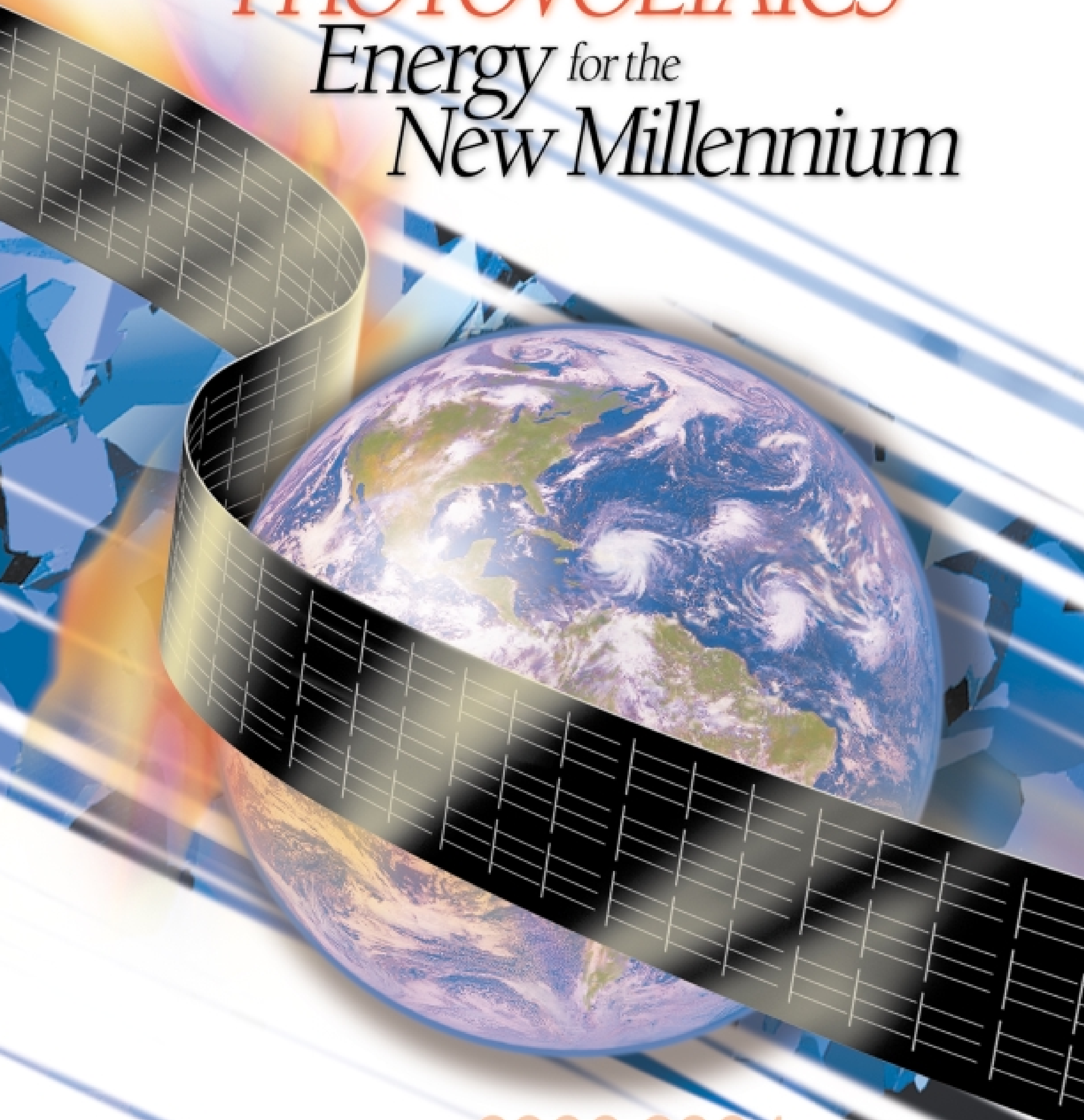
PHOTOVOLTAICS

Energy for the New Millennium



The National Photovoltaics Program Plan 2000-2004

Taking Steps Toward a New Energy Front

This Photovoltaic Program Five-Year Plan is being published today, January 1, 2000. It is the first day of a new century that will eventually be powered by renewable energy technologies like photovoltaics (PV).

In the PV community, there is a sense of excitement and challenge — the same feeling members of the Apollo program must have felt at the start of the moon race. In 1999, we celebrated the 30th anniversary of Apollo 11's successful mission. A little more than a year ago, the Mars Sojourner Rover, entirely powered by PV, completed its mission. The challenge we face in this century is to enable PV to go as far as any other energy technology here on Earth by making the scientific and technological advances that will put PV on every rooftop and in every corner of the globe. Like the space program, a balanced, aggressive PV research and development program has the potential to open a new frontier here on Earth.

When John F. Kennedy challenged the nation to put a man on the moon within a decade, the scientists who would lead the effort had little more than a mission from their President to guide them. But that was enough to inspire them to the hard work and dedication it took to create a plan, a program, and finally, the technology that would open a new frontier in space. Our mission is also bold and inspiring — to offer the world a cost-effective, reliable technology that turns sunlight into energy with no pollution, wherever it is needed.

Apollo's scientists, engineers, and astronauts pursued their mission with perseverance, ingenuity, and scientific curiosity and in the process changed the way we view our planet and our future. They were the first to capture the view, featured on the cover of this five-year plan, of the Earth as a lone planet surrounded by the vastness of space. For many, it signified the limits of the Earth and our resources, and the overriding need to protect our environment. For others, the fact that science and technology had allowed people to leave Earth and look back on our planet from the moon signified the ability of science and technology to overcome all limitations. The entrepreneurs, scientists, and engineers that make up the PV community represent the best of both views — a belief that science and technology, guided by purpose and vision, can overcome all limitations and tap new energy resources that also protect our global environment.

The PV industry has created a new technology roadmap to chart industry's course. This five-year plan provides a strategy for research and

ier

development to advance the technology. Considering just the opportunities that we can foresee from where we stand today, at the start of the century and with a new five-year plan, PV has enormous untapped potential.

Early in the new century, highly efficient PV cells will power the exploding market in telecommunications. New technologies will link automobiles to satellites and the Internet for communications, information, location and directions, tracking, and even video on demand for the backseat — all of which will rely on direct-current electricity coming from PV integrated into the car roof or hood.

As the use of personal computers, digital cellular phones, and other portable electronic devices flourishes, more of the appliances we value most will be powered by batteries and encased in PV materials so they can recharge themselves — the ultimate wireless convenience.

As the next century rolls on, we will see PV systems grace millions of American homes. We'll see a proliferation of PV systems built onto the rooftops of factories and businesses, or integrated directly into the "skin" of houses, skyscrapers, and commercial buildings to provide supplemental or stand-alone power. And we'll see the emergence of "PV farms" that range in size from a few acres to square miles of PV systems, to provide electricity for entire communities or for entire regions of the nation.

We'll also witness the growing impact that PV will have in developing countries, home to the 40 percent of the world's population that has no access to electricity. Modules on the rooftops of houses and huts will provide families with electricity for light and other essentials. Ground-mounted arrays will provide power for pumping water for drinking and irrigation. Moderate-size systems will supply entire villages with power to run lights, communication, and small industries, and will supply health clinics with power for operations and for refrigerating medicines. Photovoltaics and satellite telecommunications will open remote villages to world commerce, education, and virtual medicine. All of this will happen without building power lines or telephone poles.

The new energy frontier that PV will help open is vast. Opening it will take many small, meticulous steps, like those outlined in this five-year plan. In research and development, we often fail to appreciate the implications of the steps that are taken every day to advance a program's mission. Sometime early in this new century, we will take one of those small steps for photovoltaics and suddenly realize we have accomplished our own giant leap for mankind.

James E. Rannels

Director, Office of Solar Energy Technologies

Photovoltaics — Energy for the New Mill

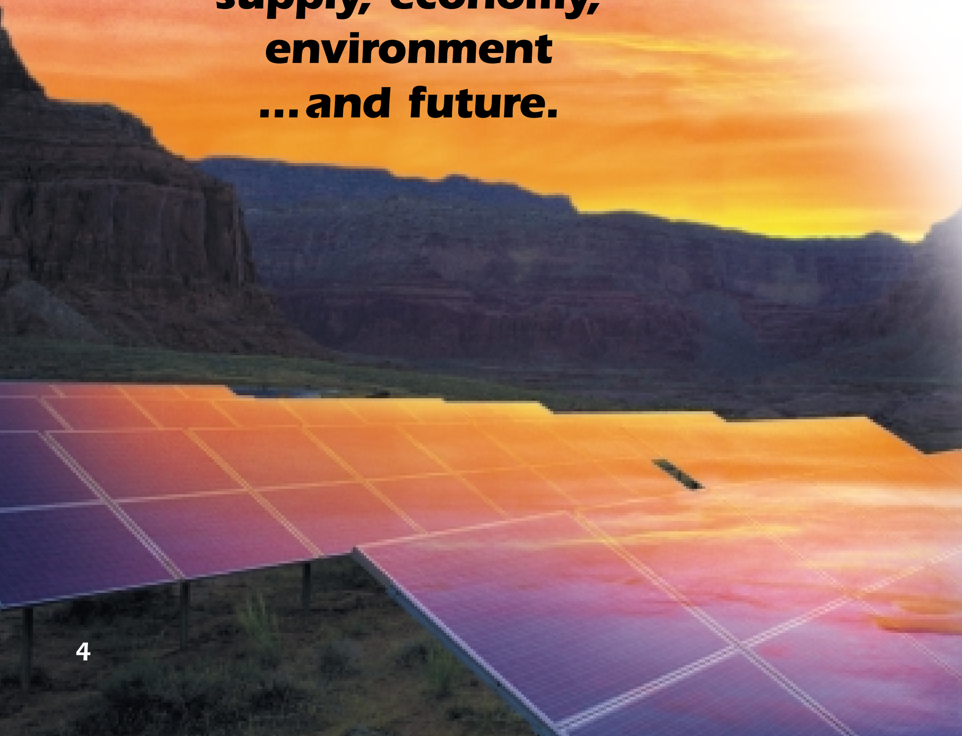
At the dawn of the new millennium, the world faces dramatic change. Nations are expanding their economies. Growing populations spawn spiraling needs for food, shelter, and materials. Burgeoning demands burden the Earth's ecosystems.

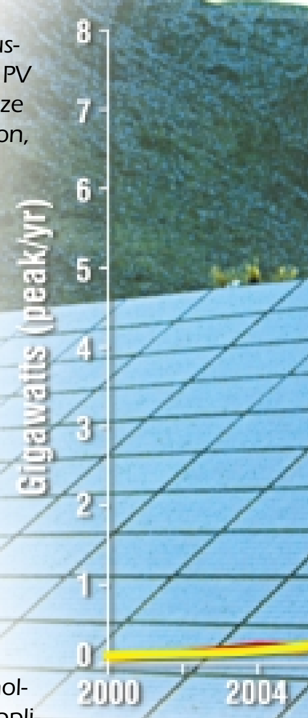
Underlying these trends is the expanding demand for energy. In the last 20 years, the world has increased its consumption of energy by 40%, to more than 390 quads of energy per year. More than 85% of this comes from fossil fuels. Although fossil fuels have long driven the engines of economic growth, consequences of their use are becoming apparent — limited supplies (in the long term), air pollution, and an increase in atmospheric carbon dioxide.

