NREL PV

Working With Industry

Fourth Quarter, 2000

Pulling Together to Pull Ahead

Much can be gained by making sure that all of us within the U.S. PV community are pulling *together*—but to pull *ahead*, we must work across a spectrum of solar technologies. We must also draw in a broader constituency of American citizens and government decision-makers, to show them that renewable energy such as solar electric power is a good investment for all of us.

Within the PV community, two new PV Program initiatives are encouraging researchers from government laboratories, universities, and industry to pull together to achieve one common goal: a dramatically decreased cost of solar electricity so that this technology can significantly contribute to our nation's economy, energy security, and environment. In the short term, researchers will explore new materials and devices to double the efficiencies of thin-film solar cells in 10 years. In the long term, researchers will target discoveries of new semiconductor materials and new ways of producing electricity "beyond the horizon" of our present knowledge. You'll see much more about these two promising initiatives in an article beginning on page 6.

In another development, PV specialists are becoming more involved with other solar energy specialists, such as engineers and researchers in the DOE's Solar Buildings and Concentrating Solar Power Programs. We know these technologies can complement each other to further reduce the cost of solar technology, and it's exciting to see this starting to happen. For example, earlier this year, DOE challenged architects, engineers, energy technology companies, and university students to design a solar wall for the Forrestal Building in Washington, D.C., using several types of solar technologies. The winner is highlighted in this issue.

As Jim Rannels, Director of the DOE Office of Solar Energy Technologies, points out in his editorial, worldwide PV shipments for 2000 will continue the trend of recent years with double-digit increases. All the while, PV manufacturing costs are coming down and conversion efficiencies are climbing. Congratulations to all concerned! It's clear we're pulling together and heading in the right direction.

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Predicting a Solar Future for America

Applied Power Corp./PIX09691

Jim Rannels is the Director of the U.S. Department of Energy's Office of Solar Energy Technologies, which includes photovoltaics, solar buildings, and concentrating solar power. Recently, he attended the dedication of one of the largest thin-film PV installations in the United States. The new system provides 100 kW of power to the U.S. General Services Administration at the Suitland Federal Center in Maryland. Pepco Energy Services and Applied Power Corp. partnered with DOE and GSA to install the thin-film, amorphous-silicon PV system. Joining Rannels (center) were Tamela Riggs, GSA Deputy Assistant Regional Administrator, and Jim Bing, Manager of Projects and Instrumentation for Applied Power.

Contact Jim Rannels at 202-586-1720

An Editorial by James Rannels

January is a prime time for predictions, so I'd like to make one of my own. When all the numbers are in, the year 2000 will be the best year ever for the U.S. photovoltaics industry.

Okay, so I'm not exactly going out on a limb here. Worldwide shipments of photovoltaic (PV) modules have averaged 20% growth over the last 10 years, with U.S. manufacturers accounting for a significant share of that total. My long-time friend, Paul Maycock, the statistics man for the PV world, tells me that the number for 2000 could well be 255 megawatts of product shipped worldwide. And that's a 25% increase versus 1999.

The increase in shipments is relentless—and it's the job of the U.S. PV industry, aided by the national labs and universities within the U.S. PV Program, to keep it that way. Just as relentless are the advances in conversion efficiencies and performance of PV systems—as well as significant reductions in the cost of those systems. Here, the national labs of the National Center for Photovoltaics (NCPV) take the leading role, in partnership industry and academia.

In my mind, it all adds up to a situation in which technology advancements, fueled by investment from the government sector, are making a positive mark. Every partner and stakeholder in the PV Program and the NCPV shares credit for that.

It's become commonplace to read about the environmental contributions of solar energy, but often overlooked are two other important issues: domestic economic benefits and energy security. The PV Industry's 20-Year Roadmap Report predicts that, in the near future, "PV module manufacturing plants will be sought after by every community in the U.S. for providing tens of thousands of jobs that are high-tech with a clean manufacturing environment." I believe wholeheartedly that this is true—and I'm going only a bit farther out on that limb with this statement.

The PV Industry Roadmap Report also makes a salient point about the value of PV as an onshore energy resource: "PV is critical to our energy security, strategic technology, and long-term economic growth. As a 'distributed' generation source, this technology acts as a network—not a grid—and is much less susceptible to large-scale outages caused by disasters of natural or human origin. It mitigates our dependence on foreign energy supplies, while providing distinct benefits to our domestic economy."

I saved my best prediction for last: that the United States will maintain its technology leadership role within the worldwide PV arena. Okay, now that limb is beginning to tremble just a bit. We all know that other countries, specifically Japan and Germany, are funding PV research and market development at much higher levels than we are. They're catching up to what once seemed an insurmountable U.S. technology lead.

But I'm holding firm. Photovoltaic and other solar electric energy technologies are vital to our national interest. They are standing ready to both supplement our nation's stressed energy grid and provide power to areas remote from that grid. They are a perfect fit for community-based manufacturing, with its concomitant job creation. They are exportable commodities in high demand around the world.

These technologies merit continued support from America's decision-makers. With that support, U.S. technology leadership *will* prevail.

PV Web Sites

DOE PV Program .... *www.eren.doe.gov/pv*
About Photovoltaics • News and Information • About Our Program

National Center for Photovoltaics .... *www.nrel.gov/ncpv*
World Class R&D • Partnering and Growth • Information Resources

The Center for Basic Sciences ....*www.nrel.gov/basic_sciences*
Capabilities • Optoelectronics • Crystal Growth and Devices

Measurements and Characterization ....*www.nrel.gov/measurements*
Virtual Lab • Capabilities • Doing Business • Data Sharing

Million Solar Roofs ....*www.eren.doe.gov/millionroofs*
Initiative Goals • Scope • Solar Technologies • Solar Registry

Photovoltaic Manufacturing Technology ....*www.nrel.gov/pvmat*
Overview • Partners • Fact Sheets • News and Events • Contacts

PV Silicon Materials Research ....*www.nrel.gov/silicon*
Thin-Layer Si Growth • Research with Industry

Surviving Disaster with Renewables ..*www.nrel.gov/surviving_disaster*
Renewables to the Rescue • NREL's Work • Solar Recovery

PVSC Gets Down to Business

by John Benner

The *business* of PV dominated the conversation at the 28th IEEE Photovoltaic Specialists Conference (PVSC) held in Anchorage, Alaska, in September. More than at any previous conference, practical issues affecting production today and designs for large, near-term production expansions carried much of the interest in all technology areas.

