SOLAR ELECTRICITY
the power of choice

Second Quarter, 2001

Features

Departments

National Center for Photovoltaics
Phone: 303-384-NCPV
www.nrel.gov/ncpv

Reporting on solar electricity research and related activities from the National Renewable Energy Laboratory and its partners within the National Center for Photovoltaics

Why Invest in PV?

Why invest in photovoltaics research and development? What does the United States stand to gain from supporting this activity? This issue of *Solar Electricity, the Power of Choice* seeks to answer those questions.

The science and technology of solar electricity is vitally linked to U.S. national stewardship of technology and research. During the last decade, the United States has made dramatic progress across a broad front of technology issues, including materials and semiconductor science, nanotechnology, and organic semiconductors. This overall revolution in science and technology can transform the potential of PV into reality—and the United States should lead in this process. But this is not merely a matter of national pride or international image. Rather, in a knowledge-based future, only an America that remains at the cutting edge of science and technology will sustain world leadership and competitive strength.

Globalization of the PV industry occurred in the 1990s because foreign countries clearly recognized the importance and significance of solar electric power technology for their own expanding markets and needs for energy. They had the best-defined markets at the time. Now, the United States is confronted with the ups and downs of a nationwide energy problem. During the winter of 2000, it was a shortage of natural gas, with the concomitant increases in the average person's energy bill. Next came the electricity crisis, along with service cutbacks, in California.

In the end, perhaps the question to ask is not why the United States should invest in photovoltaics R&D, but whether there could possibly be a better time to do it.

Dispelling the Seven Myths of Solar Electricity

An Editorial by Larry Kazmerski

SOLAR ELECTRICITY is a thriving worldwide business, making good on its promise of "delivering clean, reliable, on-demand power." Research progress continues, making current technologies better and positioning photovoltaics (PV) for the next-generation technologies required for meeting future electricity needs. These successes seem to spark criticisms and questions—some warranted, some based on partial truths, and others perpetuated from urban legends or myths about the technology. Common among these are the "seven myths of solar electricity."

NREL/PIX10128

Larry Kazmerski, pictured in his office at NREL, is director of the National Center for Photovoltaics. He's a charter member of NREL, dating back to the Lab's inception as the Solar Energy Research Institute in 1977.

Contact Larry Kazmerski at 303-384-6600.

Myth 1: Solar electricity cannot serve any significant fraction of U.S. or world electricity needs.

PV technology *can* meet electricity demand on any scale. The solar energy resource in a 100 x 100-mile area of Nevada could supply the United States with all its electricity (about 800 gigawatts) using modestly efficient (10%) commercial PV systems. A more realistic scenario involves distributing these same PV systems to the 50 states, and using sites that are available right now (such as vacant land, parking lots, and rooftops). In this case, the land requirement to produce the 800 gigawatts averages out to an area of about 17 x 17 miles per state. Alternatively, 90% of America's current electricity could be supplied with PV systems built in the "brownfields"—the estimated 5 million acres of abandoned industrial sites that exist in our nation's cities.

These are only hypothetical cases to emphasize that PV is not "area-impaired" in delivering electricity. The critical point is that photovoltaics does not have to compete with baseload power. Its strength is in providing electricity when and where energy is most limited and most expensive. It does not simply replace *some* fraction of generation; rather, it displaces the *right* portion of the load, shaving peak demand during periods when energy is most constrained and expensive. It is distributed generation at its best, providing "consumer choice," where consumers can control their own investments.

In the long run, the *U.S. PV Industry Roadmap* projects that PV will meet a "significant fraction of U.S. electricity needs." The United States expects the Alaska Natural Wildlife Refuge (ANWR) to contribute significantly to our domestic energy supply. The Roadmap expects the U.S. portion of solar electricity to surpass the equivalent energy supplied by that oil resource in 2034. Both promise significant energy production—and solar electric generation keeps producing and growing well after ANWR is depleted.

Myth 2: Solar electricity can do everything—right now!

No way. Solar electricity will eventually become a major player in the world's energy portfolio. However, the industry does not have the capacity to meet all demands now. But assuming that the proper investments are made now and are sustained, the industry will become significant in the next few decades. In 1999, for example, worldwide PV shipments grew by 32% versus the previous year. In 2000, they grew by another 37%, and this year they are expected to grow an additional 40%—perhaps even 50%. Although this will bring 2001 shipments to 400 megawatts or more, we certainly cannot meet the entire burden of U.S. or world electricity needs… yet.

Myth 3: Photovoltaics cannot significantly offset environmental emissions.

PV systems produce no atmospheric emissions or greenhouse gases. Compared to fossil-generated electricity, each kilowatt of PV electricity offsets up to 16 kilograms of NO_x, 9 kilograms of SO_x, 0.6 kilogram of other particulates, and 2,300 kilograms of CO_2 per year. And even though the current PV generation capacity does not yet offset a substantial amount of these gases (in terms of total U.S. or world emissions), as the PV industry grows, the offsets will become considerable. For example, if the industry grows by the 25% per year expected by the Roadmap, PV in the United States will offset 10 million metric tons of CO_2 per year by 2027—equivalent to the annual increase in CO_2 emitted by U.S. fossil fuel electricity generation. This means that the emission rate will become negative thereafter as the PV contribution grows!

Myth 4: Photovoltaics is a polluting industry.

The PV industry is neither "squeaky clean" nor is it a major problem for environmental, safety, and health. From the electricity-generating portion of the fuel cycle, PV is the clear winner versus fossil fuel sources with respect to emissions. However, there are concerns around semiconductor processing, especially involving the use of chemicals and toxic materials.

Some 80% of the current PV industry is silicon—basically having the same processing and risk as the semiconductor industry. The PV silicon industry abides by various codes, controls, and laws that

regulate and oversee its operations. The PV industry is also assisted by the U.S. DOE program conducted by Brookhaven National Laboratory that audits manufacturers, on a voluntary basis, for ES&H concerns. Industry has made many improvements in areas such as safer etching, lead-free solders, automated handling and robotics, product recycling, redundancy in ensuring critical operations, and stringent training. The risks involved are no greater than those at Intel or Sanyo in serving our nation's computer chip requirements.

