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Photovoltaics R&D in the United States: Positioning for Our Future

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PHOTOVOLTAICS R&D IN THE UNITED STATES: POSITIONING FOR OUR FUTURE

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ABSTRACT

This paper provides a brief look at the current U.S. research and development (R&D) investments in photovoltaics, covering the spectrum from materials and devices through electronics and systems reliability. The program is balanced among fundamental R&D, technology development, and systems performance and reliability, with more than half the funding for university and industry partners. The major activities can be categorized into two general areas: improving current and near-term technologies toward their expected performance levels (the largest portion), and positioning the United States for technical leadership, decision making, and ownership for the host of next-technology options (including some options that have been called third-generation). The investments in these higher risk, longer-term technology generations provide options that could leapfrog into more rapid use because of their promise of potentially high payoff. Solar electricity is part of America's present and future energy security and independence—as is the R&D that enables it.

INTRODUCTION

Both as a technology and as a research area, photovoltaics (PV) has evolved incredibly over the past 25 years. The U.S. industry has grown from a space-invested fledgling to a *real* $1 billion solar-electric business. And the appearance, prospects, needs, and performance of PV have likewise changed dramatically [1]. Systems have improved, from early systems that were "dead on arrival" when delivered into the first federal markets in the late 1970s, to now, where modules are warranted for 25 years and balance-of-systems components continue to extend their operational lifetimes. During this period, crystalline-silicon (Si) cells have doubled in efficiency, and thin-films have more than tripled their efficiencies. Multiple-junction devices have gone from concept to reality—with III-V concentrators now converting more than one-third of the incident photons into electricity and dual- and triple-junction amorphous thin-film cells becoming the standard structures for that technology. A wealth of new materials, novel devices, and ingenious structures have been introduced, investigated, and improved—with some approaches succeeding, several abandoned, and a few that have been "born again" as the technology has caught up with the concept. Photovoltaic technologies have come a long way, but much remains to be done. This is not the same "PV" that we had in the 1970s or 1980s. R&D has continued to add value, open new pathways, and solve problems—and it will continue to do so for the coming generations of this solar-electric technology. The events of September 11, 2001, have only brought *added* focus to this clean energy technology and its importance to our homeland energy security. Solar electricity is part of America's present and its future—as is the R&D that enables it.

The U.S. federal investments over the last decade overwhelmingly have been to nurture these R&D resources [2]. The continuing mandate for U.S. investment in PV R&D is bolstered by the President's own National Energy Policy [3], DOE Strategic Program Review [4], National Research Council Review of DOE's renewable energy programs [5], DOE National Photovoltaics Program Plan 2000-2004 [6], U.S. Photovoltaics Industry Roadmap [1], and DOE's Peer Review of the PV Program [7]—as well as the imminent strategic plans or roadmaps for zero-energy buildings, solar, and hydrogen. The U.S. program is fully an *R&D effort*, covering the spectrum from materials and devices through electronics and systems reliability. The program is balanced, with more than half the funding for university and industry partners. The major activities can be categorized into two general areas.

Activities in the first area (and by far the largest investment) help improve current and nearer-term technologies. These activities include *first-generation* crystalline Si, as well as facilitating *second-generation* thin-films into and through their introduction and initial manufacturing phases. New efforts in process research, process integration, and diagnostic development cultivate critical links between even the most fundamental studies and manufacturing in an entirely new research approach aimed at cutting the time between laboratory discovery and invention to industry introduction and use. This R&D area includes support for balance-of-systems component development, as well as module and system reliability. Building-integrated PV component development is a major R&D strategy, which aims at making the zero-energy building concept a reality.

The second area involves positioning the United States for technical leadership, decision-making, and ownership for the host of *next-technology* options, including some that have been called third-generation. These technologies include those with efficiencies beyond the conventional, organic and polymer semiconductors, nanotechnology approaches, biomimetics, photoelectrochemical production (especially for the hydrogen economy), and designer materials. R&D beyond the conventional module is part of this area, including novel and smart electronics, integration into single components, architecture-based energy, storage, and advanced power electronics. One focus will be to support our built environment with solar electricity beyond the zero-energy building environment. The investments in these higher risk, longer-term technology generations provide options that could leapfrog into more rapid use because of their promise of potentially high payoff.

