excitonic solar cells using biomimetic, organic, and nanotechnology concepts.<br>• Select university research teams for third-generation PV technologies targeting very high efficiency and very low cost.<br>• Initiate fundamental R&D with universities to enhance scientific understanding in key thin-film PV technologies; identify new university partners in key research. | • Assess efficiency potential, stability, and reliability of organic polymer, small-molecule, and inorganic/organic solar cells.<br>• Assess contributions of university centers of excellence for PV research and education. | • Experimentally validate theoretical understanding for doping high-bandgap PV materials.<br>• Demonstrate feasibility of third-generation PV devices such as hot-carrier and impact-ionization concepts.<br>• Evaluate university fundamental R&D programs and new solar cell options and make decision on research areas and pathways.<br>• Assess dye-sensitized solar cell options involving solid-state electrolytes. | • Demonstrate rapid validation of a next-generation material or cell structure through application of combinatorial research techniques.<br>• Identify commercialization pathways for promising new technologies via university/industrial partnerships.<br>• Assess potential of nanotechnologies for achieving third-generation goals of very high efficiency and very low cost. |
| | **Measurements and Characterization** | • Refine and transfer manufacturing-friendly, electro-optical-based diagnostic to the PV industry.<br>• Complete installation of a state-of-the-art, high-resolution transmission electron microscope and apply new capabilities to a technologically important problem in silicon. | • Obtain ISO 17025 accreditation for secondary cell calibration under ASTM and IEC standards.<br>• Validate surface analysis test platform for process integration. | • Complete capability to evaluate multiple-junction concentrator cells and modules to 1000x with lowest practical uncertainty.<br>• Develop characterization platforms that support the Science and Technology Facility process integration concept.<br>• Complete next in series of international module performance intercomparisons and issue final report. | • Initiate partnerships with university/industry to develop next-generation process diagnostics necessary to enhance yield and throughput.<br>• Provide assessment of PV technology measurement, characterization, and test requirements (inventory current critical requirements and new projected techniques and needs) for input to DOE Multi-Year Technical Plan and PV Industry Roadmap. | • Obtain ISO 17025 accreditation for secondary module calibration under ASTM and IEC standards.<br>• Explore and develop novel characterization techniques to obtain microstructural and chemical information with high spatial resolution and chemical sensitivity. |
| | **High-Performance and Concentrator Research** | • Assess issues of operating high-efficiency multijunction cell under high-concentration Fresnel lens.<br>• Demonstrate a monolithic, series-connected, multijunction thin-film device and identify critical-loss mechanisms. | • Evaluate optimized cells grown by molecular-beam epitaxy to assess viability of GaInNAs for multijunction cells.<br>• Assess research on exploring pathways to high-efficiency PV and initiate planning and strategy for implementation phase. | • Implement Thin-Film Process Integration Concept.<br>• Demonstrate 37% efficiency under concentration. | • Fabricate dual-junction polycrystalline thin-film cell of 15% efficiency.<br>• Test high-efficiency (35%) concentrator cell array in concentrating solar power dish system. | • Demonstrate, with participation from industry, 20%-efficient thin-film prototype submodule operating under moderate concentration.<br>• Demonstrate 39% efficiency under concentration. |
| | **Crystalline Silicon** | • Assess impact and future potential for university collaborations with crystalline silicon companies and determine future research directions.<br>• Develop high-efficiency screen-printed metallization process for commercial silicon substrates. | • Assess potential for thin-silicon technologies and identify areas for increased research emphasis.<br>• Issue competitive solicitation to universities to address key research issues in crystalline silicon. | • Identify mechanisms of hydrogen diffusion during the nitridation process.<br>• Achieve 13%-efficient thin-silicon cell (<3 microns) on low-cost substrate. | • Assist industry in demonstrating 19%-efficient, large-area multicrystalline silicon solar cell using commercial processes.<br>• Select university center of excellence for crystalline silicon PV research and education. | • Demonstrate competitive efficiency and cost potential of thin crystalline silicon technologies.<br>• Assess new opportunities and directions for crystalline silicon technologies. |
| Advanced Materials & Devices | **Thin Films** | • Support the successful transition of CIS to multi-megawatt production.<br>• Demonstrate alternative junctions in CIGS and CdTe using process control of carrier concentrations. | • Demonstrate 10%-efficient commercial CdTe module.<br>• Test water-vapor sensitivity levels for CdTe and CIS cells to provide quantitative input to industry for designing adequate module packaging. | • Complete solutions for device-level issues supporting industry 10-year warranties for CIS and CdTe modules.<br>• Assess Thin Film PV Partnership, and implement next phase of research activities. | • Support a-Si industry adoption of higher-deposition-rate process (5 Å/s).<br>• Implement process integration tools to demonstrate the deposition of CIGS with predictable properties. | • Complete solutions for device-level issues supporting industry 20-year warranties for CIS and CdTe modules.<br>• Assist thin-film industry in achieving significant (>100 MW) annual module production in United States. |