From general session opening discussions about the hiring and training of 160 employees to staff thin-film production facilities to final sessions examining barriers to production of 15%-efficient and greater multicrystalline cells, this PVSC emphasized the technology needed to realize a 10-gigawatt industry by 2010.

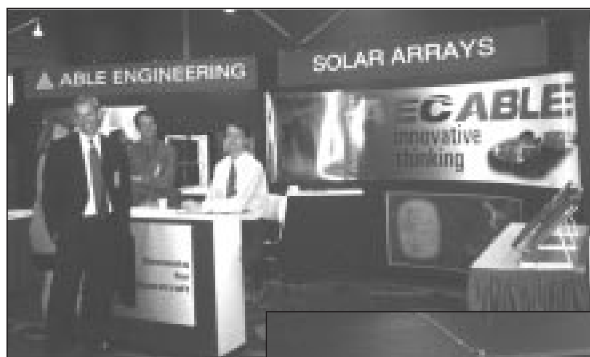
As in past conferences, record conversion efficiencies were reported, but this time, the results were for 20.7%-efficient silicon cells that produce more than two watts and 11.1%-efficient CdTe modules pushing out 50 watts. The growing maturity of the PV field was evident in the willingness to share knowledge that previously had been regarded as proprietary, including: experience from manufacturers producing tens of megawatts of silicon cells to one producing a megawatt of triple-junction III-V cells; bringing a 10-megawatt thin-film line to 90% capacity and 90% yield; and, plans for existing facilities expansion.

The science and engineering of improved materials, structures, and characterization tools appeared prominently in advancements in the technology, as well as in the addressing of the practical issues determining production yields. Consistent measurements of materials and device properties coming from several labs are providing a clearer picture of the operation of thin-film devices. New tools for in-line characterization and in-situ diagnostics promise to expand the borders of this picture.

One intriguing link among the various PV cell options was the growing attention to transparent conducting oxides (TCOs). For the first time, conducting oxides appeared as part of the contact structure in crystalline silicon cells. The CIS community is examining a number of alternatives to ZnO, including the possible formation of heterojunctions directly between the oxide and the CIS. The role of zinc stannate and cadmium stannate in CdTe devices was shown to influence alloying in the junction region. Finally, improvements in amorphous silicon were derived by using TCOs with superior properties.

The most practical aspect of PV is in the applications area. In these sessions, the growing base of experience points to strengths and challenges in PV performance. A number of presenters commented on the intriguing performance of newer thin-film modules that respond to temperature, light, and other factors in a nonlinear manner. More work is required to validate predictive models.

An old problem associated with grid-connected PV systems—islanding—was addressed for the third time. A PV system that continues to operate when power drops from the grid presents a hazard to maintenance and delays system recovery. In the mid 1980s, the PV community solved this problem to its satisfaction. In the early 1990s, it was solved again—to the utility engineer's satisfaction. In 2000, it appears to be solved once more, but this time at a level that will satisfy the lawyers.



Lauren Poole, NREL/PIX09693

Lauren Poole, NREL/PIX09694

The mood of IEEE Alaska was upbeat, with evidence of growth in all sectors. An increasing number of new ideas were presented for future cells. We saw growth in PV production and sales, growth in financial and public support for PV, and growth in the kinds of applications where PV is cost competitive. The focus on the practicalities of PV will help to continue this growth.

The next IEEE PVSC conference is scheduled for May 2002 in New Orleans, Louisiana.

For more information, contact John Benner at 303-384-6496.

Practical PV issues may have dominated the technical sessions, but space technology reigned in the exhibit hall. NASA's Glenn Research Center sponsored a special auxiliary program that brought in space technology exhibitors from around the world.

Winning Combinations—PV Complements Other **Solar Technologies**

Solar technologies, such as PV, solar thermal for heating water, passive solar for daylighting and heat, and concentrating solar power for large-scale utility applications, all share the same goal: to replace or supplement traditional energy sources with cleaner alternatives. And although these technologies are generally developed separately, there are indications this is changing.

PV researchers are collaborating with researchers from other solar technology areas to advance the market for all. Members of the NCPV are working with members of DOE's Solar Buildings and Concentrating Solar Power programs, all of which fall under the DOE Office of Power Technologies, to foster cooperative research with the common goal of reducing costs and accelerating the use of these technologies in the marketplace.

PV and Solar Buildings

Buildings in the United States account for two-thirds of all electrical consumption and are responsible for one-third of peak electrical demand. In addition, buildings typically last for 50–100 years, so how they consume energy has an impact on long-term energy use. The DOE Solar Buildings Program is challenging this energy consumption trend in buildings through its Zero-Energy Buildings initiative. The initiative supports research that combines solar energy technologies with energy-efficient construction techniques to create a new generation of cost-effective buildings that can supply their own energy from renewable resources.

Wayne Appleyard/PIX09690

The recently completed "Nature House" at the Leslie Science Center in Ann Arbor, MI, is an environmental learning center that combines PV with other solar technologies. Features include a First Solar 2-kW solar-electric array composed of CdTe thin-film modules; solar thermal panels for heating water; windows designed for direct-gain sunlight in winter; and an 8-inch Trombe wall for heat storage. Energy-efficient features include compact fluorescent lighting and appliances.

"The challenge is to achieve cost-effective and affordable zero-energy buildings," says Frank "Tex" Wilkins, team leader of DOE's Solar Buildings Program. "Every dollar is important to builders, because for every dollar a home increases in price, builders lose a certain number of people who can buy the home." If builders can significantly reduce demand with energy efficiency features and find ways to integrate PV into existing building components at a low cost, they can increase the market for both industries, he says.

