Our Shared PV Future

Sharing ideas is integral to scientific meetings and conferences. This sharing helps to pull together the PV community and drive the research, development, and deployment of PV technologies. With that in mind, we devote this issue of *NREL PV Working With Industry* to the ideas and visions shared at recent PV gatherings.

Our editorialist is Paul Maycock, publisher of *PV News* and one of the PV community's leading citizens. He sets the tone by looking 10 years into the future and confidently predicting that PV will be economically viable *on its own* at that time.

The focus of the NCPV Program Review Meeting was on how to produce less expensive and more efficient solar cells right now… while continuing the R&D that will lead to improved products 20 years from now.

At the European PV Conference held in Scotland, deployment of PV technologies in Europe held the limelight. NCPV Director Larry Kazmerski's talk, "A Tour Through the 21st Century," also drew attention, stretching people's conception of the future.

Back at home, deployment of PV and other solar energy technologies was the theme of NREL's participation in Earth Day activities in Denver. At this event, NREL volunteers shared with the public their knowledge of, and enthusiasm for, different types of solar applications. And more and more as we head toward the future, the public seems to be listening and getting involved.

NREL PV

Working With Industry

Second Quarter, 2000

A Decade to Go for "Economic" Grid-Connected PV

Seth Maycock/PIX09158

Paul Maycock and friend are pictured close to home in Warrenton, Virginia. He wants everyone to know that, in this case, the large mouth belongs to the bass. When Maycock isn't fishing, he could be doing almost anything—from publishing PV News *to promoting PV around the country and the world. In April, Maycock was presented with the Paul Rappaport Award at the NCPV Program Review. NCPV Director Larry Kazmerski lauded this "Mega Man" for his PV advocacy, long-time service to the community, and friendship to many in the room.*

Contact Paul Maycock at 540-349-4497.

An Editorial by Paul Maycock

June 1st of this year was the 25th anniversary of my arrival at ERDA—or the Energy Research and Development Administration—which became the Department of Energy in 1977. I had come from Texas Instruments, where I was director of strategic planning for the Consumer Products Group. My first task at ERDA was to assist in developing solar energy plans, which included ERDA 48 for solar hot water and ERDA 49 for photovoltaics. I even prepared the first ocean thermal energy plan.

The PV plan of 1978 called for "technology readiness" in 1982 and "commercial readiness" in 1986—leading to shipping competitively priced product in 1988. In other words, we were "10 years from 'economic' PV for central power." In 1978, oil was $60 per barrel and gas supplies were dwindling. Based on the political climate of the times, we projected that "break-even" busbar electricity costs would be 12 cents per kilowatt-hour in 1988. This meant that we needed $1.00 per watt PV modules and $1.50 per watt installed systems cost to meet our objectives.

In April, at the NCPV Program Review, the new PV Five-Year Plan and the PV Industry Roadmap were presented in detail. Results from the Photovoltaic Manufacturing Technology (PVMaT) project were compared to the goals. And most of us concluded that we were "10 years from 'economic' PV for grid-connected applications," with customer-owned PV at the point of use costing 12 cents per kilowatt-hour in the better climates of the United States in 2005–2012.

Based on the progress reported at the Program Review, I'm convinced that some of the new plants under construction or expansion have a shot at reaching or exceeding the 10-year goal of cost-effective, grid-connected PV systems.

There are plenty of exciting prospects: cadmium telluride at First Solar and BP Solarex; copper indium diselenide at Siemens; amorphous silicon at United Solar, Energy Photovoltaics, and BP Solarex; string web at Evergreen; film on low-cost substrate from AstroPower; edge-defined, film-fed growth from ASE Americas; and concentrators using high-efficiency silicon and III-V cells from ENTECH, Amonix, Photovoltaics International, and Winston.

Virtually all of these technology projects were partially funded by NREL's PVMaT and Thin Film PV Partnership projects. It is interesting to note that in 1980, DOE started four 3-year contracts on "manufacturing methods" for PV cells. The contracts were all terminated in 1981, after President Reagan took office. Could this have had something to do with our not meeting the 1988 goal?

A week after the Program Review, many of us traveled to the European PV Solar Energy Conference in Glasgow. There, we heard of nearly 90 megawatts in 1999, and possibly 120 megawatts in 2000, of *grid-connected* PV being installed in Japan, Germany, and the United States (specifically California)—all with subsidies of 30% or higher. This is good news. As one who has seen first-hand the enthusiastic reception to PV products at *off-grid* locations around the world, I'm convinced it's high time for PV to penetrate the *on-grid* market.

I do have concerns, however. All of the aforementioned subsidy programs assume that PV prices will be economic in 5 years when the subsidies are phased out. I can't help but wonder what will happen to the PV market in the 5 years between the termination of these subsidies and the proposed meeting of our goal of "10 years from 'economic' PV for grid-connected applications."

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

Is There Success in PV's Future? The Program Review Meeting Takes a Closer Look

The sun isn't going to get any closer to the Earth. We can't change that, nor do we want to. We can, however, change PV technology here on earth by making more efficient and less expensive solar cells. The question is, how?

That question, which has remained unchanged for the past 30 years, was the energy driving this year's National Center for Photovoltaics (NCPV) Program Review Meeting, held in downtown Denver April 16–19. The PV industry created goals, targets, and endpoints for a "roadmap" during a 3-day workshop held in Chicago last June. This intended to guide the PV industry's efforts through 2020. The National Photovoltaics Program Plan 2000–2004, which contains the vision of DOE and the NCPV for the next 5 years, will also be used as a research and development guide.

Both documents provide carefully crafted strategies and recommendations for achieving critical goals. Yet many of the steps required to accomplish these goals are not yet defined. At the Program Review Meeting, members from industry, universities, and national labs came together to address the goals outlined in the roadmap and five-year plan.