The U.S. approach is built on partnering among its major resources—"the best and brightest" at universities, industry, and the national laboratories. From the government level, it is coordinated with its technology partners in the Solar Program, namely, concentrating solar power and low-temperature thermal conversion. Traditionally, this approach addresses fundamental and applied R&D, technology development, and systems engineering and applications. This paper focuses more on material through module R&D, but it must be stressed that systems, balance of systems, and reliability issues are equally important R&D considerations. It is not possible to fully address *all* activities of ongoing R&D in the United States, and this paper can only give a brief introduction or "flavor" of the numerous and important facets of *America's photovoltaics R&D*.

MATERIALS AND DEVICE R&D

Crystalline silicon

Activities have focused on areas critical to the U.S. industry—led by the Department of Energy (DOE) University Center of Excellence at the Georgia Institute of Technology—and leveraging expertise in the greater semiconductor electronics community. An excellent example is the NCPV-sponsored 11th Workshop on Crystalline Silicon Solar Cell Materials and Processes [8]. This workshop has catalyzed the interactions between solar and electronic communities, and it has led to the identification of four areas of exploration: (1) mechanical strength and yield, (2) production of better materials, (3) hydrogen passivation and silicon nitride coatings, and (4) contacts and selective emitters. Seven universities have started 3-year programs addressing these issues. In addition, Sandia National Laboratories (SNL) has developed reactive-ion etching for processing multicrystalline Si cells, with the texturing process boosting efficiencies more than 10% over conventionally processed cells. Georgia Tech has continued to pioneer work in rapid thermal processing, to improve both manufacturing throughput and device parameters. They continue to provide the Si industry not only with manufacturing technique improvement, cell modeling, and understanding of the links between cell parameters and processing, but also, a critical supply of qualified engineers and scientists for that industry.

High-performance concentrators

With recent progress and advancements for multiple-junction III-V-based solar cells for space applications, attention for these approaches has again turned to their terrestrial potential in concentrating PV applications. Two terrestrial devices (32.2% under 600 suns and 34% under 200 suns) have been verified using GaInP/GaAs/Ge structures, led by Spectrolab and NREL [9]. These devices involved improved growth processes and structures, as well as contacts engineering for the terrestrial solar spectrum. These advancements led to inclusion of these very high-efficiency approaches in the High-Performance Photovoltaics Project [10], covered below. Collaborations have been initiated within the DOE Solar Program for PV concentrator incorporation into concentrating solar power hardware designs. This renewed interest in concentrating solar technologies has resulted in investigating the standard test and reporting conditions for these devices. A protocol was established in the 1980s, but a formal standard was never adopted by world standards agencies. The IEEE has approved a recommended practice, which involves an improved irradiance spectrum and conditions for these technologies. These advancements led to inclusion of these very high-efficiency approaches in the High-Performance Photovoltaics Initiative, detailed below. A variety of approaches are being pursued, which include: a 2-terminal, lattice-mismatched $Ga_xIn_{1-x}P/Ga_xIn_{1-x}As$ dual-junction on a diffused Ge bottom cell (Emcore); adding a 1-eV GaInAsN junction to the existing 3-junction monolithic structure (NREL, SNL); further optimizing the performance of the 3-junction monolithic cell; and single-crystal CIGS on GaAs devices (University of Illinois). Spectrolab is pursuing monolithic structure, mechanical stacking, and wafer-bonded integrated cells for an ultra-high-performance, lower-cost module. Lens-based concentrator modules—primarily assessing the optical options for Fresnel lens concentrators—are being addressed by SunPower Corporation, which is also examining reliability issues and novel, emerging optical technologies that can improve PV concentrators. Among the goals of this project are to realize *modules* capable of converting a third of the incident photon power into electricity [10].

Thin films

Efforts in thin films remain the bulwark of the U.S. program. Progress has been evolutionary, as suggested by the sustained incremental advances in performance illustrated in Fig. 1. Three technologies—thin silicon, copper indium diselenide (CIS) and alloys, and cadmium telluride (CdTe)—dominate the activities. The efforts are generally fostered under the banner of the DOE/NCPV Thin Film PV Partnership—and its National R&D Teams (a-Si, CIS, CdTe, a new thin-film Si, and the just-announced, thin-film module reliability), comprising industry, university, and national laboratory collaborators.