| | **Manufacturing Research and Development** | • Solicit new partnerships to address processes capable of $1/watt direct module manufacturing costs with gigawatt production capacity and emphasis on module and component yield, durability, and reliability.<br>• Assess environment, safety, and health issues associated with multi-hundred-megawatt manufacturing and deployment of PV. | • Initiate new Manufacturing R&D projects directed to durability and reliability issues, identified through lab and field experience. | • Complete development (achieve manufacturing-line-ready status) for at least three in-line diagnostic processes initiated in FY 2002 awards from In-Line Diagnostic, Intelligent Processing Solicitation.<br>• Assess and determine needs for additional manufacturing R&D, and select areas for elimination or support. | • Achieve module manufacturing processes capable of $1.50/watt direct module manufacturing costs with 500-megawatt production capacity. | • Solicit new partnerships, as appropriate. |
| | **Module Performance and Reliability** | • Investigate and document dominant factors influencing energy production by PV module technologies.<br>• Accelerate R&D devoted to thin-film module reliability achievements via the Thin-Film Module Reliability National Team. | • Investigate and quantify degradation rates for all commercial PV module technologies.<br>• Designate outdoor weathering test sites in hot and humid climates. | • Validate accelerated test methods that reproduce failures/degradation observed in the field.<br>• Assist the thin-film industry with advanced module-packaging designs that lead to 25-year service lifetimes for advanced technologies. | • Facilitate improved and cost-reduced standardized qualification test protocols for technologies that are being commercialized.<br>• Evaluate accelerated environmental and field reliability test protocols for concentrator module technologies. | • Assess and document correlation of accelerated environmental stress testing with results from long-term field data and observations. |
| Technology Development | **Systems Engineering and Reliability** | • Technically assess thin-film system performance.<br>• Incorporate statistical analysis tools into systems-reliability database.<br>• Complete Phase I of High-Reliability Inverter Initiative.<br>• Begin formal events and administration of the National Voluntary Practitioner Certification Program.<br>• Initiate a system design and evaluation project. | • Develop protocol for testing and evaluating PV systems to improve performance and reliability.<br>• Develop PV system test protocol for qualification testing.<br>• Begin Phase II (Prototype Development) of the High-Reliability Inverter Initiative.<br>• Begin System Design and Evaluation Program to assess barriers to 25-year system lifetimes.<br>• Baseline the operations and maintenance costs for off-grid residential hybrid systems.<br>• Initiate feasibility studies for AC PV building-integrated module. | • Deliver advanced PV system design tool.<br>• Demonstrate AC PV building-integrated module prototypes.<br>• Document progress toward making PV systems a viable energy option for rural utility applications.<br>• Baseline the operations and maintenance costs for utility-scale PV systems.<br>• Verify test procedures for PV systems performance and qualifications.<br>• Begin Phase III (Final Product) of the High-Reliability Inverter Initiative. | • Document progress toward 25-year system lifetimes.<br>• Designate center(s) of excellence for PV systems studies.<br>• Complete High-Reliability Inverter Initiative.<br>• Demonstrate advanced inverter concepts. | • Update system design and simulation tools to include documented failure and degradation rates at the component level.<br>• Revise Systems Multi-Year Program Plan to reflect review of requirements by the systems-driven approach.<br>• Demonstrate systems-driven approach advances in inverters and power electronics for PV systems. |
| | **Partnerships for Technology Introduction** | • Assess Million Solar Roofs Initiative, documenting successful partnership contracts.<br>• Solidify international partnering efforts in concert with industry and DOE guidance. | • Accelerate adoption of building-integrated PV in new residential and commercial construction through successful collaborative industry partnerships among PV manufacturers, installers, builders, designers, and the trades. | • Carry out the next Solar Decathlon university competition of 100% solar-powered homes that demonstrate building-integrated PV and solar technologies in marketable residential applications. | • Assess international partnering activities facilitating market acceptance of U.S. PV products. | • Assess NCPV's contributions toward building capacity and expanding markets, leading to 20-Year Industry Roadmap goal of domestic markets gaining parity with continual growth of international markets. |
| | **Program Integration and Facilities** | • Apply systems-driven approach to assess PV component and analysis tools, identify gaps, and initiate expanded model development.<br>• Complete Science and Technology Facility Title I Design.<br>• Issue revised DOE PV Subprogram Five-Year Technology Plan. | • Examine PV Subprogram contributions to meeting 20-Year Industry Roadmap.<br>• Start construction of NREL Science and Technology Facility.<br>• Assess NCPV research facilities and prepare multi-year capital equipment plan. | • Review all milestones and targets and revise within framework of systems-driven management and implementation approach of Solar Energy Technologies Program.<br>• Facilitate revision of PV Industry's 20-Year Roadmap for 2005-2025.<br>• Issue revised DOE PV Subprogram Five-Year Technology Plan. | • Start operations of NREL Science and Technology Facility. | • Issue revised DOE PV Subprogram Five-Year Technology Plan. |