Wilkins opened the Zero-Energy Buildings meeting held at NREL in late October. Some 60 people attended, including representatives from the building, PV, and solar thermal industries, as well as from the NCPV and DOE. The purpose of the meeting was to introduce the solar community to the building community to foster cooperation and reduce costs.

Building industry representatives spoke openly about their concerns. They expressed the need for further PV system cost reductions to allow builders to install a PV system on a $300,000 home for about $4,000. The building industry also let members of the PV industry know that it can't sell PV for them. Builders will need assistance with marketing and sales. Among the other barriers discussed were the proliferation of complex roofs that make it more difficult to adopt PV technologies, as well as regulations imposed by municipalities.

Key points from the PV manufacturers' perspective during the panel discussion included the need for "solar-ready" roofs from builders and design features that make it easier to integrate PV into the house. In addition, the PV industry needs help from builders to get its products into the mainstream marketplace and a "visionary" builder to lead the way.

Increasing the market for zero-energy buildings on a broad scale within 10 years is the goal of the Zero-Energy Buildings initiative. These buildings will have no carbon emissions and be healthier places to live and work. They will reduce utility peak electrical demand and provide their occupants with extra security from the results of severe thunderstorms and natural disasters such as fires, tornadoes, and hurricanes—results that often include extended power outages and financial loss for businesses.

To realize this goal, however, further research is needed to integrate PV with air-conditioning systems, energy-efficient building techniques, and natural cooling strategies for hot climates. Research is also needed to determine how various solar technologies contribute to the zero-energy building's goal when used in different climates and in different building types.

Warren Gretz, NREL/PIX02316

Dish concentrator system.

PV and Concentrating Solar Power Technologies

Concentrating solar power (CSP) technologies convert solar energy into electricity by using mirrors to focus sunlight onto a receiver. The receiver transfers the heat to a conventional engine-generator—such as a steam turbine—that generates electricity. There are three types of CSP systems: power towers (central receivers), parabolic troughs, and dish/engine systems. These technologies can be used to generate electricity for a variety of applications, ranging from remote power systems as small as a few kilowatts up to grid-connected applications of 200 megawatts or more. A 354-megawatt power plant in Southern California, which consists of nine trough power plants, meets the energy needs of over 350,000 people and is the world's largest solar energy power plant.

In the last decade, the development of cost-effective and reliable means for concentrating sunlight using dish technology has made considerable progress. Dishes composed of single and multiple reflector elements have been developed. Lightweight stretched-membrane facets have been introduced. Yet all of this innovation is being put into the service of a conversion technology that was patented by a Scottish minister in 1816—the Stirling engine.

In contrast, the energy conversion technology of highly efficient tandem solar cells made from GaInP/GaAs has made great progress. NREL researchers have achieved 32.4% efficiency for a three-junction solar cell device. Researchers are

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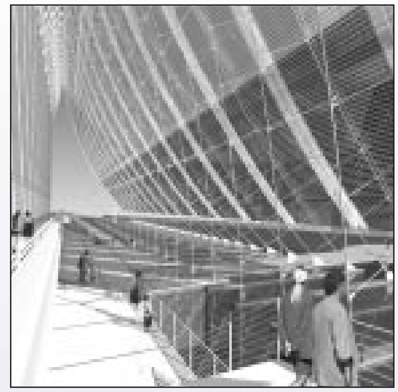
PV to Become Landmark in DC



The winning designer, Solomon Cordwell Buenz & Associates, was awarded $20,000 by DOE.

The U.S. capital may one day have a new landmark—a huge solar wall. The solar wall is the product of a national solar design competition sponsored by DOE and the American Institute of Architects (AIA). DOE and AIA joined forces for the competition to get people excited about solar energy. In March 2000, they challenged architects, engineers, energy technology companies, and students to design a “solar wall” to cover the windowless south wall of the Forrestal Building, DOE's headquarters in Washington, D.C. The wall spans an area of nearly two-thirds of an acre (32,100 square feet). When the contest ended in August, DOE, AIA, and other experts picked a winner among 115 applicants; each entry was judged on aesthetics, potential energy production, and its potential for cost-effectiveness. The winner was announced during Energy Awareness Month in October.

And the winner is....

Martin Wolf and three coworkers from the architectural firm Solomon Cordwell Buenz & Associates in Chicago came up with the winning solution: a “solar skin” made from both PV and solar thermal panels that sweeps out on cable trusses from the top of Forrestal's south wall to the ground. The solar skin will allow pedestrians to enjoy shaded walkways surrounded by pools of water, which will be used to cool hot air generated by the wall's solar systems. There will be underground parking below.

The winning design's main feature is the solar skin, which uses solar collectors organized in patterns of solids and voids to allow light transmission to interior spaces. Each collector surface has its own texture, giving the composition a visually stimulating appearance. During the fall and winter, when the sun is lower in the sky, solar thermal collectors in the upper part of the wall will use the sun's energy to heat water for the building's heating systems. In the summer, when the sun is higher in the sky and building electrical demands are at their peak, PV panels in the lower part of the wall will generate electricity for the building. The PV system's peak generating capacity is expected to reach approximately 100 kW in June.

The “sun wall” could be one of the largest such systems on any building in the world. It is expected that the installation of the winning design will be funded by a combination of public and private resources. Before construction can begin, however, the design must first be approved by the Commission of Fine Arts in Washington and the National Capital Planning Commission. Approval, design, and cost estimates for the solar wall could be completed within 12 months. The winning team estimates the sun wall could slash DOE's energy costs by $30,000 to $50,000 per year. Further, because of the high visibility of the building combined with rising energy prices, the new solar wall could help to boost PV sales in the United States.

Paths of Discovery

"The Object of your mission is to explore the Missouri river and such principal streams of it as by its course and communication with the waters of the Pacific Ocean, whether the Columbia, Oregon, Colorado or any other river may offer the most direct and practicable water communication across this continent for the purpose of commerce."