But nations can continue their economic ascent and increase their energy consumption while becoming more harmonious with the environment and while ensuring sufficient supplies of energy. Key to the success of this vision is technology and its ability to provide the world with a wide portfolio of energy choices. Significant among these is photovoltaics, a semiconductor technology that converts sunlight directly into electricity.

The Photovoltaics Program is helping to turn the promise of PV into a reality. The partners of the program — the National Renewable Energy Laboratory (NREL), Sandia National Laboratories, the U.S. Department of Energy (DOE), and the nation's universities and PV industry — explore the interaction of PV materials with sunlight, synthesize materials to exploit the interaction, model devices, engineer systems, and develop technologies that will help the nation and the world make the transition from today's fossil fuel reality to a sustainable, clean, and prosperous world.

Photovoltaics promises great things for our nation's energy supply, economy, environment ...and future.





The Promise of Photovoltaics

Good for Our Nation's Energy Supply

PV is a versatile electricity technology that can be used for any application, from the very small to the very large. A modular technology that enables electric generating systems to be built incrementally to match growing demands. A technology in which systems are easy to install, maintain, and use. A convenient technology that can be used anywhere there is sunshine and that can be mounted on almost any surface.

PV gives us domestic reserves of energy that we will never deplete. PV semiconductor materials are abundant. And sunshine, the "fuel" for PV, is something we can never overtax or squander. Yearly, the Earth receives 6000 times more sunlight energy than humans consume.

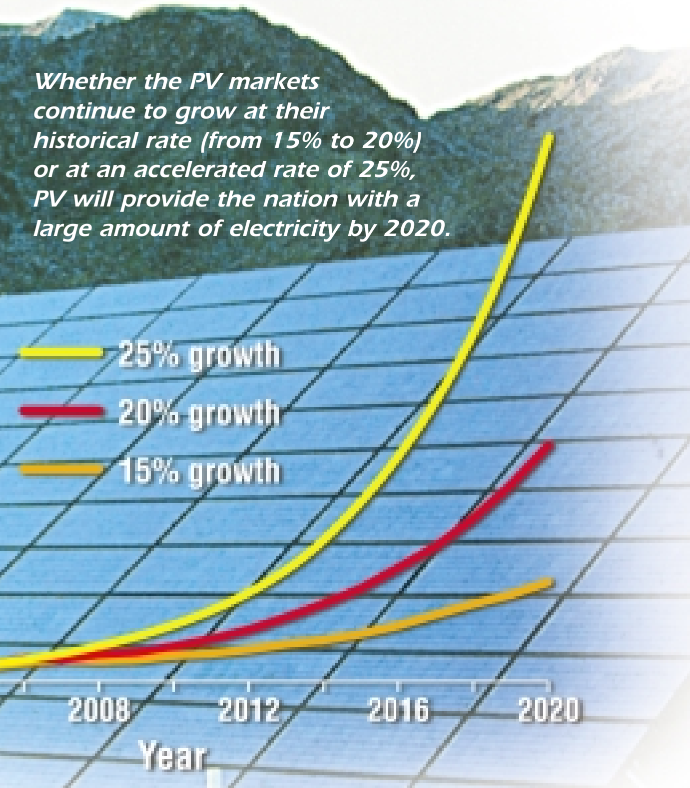
Moreover, because sunshine is available everywhere to everyone, any nation that builds a PV infrastructure will be less vulnerable to international energy politics and volatile fossil fuel markets.

Good for Our Economy

In 1998, worldwide PV module shipments jumped to more than 150 million watts, resulting in about $1.5 billion in sales. When the PV Program first began in the 1970s, there was no market for terrestrial photovoltaics. The market since that time has grown steadily. And in the last five years, it has grown at an annual rate of 20%.

This is just the beginning. The Program and industry feel that a sustained growth rate of 25% is achievable. At such a growth rate, worldwide shipments would approach 18 billion watts per year by

ennium



Whether the PV markets continue to grow at their historical rate (from 15% to 20%) or at an accelerated rate of 25%, PV will provide the nation with a large amount of electricity by 2020.

2020, representing a direct PV market of about $27 billion and an indirect market double that. And U.S. PV shipments would reach 7 billion watts by 2020, with more than 3 billion watts for domestic use. This means that PV would be supplying about 15% of America's added generation capacity.

A large, growing market bodes well for American workers. According to some estimates, the PV industry creates more than 3000 direct and indirect jobs for every $100 million in direct module sales. As this industry grows toward its potential, it will generate hundreds of thousands of jobs.

The race for technology and market leadership, however, will be hard fought. Although PV technology is American born and bred, and although the United States has long been the technological leader, any nation that makes the commitment can build a PV industry. Those that do will create domestic jobs, export energy technology, keep energy dollars at home for further domestic investment, and reap the ancillary economic benefits of controlling a technology whose impact will reach well beyond energy.

Good for Our Environment

PV produces no greenhouse gases, so its use will help offset carbon dioxide emissions. Consequently, building a PV infrastructure will provide insurance against global warming and climate change. A 4-kilowatt (kW) system, for example, will supply the electricity for a typical U.S. home; furthermore, the annual amount of carbon dioxide saved by the system is approximately equal to that emitted by a typical family car.

PV also produces no atmospheric emissions. Its use curtails air pollution, which produces acid rain, soil damage, plant and animal damage, and human respiratory ailments.

Good for Our Future

Photovoltaics is sophisticated science and high technology — an open-ended technology in which there is yet much to discover and much to reap. It will have an important impact on technologies ranging from computers, to thin-film transistors, to uninterruptible power supplies, to space power and the increasingly important field of telecommunications.

As such, PV will be an integral part of the march of technology that will spur economies and promote a more cohesive and affluent world.

Photovoltaics will help create a more prosperous world because it can be used by anyone, anywhere, for any application requiring electricity. It will promote a more equitable world because the resource is huge and universal, and because the technology can be used by everybody.

But the promise of PV goes well beyond electricity. Photovoltaics is a versatile technology that can be integrated with electrochromic windows, to help conserve energy while providing electricity. It can also be used to electrolyze hydrogen from water; the hydrogen can then be used to produce electricity, heat our buildings, and run our transportation. Electricity, conservation, and hydrogen from PV and the sun — inexhaustible, clean, and for everyone.

A bright future at our fingertips — hydrogen from sunlight, water, and PV electricity. Electricity, fuel, and heat — inexhaustible and clean.

A National Endeavor

The purpose of the U.S. Department of Energy PV Program is twofold: to accelerate the development of PV as a national and global energy option, and to ensure U.S. technology and global market leadership.

Building Technology Leadership

Technological leadership is essential to U.S. industrial competitiveness in photovoltaics. Although PV is fast becoming a multibillion-dollar industry, to become a significant energy player, it must extend its influence into more and larger markets. To do this, costs must be decreased by addressing key technical issues, including:

- Making dependable PV devices that convert sunlight to electricity efficiently
- Developing low-cost, high-yield processes for manufacturing PV modules
- Developing a strong scientific base to ensure the continued technical progress that will enable PV cost to become competitive for large, price-sensitive energy markets.

Working with the U.S. PV Community

To address technical issues, the DOE PV Program follows a well-established national paradigm — the forming of partnerships among national laboratories, industry, and universities — that has built U.S. leadership in many important technologies, including integrated circuitry, computers, and biotechnology.

The PV Program works with the nation's PV community to build technology leadership that is paying off.

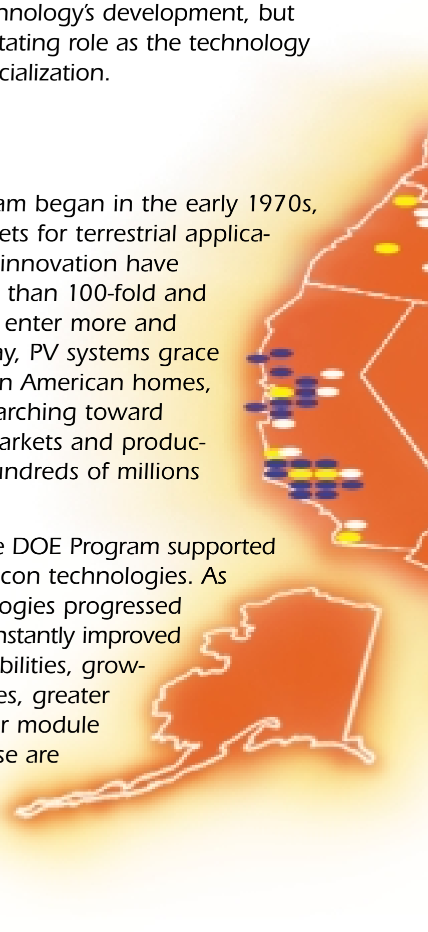
In its version of the paradigm, the Program has helped build a national effort, supporting partnerships that span the range from basic and applied research, to manufacturing technology, to product development, to commercialization. The work is performed by the National Center for Photovoltaics (NCPV) and other associated research centers at the National Renewable Energy Laboratory, Sandia National Laboratories, and Brookhaven National Laboratory, and by more than 180 leading companies, universities, and utilities from 40 states across the nation.

Companies compete for contracts and share in their costs. They then integrate results of successful research with their own considerable in-house efforts and apply them to manufacturing processes and products. Industry generally provides a supporting role for basic and applied research and development (R&D); but when the technologies approach manufacturing and commercialization, industry assumes the lead.

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.

The 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, and conduct innovative research on materials, devices, and processing. The laboratories generally take a lead role in the early stages of a technology's development, but assume a more facilitating role as the technology approaches commercialization.

Paying Off



When the PV Program began in the early 1970s, there were no markets for terrestrial applications. But R&D and innovation have dropped costs more than 100-fold and have enabled PV to enter more and larger markets. Today, PV systems grace a quarter of a million American homes, and the industry is arching toward multibillion-dollar markets and production capacities of hundreds of millions of watts per year.

In the early days, the DOE Program supported mainly crystalline silicon technologies. As a result, the technologies progressed significantly, with constantly improved manufacturing capabilities, growing device efficiencies, greater reliability, and longer module lifetimes. Today, these are the dominant PV technologies.

But other PV materials — most notably, thin-film amorphous silicon — are grabbing market share. And products made of the thin-film materials of copper indium diselenide and cadmium telluride are also being introduced.

The commercialization of copper indium diselenide, cadmium telluride, and (earlier) amorphous silicon are particular success stories of Program partnerships. It was the Program that performed the initial R&D on these materials and nurtured the technologies to the point where they could begin to be commercialized.