1961

**1961** — 256 lighthouses in Japan are "solarized" by Sharp Electronics from 1961-1972.

**1966** — Lighthouse in Nagasaki, Japan, with Sharp PV modules is the world's largest PV terrestrial installation at the time. *(Sandia National Laboratories, PIX03691)* ↑

**1970** — Silicon violet cell with 13.5% efficiency, developed by COMSAT, becomes the standard for space use. ↓



**1971** — Ribbon process for growing crystalline silicon introduced by Tyco Corporation.

**1972** — PV-powered navigation lights on offshore oil rigs off Grand Island (LA), USA, installed by Solar Power Corporation as the first such cost-competitive system.

**1973** — World's first PV-powered calculator assembled. *(photo courtesy of Guy Ball)* →

**1974** — PV-powered telephone system installed by Telecom Australia as first such remote system.

**1974** — World's first PV-powered railroad crossing warning lights installed at Rex (GA), USA.

**1974** — First PV-powered microwave repeater developed. *(John Masson, PIX11040)* ↓

**1975** — PV-powered cathodic protection engineered in mid 1970s.

**1975** — Sandia National Laboratories initiates its photovoltaics R&D program. ↑

**1976** — Copper indium diselenide cells with significant efficiencies reported. *(Rick Matson/NREL,PIX06674)* ↓

**1976** — Amorphous-silicon solar cells achieve 5.5% efficiency.

**1976** — First practical PV water pump designed and built.

**1977** — U.S. Department of Energy (DOE) is formed.

**1977** — DOE launches the Solar Energy Research Institute, a federal facility dedicated to harnessing power from the sun.,

**1978** — First PV-powered microwave relay established between Tenant Creek and Alice Springs, Australia.

**1978** — First off-grid PV electrification program for homes (in French Polynesia) established by French Energy Commission.

**1980** — PV street-lights introduced by Kyocera. *(Bob McConnell/ NREL,PIX02865)* ↑

1980

is thin-film silicon, where the absorber layer can be as thin as 5 microns while retaining high efficiency by using creative designs, such as porous polycrystalline silicon and techniques that trap light for total absorption. The goal is a 13%-efficient thin-silicon cell by 2007. Another approach is to cut costs by developing high-throughput processes for junction formation, metallization, and antireflection coatings.

**Advanced Materials & Devices.** This part of the Plan covers advanced materials, manufacturing R&D, and ways to increase module reliability and performance.

*Thin Films* — Because they use very little material and exploit mass-production techniques, thin films could greatly drop PV costs. After years of progress in resolving fundamental material, device, deposition, and manufacturing issues, the most-promising thin-film material technologies—amorphous silicon, copper indium gallium diselenide, and cadmium telluride—are commercial and gaining market share. The goals are to increase device efficiencies, increase module reliabilities to where industry can offer 20-year warranties, and help industry develop deposition and manufacturing capabilities to exploit economies of scale.