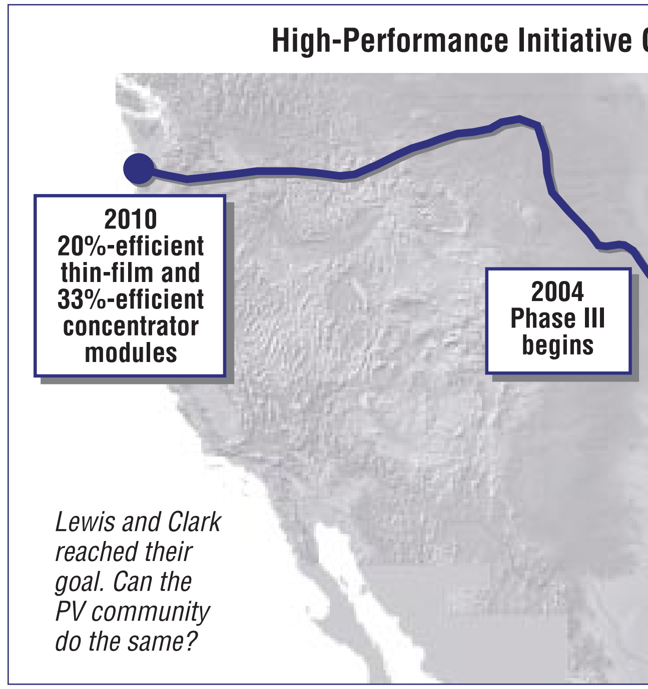
With these words, President Thomas Jefferson set in motion the Lewis and Clark Expedition of 1804, a 2-year journey that was to link the eastern coast of the new American republic to the shores of the Pacific Ocean. Jefferson called the expedition "The Corps of Discovery," because it was to be a quest for both commercial advantage and scientific knowledge.

Although researchers may not realize it, this same challenge is being presented to PV researchers involved in two new R&D initiatives for 2001. But this time, the new frontier is the laboratory and their Pacific Ocean is the dramatic advancement of PV. Funds for the two initiatives will come from the $75.8 million designated for the 2001 PV Budget recently approved by Congress. The two initiatives, called "High Performance PV" and "PV Beyond the Horizon," will challenge researchers to explore limitless possibilities and unparalleled opportunities in solar technology development. Just as for Lewis and Clark, the difficult thing for researchers will be deciding which path leads to commercial advantage and increased scientific knowledge.

High Performance PV

"The hardest thing will be identifying the right path to our goal because there are so many to choose from," says Ken Zweibel, who is leading the High Performance PV Initiative. "This initiative is so different from anything that we have done before because it's more open ended. There are literally hundreds of possible solutions to reaching our goal." Zweibel understands how Lewis and Clark must have felt. The initiative has only one goal, but it's a big one—double the efficiencies of thin films and concentrators by combining under one program research of single-junction thin films with multijunction and III-V thin films. "The difficult thing will be identifying the best combinations of these technologies to increase efficiencies because each solution is difficult and each is unique."

For example, Zweibel says, layers of single-junction thin film could be combined on top of each other like traditional multijunction solar cells, or different substrates could be used for each layer, or a substrate could be used as a top cell that normally goes on bottom, or material could be put on the bottom with a bandgap that normally does well on top.



Both traditional thin films and III-V thin films were chosen for the initiative because scientists and manufacturers alike believe these materials have the greatest potential for producing low-cost solar electricity.

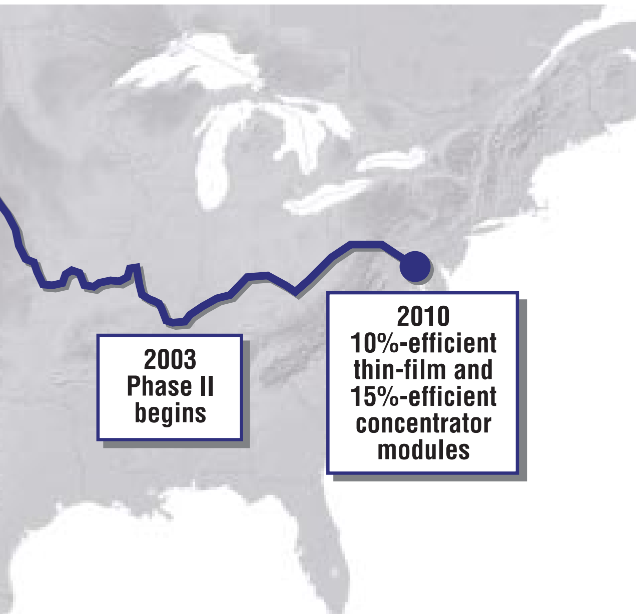
Two-junction or tandem thin-film multijunction solar cells, such as gallium arsenide (GaAs) and gallium indium phosphide (GaInP), are valuable to the space industry for use in satellites. With the addition of germanium (Ge), the three-junction solar cell may be of great interest to the public utility sector for use in high-efficiency concentrator systems.

Bob McConnell, who manages the initiative's III-V concentrator component, says "concentrators have long been a promising technology, but they've needed higher efficiency solar cells. Now we've targeted this as the critical goal to achieve their promise."

Thin films such as amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CIS) have low-cost potential and efficiencies that make them good candidates for both higher performance multijunctions and concentrators. The High Performance PV initiative will fund research in both areas under one program to further develop highly efficient solar cells, something that will require a multidisciplinary effort. The new initiative will fund research of multijunction thin films, thin-film concentrators, and III-V concentrators.

By combining high-bandgap and low-bandgap single-junction thin films, it should be possible to fabricate thin-film multijunction cells with efficiencies greater than 25%. Among the

Goals—Thin-Films and Concentrators



leading candidates for thin-film bottom cells are CIS alloys and low-bandgap CdTe alloys. Candidate top cells include CIS alloys mixed with gallium and higher-bandgap CdTe alloys. Researchers in this area will also explore the use of polycrystalline silicon for thin-film multijunction cells. Device design alternatives will also be investigated. For example, two- and four-terminal approaches to device design each have advantages and disadvantages when it comes to cost and performance potential. Researchers will try to determine which approach works best for thin-film multijunction solar cells.