Those PV materials that incorporate heavy metals or toxic materials are continuously scrutinized to ensure safety. To date, testing and investigations by the Environmental Protection Agency, Underwriters Laboratories, and others indicate no "show-stopping" problems—but the programs and companies involved remain vigilant and active in ensuring safety.

Myth 5: Photovoltaics is merely a cottage industry, appealing only to small niche markets.

This year, PV module shipments are expected to surpass the 400-megawatt-per-year mark, representing a $2.5 to $3 billion market. The U.S.-based industry itself, which now approaches $1 billion per year and provides 20,000 jobs, is expected to grow to the $10–$15 billion level in the next 20 years and to provide 300,000 jobs by 2025—which is about the size of General Motors. This is a real business—one that has been growing by more than 35% per year during the past 2 years, and in the range of 25% per year for the last 5 years. This sustained growth exceeds that of the semiconductor industry over the same period.

Much of the reason for the recent growth is that the markets have shifted from almost completely remote, off-grid, and consumer products to nearly 60% grid-connected, distributed power. These applications are not small niches. They represent the significant growth path for PV—which is the true distributed power source.

Myth 6: PV is too expensive and will never compete with "the big boys" of power generation. Besides, you can never get the energy out that it takes to produce the system.

The cost of producing PV modules, in constant dollars, has fallen from as much as $50 per peak watt in 1980 to as little as $3 per peak watt today, dropping PV electricity to 15¢–25¢ per kilowatt-hour—which is competitive in many applications. In the California market, where state incentives and net metering are in place, PV electricity prices are approaching 11¢/kWh, on par with some utility-delivered power. Moreover, according to the PV Roadmap, solar electricity will continue this trend and become competitive by 2010 for most domestic markets.

The energy payback period is also dropping rapidly. For example, it takes today's typical crystalline silicon module about 4 years to generate more energy than went into making the module in the first place. The next silicon modules, which will employ a less expensive grade of silicon and will use thinner layers of semiconductor material, will have an energy payback of about 2 years. And thin-film modules will soon bring the payback down to one year or less, which means that these modules will produce "free" and clean energy for the remaining 29 years of their expected lives.

Myth 7: Nothing remains to be done. Essential R&D is complete, the product works—just close the laboratory doors and let industry fight it out.

As a high-tech energy supply, PV has immense potential to evolve, develop, and advance. Our current technologies still have substantial potential for improvement. R&D on processing, process understanding, and manufacturing is in its infancy. There is much important R&D still to be performed, not just on cells and modules, but also on balance-of-systems components and on systems themselves. Many new and next-generation materials, devices, and physics are only concepts; others are still to be discovered. Among these will be authentic breakthroughs that will boost PV to the next levels of performance. It is up to us to make and manage the investments to own these. Delays in making these investments will mean lost opportunities, a longer time in bringing this clean energy source into widespread use for us and our descendants, and the loss of technology leadership and ownership. On the other hand, targeted and increased investments in R&D could greatly accelerate technology and business goals—making the PV Roadmap expectations a reality for the consumer *even sooner*.

Failing to take R&D leadership poses a pathway of diminished U.S. innovation, technology ownership, and energy ownership and control, as well as the loss of substantial economic benefits. We must therefore continue—and enhance —our U.S. investments in PV R&D, as argued in the following articles of this newsletter.

The investment in PV research and development and clean, solar electricity for our nation's future is good, sound business. And that's the truth.

PV Research and Development

Breaking Through to the Next Level

The PV myth "solar electricity can do everything" has several surrogates, some of which are long-standing and have even attained the status of "urban myth." Many in the solar community will remember, for example, a solar pioneer who made the claim during the early years of the PV Program that "someday we may be able to spray paint our houses with a PV coating."

A farfetched claim? Perhaps. But consider that some of today's up-and-coming concepts employ titanium dioxide—the primary ingredient in white paint. Also consider, because of past R&D, that we're now using thin, flexible solar panels, solar shingles that substitute for regular shingles *and* provide electricity, solar panels that form an integral part of a roof's structural integrity, and translucent solar electric awnings, windows, and spandrels. And these are just some of the more clever designs; during the past two decades, R&D has given us steady progress over a broad front:

- Advances in module production techniques for crystalline silicon and polycrystalline silicon technologies
- The emergence of thin films—amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS)
- Two- and three-junction devices that are reaching conversion efficiencies above 30%
- Increased efficiencies for all material technologies
- Better antireflection coatings, grid concepts, and methods for capturing and converting more sunlight to electricity
- Manufacturing processes that have become more efficient, have greater throughput, and that use far less materials and less energy.

Ten years ago, the concept of making a structural component of a building, such as a roofing shingle, that provided electricity might have seemed farfetched. Today, such products are a reality, as shown in this photo of the Urban Options' Energy and Environmental Demonstration House in East Lansing, Michigan. United Solar Systems Corp., a participant in the Thin Film PV Partnership and a recent awardee in the PV Technologies Beyond the Horizon solicitation, manufactured these solar electric shingles.

Patrick Hudson/PIX09508

This R&D progress has succeeded in dropping the cost of solar electricity by about five- to sixfold since 1980. Yet, there are still many things to be done, questions to be answered, and R&D avenues to be explored. For example:

- How do we drop the cost of solar electricity another five- to sixfold to make it competitive with the cheaper conventional generation technologies?
- How do we take device conversion efficiency beyond 40%?
- How can we most efficiently exploit the entire solar spectrum?
- Can we find thin-film avenues that do not rely on toxic materials or on materials in short supply?
- Can we adequately solve or circumvent the Staebler-Wronski effect?

Many will argue, with good reason, that we can do most of this *incrementally* by extending the R&D—into devices, modules, and systems—using materials technologies that we have been exploring for some time. There is much to be said for this approach, for it has taken us far in the last 20 years.

But others will argue that much of what we have been exploring has itself been built on *breakthroughs*—in the 1970s for a-Si, in the 1980s for CIGS and CdTe, and in the late 1980s and early 1990s for III-V multijunction technology. And, although continued research in these technologies will increase efficiencies, drop costs, and improve lifetimes and stabilities, there are greater possibilities out there. Possibilities that will improve efficiencies and costs by a quantum leap, that will give us a new generation of solar technologies, and that will present us with a whole new solar electric superhighway. As a result, such R&D could help vault the United States into the catbird seat for the new world of energy technologies.