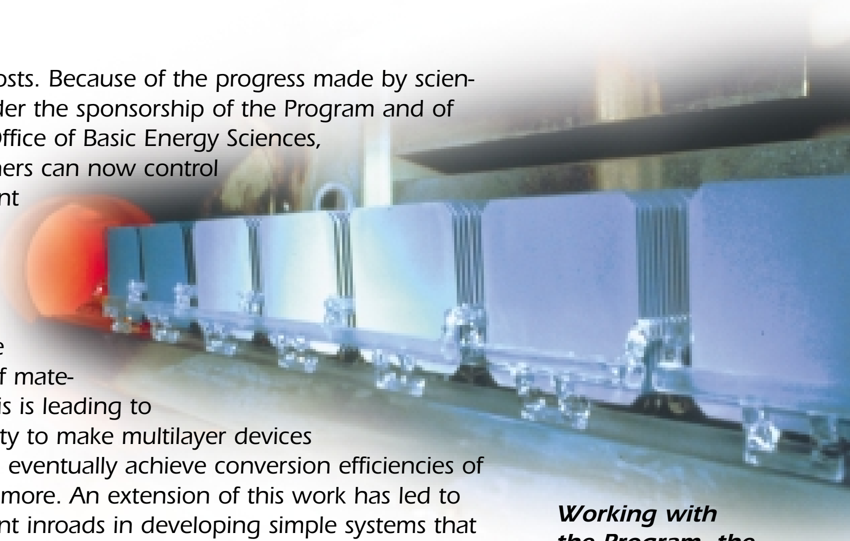
The same is true with multijunction high-efficiency devices made from gallium arsenide and its alloys. The Program and its partners have brought these technologies to where companies are now introducing them to markets as varied as space, concentrator, and thermophotovoltaic applications (in which PV systems exploit infrared radiation from heat to produce electricity).

An Even More Promising Future

Crystalline silicon technologies are beginning to enter a new era, in which structures that increase sunlight absorption will enable crystalline cells to be made with very thin layers. This will cut device costs while increasing conversion efficiencies.

New approaches for thin-film technologies are pushing conversion efficiencies nearly as high as those of crystalline silicon. By continuing this trend and consolidating improvements, thin films will substantially lower the cost of PV electricity to where PV will be able to compete for large markets.

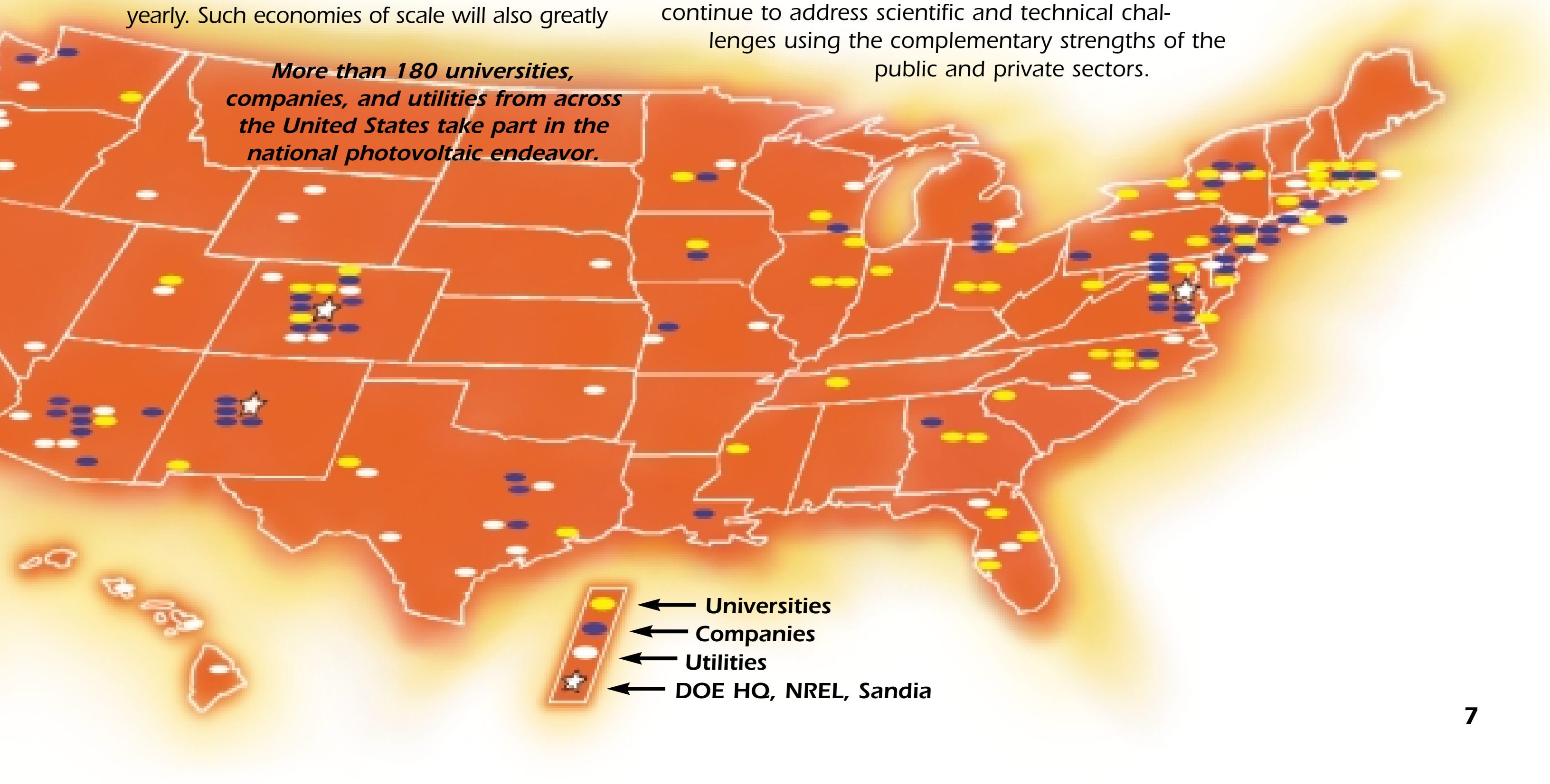
Companies are developing manufacturing technologies for thin-film photovoltaics that will produce 50 to 100 million watts of modules on a single production line yearly. Such economies of scale will also greatly lower costs. Because of the progress made by scientists under the sponsorship of the Program and of DOE's Office of Basic Energy Sciences, researchers can now control important properties of the gallium arsenide family of materials. This is leading to the ability to make multilayer devices that will eventually achieve conversion efficiencies of 40% or more. An extension of this work has led to important inroads in developing simple systems that efficiently split water into hydrogen and oxygen, which has implications for fuel cells and clean power for the nation's industries and transportation.



Working with the Program, the U.S. PV industry has greatly increased its manufacturing efficiency and capacity and has substantially decreased the cost of modules.

And, looking into the needs of the future, the Program is working with its university partners, the Center for Basic Sciences at NREL, and others to explore futuristic concepts that may someday supplant even today's most advanced and sophisticated technologies. Among the ideas being investigated are PV devices that do not need the junction that has heretofore been necessary to separate charge carriers, and PV systems that mimic biological sunlight-to-electricity conversion.

By working with the U.S. PV community, the PV Program is paying off today, and will pay off in a big way in the future. Photovoltaics is a fast-paced semiconductor technology with the potential to become one of the world's most important industries. To reach that potential, the Program and its partners will continue to address scientific and technical challenges using the complementary strengths of the public and private sectors.



More than 180 universities, companies, and utilities from across the United States take part in the national photovoltaic endeavor.

Guiding the Effort

Something as crucial to the nation's well-being as energy R&D requires national guidance — a federally coordinated effort that relies on national policies, a national organization, national strategies, and national funding.

Establishing Policies

Reflecting the recommendations of the Chief Executive and national energy advisory boards, the Secretary of Energy develops overarching federal energy policies that guide the DOE PV Program. The Secretary also develops a national energy strategy with broad national goals for R&D that promote:

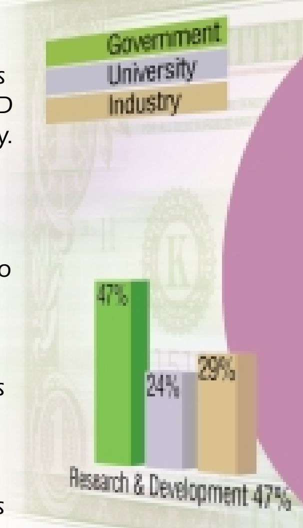
- Energy system efficiency and increased economic productivity
- Energy security for the nation
- Environmental quality and health
- Future energy choices for Americans
- Solutions to international global issues.

Through policies, organization, strategies, and funding, the PV Program coordinates the nation's R&D for photovoltaics.

Managers of the PV Program develop operating plans that respond to national policies and goals, to Congress, and to the Program's constituents. The managers also ensure that the budget allocations, direction, and individual elements of the Program meet their objectives and stay on target.

Organizing the National Program

DOE's Office of Energy Efficiency and Renewable Energy (EERE) oversees the PV Program through its Office of Solar Energy Technologies. To ensure that the national photovoltaic effort meets its promise in an efficient and timely manner, the PV Program is organized to effectively usher technologies along the development path from basic R&D, through applied research, through technology development, to engineering and applications. These efforts are augmented by the Office of Basic Energy Sciences, which provides substantial support for basic R&D in several areas of PV technology.



To mobilize national resources in photovoltaics, the PV Program recently established the National Center for Photovoltaics at its two primary research centers: the National Renewable Energy Laboratory in Golden, Colorado, and Sandia National Laboratories in Albuquerque, New Mexico. The Center performs world-class R&D, promotes partnering and growth opportunities, and serves as a forum and information source for the PV community.

NREL and Sandia not only serve as core members of the NCPV; they are also responsible for the day-to-day operations of the Program and for meeting the Program's technical goals. Staff members at these labs perform R&D, form R&D partnerships with universities and industry, and manage subcontracts.

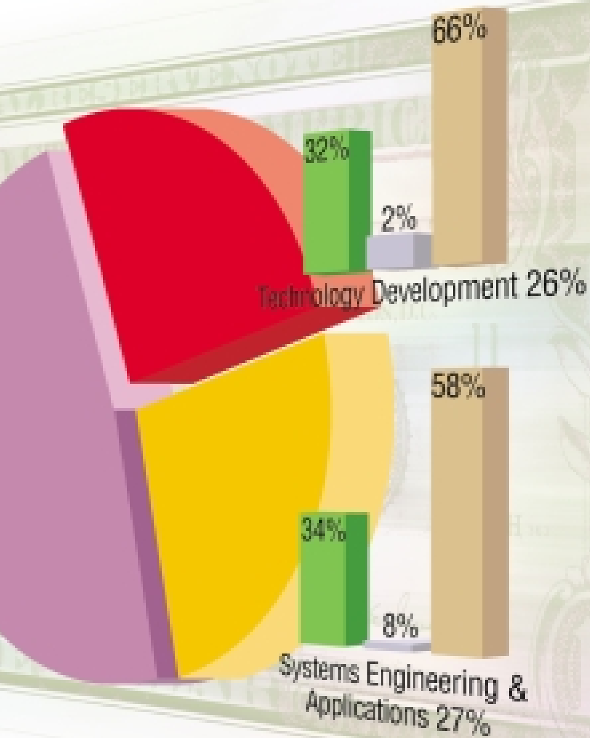
Other NCPV members also have Program responsibilities. For example, Brookhaven National Laboratory in Upton, New York, is responsible for the Program's environmental, safety, and health research. DOE's Golden Field Office administers contracts with the private sector in some program areas. The University Centers of Excellence at the Institute of Energy Conversion (University of Delaware) and at the Georgia Institute of Technology support the industry and the R&D infrastructure with research to advance thin-film and crystalline silicon technologies. And the Florida Solar Energy Center and the Southwest Technology Development Institute are regional experiment stations that test modules and systems under different environments and field conditions.