In terms of thin-film concentrators, the initiative will explore using low-cost thin films for single-axis concentrators, which have the potential to reduce cell cost. For example, cells of 17% efficiency (measured at one sun) have been made for CIS. If CIS cells were used on stainless steel, this design could reduce costs while allowing for the thermal dissipation needed in concentrators.

For III-V concentrators, the goal is to do the fundamental research needed for a 33%-efficient prototype concentrator module that could be sold on the market with further engineering. Researchers plan to achieve this 33% prototype module in 10 years by making a 40%-efficient concentrator cell. Theoretically, the efficiency of a four-junction concentrator cell could surpass 50%. For example, the three-junction (three-layer) GaInP/GaAs/Ge cell that achieved 32.3% efficiency could reach 40%, if a GaAs-lattice-matched fourth layer of material can be identified. Any number of element combinations could be incorporated into the device, including boron, nitrogen, and zinc. Only time will tell which combinations of elements offer the greatest reward.

Fortunately, there is time. The initiative will take place over 10 years and is broken down into three phases. Phase I, called "Identifying Critical Paths," will take place over a 2-year period and is considered one of the most difficult parts of the initiative. It will determine research problems, approaches, and alliances, and Phase II will implement them. Phase III will bring work to fruition in terms of prototype modules. Information gained in the first two phases will help in selecting the most promising approaches for funding in subsequent phases. Research for this program will complement the 20-year cost and production goals from the PV Industry's Roadmap for the period after 2010. Those goals are to reduce the cost per watt for installed systems to $1.50, to increase PV production by 25% per year through 2020, and to ship 7 gigawatts of PV product by U.S. manufacturers in 2020.

PV Beyond the Horizon

Although today's solar electric technology is based on innovative research conducted 30 to 40 years ago, there is no reason to believe PV has gone as far as it can go or that revolutionary PV technologies don't exist "beyond the horizon" of our present knowledge.

The "PV Beyond the Horizon" initiative will support scientific research leading to nonconventional PV technologies that might "leapfrog" others toward the goal of dramatically decreasing the cost of solar electricity so it can make a significant contribution to our nation's energy supply and environment. This could be in the form of an entirely new way to produce electricity or discoveries to increase efficiencies far beyond what we think is possible today using conventional PV materials.

A number of exciting technologies are scheduled for exploration by researchers from industry, universities, and national laboratories, many of whom are considered the best in the country in their field. The technologies include: liquid-crystal organic solar cells, novel group IV solar cells, polymer solar cells, microcrystalline silicon cells, tandem organic cells, innnovative Si substrates for III-V solar cells, low-temperature CIGS deposition, nanoscale silicon theory, determination of technical feasibility of an optical rectenna solar cell, non-vacuum CIGS processing, dye-sensitized solar cells, molecular-array solar cells, ultrahigh-efficiency heterostructures, nanoscale characterization for GaInNAs for high-efficiency cells, an optical filter concentrator for multiple-bandgap solar cells, and solid-state electrolytes for dye-sensitized solar cells.

Many of the research proposals submitted for review are based on the revolution in organic semiconductors. For example, many researchers have been taught that plastics, unlike metals, can't conduct electricity. Yet this year's Nobel Prize Laureates in Chemistry were rewarded for their discovery in 1977 of conducting organic polymers, or plastics that can be made electrically conductive after certain modifications.

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NREL PV researchers and managers interact with industry on several levels. Although we freely share our research results and the nonproprietary results of our subcontractors, many of our interactions involve the exchange of confidential information, including the results of certain measurements. The following are some notable recent interactions.

Approximately 5 kilowatts each of 5 thin-film technologies were procured from **BP Solar, Siemens Solar Industries, Bekaert ECD Solar Systems LLC,** and **Energy Photovoltaics, Inc.**, representing a-Si (three types), CIS, and CdTe. The modules will be installed and integrated into PV systems at the Solar Energy Centre (SEC), New Delhi, India, as part of the recently renewed Memorandum of Understanding (MOU) between NREL and SEC following **DOE Under Secretary Moniz**'s visit to India in March 2000. SEC will be paying for the custom duties, inverters, balance of systems, data acquisition, and site preparation. The total value of the 50:50 cost-shared project is $150K. This MOU could lead to potential market opportunities for the U.S. thin-film PV industry. Contact: **Jack Stone, 303-384-6470**

Working together through **NREL's Thin Film PV Partnership Program, ITN/Energy Systems** (ITN/ES), Wheat Ridge, CO, and **Colorado School of Mines** (CSM), Golden, CO, have jointly fabricated the world's first 10.6% thin-film CdTe solar cell using the atmospheric pressure chemical vapor deposition method (APCVD). The thin-film CdTe solar cell structure is glass/SnO_2/CdS/CdTe/contact. The cell parameters are J_{sc} = 21.1 mA/cm^2, V_{oc} = 0.79, FF = 0.64, and Eff = 10.6%. There were several cells in the efficiency range of 9.8% to 10.6%. The advantage of the APCVD process is that it does not have load-locks, which add to the cost of the deposition system. Interaction with **NREL** scientist **Sally Asher** and her co-workers, who specialize in static SIMS (secondary ion mass spectroscopy), have helped ITN/ES and CSM reach this important milestone. SIMS analysis had identified high O_2 content (about 30%) caused from leaks in the APCVD system, which was detrimental to device performance. Further optimization of the processing and device design should approach a solar cell efficiency of 12.0% in the near future. Contact: **Harin Ullal, 303-384-6486**

A collaborative effort between **NREL's Amorphous Silicon Team and United Solar Systems Corporation** (Uni-Solar) has produced an efficient midgap solar cell whose active layer—a-SiGe:H alloy—is deposited at the high rate of 10 Å/s using the hot-wire CVD technique. A power of 4.2 mW/cm^2 was measured through a 530-nm cutoff filter, which means that this cell would contribute about 4.2% as the midgap middle cell in a 12%- to 14%-efficient triple cell. Uni-Solar's best 6 Å/s midgap cell delivers 4.4 mW/cm^2. This new result shows the potential of fabricating high-efficiency tandem or triple-junction amorphous silicon solar cells at higher deposition rates, an important result for low-cost production of PV modules. The delivered power of 4.22 mW/cm^2 is an active-area measurement, with a short-circuit current density of 8.05 mA/cm^2 after correction by quantum efficiency measurement. The fill factor is 0.69 and the open-circuit voltage is 0.76 V. Light soaking of this cell to determine its stabilized efficiency is under way. Contact: **Qi Wang, 303-384-6681**