*Manufacturing R&D* — During the last decade, R&D partnerships between industry and national laboratories have helped drop manufacturing costs by nearly 50%—to as low as $2.46 per watt. They have also helped to increase manufacturing capacity more than 13-fold to 150 MW per year. Over the next five years, the Plan will rely on these partnerships to develop intelligent diagnostic systems to enhance manufacturing processes, achieve processes capable of making modules for $1.50 per watt with a 500-MW manufacturing capacity, and explore ways to reduce module costs to less than $1 per watt.

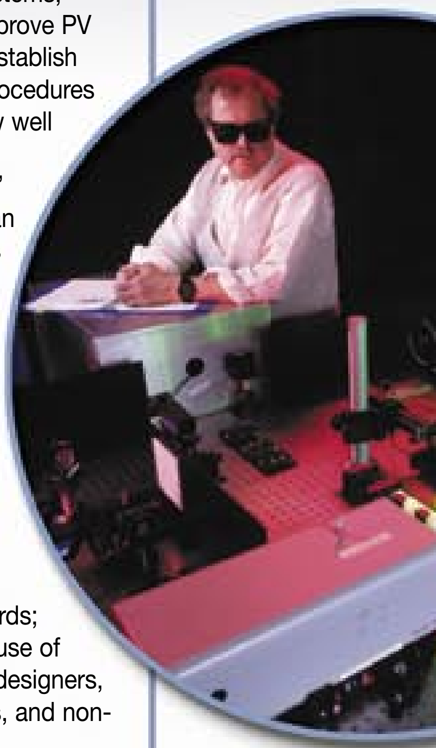
*Module Performance & Reliability* — Researchers have used simulated and outdoor testing and analysis techniques to identify failure mechanisms and improve module performance to where crystalline silicon modules are typically 15% efficient and last 20 to 30 years. For the next five years, researchers will continue to improve module reliability and performance, with an emphasis on helping thin-film modules reach lifetimes of 10 to 20 years and developing advanced testing protocols for concentrator modules.

**Technology Development.** Here, partnerships among industry, government, and others improve the performance and reliability of PV systems and introduce PV to domestic and foreign markets. Here also, all aspects of the Plan's technology and R&D efforts are integrated.

*Systems Engineering & Reliability* — Under this part of the Plan, researchers test entire systems, under real and simulated conditions, to improve PV system reliability and performance. They establish protocols, under which accelerated test procedures and statistical analyses can determine how well systems can be expected to perform. And they develop standards for "plug and play" systems, so that "off the shelf" systems can be simply plugged into typical applications or building planners can more easily integrate PV systems into structures.

*Technology Introduction* — The Plan provides a focal point for PV technical information and education to show the viability of domestic and foreign applications, such as through the Solar Decathlon university competition; to cooperate with national and international organizations to develop performance, measurement, and interconnection standards; and to aid the domestic and international use of PV by working with PV industry, builders, designers, government agencies, financial institutions, and non-governmental organizations.

*Program Integration & Facilities* — The Plan provides a hub for integrating R&D activities to assist the U.S. PV industry's 20-year roadmap planning. These activities complement the roadmap and ensure the right facilities to secure the progress of PV technology and the industry. A primary near-term goal is to build a Science and Technology Facility to support the integration of material, device, characterization, and diagnostic advances into manufacturing processes.



*Characterization techniques developed by program researchers include in-line diagnostic tools for manufacturers.*
*(Jim Yost Photography, PIX07103)*

**1981** — First roof-integrated PV system installed on Carlisle House, Boston (MA), USA.

**1981** — Paul MacCready builds first solar-powered aircraft, the Solar Challenger, and flies it across English Channel.
*(NASA, ECN-13413)* ↓