The fundamental science of thin-film solar cells is enhanced by its excellent university and NREL resources. This is underscored by the DOE Center of Excellence for Thin-Film Photovoltaics at the University of Delaware's Institute of Energy Conversion. They lead work on thin-film deposition onto flexible substrates, during-growth thin-film monitoring, and thin-film deposition onto moving (continuous) substrates.

On one hand, these programs can be described as science-based approaches in providing the understanding and direction to closing the gap between current performance levels and what can be expected. Recent successes include research-cell records in CIGS (18.9%, NREL), CdS-free CIGS (15.7%, NREL), $Cu(In,Al)Se_2$ (16.9%, IEC), CdTe (16.5%, NREL), and high-deposition rate a-Si:H (9.6% at 2 nm/s, deposited at NREL/United Solar [9].

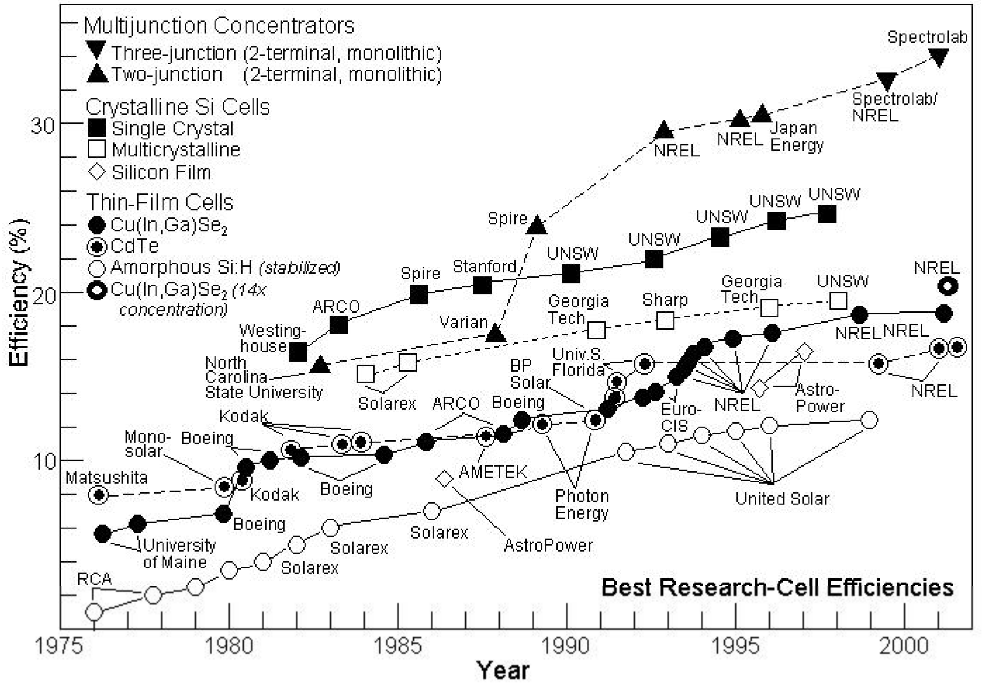

Fig. 1. Evolution of research solar-cell efficiencies.

Another approach has been to investigate the use of thin-film polycrystalline devices in low-concentration modes to boost performance. NREL has reported a 21.5% CIGS cell, under 14 suns [9,11]. Again, it is not only the records that are significant—it is also the science and device engineering behind these improvements. Examples of these abound. Understanding and control of the defect densities at the mismatched junction regions in CIGS and CdTe [12,13], and developments in new transparent conducting oxides (TCOs, e.g., zinc stannate, oxygenated amorphous cadmium sulfide) have provided new directions for improvements in the polycrystalline CdTe cell [12]. Advances in understanding of materials deposition, growth, and processing have led to the viable use of flexible substrates (stainless steel, polymers) for lightweight devices. Global Solar, for example, verified a record 9.2% flexible CIGS module on thin stainless steel [9]—almost doubling the previous mark. This effort was in cooperation with IEC, which lent its expertise in large-area processing and in-situ diagnostics to help optimize the production. United Solar has produced exceptional devices on thin stainless steel (down to 1 mil) and kapton—with performances that have captured the attention of the space power community.