What are some of these possibilities that wide-ranging R&D will give us? What are the next breakthroughs? Perhaps we have already seen a glimpse of where those breakthroughs may occur.

The high-efficiency multijunction avenue:

- Today, we have a triple-junction cell (GaInP/GaAs/Ge) that is getting 34% conversion efficiency at 600-suns concentration. The next step would move to four junctions, perhaps by using a nitrogen compound to achieve a 1-eV cell that could be lattice-matched and sandwiched between GaAs and Ge cells. Such a device could convert more than 40% of incident light to electricity and lead to the use of even more junctions.

(Continued on page 11)

Energy Security and Technology Ownership

Are There Imported PV Modules in Our Future?

Solar electricity offers our nation a secure energy option, giving us the freedom and flexibility to chart our own course and establish our independence. But the United States must invest in photovoltaics R&D to ensure that our technical preeminence is not lost, and that we can capitalize on the advantage it brings us. Photovoltaic industry leaders in the United States agree: the technology is ours to develop and keep, and we should not accept importing PV technology from, or depending on, foreign sources in the future. Falling behind in the international technology race should not be an option.

The current state of photovoltaics R&D can be compared to basic electronics engineering—the two are closely related disciplines. Both rely on semiconductors, and both are high-tech industries that afford enormous economic opportunities to the country that gets there first with the best innovations. But because of the scaling back of U.S. R&D in basic electronics engineering, the next generation of chip processors and manufacturing technology will come from an international consortium (U.S.-German-Dutch), rather than from the United States alone. This same scenario will be repeated for photovoltaics—unless there is continued strong support for our domestic development.

Roger Little, chairman, CEO, and president of Spire Corporation, says that he addresses this possibility every day. He is optimistic for now, saying, "We have not yet fallen behind in the R&D world—we're still in good shape. With the new projected budgets, we may be able to hold our own."

But Little, whose company produces the equipment used to manufacture PV modules, adds a disquieting note. "Right now we're getting serious competition in the PV equipment business. The strong Japanese government support of their own photovoltaics R&D and deployment allows our competitors to bid low prices. For us to compete, we have to lower our prices, thereby cutting into our margins. These reduced margins put a strain on our operations, and do not allow us to reinvest in all the new products and services that our customers would like."

Other industry leaders agree that such situations must not be allowed to proliferate in the future. Adding a business slant to the issue, Little says that competitiveness and profitability are driven by intellectual property, and keeping R&D in the United States allows us to create intellectual property that can be leveraged into pricing. That profitability is fuel for growth.

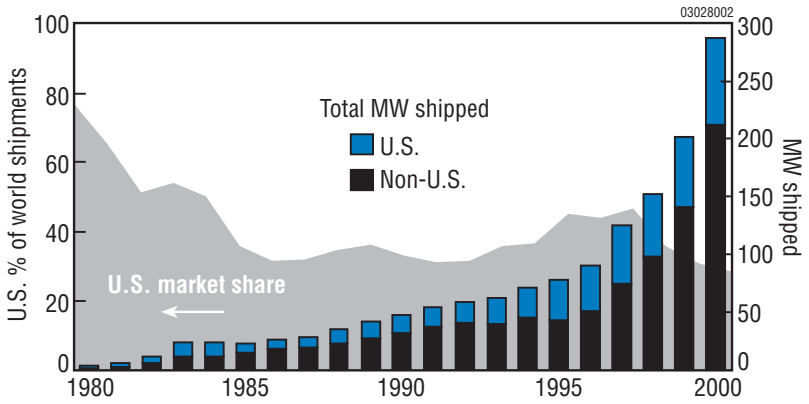
U.S. PV research has demonstrated its innovation, creativity, and contributions. At the national laboratories alone, some 15 R&D 100 Awards have recognized these accomplishments. There are also 140 patents, spanning materials innovation (such as electromagnetic Si casting, new transparent conducting oxides), through devices (GaInP/GaAs/Ge triple-junction cells, CIGS and CdTe thin-film cells), to the development of novel characterization methods transferred to industry (PVScan Defect Mapper, module laser scanner). This intellectual property has served, and continues to serve, technology development paths in the United States. The U.S. university-industry-national lab partnership in photovoltaics R&D is distinctive in the world and has facilitated sharing of results, complementary (non-redundant) shared facilities, and integrated R&D planning.

If this partnership continues, Little says, "I feel we will be able to compete effectively with other international programs and developments." But the possibility still exists for the United States to become dependent on other countries' research in the future.

Such dependence on foreign groups to support the research needs of our domestic industry is contrary to what is now the *modus operandi* of these foreign research efforts. Because they are commonly tied directly to their own countries' industry, these foreign organizations and countries protect their interests and do not easily "share" critical research results. Important research results would either not be readily available or would be delayed for use by U.S.-based organizations.

By failing to support a domestic research competency, the United States would not only relinquish our technology lead, but would also forfeit large segments of our solar electric markets to foreign companies. In essence, we would also take away the technical edge from our own domestic industry. If we assume that research conducted elsewhere will provide this support, we are dangerously shortsighted and are putting our future into the hands of others.

The graph below shows that U.S. market share of world PV shipments has dropped dramatically in the last 3 years. R&D drives the high-tech world, and, in recent years, government funding in the United States has not kept pace with that of other nations—particularly Japan and Germany.



Source: *PV News, PV Insider's Report*, Feb. 2001

PV and Related Technologies

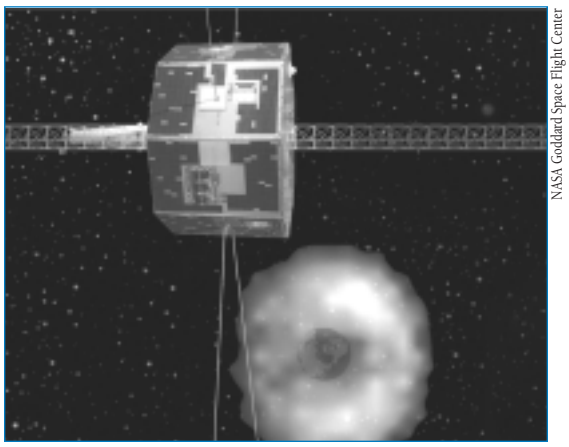
Measuring the Value of Synergism

How do you measure the value of a technology, specifically solar electric technology? Some might point to the current market, noting that solar electricity generates about $2 billion worth of business. Others might look at the projected future markets claiming, for example, that by 2020 the worldwide solar electric market will be as much as $15 billion a year and rising.