Strategies, Schedules, and Plans

"*The Plan is nothing. Planning is everything.*"
– Winston Churchill

Although meant for the process of planning war-time strategy, this saying is also germane for planning and executing R&D. It is through the planning process that the Program sets the wheels in motion toward important goals and milestones. The Program then revisits and revises plans in accordance with progress, growth, competition, and emerging priorities.

In simple terms, PV planning consists of three cycles: long-range, mid-range, and short-range. Long-range planning is done by industry with a planning horizon



For FY 1999, the Program split its $72.2 million budget among its three program elements in this manner: $33.6 million (47%) to Research & Development, $18.9 million (26%) to Technology Development, and $19.7 million (27%) to Systems Engineering & Applications.

of 20 years. The NCPV provides a forum for this planning and facilitates its process. Industry's primary concerns are goals for growth and markets and the processes, equipment, systems, and R&D it will need to meet these goals.

The Program's approach to planning not only encompasses American industry's long-term agenda for technological and industrial preeminence, but also heeds the national agendas for economic growth, energy security, and environmental quality and health.

The Program's principal planning cycle has a five-year horizon. This effort is performed under the guidance of the Director of the Office of Solar Energy Technologies. Planning is coordinated by the NCPV and involves project leaders and managers from NREL and Sandia, and program managers from the DOE in Washington, DC, and the Golden Field Office.

The planners determine the direction for the Program, set five-year goals for each of 10 major project areas in three R&D categories, establish annual or biannual milestones for each of those areas, and devise strategies for meeting milestones and goals. The plan then is sent out to the entire PV community for review. The published plan serves as a guide for all the participants in the DOE PV Program.

Although this is a five-year plan, it is scheduled for revision every two years in accordance with new progress, a new five-year horizon, and new requirements and funding.

Short-term planning is done on an annual basis in an Annual Operating Plan. Program managers and project leaders detail the R&D, facilities, equipment, expertise, and progress needed to reach the milestones stipulated in the five-year plan. The NCPV coordinates this planning to make sure that participants are heading toward the correct goals, to pare redundancy, and to ensure that the Program efficiently performs its R&D mission.

Funding the Program

Congress provided $72.2 million for photovoltaics in fiscal year (FY) 1999. (An additional $2.8 million was allocated to the Office of Basic Energy Sciences for use in basic R&D on PV sciences and technologies.) With an eye on how best to achieve its strategic goals, the Program distributed this funding among the Program's major elements and participants.

Federal support for the PV Program is more than matched by industry. The private sector outspends the government PV R&D by more than a factor of two — by typically paying for at least 50% of the costs of shared R&D projects, by pursuing their own R&D, and by developing manufacturing facilities.

More than 70 U.S. companies participate in the program. By doing so, they and the government leverage funds and expertise, accelerating the technology toward the goals of industry and of the nation.

These collaborations with industry and academia are spurring PV to its incredible promise of taking the nation along the high-tech highway toward its energy, economic, and environmental future in a sustainable and clean manner.

	1995	2000	2005	2020–2030
Module efficiency* (%)	7–17	8–18	10–20	15–25
System cost ($/W)	7–15	5–12	4–8	1–1.50
System lifetime (yrs)	10–20	>20	>25	>30
U.S. cumulative sales (MW)	175	500	1000–1500	>50,000

***Range of efficiencies for commercial flat-plate and concentrator modules**

Relying on past progress and prognoses for further technological progress, the Program sets general mid- and long-term goals (costs given in 1999 dollars).

The Research Program — Delivering the

Photovoltaics has come a long way since the DOE PV Program began more than two decades ago. We have seen a profusion of technologies — new materials, new device concepts, and new growth techniques and manufacturing processes. We have seen efficiencies rise consistently, module lifetimes increase beyond 20 years, and costs plummet more than 100 fold.

And we have witnessed a fledgling industry strengthen and grow, producing new products for new applications, and penetrating new markets.

Yet, there is much to be done. To deliver PV's promise for the new millennium, we must reduce its cost, make it more competitive for more applications, make devices more efficient and reliable, and make systems that last longer.

To deliver the PV promise of plentiful clean, versatile, low-cost, high-tech energy, the Program explores a wide portfolio of technologies.

To accomplish these aims, we have crafted a program in which we explore a wide portfolio of concepts, materials, and technologies; a program that steers the technologies from seminal idea, through basic and applied research, through engineering, to commercial readiness. This program involves three major elements — research and development, technology development, and systems engineering and applications — each of which is guided by technical goals.

Research & Development

In this area, scientists conduct basic research on promising new materials, processes, devices, and production techniques. This includes research in thin films, high-performance concepts, crystalline silicon, characterization techniques, and basic research on unconventional ideas.

Thin Films

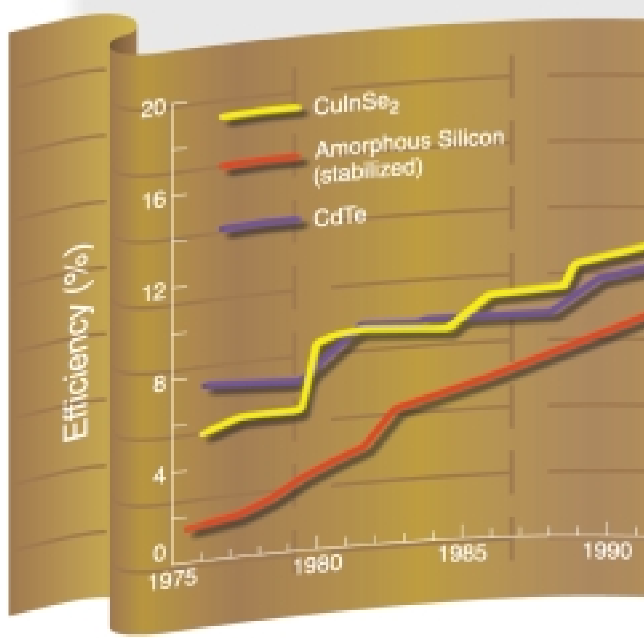
Imagine making PV absorbers less than 1 micrometer thick on long, thin, flexible sheets. Or mass producing square miles per year of inexpensive, efficient PV modules. Such is the motivation behind the Program's research on thin-film PV materials.

Thin films represent a success story. In the late 1970s, the Program began research on what were then "nonconventional" thin-film materials. For those materials that showed promise, the Program cooperated with industry and universities to further develop the technologies. Today, these materials — amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium diselenide (CIS), and thin-film silicon — are among the leading candidates for low-cost photovoltaics.

A success story in progress is the cooperation that is taking place under the Thin Film PV Partnership. Each thin-film technology has formed a national team comprising the nation's best research and engineering talent drawn from industry, universities, and the national labs. Together, the teams are overcoming technical barriers and are accelerating the state of the art.

Amorphous silicon. This was the first thin-film material to go commercial. Initially, a-Si was used mostly in consumer items such as calculators. With increasing efficiencies, proven manufacturability, and innovative products such as modules that double as roof shingles, a-Si is rapidly expanding its markets.

The primary challenge is to raise the stabilized conversion efficiencies for a-Si devices, which lose efficiency



Since the inception of the Program's R&D on thin fil
of cells have risen steadily, reaching today's highs o
15.8% for CdTe cells, and greater than 12% for a-Si

Promise

when first exposed to light. The national a-Si research team is pursuing the challenge by investigating degradation mechanisms that cause this initial loss of efficiency and by exploring innovative designs to increase efficiencies. The team has already made progress, with the best stabilized efficiencies to date around 12% and 10% for cells and modules, respectively. The goal is to produce a stable 15%-efficient device.

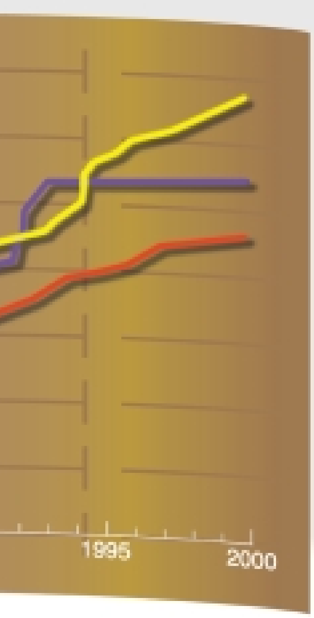
Copper indium diselenide. After two decades of R&D, CIS has been introduced to the market, with modules consistently reaching stable efficiencies greater than 11% — beating the goal set in the last five-year plan by more than a year.

CIS is also enjoying success in the lab, with cell efficiencies climbing to a world-record 18.8% (nearly as high as that of polycrystalline silicon cells). This progress bodes well for meeting the year 2001 cell-efficiency goal of 20%.

Researchers are investigating ways in which to push efficiencies even higher, by exploring the chemistry and physics of the junction formation, and by examining concepts to allow more of the high-energy part of the solar spectrum to reach the absorber layer.

They are also trying to drop costs and facilitate the transition to the commercial stage by increasing the yield of CIS modules (i.e., by increasing the percentage of modules and cells that make it intact through the manufacturing process).

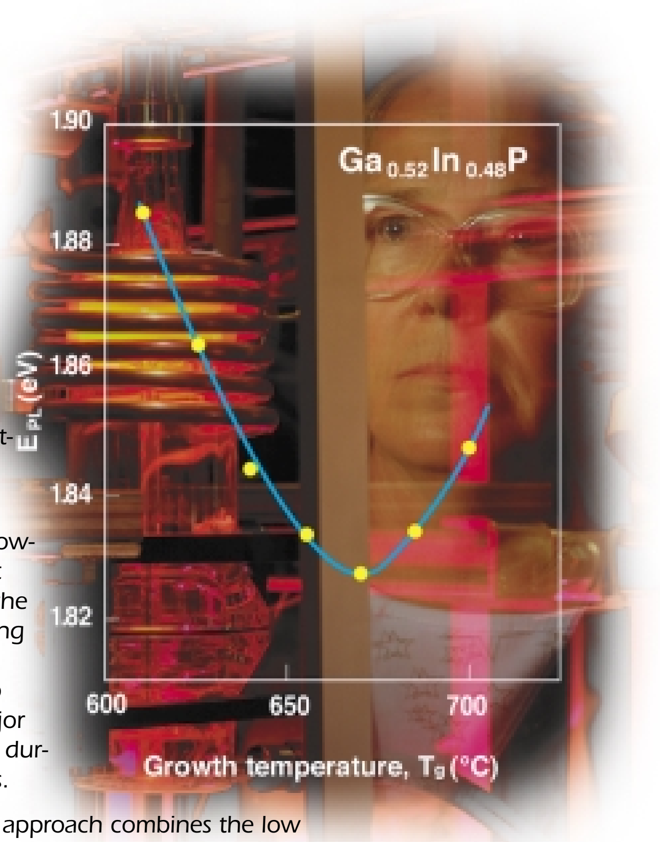
Cadmium telluride. With more than 50,000 watts of modules being field tested, CdTe is on the verge of going commercial. This material is considered promising largely because it can be made using low-cost techniques, such as electrodeposition and high-rate evaporation. Using a variation on this last method, one company is obtaining a throughput rate of one large module every 30 seconds. This approach could be geared up to produce 100 megawatts of modules per year, which would considerably drop the cost of PV electricity.



ms, conversion efficiencies of 18.8% for CIS cells, cells.