Interest in flexible, lightweight PV has also brought attention to a-Si:H from the space industry. United Solar just had a 9% AM0, large-area a-S:H triple-junction on 1-mil kapton submodule verified at NASA. Of course, fundamental R&D continues to highlight these thin-film programs. Hydrogen dilution (plasma-enhanced chemical vapor deposition [PECVD] of hydrogen-rich H_2/SiH_4 gas mixtures) has helped to reduce the light-induced degradation (by about one-third) of amorphous-silicon-based solar cells, and it causes stabilization after shorter exposure times. It has been implemented to some degree in the manufacturing processes at United Solar, BP Solar, and EPV. A drawback is that hydrogen dilution tends to reduce deposition rates and, therefore, manufacturing throughput. These films are often grown in the so-called "protocrystalline growth regime." Amorphous silicon films grown with high hydrogen dilution on a foreign substrate remain amorphous up to a certain (dilution- and condition-dependent) thickness and then turn into a mixed-phase amorphous and microcrystalline film. The term *protocrystalline* (sometimes referred to as "on the edge") implies that the film growth is stopped before such transition occurs. A similar benefit of protocrystalline growth is reported for the p-layer of a-Si:H solar cells, leading to higher values of open-circuit voltage (V_{oc}) than microcrystalline p-layers [14]. Using higher hydrogen dilution, several groups (United Solar, Energy Conversion Devices, EPV) have begun to grow solar p-i-n solar cells with even greater H-dilution, where the i-layer (typically 1 to 2 micrometers thick) has a mixed-phase microcrystalline structure with some amorphous tissue. These cells have reached efficiencies >9% (although 7% is a more typical number achieved routinely in various laboratories) and show optimum performance when the absorbers are small-grain mixed-phase structures (i.e., again, grown "near the edge" of being almost amorphous). The performance of such microcrystalline p-i-n cells is not considered high enough for stand-alone single-junction devices at this time, but is nearly adequate to replace the a-SiGe:H bottom cells in multijunction structures. Low growth rate of such layers grown by PECVD (<1 nm/s) appears to be a concern, but higher growth rates (up to 2 nm/s) were demonstrated using the "hot-wire" PECVD deposition technique.

U.S. R&D has made only moderate investments in thin-film polycrystalline Si, which is becoming more promising with evolving technology and methods to produce and control the properties of the semiconductor and devices at thicknesses below 25 µm. Although some of the interest in nano- and micro-crystalline films from the "amorphous community" has increased activity in this general area, the research community and funding agencies have not yet been able to make this important area a priority. Fundamental work at several universities and AstroPower's development R&D (under the Thin Film PV Partnership) are the major activities. NREL has used internal funding to investigate some novel methods of Si-film growth using iodine transport [15]. The initial results have been promising, but support has been inadequate to maintain this work at a critical level. We hope that additional funding through a new science initiative (discussed later) will bring this important research activity to a level that is competitive with the rest of the world.

R&D has been key to the technology development of rigid and flexible thin-film modules [16]. The best of these are listed in Table 1, which includes commercial a-Si:H, as well as CIGSS and CdTe—technologies that are in their nascent stages of commercialization [16]. The highest power output for any thin-film monolithic module is BP Solar's 92.5-W (11.0%-efficient) CdTe module. Several U.S.-based manufacturers have exceeded 10% with these larger-area products, including Siemens Solar (now Shell Solar) with CIGSS, BP Solar with CdTe, and First Solar with CdTe [16]. However, substantial gaps still exist between manufactured (large-area) module and research-cell efficiency demonstrations—giving encouragement that this "performance gap" will shrink. Much of this confidence lies with the close relationships between the industry and the research community via the Thin Film PV Partnership and other collaborations that are helping with the transfer of improved materials and technology options. Additionally, the imminent programs and facilities directed toward new process research and process integration are expected to enhance technology development. Finally, there are concerns and some problems with these early-generation thin-film modules. They modules possess materials, geometries, processing and contacting schemes, current generating levels, and interfaces that their bulk-crystalline Si relatives do not. The NCPV industry-research organization module-reliability alliance through the NCPV provides a backbone to overcome barriers through a focused alliance based on science, engineering, and shared knowledge. Certainly, major manufacturers who have stakes in both crystalline Si and thin-film technologies have stated that these new approaches will constitute a large portion of their markets in the near future (5-10 years).