But these and other valuation methods ignore the technological milieu in which solar electric technology is embedded. No technology (or science, for that matter) exists in isolation from others. All form an intricate web of knowledge, belief, and advance. Pluck a string in one place and you'll find that the signal reverberates throughout the entire instrument.

In particular, solar electricity has become an important strand in the web of solid-state technologies. Advances in solar electricity often have an effect on other solid-state technologies, and advances in other technologies are often incorporated into solar electricity. This synergism among solid-state technologies has a major impact on the U.S. economy. For example, solid-state technologies are the foundation of the information technology industries—whose total annual market in the United States approaches $1 trillion.

The technology of solar electricity affects this market in several ways. Consider as illustration the two R&D 100 Awards that *R&D Magazine* recently awarded the National Center for Photovoltaics and its partners in industry. Both award-winning technologies—the triple-junction terrestrial concentrator solar cell and the DRWiN electronically scanning antenna—have important connections to the telecommunications industry, which, as a subset of the communications industry, does more than $300 billion of domestic business per year.



NASA Goddard Space Flight Center

Solar cells—such as the high-efficiency triple-junction cells that power the IMAGE satellite shown here—have not only enabled us to explore space, the solar system, and the Earth in great detail: they also have enabled the emergence of the telecommunications industry. Without solar cell technology, we might find ourselves with a paucity of information about our place in the universe and lacking the ease of communicating across the globe and through the eons.

The Spectrolab/NREL terrestrial triple-junction cell is a direct descendent of the triple-junction cell that Spectrolab (and others) use in space to power satellites. And the space cell is a direct consequence of the III-V multijunction technology pioneered by NREL scientists. Because of the efficiency of the triple-junction space cell, its weight-to-power ratio, and its resistance to radiation, this cell has quickly become the preferred one to use in space. One connection of the cell with telecommunications is obvious—the cell (and its progeny) will be used to power hundreds (if not thousands) of communication satellites that will be launched in the next decades. Another connection is not so obvious. The cell is based on gallium indium phosphide/gallium arsenide—the up-and-coming III-V materials technology that is becoming increasingly important in telecommunications, electronics, light-emitting-diode, and laser technologies.

The DRWiN antenna, which NREL helped ElTech and Paratek Microwave to develop, is the world's first commercially available electronically scanning antenna. Simply put, the DRWiN antenna may help revolutionize the wireless world; minimally, it will help an already burgeoning industry to explode. The antenna's characteristics, including a unique tunable dielectric material and its low cost, support that statement. It is three orders of magnitude less expensive than systems with comparable capabilities (which are used primarily by the military).

But with respect to our viewpoint here, the salient question to ask about DRWiN is "What exactly was transferred between the solar electric and antenna technologies?" It wasn't technology, per se, in the form of a new material or device design that was transferred. Rather, it was knowledge or, more precisely, expertise—an expertise that was fostered by NREL's PV Program in conjunction with its Superconductivity Program. The NREL team provided expertise in deposition of barium strontium titanium oxide materials.

So we come back to the question "How do you value a technology?" Where, for example, would the telecommunications industry be without the facile ability of solar cells to power satellites? In this case, we can view solar cells as a vital element—an enabling technology—for space-based telecommunications. Without it, we could reasonably hypothesize that the growth of the telecommunications industry would falter. In this case, as an enabling technology, the value we would have to place on solar cells would far exceed the value you would place on the market for solar electric power as power.

(Continued on page 8)

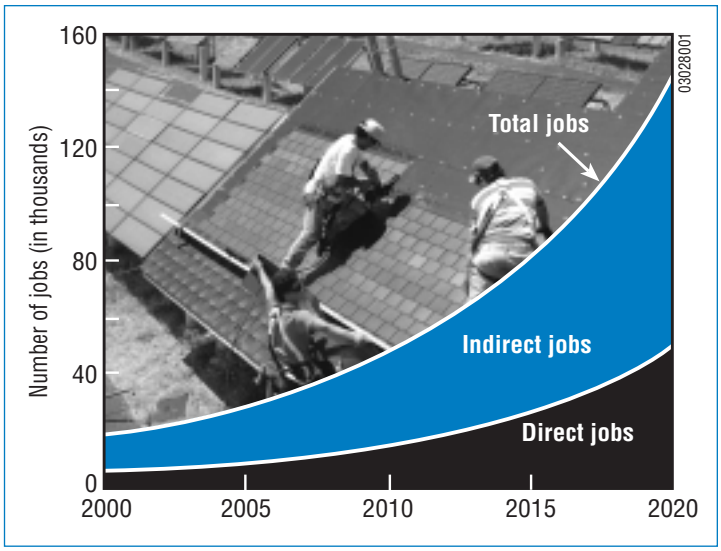
Investing in PV is Good, Sound Business

"I like to focus on sales," says Roland Hulstrom, deputy director of the National Center for Photovoltaics (NCPV). "Just think about the difference when you go from a couple billion in PV business today to $10 to $15 billion by 2020. As the PV industry grows accordingly, think about what it will mean for the world, *and particularly the U.S., economy*."

That projected growth, described in the *U.S. Photovoltaics Industry Roadmap*, translates to about 150,000 high-tech jobs for our nation. And, because PV systems are exportable commodities in high demand around the world, it also translates to taking a sizable bite out of the U.S trade deficit.

"The Roadmap goal of a 25% annual increase in PV shipments requires that industry double its shipments every 3 years," says Hulstrom. "This is not going to happen without spending some money on research and development. R&D needs to feed that growth."