"The roadmap belongs to industry—it's not an NREL, Sandia, or DOE plan," said NCPV Director Larry Kazmerski. The five-year plan is a "rolling plan" that should be reviewed every 2 years, he said. "One plan reflects another—the roadmap, the five-year plan, and the annual PV operating plan."

What are the first steps?

Jeff Mazer, who spoke for DOE's Office of Solar Energy Technologies, kicked things off with suggestions for where to start—continue to decrease module manufacturing costs and increase efficiencies. The PV community will have to work within the proposed federal 2001 PV budget—$82 million ($20.3 million for fundamental R&D, $27 million for advanced materials and devices, and $34.7 million for technology development). DOE leadership sees technology development as key to accomplishing the goals of the PV industry. Development of tandem-junction technology appears especially promising. DOE hopes to see a four-junction solar cell by 2008 and a four-junction concentrator system by 2010. "Our mission is to make PV a vibrant, independent technology—part of the national energy portfolio," Mazer said.

Allen Barnett, president and CEO of AstroPower, followed Mazer with the statement that technology development alone won't take the PV industry where it wants to go. Capitol Hill must be made to understand the value of PV technology. "We undersell this technology. If the public understood how good and how versatile this technology really is, budgets would go through the roof." With proper support from government to reduce cost, the PV market in this country would increase dramatically, he declared. "That's what happened in Germany. Germany had the biggest growth market this year, primarily because of government support."

How do we get there?

Because a major focus of this year's Program Review meeting was discussing the means to achieve the roadmap goals, technical sessions were structured around the same four areas marked as high-priority research and technology transfer needs in the roadmap report. Two poster sessions with some 125 poster presentations provided participants the opportunity to discuss in more detail individual research and development areas.

Paul Maycock/PIX07174

This year's Rappaport honoree, Paul Maycock, discussed his travels to Uganda to help some of that country's citizens access their first electricity—via PV systems provided by the Solar Electric Light Fund/ Habitat project. In this photo, Maycock stands beside the first homeowner to receive a PV solar home system. She displays the lantern and oil lamp used for lighting the day before PV brought electricity to her home.

Open Markets and Reduce Demand

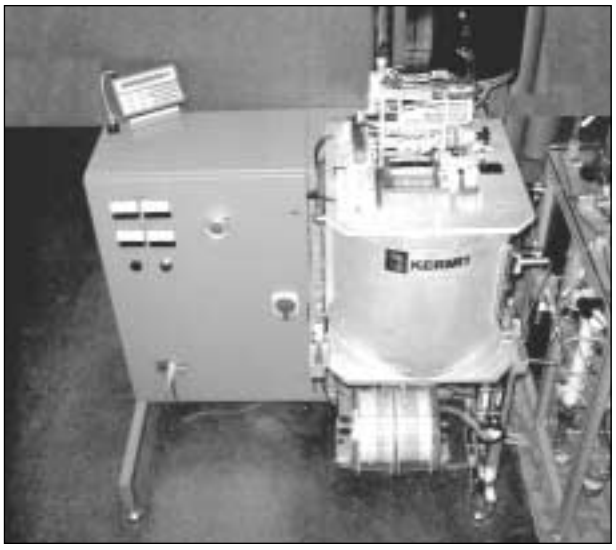
In the first general session, Roger Taylor, who heads NREL's International Programs, discussed market opportunities in developing countries. "Of the 6 billion people on the planet, 80% are in the developing world," he said. "In the next 25 years, world population will increase to 8 billion. Most of that growth will be in the developing world. Therefore, the biggest market is in the developing world." But the developing world is not without challenges. Market access and the rate of economic development in these countries will determine market growth, he said. Solar energy can be used to increase wealth and progress technology in the developing world. How the PV industry defines, develops, and implements product delivery pathways in these countries will be very important to successful market growth.

NREL's Sheila Hayter led the applications portion of this session with a discussion about high-performance buildings. Her mantra is "Reduce demand, reduce demand, reduce demand!" High-performance, low-energy buildings are at least 70% more efficient than the average house. If a home is built right, a 5-kW system will meet 87% of the load. Energy efficiency maximizes the value of PV, so consumers see PV systems as having more value.

Improve System Integration and National Standards

The second session was dedicated to improving national standards and PV system integration into the marketplace. Lynne Gillette of DOE lauded NREL's Dick DeBlasio and Sandia's John Stevens for developing and getting approval for the PV Utility Interconnection Standard IEEE 929-2000. The two were given a certificate of appreciation for their "contribution to safe and reliable grid-connected power."

Chris Cameron presented for Sandia National Laboratories and spoke about expanding the grid-tied residential power systems market in the United States and abroad. "The PV industry needs to bridge the gap between customers and the technical PV community. The main barrier is a lack of understanding of the technology," Cameron said. The people buying PV today are buying it because they believe it's good for the environment, or they want to produce their own energy. But, he warns, these benefits could be easily overshadowed by hassles caused by poor module reliability and lack of affordable technical support once the system is installed.



Jack Hanoka/PIX09158

Evergreen Solar is now commercializing a vertical silicon ribbon growth method called "String Ribbon," which was designed and built under a PVMaT subcontract, that it expects to be operational by the end of this year.

Increase PV Manufacturing Growth

For the PV Manufacturing session, NREL's Roland Hulstrom spoke about the growth of domestic PV manufacturing. He compared the roadmap "endpoints" and "targets" for domestic PV growth with year 2000 starting points. Over the past 5 years, the annual growth rate of PV shipments has been 20% per year. Between 2000 and 2020, the PV roadmap goal is to increase that percentage to 25%. The challenge will be developing and sustaining the markets and manufacturing capacity to support a 25% annual growth rate in shipments and installations. That will require a tripling of shipments (peak megawatts) every 5 years. Further, industry must ensure product performance, reliability, and quality to develop and maintain market demand from consumers.