Advanced and exploratory R&D

Exploring and evaluating options that could take PV to the next levels are the themes of these programs. These options were introduced as initiatives over the past year and have just started to record their progress.

High-Performance PV R&D. This project is exploring the ultimate performance limits of existing PV technologies, with the goal of doubling their conversion efficiencies [10]. This project encompasses thin-film multijunction cells (primarily 2-junction approaches with 25% efficiencies) and modules (at 20%). (Research on pre-commercial concentrator modules was cited previously.) The first phase is under way—identifying critical paths—which seeks to identify problems and approaches and to establish alliances.

The thin-film tandem-cell work covers a variety of activities and approaches [10]. Modeling has predicted that the 25% performance level can be reached using a 1.7-eV top cell and a 1.1-eV bottom cell partner. The high-bandgap cell R&D is focusing on several options: $Cd_{1-x}Zn_xTe$ (University of Delaware, University of South Florida, and NREL), $Cu(In_x,Al_{1-x})Se_2$ (University of Delaware), and $CuGaSe_2$ (University of Florida and NREL). The major thin film for the low-bandgap cell is currently CIGS, although some considerations are directed toward alternative semiconductors (including Si).

Further improvement of CIGS is being addressed, especially over the larger scales needed for modules (University of Delaware and Global Solar). In addition, Global Solar is working to improve efficiency of CIGS devices on metal foils, eliminating the CdS layer. Contacting is a concern, and efforts to establish reproducible and reliable contacts to this host of semiconductors is an area of intense interest (University of Toledo). The interconnect between the cells is a major issue, and several approaches have been proposed based on tunnel junctions, n- and p-type TCOs (Northwestern University and NREL), and possible mechanical stacking schemes.

Table 1. U.S.-Based Manufacturers—Best Large-Area, Thin-Film Modules (Standard Conditions).

Module	**Efficiency (%)**	**Power (W)**	**Aperture Area (cm^2)**	**Manufacturer**
a-Si:H/a-SiGe:H/a-SiGe:H	7.6	70.8	9276	United Solar (9/97)
a-Si:H/a-SiGe:H	7.6	56	7414	BP Solar (9/96)
a-Si:H/a-SiGe:H/a-SiGe:H	7.9	35.7	4519	United Solar (6/97)
CdS/CIGSeS	12.1	44.3	3651	Shell Solar (Siemens) (3/99)
CdS/CIGS	6.2	19.7	3158	EPV (4/97)
CdS/CIGS/metal foil	7.4	57.3	7714	Global Solar (3/02)
CdS/CdTe	11.0	92.5	8390	BP Solar (9/01)
CdS/CdTe	10.1	67.1	6612	First Solar (12/01)

One intriguing approach is the recent NREL work on a 4-terminal, non-mechanical stack tandem, depositing a CIGS device on one side of a glass substrate and a CGS device on the other [17]. Illuminating through the CGS and using an optical reflector on the CIGS side has led to a 3.7%-efficient device that is limited currently by the low quantum efficiencies of the individual cells. This device is only in its conceptual demonstration phase, but the processing feasibility has been shown—as well as some indications for optimizing the configuration and light-exposure paths.

Process research and process integration. These new R&D areas are expected to have substantial impact in cutting the time from invention and laboratory bench demonstration to the manufacturing environment [1,5,7]. These projects address key elements that are missing from our current R&D approaches, including the fundamental understanding of how processes integrate with one another, the direct characterization of process dynamics, and the ability to control surfaces and interfaces (especially understanding how they influence and can be adjusted to produce desired device performance) [18]. This work includes the development of diagnostics (many of them specialized for their PV applications) needed by both R&D and industry communities to gain real-time characterization and control of the materials and interface growth, to understand the fundamental mechanisms involved, and to have the basis to optimize processing. We expect that this will require specialized platforms that researchers and industry can use with minimal disruption to their own facilities—and dedicated facilities to enable these new research directions. Consider transitioning a technology from "fundamental and applied R&D" to "prototype manufacturing" to "full-scale manufacturing." First, by necessity, a manufacturer must lock in a technology, thereby providing less future flexibility. Second, capital costs increase dramatically, especially in the full-scale manufacturing phase. Considering these facts, it is important that industry has the fundamental understanding that can drive solid business decisions that will support the increase in capital expenditure. The process integration concept is meant to narrow this knowledge gap by providing a research platform that encourages the development of this important fundamental knowledge. Furthermore, once industry develops and implements a process, it is often difficult or even impossible to prototype variations in that process. This process integration concept will provide a flexible platform that will allow prototyping of new process streams, thereby providing valuable information *prior* to making difficult and expensive decisions. This new research emphasis specifically addresses guidance in the recent National Research Council Review [5] of the DOE Program and the U.S. PV Industry Photovoltaics Roadmap [1].