Prototype CdTe modules are reaching efficiencies beyond 9%, while laboratory cells are approaching 16%. Researchers on the CdTe team are trying to boost efficiencies by, among other things, exploring innovative transparent conducting oxides that let more light into the cell to be absorbed and that more efficiently collect the current generated by the cell.

Some CdTe devices, however, appear to exhibit some degradation at the contacts. Understanding the degradation and redesigning devices to minimize it will be major efforts of the Program during the next few years.



NREL scientists have pioneered the capability of tuning band gaps of III-V materials, by precisely controlling temperature and growth parameters. Such a capability is leading to the design of 3- and 4-junction high-efficiency cells.

Thin-film silicon. This approach combines the low cost of thin films with the high efficiency of crystalline silicon by using innovative designs that employ low-cost substrates, porous polycrystalline silicon, and techniques that trap light in silicon for total absorption. This allows the use of silicon layers as thin as 10 micrometers (20 to 30 times thinner than traditional crystalline silicon) while getting high efficiencies. Although this approach is relatively new, the Program is already making working modules.

High Performance

Consider a 40%-efficient cell 2.5 centimeters in diameter. Under a normal sun in the southwest United States, it could produce about 0.2 watt of power. Now consider concentrating the sun 1000 times on just 100 of these cells — it would produce 20,000 watts! That is the attraction of high-performance cells: using small, highly efficient cells with inexpensive concentrators produces large amounts of low-cost power.

This avenue of research represents another Program triumph. Researchers have gained a deep understanding into the microscopic order of gallium arsenide alloys, allowing them to control the growth parameters of the alloys and "tune" their band gaps. This enables them to routinely make 2-junction devices (which employ two cells with different band gaps grown one on the other, to capture a larger portion of the solar spectrum) that obtain efficiencies greater than 30%.

This technology is now being used by industry to make cells that power satellites. Although this has great potential for satellite power and telecommunications, it has greater potential for power on Earth. And it is already leading to 3- and 4-junction cells that promise 40% efficiency, which could double the efficiency of current commercial concentrator systems.

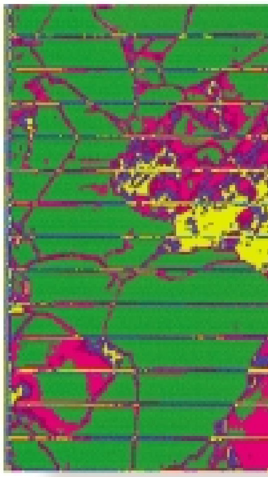
This approach can also be applied to polycrystalline thin-film materials to get the best of both worlds: low cost with high efficiency. By first optimizing single junction concepts, and then tuning band gaps and monolithically (i.e., one on top of the other) growing 2- and 3-junction polycrystalline, thin-film devices, we may be able to double the efficiencies of today's thin-film modules. This could nearly halve the cost of thin-film PV electricity.

Crystalline Silicon

Crystalline silicon (c-Si) has a well-established technology base and the c-Si industry controls nearly 90% of the PV market. It should continue to dominate the market for at least five more years. The technical progress will be evolutionary, but the advances will be quickly integrated into the marketplace. This will help build the infrastructure required for continued rapid growth. The Program is pushing technological advancement in two ways: through research on materials and research on process and devices.

R&D on thin films, high-performance devices, silicon materials, characterization techniques, and innovative concepts will deliver low-cost PV and fill the technology pipeline for future progress.

Materials. The concept is simple: improve the starting material and your knowledge about it, and you'll improve devices made with the material. To this end, researchers are investigating the fundamentals of impurities and defects in crystalline silicon — their effects and their evolution during different types of processing steps. As an example, researchers are exploring a method widely used in the computer industry ("gettering") to remove impurities from crystalline silicon using heat treatments. Such methods along with fundamental understanding may allow the use of less pure materials, which can reduce the cost and increas the availability of startingmaterial.



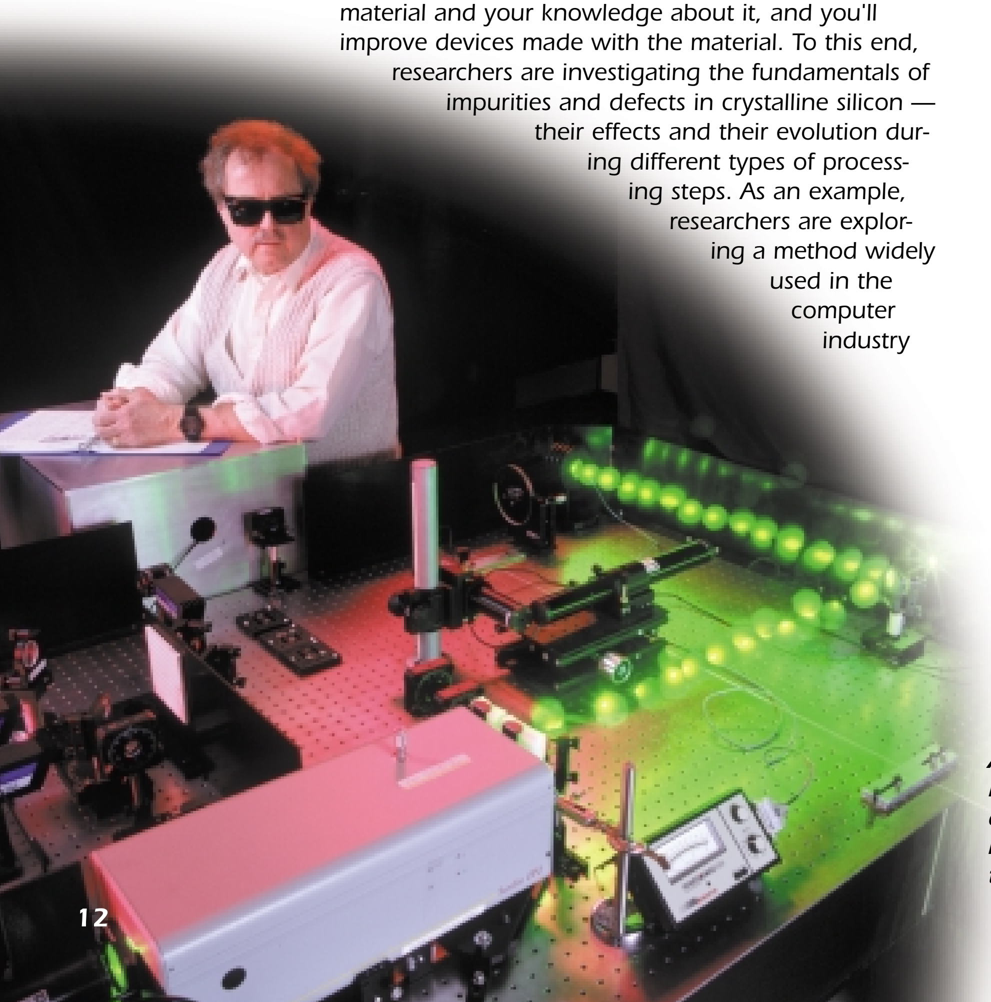
Process and devices. Another simple concept: improve processing and innovative device structures, and you'll increase efficiencies while decreasing fabrication costs. For example, expensive laboratory cells have achieved efficiencies as high as 24.7%, whereas commercially produced cells typically have efficiencies less than 16%. The trick is to develop fabrication processes and device structures that can translate some of the performance features of laboratory cells into manufacturing. To master this trick, researchers are exploring highly versatile techniques — such as plasma processing, which can etch surfaces, deposit dielectric coatings, and passivate surface and bulk defects — to form high-efficiency cell structures using manufacturing procedures.

A second thrust of c-Si research is to develop new processes that require less energy, material, and labor than conventional approaches and that will result in greater throughput. The goal is to double the output of a manufacturing plant without increasing its size; this will help industry reduce manufacturing costs while increasing output. One research approach that could help reach this goal is rapid thermal processing, a low-cost method that uses high-intensity light to rapidly heat substrates and optically enhance processing steps.

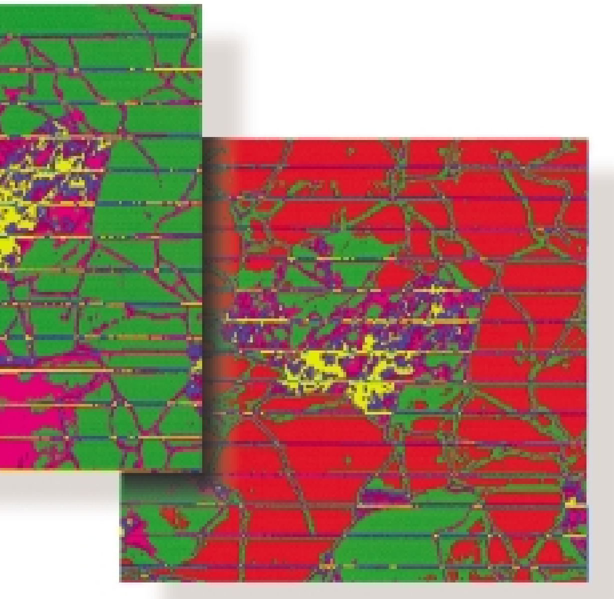
Finally, researchers are investigating radically new device structures that have the potential to significantly reduce the cost of cells and modules. Although the Program and its partners have continually reduced costs, it has been done largely through constant refinement in manufacturing processes. The basic design of crystalline silicon devices has remained essentially the same for 20 years. New approaches that are based on cells and modules specifically designed for easy manufacturability will considerably simplify the assembly of PV modules and reduce costs.

Measurements and Characterization

To make a device that works well is not enough. To optimize the device or to push the concept beyond its present confines requires knowing the doping profile,



An early candidate for in-line diagnostics is this NREL-developed technique — radio-frequency photoconductive decay. It quickly and easily measures the minority-carrier lifetimes of wafer material, an important characteristic indicative of material quality.



Cell performance can be improved by gettering, which removes impurities. Once a cell has been gettered (right), its photoresponse is better than before (left). A higher photoresponse (denoted by going from pink to green and from green to red) indicates a greater generation of charge carriers that can be collected by the grid.

morphology, short-range order, stoichiometry, performance characteristics, and more.

Such knowledge is garnered using measurement and characterization capabilities that span more than ten orders of magnitude — from atoms to arrays — and that precisely determine microscopic and macroscopic properties of a material, device, or process. Once we know the properties, we are in a position to push the technology.

This area of research cuts across all strata of the Program, from basic R&D to module and system performance. Researchers also work with the national and international PV communities to set standards so that devices and systems can be fairly and adequately measured and compared.

And now, the Program is extending its analytical services. Together with the PV community, the Program is defining the needs of manufacturers for diagnostic tools. In accordance with these needs, the Program will develop techniques and tools for in-situ diagnostics and smart processing. These will include tools that can be inserted into growth chambers to analyze growth parameters, and tools that can be incorporated into processing lines to analyze wafer and device quality. Such tools will help manufacturers make better products, with better material utilization, and greater manufacturing yield and throughput.