PV industry leaders acknowledge the substantial contribution that U.S. government support, under the auspices of the DOE PV Program, has made to their industry. They recognize that this support has been instrumental to making the United States among the PV technology leaders worldwide. But those same leaders argue for taking this a step further and making it a priority to invest in a reasonable domestic PV R&D program. If not, the impact of the technology is in danger of being delayed—or lost completely—to the economic and technological detriment of the United States.



If the targets of the U.S. PV Industry Roadmap are met, the PV industry will support about 150,000 domestic high-tech jobs in 2020.

The targets and objectives of the PV Roadmap include providing a significant share of the new, added U.S. peak electricity capacity by 2020 and meeting 10% of the U.S. peak generation capacity with photovoltaics by 2030. To attain these goals, the U.S.-based PV industry drives home the point that *the investment must be made now*. The benefits of success have an enormous economic impact.

Currently, solar electricity is not cost competitive with bulk, baseload power—but it does not have to be. Instead, it provides electricity when and where energy is most limited and most expensive, which is a highly valuable and tremendously strategic contribution. It does not simply replace some *fraction* of the generation; rather, solar electric power displaces the *right* portion of the load. Solar electricity mitigates the risk of fuel price volatility and improves grid reliability. Electricity from PV technologies allows consumers to spend their own money on energy, thus giving them control over their own investment. And it is a free-market commodity, involving a mix of both large and many small businesses—with customer choice underpinning success and growth.

The PV industry will grow and provide economic value, building toward a $15 billion industry in 2020. In the past 3 years, the industry has grown by an average of 36% per year worldwide—and the United States will benefit immensely from this rapidly expanding business. Within 20 years, the industry is expected to employ more than 150,000 Americans in high-value, high-tech jobs, which is about the size of the current glass industry. By the end of the 2020s, the industry expects to double this employment—with jobs at the same level currently supported by General Motors or the U.S. steel industry.

Another aspect of photovoltaics is its market diversity. Whether now or in 2020, a significant portion of the PV product manufactured domestically will be exported. This situation provides a balance-of-payments benefit to the United States. As urged in the *U.S. PV Industry Roadmap*, we must continue to invest in PV R&D. This small investment anchors the disproportionately huge benefit of ensuring *U.S.* leadership and *U.S.* technology, *U.S.* economic gain, *U.S.* markets, and *U.S.* jobs.

So, is investing in PV a good, sound business decision for the United States? Hulstrom and his colleagues in the NCPV and throughout the PV industry believe that it is. And they have a Roadmap to show the way.

Industry Activity Update

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.

Evergreen Solar dedicated its new, full-scale manufacturing facility in Marlboro, MA, on May 23. Several state and local dignitaries participated in the inaugural ceremonies attended by some 80 invited guests and media. **Mark Farber**, president and CEO of Evergreen Solar, hosted the event, and **Tom Surek** attended as **NREL's** representative. The new plant currently employs some 100 people and is intended to produce, in full operation, 10 MW of PV modules annually based on Evergreen Solar's patented String Ribbon silicon technology. The early innovation of the technology was supported at both NREL (with **Ted Ciszek's** research on edge-supported pulling) and **A.D. Little, Inc./Massachusetts Institute of Technology**, with Evergreen Solar licensing the technology in 1994. The time frame for moving this technology from the laboratory to commercial production has been significantly shorter than for any other innovative silicon technology (or any other PV technology to date). Evergreen Solar has secured both private venture funding and a public offering for building the new facility. The new plant will initially produce some 3 MW of modules. Evergreen Solar is a participant in NREL's PV Manufacturing Technology project. Contact: **Tom Surek, 303-384-6471**

Siemens Solar Industries (SSI) made **DOE's Energy 100 List** for the research and development of its thin-film CIGSS power modules. This research effort, through 50-50 cost-shared subcontracts with SSI, has been supported by **DOE/NREL/NCPV** for the past several years by the **Thin Film PV Partnership Program**. SSI has performed considerable collaborative R&D with NCPV's Measurements and Characterization Division, NCPV's in-house CIS team and Outdoor Test Facility staff, and the National CIS R&D team. The Energy 100 awards represent the outstanding science being advanced from DOE's sites across the country that saves taxpayer money and improves the quality of life. "Being nominated for the Energy 100 list by DOE labs is a significant accomplishment for Siemens Solar, and we are very proud to be part of the elite group recognized on this list," said **Chester Farris**, COO and EVP of SSI. Contact: **Harin Ullal, 303-384-6486**

Global Solar Energy and **ITN/Energy Systems**, in collaboration with the **Institute of Energy Conversion**, have fabricated a total-area 11.0% thin-film CIGS solar cell grown on lightweight, flexible polyimide substrate, as verified by **NREL**. The cell parameters are J_{sc} = 36.5 mA/cm^2, V_{oc} = 0.494 V, and FF = 0.61. The cell structure is ITO/CdS/CIGS/Mo/polyimide. The CIGS is deposited by the physical vapor deposition method at temperatures below 450°C on a continuous moving web. There were four cells in the efficiency range of 10.4% to 11.0%. This is the highest efficiency verified for a thin-film CIGS solar cell deposited on a lightweight, flexible polyimide substrate. Contact: **Harin Ullal, 303-384-6486**

A three-junction solar cell with improvements to the GaInP/GaAs/Ge device structure was recently grown and processed at **Spectrolab** into a 1-cm x 1-cm cell with a heavy concentrator metallization grid. Using the air-mass 1.5 global reference spectrum, **NREL** measured the efficiency of this 1.050-cm^2 (total area minus busbar area) cell as 34.0±1.5% for solar fluxes between about 130 and 630 suns. (Under the direct spectrum, this same cell showed a 30.6% efficiency.) This result exceeds the previous record of 32.4% on a 0.1-cm^2 GaInP/GaAs cell measured under the direct reference spectrum. The NREL-developed cell has been in production for space applications by Spectrolab and other companies for a number of years. Now Spectrolab is considering developing these cells for terrestrial applications. Although concentrator cells have historically been measured under the direct reference spectrum, recent work at NREL implies that concentrator systems used in sunny locations such as Phoenix or Denver will perform better if designed using the global reference spectrum. Space solar cell work at Spectrolab to improve multijunction cell device structure was funded in part by the **Air Force Research Laboratory**, and in part by Spectrolab. Contact: **Keith Emery, 303-384-6632**

Measuring the Value, Continued from p. 6

This web of synergism among solid-state technologies is also wide and deep. Telecommunications is just the beginning. Advances in solar electric technology will also have an impact on xerography, display technology, electronics and microelectronics, materials analysis, printed circuits, and nanotechnology. Further improvements and breakthroughs will influence medicine and medical technologies, especially when considering solar electricity as a vital power source for remote hospitals and mobile clinics or as miniscule power sources for future micro-medical techniques.