NREL's Outdoor Test Facility (OTF) is testing a new inverter. A new **Trace Engineering** SunTie 2000 inverter was installed on the 1.4-kW Advanced Energy Systems America PV system at the OTF. The inverter represents Trace Engineering's new grid-connect PV inverter series. The SunTie operates interactively with the utility, without the use of batteries. The SunTie is available in four models, with output capacities of 1.0, 1.5, 2.0, and 2.5 kVA. All National Electric Code required DC input and AC output connections, disconnects, and circuit breakers are housed within the SunTie's compact case. A built-in LCD panel provides easy-to-read system status and daily cumulative power production information. The SunTie uses sophisticated software to track and adjust the output of the PV array once a minute. The inverter is listed by Underwriters Laboratories to UL 1741 and is designed to comply with IEEE 929. Plans are to test the inverter for long-term performance and reliability. Contact: **Robert Hansen, 303-384-6364**

Warren Gretz, NREL/PIX09671

NREL's PV Reflectometer, developed by Bhushan Sopori, Yi Zhang, and Wei Chen, provides solar cell manufacturers with the previously unavailable capability of online monitoring and quality control of their fabrication process. The noncontact measurement of key parameters takes less than 1 second. The Reflectometer can be installed directly on the fabrication line without interfering with the process. Sopori has used the system to test material samples for several companies. Contact: Bhushan Sopori, 303-384-6683

Subcontracts

Subcontracted research with universities and industry, often cost-shared, constitutes an important and effective means of technology transfer in NREL's PV Program. From October 1999 through September 2000, we awarded more than $21.5 million to new and existing subcontracts (examples listed below). For further information, contact Irene Medina (303-384-6492).

Arizona State University, Tempe, AZ
High Resolution Chemical Electron Microscope

Astro Power, Newark, DE
Monolithically Interconnected Silicon-Film Module Technology

Bekaert ECD Solar Systems, Troy, MI
Technology Validation Project on Thin Film PV Systems

BP Solar, Linthicum, MD
Improvements in Polycrystalline Silicon PV Module Manufacturing Technology

Cornell University, Ithaca, NY
Elastic Properties of Thin-Film Silicon

First Solar, Toledo, OH
Technology Support for High-Throughput Processing of Thin-Film CdTe PV Modules

University of California, Santa Barbara, CA
Growth and Characterization of GaInNAs for High-Efficiency Solar Cells

University of Colorado, Boulder, CO
RGA Analysis of the HWCVD Process

Publications

Dissemination of research results is an important aspect of technology transfer. NREL researchers and subcontractors publish some 300 papers annually in scientific journals and conference proceedings, as exemplified by the recent publications listed below. PV program and subcontractor reports are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161. For further information, contact Irene Medina (303-384-6492).

Benner, J. P. (2000). "Making the Photovoltaic Industry PV Technology Roadmap: Issues and Next Steps." *10th Workshop on Crystalline Silicon Solar Cell Materials and Processes*. 14–16 August 2000, Copper Mountain, Colorado. NREL/BK-520-28844. Golden, CO: National Renewable Energy Laboratory; pp. 3–5; NICH Report No. 29135.

Coutts, T. J.; Young, D. L.; Li, X. (2000). "Characterization of Transparent Conducting Oxides." *MRS Bulletin*. Vol. 25, August 2000; pp. 58–65; NICH Report No. 29025.

Delahoy, A. E.; Bruns, J.; Ruppert, A.; Akhtar, M.; Chen, L.; Kiss, Z. J. (2000). "Thin-Film CIGS Photovoltaic Technology: Annual Technical Report, Phase II." 16 April 1999–15 April 2000. 30 pp.; NICH Report No. SR-520-28786.

Dhere, R. G.; Al-Jassim, M. M.; Yan, Y.; Jones, K. M.; Moutinho, H. R.; Gessert, T. A.; Kazmerski, L. L. (2000). "CdS/CdTe Interface Analysis by Transmission Electron Microscopy." *Journal of Vacuum Science and Technology*. Vol. 18(4), July/August 2000; pp. 1604-1608; NICH Report No. JA-520-27515.

Fend, T.; Jorgensen, G.; Kuster, H. (2000). "Applicability of Highly Reflective Aluminium Coil for Solar Concentrators." *Solar Energy*. Vol. 68(4), 2000; pp. 361–370; NICH Report No. 29052.

Herndon, M.K.; Bradford, W.C.; Collins, R.T.; Hawkins, B.E.; Keuch, T.F.; Friedman, D.J.; Kurtz, S.R. (2000). "Near-Field Scanning Optical Microscopy Cross-Sectional Measurements of Crystalline GaAs Solar Cells." *Applied Physics Letters*. Vol. 77(1), 3 July 2000; pp. 100–102; NICH Report No. 29070.

Kazmerski, L. L. (2000). "Photovoltaic Devices: A 2000 Overview." *Energy 2000: State of the Art*. Italy: Balaban Publishers and International Energy Foundation; pp. 1–22; NICH Report No. 29018.

Morel, D. L.; Ferekides, C. S. (2000). "Advanced Processing of CdTe- and $CuIn_xGa_{1-x}Se_2$-Based Solar Cells: Phase I Report." 59 pp.; NICH Report No. SR-520-28796.

Rohatgi, A.; Yelundur, V.; Jeong, J.; Ristow, A.; Ebong, A. (2000). "Advances in Low-Cost Multicrystalline Silicon Solar Cell Processing in the Last Decade." *10th Workshop on Crystalline Silicon Solar Cell Materials and Processes.* 14–16 August 2000, Copper Mountain, Colorado. NREL/BK-520-28844. Golden, CO: National Renewable Energy Laboratory; pp. 12–20; NICH Report No. 29136.