Basic Research

Where do innovative ideas come from? Ideas that allow you to meet or beat cost and performance goals? Ideas that help reinvigorate the Program? Many of them come from the Program's own researchers, or from researchers supported by related areas (such as the Office of Basic Energy Sciences), and from universities across the nation. The Program funds promising concepts, eventually winnowing out those that do not come to fruition and backing those that continue to flourish. Some of these become Program triumphs.

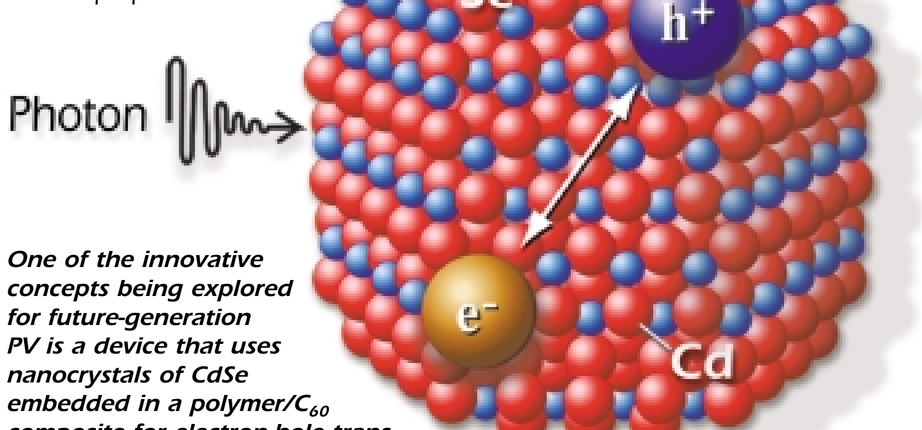
Recently, the pipeline of innovation was refilled with concepts whose success could eradicate remaining barriers to our goals or could take us well beyond to the next generation of technologies.

To tap the latest ideas for innovation, the Program held a conference on future-generation technologies and funded some of the most promising concepts. It also solicited unconventional ideas from the nation's universities, funding 18 of the proposals.

Among the ideas being explored under this project are:

- High-efficiency devices that use III-V nitride alloys and various growth methods to make 3- and 4-junction cells. The nitride alloys can be used to lower band gaps, enabling the cells to efficiently convert the red end of the spectrum.
- Quantum dot solar cells, in which semiconductor absorbers are grown at nanoscale sizes and embedded in a polymer/C_{60} composite. This uses quantum confinement for controlling band gaps. It also promotes the rapid transfer of charge carriers across the nanocrystal/composite interface, which mimics one part of the photosynthetic process.
- Dye-sensitized photochemical cells, which use nanocrystalline titanium oxide (TiO_2 — the cheap white pigment in most paints and in toothpaste) to convert sunlight to electricity, and inexpensive dyes to make TiO_2 sensitive to a broader range of the solar spectrum. When used with an electrolyte, this system generates electricity through electron and hole transfer to electrodes.

From this work may arise technologies that require no p/n junction, that can produce "square miles" of cheap but high-quality PV material, and that give us new insight into material properties.



One of the innovative concepts being explored for future-generation PV is a device that uses nanocrystals of CdSe embedded in a polymer/C_{60} composite for electron-hole transfer. This concept has the potential for low-cost, large-area fabrication.

Technology Development

In its roadmap, the U.S. PV industry set its long-term goals — 40% of the world PV market with annual sales of 7 billion watts and domestic sales of 3.2 billion watts by 2020. Reaching these goals will require the industry to increase manufacturing capacity by nearly 100 fold and domestic sales by even more.

The Program and industry work together to move technology from the laboratory to manufacturing, and to increase the reliability and performance of modules.

This calls for strenuous efforts. It calls for translating R&D advances in materials, devices, and processes to the manufacture of products. It calls for decreasing costs to capture wider markets. It calls for increasing the reliability of modules, components, and systems so that they last longer and perform better throughout their lifetime.

And it calls for close cooperation between the PV industry and the Program, to leverage expertise, facilities, and funds and to accelerate the development of technology.

Manufacturing R&D

R&D partnerships. Since the early 1990s, the Program and the PV industry have worked assiduously to push the state of the art in manufacturing technology. This has been a model of cooperation in which the Program has formed a series of R&D partnerships with more than two dozen PV companies, and in which the companies have shouldered 50% of the R&D costs.

These partnerships have improved manufacturing technology by improving equipment, reducing the number of steps in a process, automating assembly processes, reducing breakage and waste, and increasing throughput — the rate at which PV materials and devices are passed through the manufacturing process.

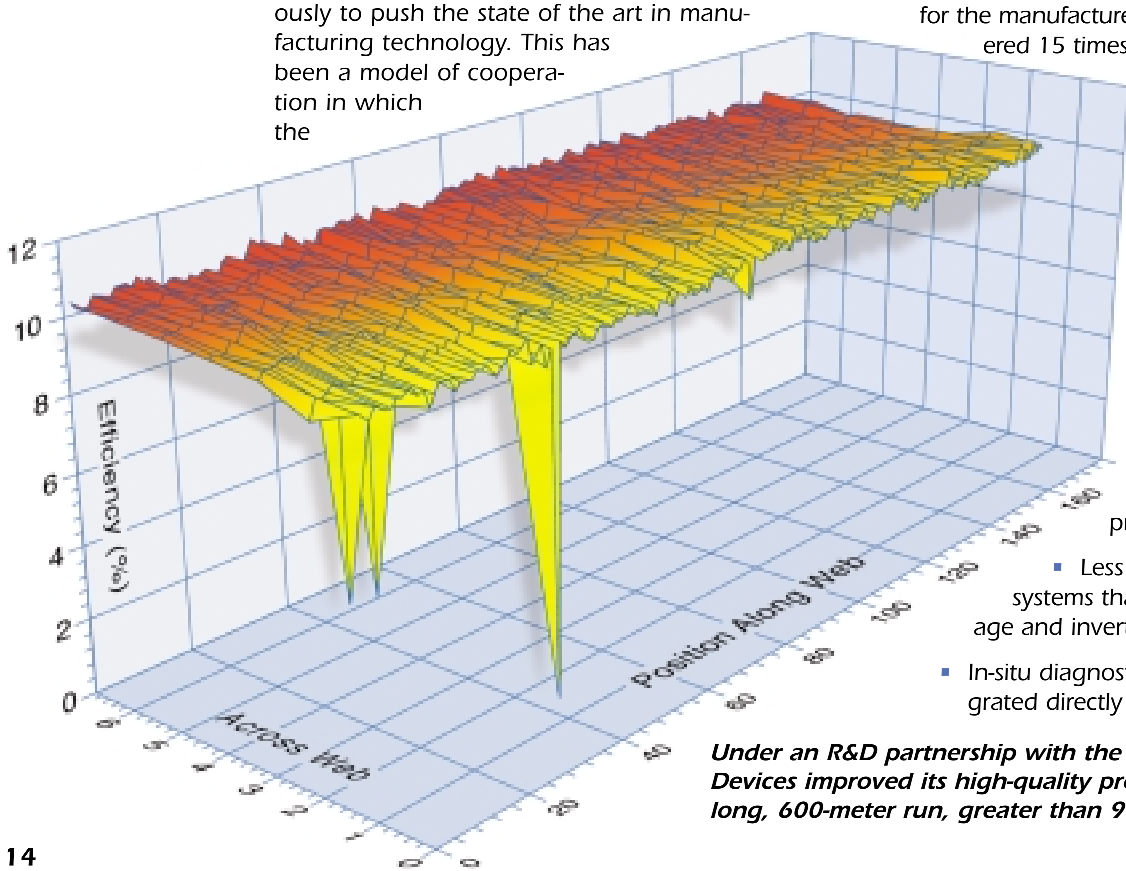
The R&D partnerships have strengthened the performance and reliability of products by increasing the conversion efficiencies of cells and modules, increasing module lifetime with better mounting techniques and encapsulants, and by implementing internationally recognized quality assurance procedures.

Since 1992, this R&D has helped drop module manufacturing costs for industry partners by more than 30%. It has helped increase production capacity by more than five fold. And we anticipate that this type of progress will continue, so that by 2004 we expect to see manufacturing capacity grow another seven fold and module manufacturing costs drop another 50%.

All of this has resulted in a win-win situation, with the public and industry recovering their investments, through cumulative decreased product costs for the consumer and through increased profit (decreased loss) for the manufacturer. By 2004, industry will have recovered 15 times its initial investment, and the public will have benefited by a factor of 23. This trend will enhance the opportunity for investment in greater production capacity for U.S. PV manufacturers.

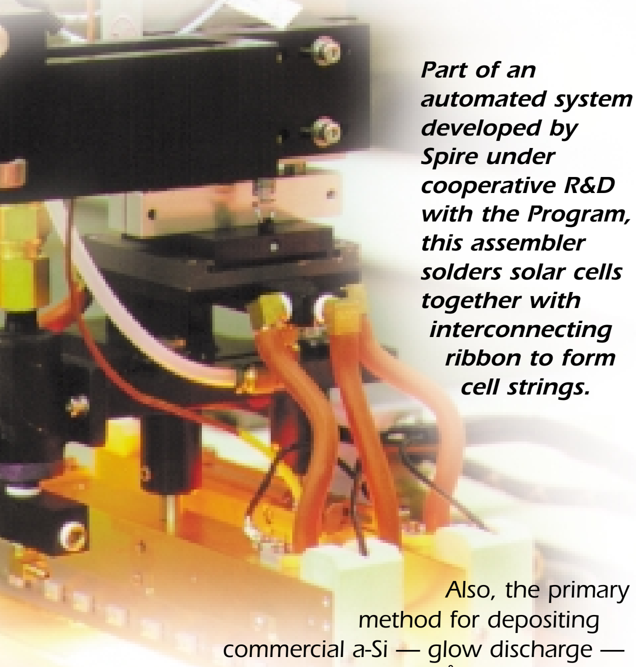
The investment opportunities will be further enhanced with ongoing manufacturing R&D partnerships, which are continuing to improve module manufacturing processes as well as investigating concepts such as:

- AC modules for easy plug-in residential use (PV modules normally produce DC electricity)
- Less expensive, easy-to-install residential systems that integrate the modules with storage and inverter capabilities
- In-situ diagnostics and intelligent processing integrated directly into manufacturing lines.



Under an R&D partnership with the Program, Energy Conversion Devices improved its high-quality production yields of a-Si cells. In this long, 600-meter run, greater than 98% of the cells met specifications.

Other R&D issues in manufacturing include concerns about materials utilization in thin films. For example, in manufacturing a-Si modules, more than 90% of the germanium (to alter the band gap of a-Si) is wasted during deposition. Increasing the utilization rate to 25% or higher would result in significant savings.



Part of an automated system developed by Spire under cooperative R&D with the Program, this assembler solders solar cells together with interconnecting ribbon to form cell strings.

Also, the primary method for depositing commercial a-Si — glow discharge — has a deposition rate of 1 to 3 Å/sec. Increasing this rate to 10 to 100 Å/sec would also drop costs appreciably. A possible candidate for this would be a variation on the hot-wire deposition developed by NREL researchers.