Next-Generation and Beyond-the-Horizon Photovoltaics. A vigorous university research activity involves the investigation of inorganic semiconductor technologies, focusing on the fundamental mechanisms that might "leapfrog" some approaches over existing technical barriers [19]. This activity includes critical work on the Staebler-Wronski effect, with a focus on uncovering the origins using new, sophisticated, and sensitive characterization techniques, such as fluctuation transmission electron microscopy (University of Illinois), femtosecond spectroscopy and positron annihilation spectroscopy (University of Washington), and double-paddle oscillator characterization (Cornell). Pennsylvania State University has successfully developed optical characterization methods, including spectroscopic ellipsometry used to monitor and evaluate the growth processes of these materials in real time. Photocapacitance techniques have been applied for defect-state determinations in compound semiconductors. The State University of New York supports PV needs with an array of synchrotron-based characterization techniques.

Fundamental research on III-V materials and devices—supporting the ultrahigh-efficiency cell development by investigating the growth facets and characterization of GaInAsN—is under way at the University of California at Santa Diego, North Carolina State, University of California at Santa Barbara, and Harvard University. This basic R&D assisted progress through bandgap engineering, understanding N incorporation, uncovering band structures, and understanding growth mechanisms for metal-organic chemical vapor deposition and molecular-beam epitaxy processes [20].

So-called "third-generation" photovoltaics (i.e., technologies for the decades beyond 2010) position us to meet requirements for future generations of energy users [20]. These longer-term, higher-risk R&D investments range from devices that promise efficiencies beyond 50% to those that have potential for significantly less-expensive materials, processing, and manufacturing—while maintaining required performances. These approaches include quantum dots, thermophotovoltaics, multiple junctions, and defect-layer solar cells.

Among these approaches is growing interest in organic semiconductors, biomimetics, nanocrystalline materials, combinatorial techniques, and nanotechnology devices. "Plastic" solar cells are being developed using a variety of approaches, spurred on by the rapid successes of their close relative, the organic light-emitting diode [21]. Much attention has been given to the University of California-Berkeley work on nanocrystalline composites, especially the quantum structures using tetrapods, which has led to cells exceeding 4% efficiency. Double-heterostructure and tandem organic cell work at Princeton has provided efficiencies to the 3% range. Liquid-crystal molecular organic-based cells have been reported by the University of Arizona, which has also provided much insight into the interface chemistry and electronic structure of these newer electronic materials. Hybrids of dye-sensitized cells and polymer/quantum concepts are also being investigated including next-generation dye cells that are totally organic (North Carolina State and Johns Hopkins) and hybrid inorganic/organic exciton concepts (California Institute of Technology).

MANUFACTURING R&D

Over the past 10 year, the United States has conducted special, high-value cost-shared manufacturing R&D—and it must be emphasized that this is an *R&D* program—with the PV industry [22]. Research has focused on improving PV manufacturing processes and products, lowering manufacturing costs, and providing a foundation for the scale-up of U.S. PV manufacturing. There has been a direct correlation between these U.S. R&D investments and the reduction in the industry's direct PV module manufacturing costs, as well as notable increases in capacity. The current emphasis of the program is in developing needed in-line diagnostics and intelligent processing—again, to assist manufacturing scale-up by giving attention to R&D problems and barriers to present-day manufacturing [1,18,22]. Research is under way in two categories: PV systems and component technology, and PV module manufacturing technology.