Soo, Y. L.; Huang, S.; Kim, S.; Kioseoglou, G.; Kao, Y. H.; Compaan, A. D.; Grecu, D.; Albin, D. (2000). "Effects of Heat Treatment on Diffusion of Cu Atoms into CdTe Single Crystals." *Applied Physics Letters*. Vol. 76(25), 19 June 2000; pp. 3729–3731; NICH Report No. 29060.

Yu, K. M.; Walukiewicz, W.; Shan, W.; Ager, J. W. III; Wu, J.; Haller, E. E.; Geisz, J. F.; Friedman, D. J.; Olson, J. M. (2000). "Nitrogen-Induced Increase of the Maximum Electron Concentration in Group III-N-V Alloys." *Physical Review*. B, Condensed Matter. Vol. 61(20), 15 May 2000-II; pp. R13337–R13340; NICH Report No. 29076.

The **University of South Florida** hosted a meeting that brought together local utility companies and state solar energy organizations to discuss the University of South Florida's economic development analysis of implementing solar technologies in West Central Florida. Participants included **NREL's Christy Herig, Florida Power Corporation, Florida Power and Light, Tampa Electric, Lakeland Electric, Florida Public Utility Commission, Florida Distribution Coops, Florida Solar Energy Center,** and the **Florida Solar Energy Industries Association**. The analysis looked at a 30-year program to implement solar hot-water first and then PV technologies to meet up to 50% of the region's load growth. The results indicated that all three ownership scenarios (investor-owned utility, municipal utility, or independent power producer) could implement such a program profitably. Contact: **Christy Herig, 303-384-6546**

The **Sixth International Symposium on High-Purity Silicon**, held in Phoenix in August 2000 and sponsored by the Electrochemical Society, brought together company and university researchers from more than a dozen countries. Discussion centered around the advances and research needs for silicon in the electronics industry. **NREL**'s **Ted Ciszek** and **Tihu Wang** opened the session on Intrinsic and Impurity Related Defects which described the unique role that float-zone crystal growth can play in quantitatively studying a wide range of defects and impurities in a controlled fashion. Interest was especially high in their work on silicon self-interstitials, fast-cooling defects, and nitrogen doping because parallels were seen in applying the concepts and findings to silicon crystal growth in the semiconductor industry. The director of the **Industry/University Cooperative Research Center for Silicon Wafer Engineering and Defect Science** extended an invitation for Ciszek and Wang to participate in future activities of the consortium, whose members include **Komatsu Silicon, MEMC, Mitsubishi Silicon, Nippon Steel Corp., SEH America, Sumitomo SiTIX, Wacker Siltronic, University of Arizona, Arizona State University, MIT, North Carolina State University, South Florida University, Stanford University**, and **University of California Berkeley**. Contact: **Ted Ciszek, 303-384-6569**

The **University of Toledo** hosted the annual meeting of the Ohio Chapter of the American Physical Society October 13–14. Photovoltaic research and development was the main theme of the meeting. **NREL**'s **Sarah Kurtz** and representatives of **United Solar Systems Corp.** and **First Solar** gave presentations. NREL's **John Thornton** delivered the keynote address on using PV to prevent, respond to, and recover from natural and human-caused disasters. John Thornton was also given an extensive tour of the new First Solar production facility. Contact: **John Thornton, 303-384-6469**

Winning Combinations, Continued from p. 5

adding a fourth junction that could increase practical efficiencies to almost 40%. Researchers say the 30%-efficient GaInP/GaAs devices that are entering production today could rival the output of the current Stirling engines being used in dish concentrating systems. Potential advantages to replacing the Stirling engine with concentrating PV include reduced price, mass, and maintenance costs for manufacturers, as well as increased electrical production and reliability.

However, PV's thermal properties are a problem. Only about one-third of the sunlight hitting a conventional high-efficiency PV device is converted into electricity, whereas two-thirds is converted into heat. “You can really fry the device under those conditions,” says NREL's Scott Ward, who is working with other researchers to develop a low-heat absorbing PV converter. The new converter will only absorb the sunlight that is to be turned into electricity and the rest will be reflected out of the device. Currently, several companies, including Spectrolab, are working with dish manufacturers on making and deploying dish reflective systems with PV converters for moderate-sun concentration levels (250x). Ward expects his research team to have a next-generation prototype converter for high-sun concentration levels (1000x) made from multijunction devices in about 4 to 6 months. “Dish manufacturers wouldn't have to change anything, except plug in a better converter.”

Allan Lewandowski, a researcher with the Concentrating Solar Power program, says “The relative simplicity of a PV converter in a concentrating solar dish holds great promise for reducing the cost and improving the reliability of CSP systems.” In addition, the promise of even higher efficiencies in improved PV devices gives CSP an alternative that deserves serious consideration, he says. “We are now beginning an effort to develop solutions to the main technical issues (flux uniformity and thermal control) that will promote the successful combination of these CSP and PV technologies into a new option for consumers.”

Because 95% of the population gets its electricity from large utilities, a marriage between the concentrator technology developed by the solar-thermal community and the latest generation of high-efficiency PV energy converters makes sense. Further, if new concentrator systems using PV could be developed and then scaled down, they could be used to power homes with dishes similar in appearance to the 8- to 10-foot-high dishes once commonly used for satellite television. This would be attractive to the PV industry from a business perspective. However, potential first markets will be for small, remote systems because their total capital cost is lower compared to utility-scale systems and they compete with locations where the cost of fuel or energy is usually very high.

Challenges and Opportunities

The world market for PV could exceed 260 MW by early 2001 and reach 550 MW in 2005 and 1800 MW in 2010. Those figures could increase further if NCPV researchers are successful in combining their efforts with DOE's Solar Buildings and CSP programs.

Already, more builders are looking for ways to add renewable energy components such as PV to new buildings, but use of PV technology by large developers won't occur until costs can be further reduced. Combining energy efficiency with solar technologies may be the answer.