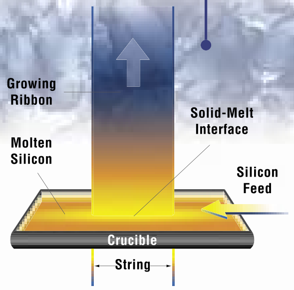
1981

**1984** — Multiple wire saw first used for slicing PV crystalline silicon.

**1984** — Laser-grooved, buried-contact silicon solar cell created.

**1985** — GaInP/GaAs multijunction patented by DOE's Solar Energy Research Institute.
*(Warren Gretz/NREL, PIX03302)* ↑

**1986** — String-ribbon process invented for manufacturing solar cells. ↓



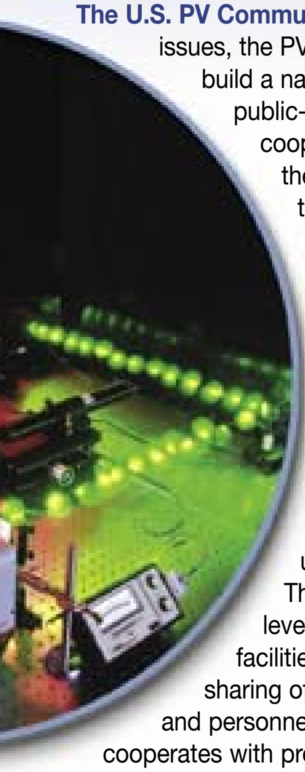
**1986** — PV rooftop programs throughout the developed world initiated in Project Megawatt.

**1987** — Double-heterojunction AlGaAs/GaAs cell demonstrated by Varian Associates.

**1988** — Sheet silicon fabricated from octagonal tubes begun by Mobil Solar Energy Corp.

# A National Endeavor

The primary purpose of the U.S. Department of Energy's PV subprogram (which is part of the DOE Solar Energy Technologies Program) is to accelerate the development of PV as a national and global energy option. Meeting this challenge requires the PV subprogram to work in close cooperation with the U.S. PV R&D and manufacturing community, and federal, state, and local agencies and organizations.



**The U.S. PV Community.** To address technical issues, the PV subprogram has helped build a national effort, supporting public-private partnerships whose cooperative endeavors span the range from basic research to applications. The work is performed by the National Center for Photovoltaics (NCPV) and its associated research centers at the National Renewable Energy Laboratory (NREL), Sandia National Laboratories, and Brookhaven National Laboratory, and by nearly 150 companies and universities across the nation. This partnership approach leverages expertise, funding, and facilities, and greatly enhances the sharing of data, information, ideas, and personnel. This national endeavor also cooperates with professional and industry trade associations to gain insight into the markets, products, and services for solar energy.

*National Laboratories of the NCPV* — NREL, Sandia, and Brookhaven provide the PV community with program management and centralized technical support, characterize PV materials and devices, perform research on fundamental concepts, provide facilities and expertise for module and system testing, conduct innovative research on materials, devices, and processing, and address environmental health and safety issues. The laboratories generally assume a lead role in the early stages of a technology's development, but assume a more facilitating role as the technology approaches the application end of the spectrum.

*Universities* — Working closely with the national laboratories and companies, universities perform advanced R&D, explore fundamental scientific phenomena, create innovative concepts, and provide a fertile learning ground for tomorrow's PV scientists and engineers.

*Industry* — Companies generally perform engineering and manufacturing R&D under cost-shared partnerships, integrate the results with their own in-house research, and apply them to manufacturing processes and products. Industry generally provides a supporting role for basic and applied R&D, but assumes a leading role when the technologies approach manufacturing and application.

**Government Agencies.** The PV subprogram also works with a wide variety of federal, state, and local government agencies and programs, cooperating in R&D, providing technical information and services, educating consumers and legislators, providing information for policies, regulations, and utility restructuring, promoting the use of PV and solar technologies, and providing venues for the incubation of technology companies. Particularly noteworthy are the activities the subprogram has with:

- The DOE Office of Science, with whom the PV subprogram conducts fundamental research into materials, devices, new concepts, and solid-state theory.
- The National Aeronautics and Space Administration, which is a large user of PV cells for space power, and with whom the PV subprogram conducts R&D.
- The Environmental Protection Agency, which has interest in solar energy to help the nation meet air-quality mandates.
- The Department of Defense, which uses PV systems for military housing and facilities, communications,