Projections from the industry indicate that these investments will continue to assist the U.S. position by lowering product direct costs, as well as accelerating and assisting the introduction of newer thin-film technologies, which are expected to represent about 60% of the production by 2007 for the companies in this program [22]. An additional metric important to this program has been the recapture of research funding, with the project as a whole more than paying for itself.

MODULE, ARRAY, AND SYSTEMS PERFORMANCE R&D

Reliability R&D is critical to the U.S. programs and will be a growing area as the newer technologies enter first-time manufacturing and mature into market readiness. This investment is the backbone of the goal to reach 25–30-year service lifetimes, and it is an R&D area of critical importance for the viability and acceptance of solar electricity [1,3,7,23]. This R&D work is led by the national laboratories (SNL and NREL), Florida Solar Energy Center (FSEC), and Southwest Technology Development Institute (SWTDI). The first line of interest is at the module and array level. This includes extensive real-condition outdoor testing, as well as applying an arsenal of diagnostic measurement techniques in working with the manufacturers to ensure product durability. Areas of focus are accelerated life tests, certification tests, standard performance measurements, and integrity of the sub-portions of the modules (e.g., solder joints, interconnects, encapsulation, edge seals).

Balance-of-systems component development and improvement is increasingly critical to ensuring consumer confidence. The newly formed PV Module Reliability Team, in concert with the NREL/DOE Thin Film PV Partnership and FSEC, is working specifically with these tasks to ensure that new, first-time manufacturing and near-term PV modules meet the expectations and needs for the 25-year lifetime goals of the PV technology. Recently, SNL implemented an inverter reliability initiative, with a goal to double the mean time between failures of inverters to at least 10 years [23]. This initiative will combine the talents of the industry, power electronics suppliers, universities, and SNL to foster electronics development and modernization, gaining information, data, and direction toward enhanced performance.

NEW RESEARCH OPPORTUNITIES

The President's budget request for fiscal year 2003 includes enhanced activities in fundamental research [24]. This "Science Initiative" addresses *"…next-generation PV materials and devices that have the potential for dramatic cost reductions. This activity will continue funding the most promising university projects under Beyond the Horizon and Future Generation projects to accelerate their development. A new PV science initiative will be initiated to more fully develop new ideas and concepts that can replace conventional technologies with a new generation of lower cost, easier to manufacture technologies."* None of the research pathways have been completely developed; however, a strategy to address this call is under consideration.

The proposed implementation plan addresses: (1) Future-Generation PV, funding the most promising of the programs in this area defined previously in this paper; (2) Core Research for Third-Generation PV, enhancing R&D on organic polymer solar cells, polymer nanotechnology concepts, biomimetic devices, dye-sensitized solar cells, quantum wells and other nanotechnology/nanoparticle structures, PV/hydrogen generation and storage concepts, and innovative substrate approaches for multijunction III-V solar cells; (3) Basic Science of Polycrystalline Thin Films, enhancing the science base underpinning these technologies, with some emphasis on copper-indium-diselenide alloys and CdTe. Complex multijunction polycrystalline structures (toward and beyond 25% efficiencies) will be developed. A robust science base for scale up, device reliability, and critical device issues will be developed. This activity will include enhanced efforts on process integration and interface issues, the development of diagnostic needs, and process interface transfer tools for equipment design; and (4) High-Performance Concentrating Concepts, developing pathways toward higher efficiency structures for thin films and concentrators, and innovative concepts, including PV/thermal hybrids.

SUMMARY

The U.S. investment in photovoltaics is an R&D one. This activity includes work in fundamental materials and device R&D, technology development, and systems engineering and applications. PV R&D spans the spectrum from the most basic nanoscale science, to new materials and devices, to electronic components, to module and systems reliability. The approach is to bring improved current technologies toward their predicted, attainable performances; develop new concepts with performances and benefits that can "leapfrog" them over more conventional approaches; support near-term technologies toward manufacturing readiness; and explore, develop, and evaluate future-generation options for the longer term. The activities include critical university, national laboratory, and industry collaborations and partnerships—to decrease the time and barriers between laboratory invention and manufacturing.