Finally, how do you measure the value of solar electricity and its potential to offset emissions (CO, CO_2, SO_x, NO_x, and VOC)? This contribution to the health and well-being of people and communities, especially as a technology that could help mitigate the potential effects of global warming, may be immeasurable—but this makes it no less valuable

The bottom line is that solar electric technology is intricately intertwined with a broader technological and social web, and it is no simple task to measure its total value. It is, however, a relatively simple task to put a lower limit on the value of solar electric technology—namely, the value of the emerging solar electric power market itself. And this alone will provide enormous payback on the investment the nation has made in R&D. It alone also provides sufficient reason not only for continuing, but increasing the R&D investment that underlies the advance and growth of solar electric technology.

Subcontracts

Subcontracted research with universities and industry, which is often cost-shared, is an important part of NREL's PV Program. From October 2000 through May 2001, we awarded more than $19 million to 171 new and existing subcontracts. Examples are listed below.

New awards under the PV Beyond the Horizon Initiative:

Iowa State University, Ames, IA
Novel Group IV Materials for Photovoltaic Devices

Ohio State University, Columbus, OH
GeSi Buffer Layers on Si Substrates for III-V Solar Cells

Princeton University, Princeton, NJ
Double Heterostructure and Tandem Organic Devices

United Solar Systems Corp., Troy, MI
Microcrystalline Silicon Solar Cells

University of Arizona, Tucson, AZ
Liquid Crystal-Based Photovoltaic Technologies

University of California, Santa Cruz, CA
Polymer Hybrid Photovoltaics

University of Michigan, Ann Arbor, MI
Synthesis and Nanometer-Scale Characterization of GaInNAs for High-Efficiency Solar Cells

New Awards under the High-Performance PV Initiative:

Spectrolab, Inc., Sylmar, CA
A High-Efficiency, Low-Cost III-V Concentrator PV Cell and Receiver Module

SunPower Corporation, Sunnyvale, CA
Lens-Based Concentrator Modules: Exploring Critical Optical and System Integration Issues

Awards to existing subcontracts:

Energy Photovoltaics, Inc., Lawrenceville, NJ
Thin-Film CIGS Photovoltaic Technology

University of North Carolina, Chapel Hill, NC
Search for Factors Determining the Photodegradation in High-Efficiency a-Si:H-Based Solar Cells

Washington State University, Pullman, WA
Alternative Window Schemes for $CuInSe_2$-Based Solar Cells

Publications

Research papers, technical reports, and patents are one of NREL's most valuable contributions to the PV community. NREL researchers and subcontractors publish some 300 papers annually in scientific journals and conference proceedings. Listed below are a few examples (see ***www.nrel.gov/publications*** *for more). When possible, we choose publications that relate to articles in the current issue.*

S. Wu, T. J. Coutts. *Thin Transparent Conducting Films of Cadmium Stannate*, U.S. Patent No. 6,221,495 B1. 13 pp., Report 30292.

Solar Electric Power—The U.S. Photovoltaic Industry Roadmap. 36 pp., Report 30150.

M. W. Wanlass. *Electrical Isolation of Component Cells in Monolithically Interconnected Modules*, U.S. Patent No. 6,239,354 B1. 4 pp., Report 30518.

The following are a sampling of the NREL papers in the Conference Record of the 28th IEEE Photovoltaic Specialists Conference, 15–22 September 2000, Anchorage, Alaska. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc.

K. Emery et al. *Procedures for Evaluating Multijunction Concentrators*, 1126–1130, Report 28923.

D. R. Myers et al. *Outdoor Meteorological Broadband and Spectral Conditions for Evaluating Photovoltaic Modules*, 1202–1205, Report 28860.

T. J. McMahon, A. L. Fahrenbruch. *Insights into the Nonideal Behavior of CdS/CdTe Solar Cells*, 539–542, Report 28926.

D. Levi et al. *Characterization of Layer Thickness and Interdiffusion in CdTe/CdS/ZTO/CTO Solar Cells*, 525-528, Report 28985.

D. Albin et al. *Precontact Surface Chemistry Effects on CdS/CdTe Solar Cell Performance and Stability*, 583–586, Report 28937.

X. Wu et al. *High-Efficiency* $Cd_2SnO_4/Zn_2SnO_4/Zn_xCd_{1-x}S/CdS/CdTe$ *Polycrystalline Thin-Film Solar Cells*, 470-474, Report 28934.

B. Kroposki et al. *Comparison of Module Performance Characterization Methods*, 1407–1411, Report 28936.

B. Sopori et al. *Silicon Solar Cell Process Monitoring by PV-Reflectometer*, 120–123, Report 28943.

H. S. Ullal et al. *Polycrystalline Thin-Film Photovoltaic Technologies: from the Laboratory to Commercialization*, 418-423, Report 28948.

P. McNutt et al. *Procedures for Determining the Performance of Stand-Alone Photovoltaic Systems*, 1556–1559, Report 28922.

D. E. Carlson et al. *Temperature Dependence of Amorphous Silicon Solar Cell PV Parameters*, 707–712, Report 30339.

D. L. King et al. *Applications for Infrared Imaging Equipment in Photovoltaic Cell, Module, and System Testing*, 1487–1490, Report 30404.

M. Symko-Davies et al. *Decade of PV Industry R&D Advances in Silicon Module Manufacturing*, 1460–1463, Report 30401.

C. E. Witt et al. *Ten Years of Manufacturing R&D in PVMaT—Technical Accomplishments, Return on Investment, and Where We Go Next*, 1502–1504, Report 30406.