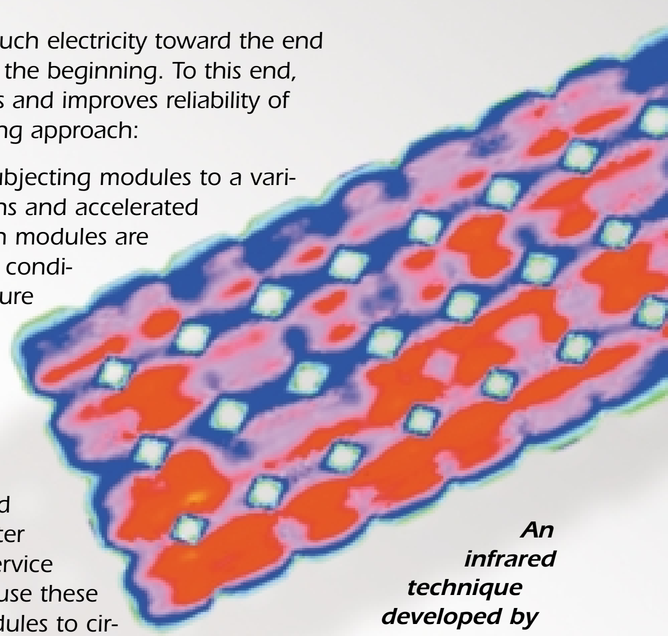
Component reliability. All PV systems use components — batteries, control systems, inverters, etc. — to convert, deliver, and store electricity generated by modules. These components represent about half the cost of a system, but are responsible for the great majority of repair problems. Notorious among these are inverters, whose failure in the field represents the primary cause of system problems.

Recognizing this, Sandia is launching an initiative to design and build an "inverter for the 21st century;" one that would cost 25 cents per watt and have failure rates less than 1%. To do so will take advances in circuit integration, packaging, custom magnetics, and manufacturing. And it will take cooperation with industry, which will specify and design the inverter. Sandia will work hand-in-hand with industry and testing labs to evaluate the inverter. Similarly, Sandia will evaluate the smaller inverters being designed and built by industry under other cooperative R&D projects with the Program.

Module Performance and Reliability

Companies bring their modules and systems to NREL and Sandia for testing and analysis, to improve system reliability. By "reliable," we mean that a system both should last long (up to 30 years, the long-term goal) and generate 80% as much electricity toward the end of its lifetime as it did at the beginning. To this end, the Program investigates and improves reliability of systems using a five-prong approach:

Module testing. By subjecting modules to a variety of outdoor conditions and accelerated stress tests (under which modules are cycled through extreme conditions), researchers measure module performance and identify failure mechanisms. Failure mechanisms and degradation rates from these tests are correlated with long-term field tests, and used to validate computer models for predicting service lifetime. Manufacturers use these tests to re-engineer modules to circumvent failures.



An infrared technique developed by Sandia for long-term testing of modules indicates "hot spots" and "cold spots" to locate short-circuited cells.

Accelerated testing of encapsulation materials. Browning, chemical decomposition (which affects optical, electrical, and mechanical properties of a module), and delamination can limit module lifetime and electricity production. Accelerated testing promotes a better understanding of the mechanisms of aging and decomposition. This, in turn, leads to better module production techniques and better encapsulation materials.

Solar radiometric measurements. Measuring the solar radiation and its spectral content, with an accuracy traceable to national and international standards, provides a base against which to measure and compare module and system performance. Also, knowing the spectral content of solar irradiance (i.e., the energy and intensity incident at particular solar wavelengths) enables us to understand degradation mechanisms, especially with respect to the ultraviolet portion of light, which can be highly damaging to some materials.

Module and array performance. How do commercial modules perform over the long haul under field conditions? Answering this question helps correlate long-term performance with failure mechanisms identified under accelerated stress testing. This helps manufacturers to design systems to overcome the failures and boost performance. Efforts include developing outdoor module and array test procedures; characterizing electrical, thermal, and optical attributes of commercial modules; and developing numerical tools that accurately model the power and annual energy production from PV systems.

Module field durability research. Thoroughly analyzing the degradation mechanisms of modules under long-term exposure helps manufacturers develop improved processes to mitigate problems. This understanding also lends to the Program's development of module qualification testing, which can help manufacturers produce long-term, high-performance modules.

Systems Engineering & Applications

Meeting the long-term goals of the PV Program and PV industry requires nothing less than launching the industry anew in the 21st century, with systems and innovative products that can accelerate expansion into whole new markets.

This obliges the PV industry to make systems that meet the performance, maintenance, and lifetime demands of the user; that meet mechanical, electrical, and safety codes and standards; and that may be easily integrated into a myriad of applications. And it obliges the Program and industry to adequately inform builders, developers, utilities, industry, and the public about PV systems, their capabilities, and applications.

Systems Engineering

In the final analysis, it is performance, reliability, and lifetime of *systems* that are important to customers. Consequently, the Program and industry are working together to test how well systems perform under real conditions for long periods of time. These data will be entered into databases and will be used to define standards by which field performance may be measured.

Similar testing is taking place to determine the reliability of systems in the field — how long they last, how well they perform during their lifetime, and how much maintenance they need. These data will be used to establish requirements for a reliable 30-year system lifetime.

To boost the confidence that new systems will perform reliably for 30 years, the Program is devising qualification protocols — establishing accelerated test procedures whereby systems are subjected to cycles of extreme temperature, humidity, mechanical, and electrical conditions to determine how long they can be expected to last and how well they can be expected to perform. For systems that pass these protocols, customers will be assured of their quality and reliability.

Grid-tied systems should also meet connection standards (e.g., producing a high-quality AC signal, and being able to automatically detach from the grid in case of emergency). To be sure they do, the NCPV is working with utilities, the Electric Power Research Institute, the Gas Research Institute, and others to devise standards for grid-tied PV systems. This will help PV be ready to meet the needs of the utility market.

The 4 Times Square Building in New York City integrates thin-film PV panels into the mirror glass spandrels from the 35th to 48th floor. The panels produce 1.5% of the building's electrical needs.

PV Buildings Integration

The more than 100 million residences and commercial buildings in the United States consume two-thirds of the nation's electricity. This need not be so. By incorporating PV systems, buildings could *produce* electricity — for lights, cooling loads, fans, and more.

The concept of integrating PV into buildings has been evolving for some time. In the 1970s, remote buildings began using PV modules to supply small amounts of electricity. In the 1980s, residences and commercial buildings started mounting PV arrays on their roofs and connecting them to the grid. In the 1990s, the Program brought together PV manufacturers with manufacturers of building products to develop PV systems for integration directly into the building envelope — to be used in awnings, windows, spandrels, skylights, roofing shingles, and other structures.

Today, the idea is spreading, with architects, engineers, and builders incorporating PV into their building designs. But more must be done for this concept to become widespread. First, costs must drop. Due to customized designs, integrated PV systems can be expensive. This may be mitigated by product standardization, which would allow PV systems to be bought "off the shelf" and integrated into buildings.

Second, the PV industry must pay close attention to the needs of the buildings industry, by making sure their products meet codes, standards, and insurance requirements, and that they design new products that meet real building needs. Toward this end, the Program, the PV industry, and the buildings industry are cooperating to develop cost-effective systems that blend well with building materials and components. These include:

- PV-powered electrochromic windows (to shade sunlight and offset heating loads)
- Transparent thin-film products
- Alternating current PV modules
- Hybrid PV products that can offset both electric and heating loads
- New inverters that can be used with a string of PV modules
- New roofing products.

Technology Introduction

In June of 1997, President Clinton announced an ambitious plan — the Million Solar Roofs Initiative — to put a million solar systems on American roofs by 2010.

This 15-kW system uses innovative modules developed in a cooperative program with industry to supply AC electricity for the Pentagon in Arlington, Virginia.

This is a plan in which Americans — communities, organizations, state and federal agencies, businesses, institutes, and private citizens — cooperate to put PV to work for clean energy.

The role of the Program and the NCPV is to act as a focal point for technical information and education on PV, provide technical services, and provide a forum through which various organizations coordinate their activities. This is a paradigm of cooperation, in which a little investment and much initiative may have important consequences.

The Million Solar Roofs Initiative is representative of the partnerships that the NCPV forms to provide technical information and services to help organizations implement the technology. The NCPV also works with:

- Insurance companies and the Federal Energy Management Agency — who want to know how PV can power communication, light, and heat to mitigate the burden incurred by natural disasters
- Federal agencies such as the U.S. Forest Service and the National Park Service — who are interested in using PV for remote power and communications
- Utilities and regulatory agencies — who want to know how to use PV for on- and off-grid applications, and who are concerned about PV performance and interconnection issues
- Farmers and ranchers — who could use stand-alone PV for electric fences and for pumping water for cattle or irrigation.

For the international market, PV is becoming a power of choice for applications ranging from water pumping, communications, and lighting, to village power. This is a fast-growing market, and the competition is fierce to bring PV to more than 2 billion people in developing countries who are without electricity.

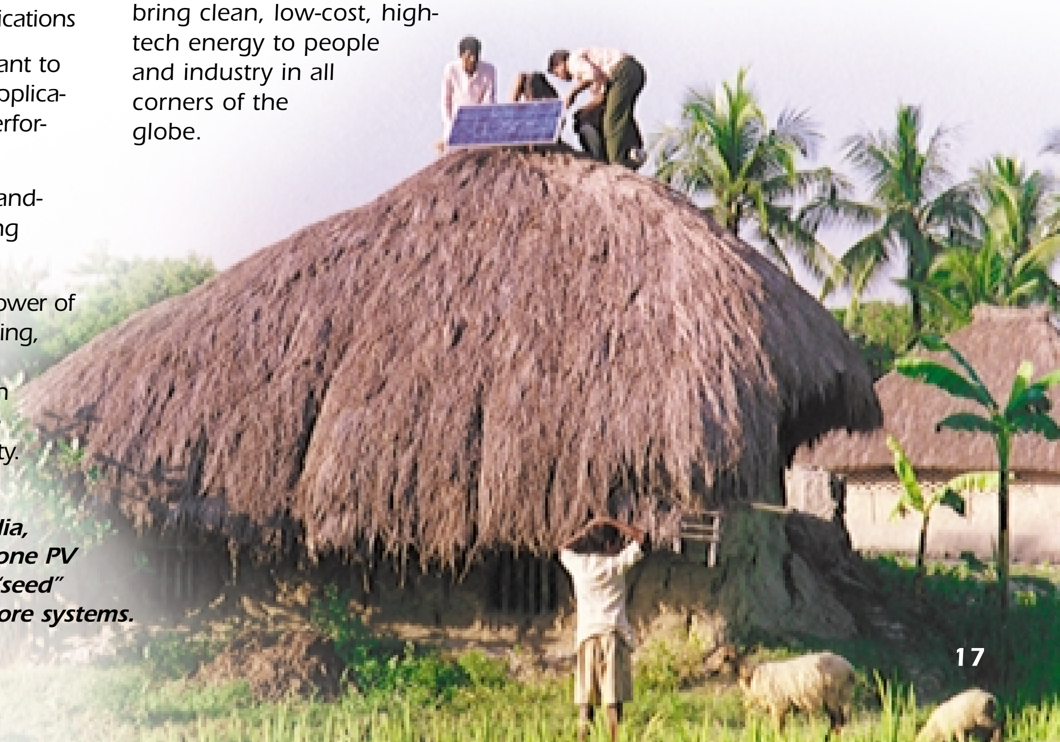
To help the U.S. industry make inroads and to help countries establish a PV infrastructure, the NCPV performs several functions, including:

- Facilitation — by working with U.S. industry, government agencies, financial institutions, technical and research organizations, and nongovernment organizations, to clear barriers to PV installations
- Education/testing — by working with indigenous groups and national institutes to provide education and training, perform testing, and devise testing protocols
- Standardization — by cooperating with national and international organizations to develop PV performance, measurement, and interconnection standards
- Evaluation — by performing studies to assess the social, economic, environmental, and technological impacts of PV
- Demonstration — by demonstrating new technologies to ascertain their technical feasibility for new or remote applications.