Terry Jester, who spoke for Siemens Solar Industries, stated that the challenges are substantial for crystalline-silicon cells to meet the road-map goals. At the projected production levels, it will be necessary to manufacture 125,000 cells per hour. That's an increase of 50 to 100 times for most manufacturers. Costs will have to be decreased by a factor of 4 to 5 to meet the \$1.50 W_p cost target. Reducing wafer thickness will help. The cost for producing PV modules is almost 50% incurred at the wafer slicing level. The ideal wafer would be made thinner, without losing efficiency. The advent of high-throughput growth processes with low defect and impurity concentrations and high-throughput cell processing for higher device efficiency and low-cost material will also go a long way toward achieving roadmap goals.

An industry panel discussion followed. Among the participating companies were First Solar, Spire Corporation, BP Solarex, and Powerlight Corporation. One panel member stated that because the United States falls behind several international companies when it comes to government support, the leading PV companies in the 21st century will be international. However, the United States still leads in manufacturing capabilities, he said. For example, packing, shipping, and delivery of PV systems is a big part of the system cost. If more could be done to help reduce shipping and delivery costs, it would boost the PV industry. Another important issued raised was product development and marketing. Value must be added to the PV systems: PV products must do more than just make electricity; they must have a dual usage, such as a design feature of the home, for example.

Ed Witt, who manages NREL's PV Manufacturing R&D project, was happy that the panel discussion provoked much discussion regarding what is the best way for government to help private industry. "I believe it reconfirmed our opinion that an open program where the problems are identified by the problem solvers is a very effective way to perform manufacturing R&D." Expect to see a new solicitation issued for manufacturing R&D that will be open to all companies manufacturing PV-related products, he said. Some R&D areas will

take precedence as they are particularly important in the continued development of PV manufacturing processes. Examples are improved in-situ diagnostics and monitoring with real-time feedback for optimal process control, larger-scale automation, and increased yield in the fabrication of PV modules, systems, and other system components.

Continue Research of New Technology

Because fundamental research is so crucial, discussion of ideas took place during three separate sessions: crystalline silicon, thin-film technology, and new technologies for the future. NREL's Ted Ciszek spoke about research needs from a national laboratory perspective. He said throughput, impurity and defect control, and silicon feedstock material must all be improved.

The hot topic of discussion during the crystalline materials session was using multijunction solar cells in PV concentrator systems. David Lillington, of Spectrolab, talked about the fabrication of triple-junction concentrator cells based on very mature space manufacturing technology, with a new record efficiency greater than 32% at 47 suns. Improvements in this area will allow high-volume, industry-wide availability of cost-effective, 30%-efficient cells in the near future, he said. Longer term, the opportunity exists for cells costing less than $0.30 per watt through the introduction of a four-junction cell based on new 1-eV materials.

During the thin-film session, company representatives spoke about research potential and concerns. United Solar Systems Corp. is concerned about improving amorphous-silicon (a-Si) efficiencies and deposition rates during production. The challenges that lie ahead for copper indium diselenide (CIS), according to Dale Tarrant of Siemens Solar Industries, are to scale processes to even larger areas, to reach higher production capacity, to demonstrate in-service durability over even longer times, and to advance the fundamental understanding of CIS-based materials and devices with the goal of further efficiency improvements for future products. Allen Barnett said AstroPower wants to create the ultimate solar cell: thin, light-trapped crystalline silicon. NREL's Tim Gessert presented a paper on copper contacts in cadmium telluride (CdTe) and his team's role in further understanding the effect of copper on device formation in the thin-film CdS/CdTe PV device.

For the last session on future technologies, Angus Rockett, from DOE's Office of Science, spoke about basic research opportunities in PV. In his opinion, further improvements in a-Si and chalcopyrite technologies could lead to expanding the application of these materials outside their current niche markets. The same is true for CdTe contact technologies and transparent conductors. Novel materials and revolutionary concepts such as photoelectrochemical cells are of great interest and show great potential, he said. Revolutionary concepts, sometimes referred to as disruptive technologies, need exploration if only because other countries are doing just that. And if we look outside of PV, we see dramatic and abrupt changes in high technology as disruptive ones "leapfrog" over earlier technology generations. For example, dye cell and quantum dot solar cells do not have p-n junctions and can be manufactured without expensive high vacuums.

A talk on industry research needs for future technologies from a university perspective was given by Ajeet Rohatgi, a professor at the Georgia Institute of Technology. Industry primarily needs to focus its research on developing and demonstrating new materials: thin glass and semiconducting materials, new encapsulants, low-temperature conducting epoxy, optimized transparent conducting oxides, and alternate substrates. Cell efficiencies must also be improved to reduce material costs. Low-cost, high-efficiency materials and devices must be developed through research and development with specific targets. In addition, improvements in automation, process control, and scale up and increases in throughput must be achieved. High-speed interconnect, rapid thermal processing, and high-rate deposition must be further developed. Thin-film manufacturing issues and basic R&D must be addressed to develop better process control, process models, in-situ diagnostics, reactors, and equipment design.

Vijay Kapur, president of International Solar Electric Technology, gave an industry viewpoint on fundamental and exploratory research. Most R&D in industry is done empirically, he said, wherein scientists see a need, set a goal, and then use their intuition based on cumulative experience to solve the problem. While this system is fine for the research stage, when it comes to technology commercialization, scientists need to understand the technology in depth. They must think like engineers and others who will be dealing with the technology later on to anticipate problems and solve them early on. "We are in the early stages of a potentially huge business. We need to look way beyond 10, 20, even 30 years down the road," said Kapur. "But PV is highly incestuous. It needs to go beyond PV and the semiconductor industry when looking at new technology."