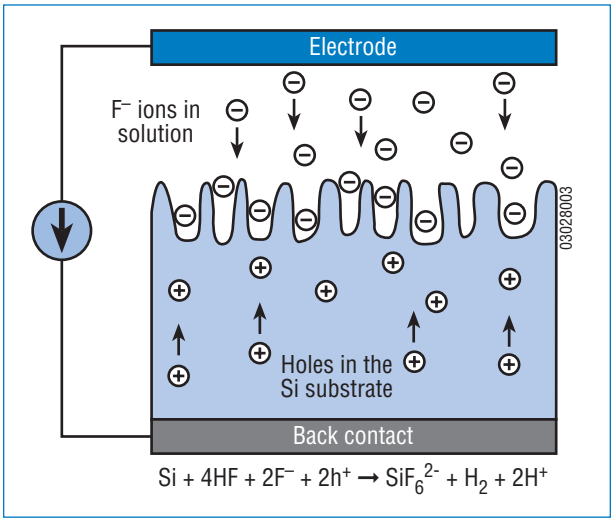
S. H. Wei, S.B. Zhang. *Electronic Structures and Defect Physics of Cd-Based Semiconductors*, 483–486, Report 30322.

Blue Sky Projects Touch the Earth

During the past 6 months, Bob McConnell and Rick Matson of the NCPV have visited 17 universities participating in DOE Fundamental and Exploratory Research projects. Some of these visits were to existing Future Generation PV subcontractors and some to recent awardees under the PV Beyond the Horizon initiative. And, although the scope of these projects may seem to represent far out or "blue sky" thinking, the following projects clearly have already "touched the Earth."

The **University of Rochester** group is investigating rapid, nonvacuum, antireflection (AR) coatings for thin-film silicon substrates. They have found that highly uniform films with excellent AR properties can be formed on any Si substrate using a simple electrochemical etching technique. This anodization process forms a layer of porous Si with adjustable optical, electrical, and mechanical properties. The work is aimed at maximizing light-trapping in the solar cell while maintaining the electrical properties of the device—that is, without disturbing the underlying junction properties. They have achieved reflectivities as low as 2% and increases in short-circuit current of 50%, while maintaining fill factor and open-circuit voltage.

The University of Rochester group touched Earth relatively quickly and is currently working with Evergreen Solar to texture their String Ribbon silicon and to explore ways in which this texturization method could be applied in a manufacturing scenario. In commenting on the importance of this research, Andrew Gabor, a principal scientist with Evergreen Solar, said that "implementation of light-trapping in multicrystalline-Si solar cells could significantly increase cell efficiencies. Yet few companies actually implement effective light-trapping. The challenge is to find a cost-effective and manufacturable method."



Research at the University of Rochester shows that holes drifting toward the substrate surface drive the electrochemical process that forms porous silicon. These holes are most likely to react with fluorine ions at the bottoms of pores or pits, deepening these features and creating a porous surface film.

The **Northwestern University** group is developing novel high-mobility n- and p-type transparent conducting oxides (TCOs) for future-generation PV applications. Exploring the CdO-SnO_2-In_2O_3 phase diagram, they have developed: Sn-doped CdO films with conductivities five to ten times greater than that of a conventional indium tin oxide TCO; In-doped CdO films on glass that are four times more conductive; tunable-bandgap TCOs; and a novel low-temperature/pressure hydrothermal synthesis method for p-type TCOs. Some ramifications of this work are the promise of lower current losses, more efficient PV cells, flexible PV design (p-type TCOs), and improved electrodes for polymer-based PV devices via "tailorable" work functions.


NREL/PIX10142

Andrew Metz, a chemistry student at Northwestern University, explains his experiment to NCPV's Bob McConnell during a recent site visit. Metz uses this metal-organic chemical vapor deposition apparatus for growing thin films of transparent conducting oxides.

A joint project of the **John Hopkins University Physics Department** and the **North Carolina State University Chemistry Department** reaches a bit further into the solar electric future. These groups are using a novel approach to develop molecular solar cells based on chromophore rods that will be assembled into ordered, molecular, light-harvesting arrays on electrode surfaces. Although the approach is certainly new—in fact, revolutionary—it borrows from lessons learned in dye-sensitized and "organic" solar cells and takes advantage of recent advances in synthetic chemistry that allow the rational construction of linear chromophore arrays. What is very exciting, in terms of transforming this fundamental laboratory research into a viable technology, is that the PV industry has shown interest in this possible new solar electricity technology.

In short, it looks very much like this fundamental and exploratory research effort is leading us "beyond the horizon" on to the "future generation" of solar electric technology. It promises to be both an exciting and rewarding ride.

For more information, contact Bob McConnell at 303-384-6419.

Breaking Through, Continued from p. 4

- Or how about a concentrator concept that uses inexpensive filters that transmit precise, selected wavelengths of light and reflect the rest of the light? Each filter can be used in conjunction with a given cell that efficiently absorbs the wavelengths of light passed by the filter. A large variety of filter and cell combinations can be used to line the cavity at the focus of a dish concentrator. This arrangement will concentrate the light at the appropriate wavelengths for the filter/cell combinations. Light that is reflected by filters will bounce around the cavity until it is absorbed by the appropriate combination. This becomes an inexpensive multijunction concentrator that efficiently converts a wide portion of the solar spectrum, with a possibility of reach ing efficiencies of 50% or more.

- Let's take this a step further and use the entire spectrum efficiently by employing quantum dots embedded in polymer matrices to transfer the charge. By growing quantum dots of the appropriate size, we can—according to the Heisenberg uncertainty principle—vary the bandgaps of the quantum dots to absorb precise, chosen wavelengths of light. This multi-multijunction concept could efficiently convert the entire solar spectrum to reach 60% efficiency and drop the cost of solar electricity to below 50 cents per watt.

- But why stop here? One more step takes us beyond the quantum dot to the quantum tetrapod. Think of this as a quantum version of the game of jacks we all used to play as children, except that this is a quantum structure with four cylinders as legs extending from a center pod. No matter which way you deposit these tetrapods, one cylinder will always be facing up to receive the sunlight. This is a self-aligning solar cell that can be configured to be a multi-multijunction device that absorbs the entire spectrum efficiently.