The Program — with industry, governments, national and international organizations — improves performance and reliability of systems and introduces technology to domestic and foreign markets.

To date, the Program has helped introduce PV to Brazil, China, Ghana, India, Indonesia, Kenya, Mexico, Morocco, Pakistan, the Philippines, Russia, South Africa, and Venezuela. In the next five years, the Program will continue to extend and deepen this list.

As this list is extended, and as domestic and international markets expand throughout the next century, we will witness the unfolding of PV's promise to bring clean, low-cost, high-tech energy to people and industry in all corners of the globe.



In a cooperative effort between DOE and India, 300 homes in West Bengal installed stand-alone PV systems to provide electricity for lights. This "seed" project stimulated the installation of 2000 more systems.

Serving America

Photovoltaics is an investment in America's future. As we expand the boundaries of energy, PV serves America and improves the quality of life on Earth. Our exploration is covering new frontiers in:

- Science — where we investigate condensed matter physics, quantum physics, photochemistry, photosynthesis, and biological systems to push the limits of knowledge on the interaction of light with matter . . . and where we synthesize new materials and create new device structures to convert light to electricity.
- Technology — where we develop modules and systems and engineer new technologies to enhance manufacturing capabilities . . . and where we are introducing new thin-film and high-efficiency materials and devices that will continue to revolutionize the industry and drop the cost of electricity.
- Applications — where PV systems today are being used in space, for communications, on houses, and in remote places, expanding to every corner of the globe . . . and where tomorrow's systems will be used in ever larger, more energy-significant applications as new materials and devices emerge into the marketplace.

The promise of photovoltaics, however, goes beyond energy. In synergy with other advancing technologies — biology, solid-state and other materials, medicine, telecommunications, superconductivity, and renewable energy — PV will greatly influence our lives. It will help bolster our economy and will spur us to redefine how we work and how we communicate.

The year 2000 is more than the start of a new millennium. It is the start of a new energy era, in which PV will touch the lives of billions of people on our planet.

Research and Development	**Thin Films**
	High-Performance and Concentrator Research
	Crystalline Silicon
	Measurements and Characterization
	Basic and University Research
Technology Development	**Manufacturing Research and Development**
	Module Performance and Reliability
Systems Engineering and Applications	**Systems Engineering and Reliability**
	Partnerships for Technology Introduction
	Program Integration and Industry

Five-Year PV Program Technical Areas and Milestones

2000	2001	2002	2003	2004
Assess progress and structure of Thin Film Partnership and begin recompetition process	▪ Demonstrate stable 13%-efficient a-Si cell ▪ Demonstrate 20% polycrystalline thin-film cell	▪ Demonstrate 17%-efficient CdTe cell ▪ Support the successful transition of CdTe to multi-megawatt production	Support the successful transition of CIS to multi-megawatt production	Demonstrate 10%-efficient commercial CdTe module
Initiate projects targeting a doubling of PV performance from 1999 commercial levels	Assess technical issues for high-concentration systems	Demonstrate feasibility of a 3-junction device for 38%-efficient solar cell under concentration	Demonstrate a monolithic, series-connected, multijunction polycrystalline thin-film device	Demonstrate achievement of voltage addition in 4-junction device
Assess viability of back-contact Si solar cells	Demonstrate potentially low-cost, high-quality, thin-layer crystalline Si growth on a foreign substrate	Demonstrate 18%-efficient, large-area multi-crystalline-Si solar cells using commercially compatible processes	Assess processes for solar-grade Si feedstock production	Demonstrate 19%-efficient Si solar cell using all high-throughput processes
Initiate R&D on process diagnostics and integration	Develop and implement an electro-optical-based diagnostic compatible with manufacturing environments	Initiate next in series of international cell and module performance intercomparisons	Refine and transfer manufacturing-friendly electro-optical-based diagnostic to PV industry	Complete capability to evaluate multiple-junction concentrator cells and modules to 1000X with ±3% uncertainty
Expand fundamental R&D for conventional and nonconventional PV technologies	Assess viability of dye-sensitized solar cell	Assess contributions of Historically Black Colleges and Universities projects	Assess results of EERE/Office of Science collaborations	Identify promising PV options for future R&D
Identify and focus on new projects on intelligent processing, in-situ diagnostics, and related areas to meet industry needs	Evaluate balance-of-systems component progress and future needs	Achieve module manufacturing processes capable of $2/watt direct module manufacturing costs with 250-megawatt production capacity	Determine need for additional manufacturing R&D and identify areas of maximum impact, if appropriate	▪ Implement new partnerships to address processes capable of $1/watt direct module manufacturing costs with gigawatt production capacity ▪ Demonstrate soft-switching inverters with 97% efficiency and < 1% failures
▪ Help develop and publish a qualification standard for concentrator modules (Institute of Electrical and Electronic Engineers [IEEE] 1513) ▪ Update performance indicators of 30-year module lifetime	Publish comparison of module energy-rating methods	Document failure/degradation mechanisms of thin-film and crystalline modules	Document performance of commercial modules, based on energy production	Validate accelerated test methods that reproduce failures/degradation observed in the field
▪ Establish qualified databases to assess operation and maintenance and lifetime for grid-tied and stand-alone systems ▪ Facilitate development of PV interconnection standard (IEEE 929)	▪ Obtain national accreditation and certification program for installation and acceptance of PV systems ▪ Complete development of test procedure to determine performance of stand-alone systems	▪ Establish requirements for 25-year systems ▪ Facilitate and lead IEEE development of interconnection standard for distributed generation	▪ Technically assess thin-film system performance ▪ Demonstrate technology for remote dispatch of PV inverters	▪ Validate 25-year lifetime for PV systems ▪ Develop PV system qualification test
Assess impact of PV in developing countries and document performance from past project initiatives	NCPV to assess contributions of Technology Experience to Accelerate Markets in Utility Photovoltaics (TEAM-UP) to U.S. utility PV program	Increase adoption of PV backup power supplies by federal and state disaster relief organizations	Assess Million Solar Roofs Initiative, documenting number of residential and commercial systems installed	Support insurance industry in adopting a premium benefit for owners of PV-powered buildings
Industry publishes PV 20-Year Roadmap	Start construction of NCPV Science and Technology Facility	Issue revised DOE PV Program Five-Year Plan	Assess environment, safety, and health issues associated with multi-hundred-megawatt manufacturing and deployment of PV	Examine PV Program contributions to meeting 20-Year Industry Roadmap

Industry Roadmap 2000–2020

The U.S. photovoltaic industry has long been the world's leader in research, technology, manufacturing, and markets. During the last several years, however, other nations have recognized the importance of this technology and have accelerated their own strategic incentives toward securing dominant global positions.

To meet growing market demand, confront increasing foreign competition, and retain and build its leadership position, U.S. PV companies have devised a unified industry roadmap with a vision, and with long-term (through the year 2020) strategies and goals.

The Vision

. . . to provide the electrical/energy consumer competitive and environmentally friendly energy products and services from a thriving United States-based solar-electric power industry.

The Strategies

- Maintain the U.S. industry's worldwide technological leadership.
- Achieve economic competitiveness with conventional technologies.
- Maintain a sustained market and PV production growth.
- Make the PV industry profitable and attractive to investors.

The Goals

- Maintain a 25% annual production growth rate.
- During 2020, ship approximately 7 peak gigawatts (GW_p) of PV for installation worldwide, 3.2 GW_p of which will be used in domestic installations.
- Drop costs to the end user (including costs for operation and maintenance) to $3.00 per watt AC by 2010 and to approximately $1.50 per watt AC by 2020.

The roadmap serves as a guide for the industry and the PV community. Its success depends on the direction, resources, best scientific and technological approaches, use of the best and most advanced technologies, and continued efforts of the "best and brightest" among industry, federal laboratory, and university partners.

Credits

Pages 2-3 Sandia National Laboratories/PIX04923 ▪ p.4 Warren Gretz, NREL/PIX07158 ▪ p.5 Richard Peterson/PIX01443 ▪ p.6 Jim Yost Photography/PIX01816 ▪ p.7 Siemens Solar Industries/PIX06142 ▪ p.8 U.S. Department of Energy/ PIX04125 ▪ p.9 Idaho Power Company/PIX01585 ▪ p.10 Jim Yost Photography/PIX01436 ▪ p.11 Jim Yost Photography/ PIX01462 ▪ p.12 Jim Yost Photography/PIX07103 ▪ p.13 Bhushan Sopori, NREL/PIX03521 ▪ p.15 Spire Corporation/ PIX07526 ▪ p.15 Sandia National Laboratories/PIX08309 ▪ p.16 Kiss + Cathcart Architects/PIX06456 ▪ p.17 John Thornton, NREL/PIX06249 ▪ p.17 Harin Ullal, NREL/PIX04579.

Special thanks to Gary Cook, Ray David, Don Gwinner, and Alfred Hicks at the National Renewable Energy Laboratory for writing, design, layout, and editing. Robert McConnell and Jack Stone served as technical advisors.

For More Information

U.S. Department of Energy
James E. Rannels, Director
Office of Solar Energy Technologies
1000 Independence Ave., SW
Washington, DC 20585
(202) 586-1720

U.S. Department of Energy
Richard King, Team Leader
Photovoltaics Program
1000 Independence Ave., SW
Washington, DC 20585
(202) 586-1693

National Renewable Energy Laboratory
Lawrence Kazmerski, Director
National Center for Photovoltaics
1617 Cole Boulevard
Golden, CO 80401-3393
(303) 384-6600

National Renewable Energy Laboratory
Thomas Surek
Technology Manager
Photovoltaics Program
1617 Cole Boulevard
Golden, CO 80401-3393
(303) 384-6471

Sandia National Laboratories
Chris Cameron, Manager
Photovoltaics Program
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-3154

http://www.eren.doe.gov/pv

Produced for the U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

by the National Renewable Energy Laboratory
1617 Cole Boulevard ▪ Golden, Colorado, 80401-3393 ▪ (303) 275-3000

NREL is a national laboratory of the U.S. Department of Energy
operated by Midwest Research Institute ▪ Battelle ▪ Bechtel
Contract No. DE-AC36-99GO10337
DOE/GO-10099-940
January 2000