Sayten Deb, director of NREL's Basic Sciences Center, talked about the importance of exploring non-conventional PV technologies. He gave an analysis of what long-term and fruitful direction new PV materials may logically take during the next couple of decades. In spite of great advances, all PV materials and devices that are currently being developed have one problem or another that needs to be solved, he said. Therefore, the search for new material and novel device concepts will continue. It is reasonable to expect that the next generation of materials is likely to come from ternary and multiternary

Continued on page 11, Column 1.

Amonix, Inc./PIX09174

During the panel discussion of the concentrator session, Herb Hayden, of Arizona Public Service described how the utility is installing Amonix's large Integrated High-Concentration PV system totaling 300 kW.

Scotland Opens Its Doors to PV

Ancient castles and myths, kilts and bagpipes, and of course, St. Andrews, the birthplace of golf, attract thousands of visitors to Scotland each year. This May, people from all over Europe, the United States, Australia, and Pacific Rim countries were drawn to Scotland for another reason—the 16th European Photovoltaic Solar Energy Conference and Exhibition held in Glasgow.

The director of the National Center for Photovoltaics (NCPV), Larry Kazmerski, represented DOE's Office of Solar Energy Technologies Director Jim Rannels. He also announced a new compact disk produced by Rannel's office called "Solar Energy Showcase," a virtual photo album of various uses for PV in the United States. The CD was well received by some 1,380 attendees, and numerous people at the conference asked for a copy.

Even more than prior conferences, this year's event focused heavily on PV applications because Europe has a strong environmental commitment. The United States' primary interest is still R&D, believing it's the key to widespread deployment in the future. Because Europe is so keen on spreading PV throughout Europe and beyond, interest among attendees centered around three areas: the subsidy programs in Germany, building-integrated PV and architectural applications throughout Europe, and rural electrification and village power aimed at collaborations with developing countries. Research results were still outstanding, but were overshadowed a bit by the magnitude of the deployment and policy advances.

Hermann Scheer, Conference Chairman and Member of the German Parliament, said Europe has the leadership for PV deployment and the rest of the world should copy its programs to ensure clean energy directions. He also stated that Germany and the European Union would be the force to be reckoned with for markets and products. In part because of the difference in PV focus between Europe and the United States, Kazmerski found it interesting that a number of young European researchers inquired about collaborations with the NCPV. "This could mean that Europe's enthusiasm for deployment is putting some stress on PV research programs in Europe," he said. "Several researchers were 'impressed' at the R&D base of the U.S. PV program and expressed that solar electricity built upon sound science is still a real strength in the future."

BP Solarex/PIX08861

Holly Thomas, NREL/PIX09182

Top photo. BP Solarex high-efficiency panels are powering the headquarters of a leading German financial institution, the Berlin Bank. The panels generate 50 kW peak power and contribute to the bank's energy needs.

Right photo. At the Conference, BP Solarex showcased a triangular module in their large display area with a unique design element.

The future was also the subject of Kazmerski's presentation, as he polished up his crystal ball and guided conference attendees on a "tour through the 21st century" for PV technology. Early in the century, a linkage between PV and hydrogen as storage systems will begin to emerge, he said. This will include R&D of solar cells with various advanced storage concepts, based on new materials such as nanotubes, fullerenes, or membranes. A new chemistry will develop with modeling techniques to predict new materials and structures with exact requested properties—designer photovoltaics. Between 2010 and 2025, PV research directions will be coupled with other technologies, especially biotechnology and nanotechnology. Nature's light-excited processess, such as photosynthesis and photochemistry, will be successfully mimicked and used to improve energy conversion and storage mechanisms. Around 2020 and beyond, space exploration will begin to uncover resources that will lower PV materials costs and provide the beginning of space manufacturing. In medical science, PV will enable the implanting of diagnostic probes inside the body for monitoring/sensing that use thermophotovoltaic-type converters "tuned" to the radiation spectra of the internal body. These are just some of the future PV developments that today's research may well help to develop.

The NCPV's Christy Herig presented a paper on grid-connected PV applications located at residential and commercial customer sites. Herig compared U.S. markets and state utility restructuring policies with similar policies and markets in Europe, and concluded that, without policy incentives, the non-economic values such as saving the environment are not strong enough to affect markets in developed countries.

Other government programs were compared and discussed, as well. Policy and market value analyses were found to be complementary between Europe and the United States, with barriers such as insurance costs and utility interconnection being the same. The German subsidy programs, which provide either a partial cost grant or a full-cost zero-interest loan and a production incentive of 0.99 Deutsche mark per kWh, was perceived in both a positive and negative light. The positive side, as shown in analysis of the U.S. market, was that the German subsidy programs help to overcome financing, which is the final hurdle to market deployment of a high capital cost technology; the negative side is that too much investment is coming from the government.

Continued on page 11, Column 2.

NREL Reaches Out on Earth Day

NREL volunteers reached out to 12,000 consumers on Earth Day through workshops, information booths, and demonstrations to educate people about PV. With *clean energy* as this year's theme, it's only natural that NREL was an important sponsor of the Colorado Earth Fair 2000, held in Denver, April 14–16.

Among the NREL volunteers were John Thornton, Christy Herig, and Sheila Hayter; all are team members of DOE's Domestic PV Applications Development project. The team's number one goal is public outreach. Each year, project members reach about 500,000 people, including consumers, architects, builders, and engineers, through workshops they present at various events around the country.

At the Earth Day event, Thornton partnered with Byron Stafford, also of the NCPV, to present a solar power workshop designed for consumers, whether they live in a residential subdivision, on a ranch, or a farm. "The goal is to raise awareness and to put the consumer in contact with industry," says Thornton, shown speaking to homeowners in the photo below. The workshop included an introduction that explains how PV works as well as some basics on PV systems. A slide show provided examples of systems on a range of residences. The workshop also included information about choosing a system and vendor, as well as available financing programs.