Concentrating solar power plants are still in the early stages of commercial development and are currently more expensive than fossil fuel plants. Costs can be reduced through economies of scale, as well as through improved component design and advanced systems. Adding high-efficiency PV solar cells to these systems could reduce costs and make these new systems attractive to both utilities and homeowners.

During the next decade, worldwide demand for electricity is expected to create and expand markets for all solar technologies. Teaming up with building researchers could help PV and other solar technologies enter the mainstream market more quickly. Also, experts predict that, by 2020, more than 20 gigawatts of concentrating solar power systems could be installed throughout the world for use by utilities. The PV industry would be wise to tap into this new market for solar energy.

For more information about the Solar Buildings Program, contact Tim Merrigan at 303-384-7349. For more information about PV and CSP, contact Scott Ward at 303-384-6529.

Paths of Discovery, Continued from p. 7

Now, the race is on to bring plastic semiconductors to market. Conductive plastics are already used for anti-static substances for photographic film, shields for computer screens against electromagnetic radiation, and “smart” windows that block sunlight. Semiconductive plastics have recently been developed in light-emitting diodes, or LEDS, which are essentially the reverse of solar cells—you put electricity in and get light out. Because of this, scientists are now looking at plastics for use as displays in mobile telephones and mini-format television screens. They also think the material would make great solar cells.

Researchers involved in the “Beyond the Horizon” initiative will take part in this new technology revolution. New universities will be getting involved that have not been funded by the program in the past to do PV research. A review panel met on November 15, 16, and 17 at NREL to discuss the strengths and weaknesses of each proposal submitted for review. Out of 85 proposals submitted, 16 were recommended for funding. On the review panel were members from NREL, DOE, Department of Defense, universities, government agencies, and outside agencies. The technologies chosen for further exploration are embryonic, risky, and may or may not be successful. However, they all have the potential for high efficiency and low cost.

The Beyond the Horizon initiative gives us a new foundation for the future,” says Bob McConnell, who directs this initiative. “It gives us a chance to expand our research by looking at new ideas and getting new researchers involved.”

New Millennium Research

Most of the National PV Program's budget increase of $10 million for 2001 will fund the two initiatives to double efficiencies in 10 years and discover new frontiers in PV far into the future. NREL researchers will be active participants in these initiatives, in some cases leading multidisciplinary national teams that will include industry and university researchers.

Requests for Proposal (RFPs) for the two initiatives were sent out in April 2000 and were due back to NREL in late July 2000. The RFP solicitations were open to universities, colleges, and companies in the United States.

For the High Performance PV initiative, available program funding will be about $5 million for FY 2001. Available funding may increase during the course of the 10-year program, depending on research results. About one-third of the funding is planned for the NCPV, with the remainder for subcontracts, which will be awarded in early 2001.

Funding for the PV Beyond the Horizon initiative is anticipated to be about $2 million per year. Funding level per subcontract will range between $100,000 and $200,000 per 12-month period, with a maximum total for the subcontract not to exceed $500,000 for an expected period of performance of 3 years. NREL hopes to award 16 subcontracts under the PV Beyond the Horizon initiative, with the first subcontract award slated for early 2001.

By funding research under these two initiatives, each of which holds promise for future PV development, researchers are starting a voyage of discovery that may someday soon make PV cost-competitive with traditional energy sources. Researchers and scientists working under these initiatives will gain tremendous scientific understanding of PV materials and devices. When it comes to commercial advantage, new technology developed under these initiatives could lead to an explosive growth trend in PV sales and shipments by 2015.

To learn more about these and other PV technologies for the 21st century, consider attending Symposium 01 “Photovoltaics for the 21st Century” at the Washington, D.C. ECS meeting in March 2001. Conference information is available at *www.electrochem.org*.

For more information, contact Bob McConnell at 303-384-6419 or Ken Zweibel at 303-384-6441.

PV Calendar

January 15–19, 2001, *DOE Distributed Power Program Review and Planning Meeting.* Sponsor: NREL. Location: Washington, DC. Contact: Kimberly Taylor, 303-275-4358.

March 25–30, 2001, *Symposium 01 "Photovoltaics for the 21st Century."* 199th Meeting of the Electrochemical Society. Sponsor: ECS. Location: Washington, DC. Contact: *www.electrochem.org*

April 16–20, 2001, *MRS Spring Meeting*. Sponsor: Materials Research Society Location: San Francisco, CA. Contact: *http://www.mrs.org/meetings/spring2001*

April 21–25, 2001, *Solar Energy: The Power to Choose.* Sponsor: ASES, et al. Location: Washington, DC. Contact: *www.ases.org*

May 6–8, 2001, *North Sun 2001: The 9th International Conference on Solar Energy in High Latitudes*. Sponsors: NOVEM, ECOFYS. Location: Pieterskerk, Leiden, The Netherlands. Contact: *www.northsun.org*

June 11–15, 2001, *12th International Photovoltaic Science and Engineering Conference*. Sponsor: The Korean Ministry of Commerce, Industry and Energy/Korea Institute of Energy Research. Location: Cheju Island, Korea. Contact: *http://solarpv.or.kr/pvsec-12*

August 19–22, 2001, *11th Workshop on Crystalline Silicon Solar Cell Materials and Processes*. Sponsor: NREL. Location: Estes Park, CO. Contact: Bhushan Sopori, 303-384-6683 or bhushan_sopori@nrel.gov

October 14–17, 2001, *NCPV Program Review Meeting*. Sponsor: NREL. Location: Lakewood, CO. Contact: Kannan Ramanathan, 303-384-6454 or kannan_ramanathan@nrel.gov

October 22– 26, 2001, *17th European Photovoltaic Solar Energy Conference and Exhibition*. Sponsor: WIP - Renewable Energies, Germany. Location: Munich, Germany. Contact: *www.wip.tnet.de/pv01.htm*

November 25–December 2, 2001, *ISES Solar World Congress.* Sponsor: International Solar Energy Society. Location: Adelaide, Australia. Contact: "Events" at *www.ises.org*

This quarterly report encourages cooperative R&D by providing the U.S. PV industry with information on activities and capabilities of the laboratories and researchers at NREL.

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