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REFERENCES

[1] *Solar Electric Power, The U.S. Photovoltaics Industry Roadmap* (April, 2001).
[2] See, for example, *Photovoltaics Overview Fiscal Year 2001* (NREL, Golden, CO; 2002); also, previous Photovoltaics Program Overviews, 1990-2000.
[3] President George W. Bush, *National Energy Policy, Reliable, Affordable, and Environmentally Sound Energy for America's Future*, May, 2001. (www.energy.gov/HQPress/releases01/maypr/national_energy_policy.pdf)
[4] Assistant Secretary of Energy Garman, *EERE Strategic Program Review*, DOE Office of Energy Efficiency and Renewable Energy, Washington, DC, March, 2002.
[5] National Research Council, *Renewable Power Pathways* (National Academy of Science, Washington, DC; February, 2001).
[6] U.S. Department of Energy, *The National Photovoltaics Program Plan 2000-2004, Photovoltaics: Energy for the New Millennium,* U.S. DOE, January, 2000.
[7] U.S. Department of Energy, *2001 Peer Review of the U.S. Department of Energy Photovoltaics Program,* Office of Power Technologies, August 6-7, 2001.
[8] B. Sopori, editor, *Proc. 11th Workshop on Crystalline Silicon Solar Cell Materials and Processes* (NREL, Golden, CO; 2001).
[9] K. Emery, D. King, Green, *Progress in Photovoltaics* **10**, 55 (2002).
[10] M. Symko-Davies, R. Noufi, and S. Kurtz (this Proceedings).
[11] J.S. Ward, K. Ramanathan, F.S. Hasoon, T.J. Coutts, J. Keane, M.A. Contreras, T. Moriarty, and R. Noufi, *Progress in Photovoltaics* **10**, 41 (2002).
[12] X. Wu, R.G. Dhere, Y. Yan, M.J. Romero, Y. Zhang, J. Zhou, C. DeHart, A. Duda, C. Perkins, and B. To (this Proceedings).
[13] R. Noufi, Y. Yan, J Abu-Sharma, K. Jones, M. Al-Jassim, B. Keyes, J. Alleman, and K. Ramanathan (this Proceedings).
[14] R.J. Koval, J.M. Pearce, C. Chen, G.M. Ferreira, A.S. Ferlauto, R.W. Collins, and C.R. Wronski (this Proceedings).
[15] T.H. Wang, T.F. Ciszek, M.R. Page, R.E. Bauer, Q. Wang, and M.D. Landry (this Proceedings).
[16] H. Ullal, K. Zweibel, and B. von Roedern (this Proceedings).
[17] D.L. Young, J. Abushama, R. Noufi, X. Li, M. Keane, K. Ramanathan, T.A. Gessert, J.S. Ward, M. Contreras, M. Symko-Davies, and T.J. Coutts (this Proceedings).
[18] P. Sheldon, *Progr. in Photovoltaics* 8, 77 (2000).
[19] R. Matson and R. McConnell (this Proceedings).
[20] M. Green, *Proc. 15th European Photovoltaics Solar Energy Conf.*, Glasgow (James and James, U.K., 2000).
[21] A. Heeger, *Proc. Asia Display/IDW'01* (2001), pp.7-9; also, B.A. Gregg, in *Molecules as Components in Electronic Devices*, Marya Lieberman, ed., *American Chemical Society*, 2002, in press.
[22] K. Mitchell and E. Witt [this Proceedings].
[23] P.C. Klimas, Annual Systems Symposium, Sandia National Laboratories (SNL, Albuquerque, NM; 2001).
[24] U.S. President's Budget Submission, February, 2002.

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13. ABSTRACT *(Maximum 200 words):* This conference paper provides a brief look at the current U.S. research and development (R&D) investments in photovoltaics, covering the spectrum from materials and devices through electronics and systems reliability. The program is balanced among fundamental R&D, technology development, and systems performance and reliability, with more than half the funding for university and industry partners. The major activities can be categorized into two general areas: improving current and near-term technologies toward their expected performance levels (the largest portion), and positioning the United States for technical leadership, decision making, and ownership for the host of next-technology options (including some options that have been called third-generation). The investments in these higher risk, longer-term technology generations provide options that could leapfrog into more rapid use because of their promise of potentially high payoff. Solar electricity is part of America's present and future energy security and independence—as is the R&D that enables it.

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