Warren Gretz, NREL/PIX09166

When Thornton describes the workshop, he says, "The first big point we make is that if you don't use the energy in the first place, you don't need to generate it. If you design the house correctly, it should use half the amount of energy used in most houses. In this way, the PV is cheaper." Thornton says that the workshop works to dispel the myth that solar is more expensive, especially if a consumer can avoid connecting to the power grid in the first place. But the workshop is not just for those building new homes. It also covers the retrofits necessary in an existing home to use a PV system effectively.

Herig, Hayter, and other volunteers from NREL, as well as Shanti Pless, a graduate student from the University of Colorado who works with Herig and Hayter, were available to answer consumer questions about the DOE/NREL demonstration building, which made its debut at the Earth Fair. Herig reports that most people came to see the demonstration building in order to ask questions about PV: "It makes consumers aware that this isn't a space technology. It relates things back to their personal lives. It makes them aware that PV is market ready and usable." According to Hayter, some people were surprised by the roof-integrated system and had not realized that shingles could be part of a PV system.

Like Thornton, Herig and Hayter emphasized the importance of improving efficiency first to prepare for the PV system and make it more effective. They report that many consumers said they had always wanted to install a solar system, but needed to learn more about efficiency. Many visitors to the demonstration building had questions about insulation, windows, and other energy-efficient measures.

Fortunately, Hayter and Paul Torcellini, from NREL's Center for Buildings and Thermal Systems, were on hand to provide a consumer workshop on energy-efficient appliances and weatherization. Hayter and Torcellini demonstrated how easy it is to reduce energy consumption, and in which part of the home it is most effective to begin making changes. This workshop included information about lighting, heating and cooling equipment, hot-water heaters, and appliances. It also taught people what to consider when deciding to purchase equipment.

Warren Gretz, NREL/PIX09168

The DOE/NREL Solar Energy-Efficient Demonstration Building provides a tangible link between energy efficiency and PV. Its features include a clerestory for daylighting, overhangs and south-facing windows for solar load control, and mass for storing solar gains. With three roof-integrated PV systems (standing-seam metal roofing and shingles manufactured by United Solar and SunSlates by Atlantis Energy) that provide a total of 400 W of power, the building is completely grid independent.

Warren Gretz, NREL/PIX09167

In addition to a poster contest for young children, NREL sponsored the interactive "Mr. Science" booth. Otherwise known as Steve Spangler, Mr. Science used PV-powered motors, buzzers, and lights to teach kids how PV actually works. Spangler says that when he hooked up a PV cell to a voltage meter, the kids started asking questions: "Out in the sun, will it be more?" "What if you put a big one on your roof?" "Can I run a bike?"

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.

Dan Friedman of **NREL's III-V Materials and Devices Team** heightened the space community's awareness of the lab by participating in the 18th Space Power Workshop, sponsored by the **Aerospace Corporation** and the **U.S. Air Force**, where he spoke about approaches to greater than 30%-efficient PV. This workshop is the main forum for designers, suppliers, builders, and users of satellites and other spacecraft to discuss emerging trends in spacecraft power systems. For the solar cells used in these power systems, the NREL-patented III-V multijunction GaInP/GaAs-based technology has become the standard, obtaining "complete market penetration," according to the keynote speaker. The purpose of the NREL presentation was to provide an impartial, authoritative forecast of the prospects for further improvement in the efficiencies of these solar cells. The talk was very well received, with attendees from organizations including **NASA, Boeing,** and **Alcatel Space Industries** requesting copies of the presentation. The attendance and presentation at the workshop resulted in raising NREL's profile in the space community. It also proved to be a convenient opportunity for productive discussions with **Spectrolab** on NREL's high-efficiency concentrator collaboration. Contact: **Dan Friedman, 303-384-6472**

NREL staff at the **Outdoor Test Facility** has confirmed another world record for **BP Solar's Apollo Thin-Film CdTe Team**. BP Solar, Fairfield, CA, a business unit of BP Solarex, Lithicum, MD, set the world record with its monolithically integrated Apollo thin-film CdTe power module with an output of 91.5 W and 10.6% efficiency. The previous best output for a monolithically integrated thin-film module of any kind was 72 W. There are two primary reasons for the improvement in the module performance. Improvements have been made in the heat treatment, but more significant is the reduction in the CdS thickness. The CdS film has been reduced from about 1000 Å to about 500 Å. This has improved the short-circuit density (J_{sc}) from about 17 mA/cm^2 to about 21 mA/cm^2, without loss in open-circuit voltage (V_{oc}) and fill factor (FF). One of the primary goals of the National CdTe R&D Team has always been to demonstrate high J_{sc} without loss in V_{oc} and FF. The BP Solar Apollo module results have essentially demonstrated that this can be achieved in the pilot line and eventually in manufacturing. NREL scientists have also collaborated with the Apollo Team relating to various CdTe R&D issues. These new BP Solar results further the **Thin Film PV Partnership's** progress toward an important NCPV Program Plan milestone for 2004 (a 10%-efficient commercial thin-film CdTe module). They could also have a significant impact on how BP Solarex makes its business decision to commercialize this potentially low-cost thin-film PV technology. Contact: **Harin Ullal, 303-384-6486**

NREL's CIS Team, **Siemens Solar Industries** (SSI), and **Colorado State University** (CSU) are collaborating in research to reduce or eliminate transient effects of ZnO/CdS/CuInGa(SeS)$_2$ thin-film devices when they are subjected to heat and light exposure. In 1999, NREL and SSI conducted a series of experiments in which window layer processes at various stages were exchanged. This study showed that the transient effects were not reduced. This year, the research focus is on the nature of the interface formation between the SSI absorbers and the chemical bath-deposited CdS. Absorbers obtained from SSI were processed into devices at NREL using CdS and ZnO window layers. Some samples were treated with cyanide to remove surface contaminants and binary impurity phases. After depositing the CdS layer, some samples were post-annealed in air at 200°C for 2–10 minutes. Samples that were post-annealed exhibited a clear improvement in efficiency over the as-deposited case, primarily because of an increase in fill factors. The average cell efficiency was improved from the baseline value of 11%–12% to about 14%–15% as a result of the modified processing. Measurements made at CSU indicate that the magnitude of the transients are also reduced in the case of the higher-efficiency devices. These results give us an idea of the next steps to take in solving this problem. Further work in progress includes a comparison of the transient effect in NREL devices, and analysis of the compositional properties of the interface region. Contact: **Kannan Ramanathan, 303-384-6454**

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 May 2000, we awarded more than $18 million to new and existing subcontracts (examples listed below). For further information, contact Ann Hansen (303-384-6492).