*Domestically, the potential for PV includes more than 100 million homes and commercial buildings. Here, the Arden Realty Company in California uses a 240-kW PV system to lower electricity bills and to provide emergency backup power.*

*(Byron Stafford/NREL, PIX10730)*

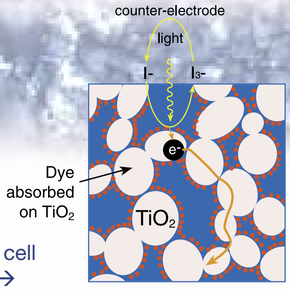
**1990** — PV Manufacturing Technology project created by DOE to help U.S. industry improve PV manufacturing processes and equipment. ↓

Photovoltaic Manufacturing Technology

**1991** — First fully building-integrated PV facade goes up in Aachen, Germany.

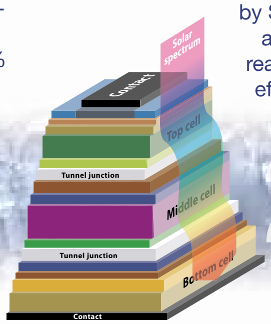
**1991** — Solar Energy Research Institute becomes National Renewable Energy Laboratory. →

**1991** — Dye-sensitized solar cell demonstrated. →



**1994** — Thin-Film PV Partnership project established by DOE to help coordinate U.S. industry research in thin-film PV technologies.

**1997** — Dual-junction GaAs/Ge cell by Spectrolab and Tecstar achieves 25.5% efficiency.



**2000** — III-V Cascade® cell by Spectrolab and Tecstar reaches 35% efficiency. ↙

**2000** — a-Si/c-Si hetero-structures developed.

**2001** — High-Performance PV initiative begun by DOE to foster research in high-efficiency polycrystalline thin films and multijunction concentrators.

and remote installations, and which cooperates in R&D on PV materials, systems, and applications.

- Department of Homeland Security/Federal Emergency Management Agency. This new department is helping to accelerate the commercialization of PV for homeland security—where PV systems are domestically made, rely on a domestic supply, can be used for communications and as distributed generators that provide reliability and redundancy—and for disaster relief applications, including mobile systems that can immediately generate electric power for energy and communications.
- The DOE Buildings Program, which has projects in which PV is incorporated directly into building envelopes or structures or where PV can be critical to the Zero Energy Buildings program goal (in which a building consumes no externally supplied energy).
- The Federal Energy Management Program, which helps promote and make available PV systems to the federal government, the largest energy user in the United States.

## Guiding the Effort

**Policies & Mission.** The National Energy Policy states that "through improved technology, we can ensure that America will lead the world in the development of clean, natural, renewable and alternative energy supplies." DOE's Office of Energy Efficiency and Renewable Energy (EERE) leads the nation's effort to develop these technologies and energy supplies, with a mission to strengthen America's energy security, environmental quality, and economic vitality through partnerships that bring clean, reliable, and affordable energy production and delivery technologies to the marketplace.

Within this context, EERE's Solar Energy Technologies Program oversees the R&D activities conducted through the national laboratories, subcontractors, and partners to develop technologies that exploit energy from the sun. This includes technologies that use the sun to produce energy in the form of electricity or heat. Among these are the photovoltaic technologies, which join forces with those of solar thermal electricity and with solar thermal technologies related to the heating of air and water.

**A Systems-Driven Approach.** To better understand, guide, and assess its activities, the Solar Program is moving toward a "systems driven" approach. This approach emphasizes the importance of how the myriad aspects of photovoltaic technology—materials and processes, components, subsystems, systems, products, applications, and markets—are related.

Using this systems-driven approach, we might consider how changes in a component affect an application or market—as in the development of low-cost plastic solar cells. Or we might examine how changes in a market modify the requirements for component cost and performance—such as the impact that interconnection standards may have on the design of power inverters.

By developing this capability for all solar technologies in the Solar Program—including photovoltaics—we can 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, and develop a standardized means of analysis to ensure that technologies meet targets related to cost, performance, and reliability.