The inexpensive dye-sensitized cell (or "Grätzel cell") avenue:

- The "Grätzel cell" is a photochemical concept that uses titanium dioxide nanocrystals coated with a dye to absorb and convert sunlight to electricity. Historically, these cells have used a liquid electrolyte to act as the electrical conduit through redox reactions. But a variation on this using a gel polymer or solid-state electrolyte could be more stable and longer lasting.

- Another variation on the concept uses molecular chromophores, instead of titanium dioxide, embedded in an organic polymer. This and similar organic concepts are relatively simple approaches that have great potential for low cost. Using C, H, O, or N, they depend on no rare elements, use low-temperature, nonvacuum processes, and have the promise to achieve throughput that is as high or higher than most thin-film technologies.

The thin-films avenue:

- A new deposition technique being explored for CIGS—ionized physical vapor deposition—is a relatively low-temperature technique that, if successful, could lead to multijunction CIGS cells. Currently, CIGS technologies tend to rely on high-temperature deposition processes. But it is precisely this high temperature that legislates against a low-bandgap cell being deposited with CIGS to form a multijunction device. A low-temperature method could enable the deposition, which could result in a device whose conversion efficiency may reach 25%—quite a step for such a thin-film approach.

- A different concept—the so-called proto-crystalline silicon approach—could help mitigate the Staebler-Wronski effect in amorphous silicon. This approach uses nanocrystals of silicon enveloped in a thin coating of amorphous silicon. The beauty of this method is that it builds on the already well-understood technology of amorphous silicon by using up-and-coming nanocrystalline technology to circumvent an old nemesis. Consequently, without taking a big R&D risk, we may see important advances.

There are, of course, other risky R&D avenues that could result in big breakthroughs, including several more organic research possibilities. Liquid crystals are organic materials that may perform quite well in solar cells. Last year's Nobel prize in chemistry recognized the discovery of organic semiconductors, the working materials for organic solar cells. Right now we are witnessing burgeoning research into organic LEDs (light-emitting diodes), pioneered in the 1980s by Kodak scientists. And because LEDs promise to be far more efficient, less expensive, longer lasting, and to provide light that is more pleasing, they may soon start to replace flat-panel displays and even incandescent and fluorescent lighting. The potential for organic solar cells is similar. If research into this area is successful, we will not only see efficient inexpensive solar cells, but ones that are flexible and that can be made with common, pervasive organic materials.

But whether we are talking about "far out" or more conventional avenues, it is R&D that enables us to bridge that gap between what *is* and the *dream* of a universal, affordable, benign technology. Without the requisite R&D, not only would we not realize the dream, we would see incremental advances slow to a crawl.

Solar Electricity, the Power of Choice *thanks NREL's Gary Cook for this guest article on several of the Future Generation PV and PV Beyond the Horizon projects initiated within the past few years. Gary has been the principal writer for several of DOE's Five-Year Research Plans.*

PV Calendar

September 30–October 5, 2001, *UPEx'01: The Photovoltaic Experience Conference and Exhibition*. Sponsor: Solar Electric Power Association (formerly UPVG). Location: Sacramento, CA. Contact: Julia Judd, 202-857-0898 or Web site: *www.SolarElectricPower.org*

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

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*

October 29–31, 2001, *First International Conference on Solar Electric Concentrators*. Sponsors: Universidad Politecnica de Madrid, NREL. Location: Marbella, Spain. Contact: Robert McConnell, 303-384-6419 or robert_mcconnell @nrel.gov or Web site:*www.nrel.gov/icsec*

November 4–8, 2001, *World Conference on Technology Advances for Sustainable Development*. Sponsors: Ministry of Water Resources and Irrigation, Ministry of Military Production. Location: Cairo, Egypt. Contact: *www.aast.edu/mceet*

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

November 26–30, 2001, *MRS Fall Meeting*. Sponsor: Materials Research Society. Location: Boston, MA. Contact: *www.mrs.org/meetings/fall2001*

May 17–25, 2002, *29th IEEE Photovoltaics Specialists Conference*, Location: New Orleans, LA. Contacts: John Benner, 303-384-6496, or Dr. Rajeewa Arya, 757-566-8770.

This quarterly report covers solar electricity research and related activities from NREL, Sandia National Laboratories, and their partners within the National Center for Photovoltaics (NCPV). These partners include the DOE University Centers of Excellence for Photovoltaics at the Georgia Institute of Technology and the University of Delaware's Institute of Energy Conversion, and the Regional Experiment Stations at the Florida Solar Energy Center and the Southwest Technology Development Institute.

Robert McConnell.....303-384-6419
NREL PV Program Communications

Tom Surek 303-384-6471
NREL Technology Manager, Photovoltaics

Susan Moon.....303-384-6631
Writer, Editor

Kristin Schnelten.....303-384-6624
Writer, Editor

Gary Cook.....303-275-3659
Writer

Jim Miller 303-384-6595
Graphic Designer

NCPV-Related 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

Sandia National Laboratories PV *www.sandia.gov/pv/main2.html*
Systems Engineering • Balance of Systems • Performance and Reliability

Georgia Institute of Technology PV . . . . *www.ece.gatech.edu/research/ucep*
Technologies • Hands-On Training • Modeling and Analysis Capabilities

Institute of Energy Conversion, Univ. of Delaware . . . . *www.udel.edu/iec*
PV Power Generation • Thin Film Solar Cell Technology

Florida Solar Energy Center . . . . . *www.fsec.ucf.edu*
PV Education and Training • Houses and Buildings

Southwest Technology Development Institute. . . . . *www.nmsu.edu/~tdi*
PV Testing • Performance Monitoring • Codes and Standards

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

NREL Report No. BR-520-30280.
NREL is a national laboratory operated for the U.S. Department of Energy under Contract No. DE-AC36-99-GO10337.

If you are not on the mailing list for this publication and would like to receive it, please send your name, affiliation, and address to: PV Program, NREL, 1617 Cole Blvd., Golden, CO 80401-3393.

Printed with a renewable source ink on paper containing at least 50 percent wastepaper, including 20 percent postconsumer waste