AstroPower, Inc. (5/00–9/00)
Monolithically-Interconnected Silicon-Film™ Module Technology
$244,000

BP Solar, Inc. (5/00–9/00)
Apollo™ Thin Film Process Development
$275,250

First Solar, L.L.C. (5/00–9/00)
Technology Support for High-Throughout Processing of Thin-Film CdTe PV Modules
$553,720

Iowa State University (5/00–9/00)
Research on Improved Amorphous Silicon and Alloy Materials and Devices Prepared Using ECR Plasma Techniques
$72,600

MV Systems, Inc. (5/00–9/00)
High Efficiency, Stable Hot Wire CVD Prepared Amorphous and Polycrystalline Silicon Film Solar Cells
$133,000

Siemens Solar Industries (4/00–9/00)
Commercialization of CIS-Based Thin-Film PV
$462,000

University of Toledo (4/00–9/00)
High Efficiency Thin-Film Cadmium Telluride and Amorphous Silicon-Based Solar Cells
$231,906

Washington State University (5/00–9/00)
Alternative Window Schemes for $CuInSe_2$-Based Solar Cells
$54,000

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 Ann Hansen (303-384-6492).

A Quick Guide to Solar Electricity. March 2000; 2 pp. NREL/BR-520-27951.

Bhattacharya, R. N.; et al. *Thin-Film $CuIn_{1-x}Ga_xSe$-Based Solar Cells Prepared from Solution-Based Precursors*. May 2000; 7 pp. NREL/CP-520-28334. Presented at the *16th European Photovoltaic Solar Energy Conference and Exhibition*, 1–5 May 2000, Glasgow, Scotland.

Contreras, M. A.; et al. *Preferred Orientation in Polycrystalline $Cu(InGa)Se_2$ and Its Effect on Absorber Thin-Films and Devices*. May 2000; 7 pp. NREL/CP-520-28379. Presented at the *16th European Photovoltaic Solar Energy Conference and Exhibition, 1–5 May 2000*, Glasgow, Scotland.

Emery, K. *Results of the First World Photovoltaic Scale Recalibration*. March 2000; NREL/TP-520-27942.

Franceschetti, A.; Zunger, A. "Addition Energies and Quasiparticle Gap of CdSe Nanocrystals." *Applied Physics Letters*. March 27, 2000; pp. 1731–1733.

Herig, C.; et al. *Customer-Sited PV U.S. Markets Developed from State Policies*. May 2000; 7 pp. NREL/CP-520-28334. Presented at the *16th European Photovoltaic Solar Energy Conference and Exhibition*, 1–5 May 2000, Glasgow, Scotland.

How To Build A Better Home Using Solar Energy and the Whole-Building Approach. June 2000; 8 pp. NREL/BR-550-26582.

Jorgensen, G. *Optical Durability Testing of Candidate Solar Mirrors*. March 2000; 61 pp. NREL/TP-520-28110.

Kazmerski, L.L. *Photovoltaics R&D: A Tour Through the 21st Century*. May 2000; 10 pp. NREL/CP-520-28407. Presented at the *16th European Photovoltaic Solar Energy Conference and Exhibition, 1–5 May 2000*, Glasgow, Scotland.

Magri, R.; et al. "Anticrossing Semiconducting Band Gap in Nominally Semimetallic InAs/GaSb Super-Lattices." *Physical Review B, Condensed Matter*. April 15, 2000; 61; pp. 10,235–10,241.

McConnell, R.D.; et al. *Qualification Standard for Photovoltaic Concentrator Modules*. May 2000; 7 pp. NREL/CP-520-28323. Presented at the *16th European Photovoltaic Solar Energy Conference and Exhibition, 1–5 May 2000*, Glasgow, Scotland.

Meyers, P.V.; et al. *Atmospheric Pressure Chemical Vapor Deposition of CdTe for High Efficiency Thin-Film PV Devices: Annual Subcontract Report, 26 January 1999–25 January 2000*. May 2000; 19 pp. NREL/SR-520-28375. Work performed by ITN Energy Systems, Wheat Ridge, CO, and Colorado School of Mines, Golden, CO.

Thomas, H.P.; et al. *Progress in Photovoltaic Components and Systems*. May 2000; 6 pp. NREL/CP-520-27460. Presented at the *16th European Photovoltaic Solar Energy Conference and Exhibition*, 1–5 May 2000, Glasgow, Scotland.

Thomas, H.P.; et al. *PV and PV/Hybrid Products for Buildings*. May 2000; 7 pp. NREL/CP-520-28334. Presented at the *16th European Photovoltaic Solar Energy Conference and Exhibition, 1–5 May 2000*, Glasgow, Scotland.

Continued on page 11, Column 1.

Stephan Heck, a **University of Marburg, Germany** Ph.D. candidate doing his thesis research with the **NREL Amorphous Silicon Team**, was presented a Silver Graduate Student Award by the Materials Research Society (MRS). Gold and Silver Award winners receive cash awards, and a description of their work appears in the *MRS Bulletin*. Spring winners were selected on April 24, after candidates gave short lectures during the MRS Meeting. In collaboration with **Howard Branz**, Heck has done an experiment to elucidate the nature of light-induced metastable degradation of hydrogenated amorphous silicon (a-Si:H), an effect that hampers the photovoltaic application of the material. He found differences in the degradation behavior of a-Si:H under pulsed and continuous illumination of equal intensities. Heck's initial experiments seemed to suggest that the light-induced degradation involves a slow precursor that is created by photocarriers and decays in milliseconds after its creation. However, his recent experiments reveal that the effect is a result of room-temperature thermal annealing of a subset of easy-to-anneal defects. These defects have unusual electronic properties, now under study at NREL. Although Heck's result excludes precursors that rise on time-scales of 40 microseconds and longer, researchers in Japan are using pairs of more closely spaced pulses and find evidence for a metastability precursor that decays in 0.3 to 3 microseconds. Further experiments may reveal whether this is the mobile H trapping predicted by Branz' H collision model of the metastability. Contact: **Howard Branz, 303-384-6694**

Materials Research Society/PIX09171

Heck was delighted to accept his MRS Silver Graduate Student award from Harry Atwater, president of MRS and physics professor with the California Institute of Technology.

A new processing system for large-area CIS deposition at the **University of Delaware's Institute of Energy Conversion (IEC)** has moved the IEC one step closer to achieving a state-of-the-art, large-area solar cells and submodules. **NREL** confirmed that co-evaporated $CdS/Cu(In,Ga)Se_2$ (CIGS) solar cells prepared under subcontract at the IEC reached 14.9% efficiency (V_{oc} = 0.606 V, J_{sc} = 33.2 mA/cm^2, FF = 74.3%, cell area = 0.462 cm^2). The cells were prepared in IEC's large-area, in-line deposition system designed to deposit CIGS-based semiconductors on a continuously moving substrate. The system can accept substrates up to 30 cm in width. It was initially equipped with Cu, In, Ga, and Se evaporation sources that can coat over a width of 15 cm. Later, the system could be adapted for using a web-type substrate (roll-to-roll deposition). The system was designed and built by **Materials Research Group** in Wheat Ridge, CO. The evaporation sources were constructed using IEC's design. Compared to 16%-efficient cells prepared earlier at IEC in a small R&D deposition system, the cell made in the large-area system suffers from lower values for open-circuit voltage (V_{oc}) and fill factor (FF). It is expected that future optimization of the junction layer processing will lead to higher V_{oc} and FF. There is no indication the cell performance would be limited by the CIGS absorber layer. This accomplishment will enable IEC to effectively support critical scale-up work for large-area CIGS deposition. Two emerging CIS PV manufacturers, **Energy Photovoltaics** and **Global Solar Energy**, are developing processes for the commercial production of CIGS-based photovoltaic modules using co-evaporation processes very similar to those employed by IEC. **Würth Solar** of Germany has announced initial manufacturing of CIGS modules in July 2000, also using a co-evaporation process. Contact: **Bolko von Roedern, 303-384-6480**

Pennsylvania State University, in conjunction with the **Thin Film PV Partnership**, has thoroughly analyzed a protocrystalline growth regime for a-Si:H layers deposited by plasma-enhanced chemical vapor deposition (PECVD).Using in-situ spectral ellipsometry, a phase diagram has been developed that distinguishes between four different growth regimes: (1) amorphous, stable surface, (2) amorphous, unstable surface, (3) mixed phase, and (4) coalesced microcrystalline. Penn State characterized the growth regime using high hydrogen dilution (H_2/SiH_4 gas mixtures). Earlier semi-empirical hydrogen dilution work at **BP Solarex** and **United Solar Systems Corp.** resulted in reduced light-induced degradation of a-Si:H solar cells. United Solar reported that it was beneficial to use PECVD deposition conditions close to the microcrystalline transition. The characterization studies at Penn State suggest that deposition conditions as close as possible to depositing microcrystalline Si should be employed, but layers with any significant amounts of a microcrystalline phase should be avoided, because films with microcrystalline inclusions cause significant degradation of cell voltages and fill factors. Penn State reported that hydrogen-dilution significantly affects the degradation kinetics of solar cell and material parameters. Contact: **Bolko von Roedern, 303-384-6480**

Review Meeting, Continued from p. 5

semiconductors belonging to a class of tetrahedrally bonded, diamondlike compounds. These are most promising because of their close similarity with traditional semiconductors that adapt to their composition, crystal structure, and natural chemical and electronic structures. In addition, opportunities exist for exploiting a variety of organic semiconductor materials that are rapidly evolving as low-cost electronic materials.

Will we all get there in one piece?

During the conference, a member of the audience asked if there was room enough for everyone in the marketplace. The answer was yes, because of the world's large untapped markets. But if the PV industry is going to tap into these markets, it better have a plan with concrete strategies for goal fulfillment. Otherwise, "it's every man for himself."

Tom Surek, the Technology Manager of NREL's PV Program, put together a survey in which he asked participants, about half of which were from industry and the rest closely divided between government and universities, to answer questions about the roadmap and five-year plan. This provided all the participants an opportunity to add to the ample discussions on research directions and priorities. Of more than 300 people in attendance, some from Japan and Europe, 38 responded to questions such as, "Are the roadmap and five-year plan goals measurable and achievable?" Most of the respondents thought they were achievable, but also acknowledged the many obstacles still lie in the way of meeting them. First, respondents said, the PV community must develop implementation strategies for both plans. Next, the PV community, which includes national laboratories, private companies, universities, environmental organizations, and private individuals, will have to work together to convince Congress that energy policy changes are needed.

For more information, contact Tom Surek at 303-384-6471

Publications, Continued from p. 9

Wei, S.H.; et al. "First-Principles Calculation of Band Offsets, Optical Bowing, and Defects in CdS, CdSe, CdTe, and Their Alloys." *Journal of Applied Physics*. February 1, 2000; 87; pp. 1304–1311.

Wu, X.; Sheldon, P. "Novel Manufacturing Process for Fabricating CdS/CdTe Polycrystalline Thin-Film Solar Cells." May 2000; 7 pp. NREL/CP-520-28368. Presented at the *16th European Photovoltaic Solar Energy Conference and Exhibition, 1-5 May 2000*, Glasgow, Scotland.

Zhang, S.B.; Branz, H.M. "Nonradiative Electron-Hole Recombination by a Low-Barrier Pathway in Hydrogenated Silicon Semiconductors." *Physical Review Letters*. January 31, 2000; 84; pp. 967–970.

Scotland, Continued from p. 6

Another NCPV member, Bob McConnell, spoke to conference attendees about qualification standards for PV concentrators. He also participated in the first meeting of the International Electrotechnical Commission working group to develop an international standard for qualifications testing of PV concentrators. However, McConnell's main focus was on fundamental R&D.

Toshiba of Japan issued a press release the day of its presentation regarding its work with a new solar electric dye cell using a polymer gel electrolyte. Toshiba reported an efficiency of 7.3%, slightly less than the 8% reported for its dye cell using a liquid electrolyte. Johannes Kepler University of Linz in Austria was among the European presenters, claiming an efficiency of 3.28% under AM1.5 solar spectrum for a device using interpenetrating networks of conjugated polymers and fullerenes. The University of Stuttgart showcased its work on the transfer of monocrystalline Si films from a Si wafer to a glass superstrate. The film thickness was about 25 microns and the cell efficiency was confirmed at 14%.

The Netherlands research lab, ECN, reported a flexible dye cell with 2.2% efficiency. Martin Green, from Australia's University of New South Wales, presented his work in "Third-Generation Photovoltaics, Advanced Structures Capable of High Efficiency at Low Cost," which described several relatively unexplored concepts for solar cells with potential efficiencies of 60% to 80%.

Also significant was the announcement that companies and governments in Europe are abandoning the term "photovoltaics" and replacing it with "solar electricity." The term is being discarded because it is believed by Europeans that only scientists and the energy technology elite know what it means. In addition, dictionary definitions of photovoltaics are often confusing and inaccurate, whereas "solar electricity" clearly describes the magic of this technology.

Holly Thomas, also from the NCPV, attended sessions related to PV manufacturing, cell processing, economics, and building-integrated PV (BIPV). Manufacturing-related topics presented at the conference included a presentation by ASE Americas on its new 6.5-MW automated wafer-cell plant in Germany, with a detailed list of lessons learned. Spire presented a paper describing its manufacturing equipment advancements, including the PV Manufacturing R&D developments. Two German firms had exhibits of equipment similar to Spire's. STR (formerly Springborn) presented a paper on its faster-curing encapsulant, and two European firms had exhibits that included their encapsulating materials, highlighting color options of the backskin. Among the BIPV applications featured in the oral presentations were PV stained-glass windows, a tracking sunshade, and modules used as building façades. Kawneer's BIPV sun shade, which incorporates amorphous-silicon modules manufactured by Kawneer and BP Solarex, won an award as well.

For more information about the conference, contact Larry Kazmerski at 303-384-6600 or Bob McConnell at 303-384-6419. For more information about the Solar CD, or to submit a photo for inclusion in the second Solar CD coming soon, contact Susan Moon at 303-384-6631.

PV Calendar

July 30–August 4, 2000, *13th International Conference on Photochemical Conversion and Storage of Solar Energy (IPS-2000)*. Sponsor: NREL. Location: Snowmass, CO. Contact: Barbara Ferris, 303-275-3781. Web site: *www.nrel.gov/ips2000*

August 8–11, 2000, *Second Historically Black Colleges and Universities Renewable Energy Academic Partnership Conference*. Sponsor: NREL. Location: Golden, CO. Contact: Fannie Posey Eddy, Phone: 303-384-6247

August 13–16, 2000, *10th Workshop on Crystalline Silicon Solar Cell Materials and Processing*. Sponsor: NREL. Location: Copper Mountain, CO. Contact: Bhushan Sopori. Phone: 303-384-6683.

August 23–24, 2000, *IEEE SCC21 P1547 Standard Development*. Conference focuses on an interconnection standard for distributed electric power systems. Sponsor: NREL. Location: Golden, CO. Contact: Cricket Pierce. Phone: 303-275-4326.

September 17–22, 2000, *28th IEEE PV Specialists Conference*. Location: Anchorage Hilton, Anchorage, AK. Contacts: Ajeet Rohatgi. Phone: 404-894-7692. Or John Benner. Phone: 303-384-6496. Web site: *http://ieeepvsc.nrel.gov/pvsc28home.html*

October 2–5, 2000, *UPVG Photovoltaic Experience Conference 2000*. Location: Baltimore, MD. Sponsor: Utility PhotoVoltaic Group. Contact: Tina Schneider, Phone: 202-857-0898. Web site: *www.upvg.org/upvg/upex2000*

October 2–6, 2000, *American Vacuum Society, 47th International Symposium*. Sponsor: AVS. Location: Boston, MA. Contact: AVS. Phone: 212-248-0200. Web site: *www.vacuum.org/call/default.html*

November 5–11, 2000, *Renewable Energy: Advancing Technology for Industrialization and Sustainable Development*. Sponsor: International Networking Events. Location: Brighton, England. Contact: *network.events@britishcouncil.org*

November 27–December 1, 2000, *Materials Research Society 2000 Fall Meeting*. Sponsor: MRS. Location: Boston, MA. Contact: MRS Headquarters. Phone: 724-779-3003. Web site: *www.mrs.org/meetings/fall2000*

December 4–7, 2000, *Village Power 2000: Empowering People while Building Markets*. Sponsors: NREL, World Bank, Winrock International. Location: World Bank HQ Building, Washington, DC. Contact: Barbara Ferris, 303-275-3781. Web site: *www.nrel.gov/villagepower*

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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