*The Department of Defense, one of many government agencies cooperating with the Solar Energy Technologies Program, uses PV for military housing, communications, and many more applications. This PV system supplies 15 kW of backup power to the Pentagon. (John Thornton/ NREL, PIX06249)*

**2001** — PV-powered Helios reaches new altitude record of 96,000 feet (29,280 meters).

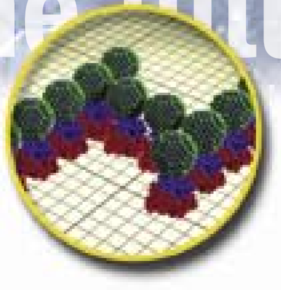
**2002** — Three acres of PV panels at Santa Rita Jail in CA generate 1.18 MW of electricity in the largest U.S. rooftop solar installation. *(PowerLight Corporation, PIX12401)* ↓

**2002** — Kenya becomes first country where more rural people use PV for electricity than the national rural utility lines.

**2003** — Tucson Electric Power's Springerville (AZ) PV system consists of silicon, CdTe, and a-Si modules, which comprise the largest PV system in the Western Hemisphere at 3.4 MW. *(Tucson Electric Power)* ↑

An innovative concept for the future is use of proteins to align quantum dots into arrays. These arrays of quantum dots and proteins can then serve as a matrix for conducting electrons and holes. Or, the proteins may be removed and the quantum dots can form their own matrix. ↓

the future



# A Clean, Secure Energy Future

Many traits combine to make PV systems important, attractive energy sources for our energy future.

**PV systems are modular.** They can provide electricity anywhere the sun shines, in any amount. They can be used in the middle of a forest or the remoteness of a desert. They can be placed on mountaintops, secured on the rooftops of America, integrated into the structures and façades of our buildings, built into our highway sound barriers or mediums, and eventually, even be embedded in the surface of our highways. They can power remote areas, be used in hybrid configurations with other technologies, and be connected to an electric grid from a million points.

**PV electricity is secure energy.** Because they can be used stand-alone or connected to a grid at any size and location, and because they rely on locally available solar radiation, PV electric systems add redundancy, security, and reliability to any system—whether for a single home, a business, a repeater station, a community, or an entire network. With solar electric systems interconnected with other resources and technologies in a distributed, “smart” grid network, there would be no single, large target whose loss could interrupt significant portions of our energy delivery system. Rather, electricity would be rerouted around any damaged portion of the network to keep vital energy flowing.

**PV electricity is clean energy.** PV systems use pristine sunshine to generate clean electricity, producing no atmospheric emissions or greenhouse gases. Building a PV infrastructure provides insurance against the threat of global warming and climate change. For example, a 2.5-kilowatt rooftop system supplies sufficient electricity to run a typical U.S. home, while offsetting the carbon dioxide produced by the family car. With projected growth trends, in 25 years U.S.-installed PV will offset the annual increase in carbon emissions from electrical utilities. In 50 years, there could be enough installed PV to offset more than 25% of the carbon dioxide produced by the nation’s vehicles.

And in 50 years, with advances in PV technology and the expected drop in costs, PV electricity will be cheap enough to produce hydrogen economically from water. In this ideal marriage, hydrogen and PV electricity will be produced in our towns, at our commercial buildings, and at our homes. PV will supply the electricity to generate hydrogen, and hydrogen will provide PV electricity with storage. Together, they will provide secure, clean, homegrown electricity and fuel for our homes, businesses, and transportation.

*A PV system at SunLine Transit Agency in Thousand Palms, California, provides electricity to the Stuart Energy electrolysis unit on the right for producing hydrogen from water.* (Richard Parish, PIX10719)

**Produced for the**
**U.S. Department of Energy**
**Energy Efficiency and Renewable Energy**

1000 Independence Avenue, SW, Washington, D.C. 20585
by the National Renewable Energy Laboratory
a DOE National Laboratory

DOE/GO-102003-1491 • September 2003

♻ *Printed with a renewable source ink on paper containing at least 50% wastepaper, including 10% postconsumer waste.*

**Photovoltaics — Past, Present, Future**
The cover of this document shows a sketch from the 1953 lab notebook of Bell Labs’ Calvin Fuller, co-inventor of the first viable silicon solar cell. Present commercial solar technologies include single- and multicrystalline silicon and several thin-film materials. New concepts for the future include quantum dots and polymer solar cells. The background is a scanning tunneling microscope image of GaAs/Ge nucleation.

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable