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Lessons Learned from the Photovoltaic Manufacturing Technology/PV Manufacturing R&D and Thin-Film PV Partnership Projects

R. Margolis, R. Mitchell, and K. Zweibel

Technical Report
NREL/TP-520-39780
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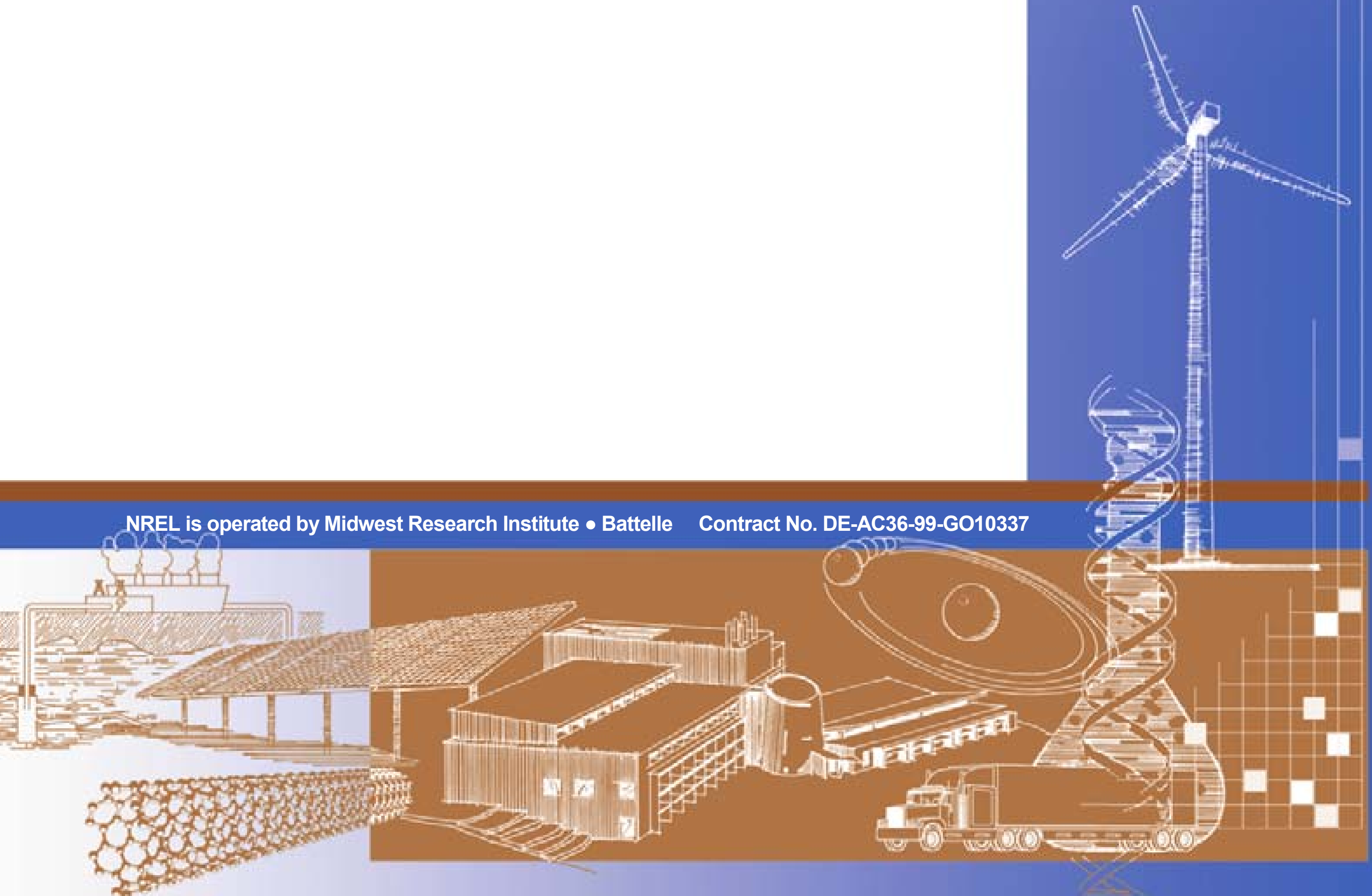

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Introduction

As the U.S. Department of Energy's (DOE's) Solar Energy Technologies Program initiates new cost-shared solar energy R&D under the Solar America Initiative (SAI), it is useful to analyze the experience gained from cost-shared R&D projects that have been funded through the program to date. This report summarizes lessons learned from two DOE-sponsored photovoltaic (PV) projects: the Photovoltaic Manufacturing Technology/PV Manufacturing R&D (PVMaT/PVMR&D) project and the Thin-Film PV Partnership project. During the past 10-15 years, these two projects have invested roughly $330 million of government resources in cost-shared R&D and leveraged another $190 million in private-sector PV R&D investments.

Each project provides unique lessons, because each targets technologies in different stages of development. The PVMaT/PVMR&D project focuses on improving PV manufacturing technology to improve manufacturing processes, reduce costs, increase product reliability, and increase overall production of proven PV technologies. The Thin-Film PV Partnership project focuses on improving the efficiency and reliability of emerging thin-film PV technologies through collaboration among industry, national laboratories, and universities.

Following a description of key findings and brief descriptions of the PVMaT/PVMR&D and Thin-Film PV Partnership projects, this report presents lessons learned from the projects on 13 topics:

1. Public-private cost sharing
2. Project proposal evaluation panel composition
3. Intellectual property and collaboration
4. Contracting delays
5. Scale of contracts
6. Company maturity, stage of development, and iterative processes
7. Addressing common problems across companies
8. Link between applied R&D and technology development
9. Limitations of cost and performance projections
10. The difficulty of first-time manufacturing
11. Module reliability problems during introduction of innovative technologies
12. Reluctance of successful companies to adopt innovative approaches
13. Budget adequacy

These topics were identified as being potentially relevant through dialogue with management/staff at DOE, the National Renewable Energy Laboratory (NREL), and Sandia National Laboratories.

For each topic, we discuss three issues: the context, the lessons learned, and recommendations. The context is the event or problem that resulted in the lessons being learned. It provides background for understanding where the lessons came from, with references to specific examples where possible. The lessons learned are the knowledge or understanding gained by the experience—the experience may be positive or negative. A lesson must be significant in that it has a real or assumed impact on performance, installed cost, operation and maintenance, or reliability; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or eliminates the potential for failures, or reinforces a positive result. The recommendations are actions that should be taken in response to the lessons learned. Ideally, these recommendations should have applicability to other similar situations.

The body of this report is divided into three sections. First, we describe key findings from across all the topics. Second, we provide brief descriptions of the PVMaT/PVMR&D and Thin-Film PV Partnership projects. And third, we discuss each of the 13 topics and their context, lessons learned, and recommendations.

Key Findings

The PVMaT/PVMR&D and Thin-Film PV Partnership projects helped move U.S. PV companies ahead at a faster pace than their previous trajectory suggested during the past decade. Mechanisms such as cost-sharing and wide-ranging collaborations resulted in companies having better products available for the rapidly expanding PV market during this period than they would have had without these projects. During the next decade, the PV industry is expected to continue to expand rapidly within the United States and worldwide. Thus, it is an ideal time to launch a concerted effort under the SAI to work collaboratively with industry to solve a wide range of R&D challenges that will enable the U.S. PV industry to play a significant role in meeting the demands of the domestic and international PV markets.

Numerous lessons about cost-shared solar energy R&D have been learned during the course of the PVMaT/PVMR&D and Thin-Film PV Partnership projects. One thing this report makes clear is that the approach used to engage the private sector in collaborative R&D must evolve as an industry matures. The lessons discussed in this report should help government navigate this process of change. Many of the report's lessons and recommendations are summarized in the three broad categories below. As an overall finding, there are no simple formulas for creating a successful cost-shared PV R&D project. The best decisions stem from in-depth knowledge of PV technologies and the PV industry as well as strong relationships with project participants.

Tailor projects to meet specific objectives

Projects have specific objectives that should influence major decisions. Different objectives call for different project specifications. This is illustrated by similarities and differences between recommendations from the PVMaT/PVMR&D project, which focuses on more mature companies and technologies; and the Thin-Film PV Partnership project, which focuses on emerging companies and technologies. Factors such as the size and history of participating companies, the risk/reward profile associated with more mature and emerging technologies, and the trade-off between selection panel independence and expertise influence project decisions. Table 1 shows examples of objective-based project recommendations. For lessons learned and recommendations particularly relevant to tailoring projects to meet specific objectives, see Topics 1, 2, 5, and 9.

Table 1: Objective-Based Recommendations of PVMaT/PVMR&D and Thin-Film PV Partnership Projects

	PVMaT/PVMR&D (More mature Companies/Technologies)		**Thin-Film PV Partnership (Emerging Companies/Technologies)**	
Decision	**Objective**	**Recommendation**	**Objective**	**Recommendation**
Evaluation panel composition	Credibility, broad stakeholder buy-in	Independent panels representing a wide spectrum of industry (knowledgeable about but not directly tied to the PV industry)	Deep, up-to-date knowledge of emerging PV technologies	Highly expert panels immersed in the technologies in question
Scale and number of subcontracts	Decrease risk of any company failing, provide sufficient funds for companies to accomplish goals	Provide large awards to a small number of highly capable companies	Decrease overall project risk ("not putting all eggs in one basket") and increase potential for innovation	Spread funding around to a larger number of companies and technologies

Cost-share	Improve PV product performance and manufacturing processes and capacity	50%+ cost-share for large companies with large-dollar-value subcontracts; 30% cost-share for small less mature companies with smaller-dollar-value subcontracts; as industry matures it is reasonable to expect large and small companies to cost-share at 50%+	Advance the technological development and commercial introduction of emerging thin-film PV technologies	40% cost-share for large company technology partnerships; 20% cost-share for large company R&D partnerships; 20% cost-share for small company technology partnerships; 10% cost-share for small company R&D partnerships

Understand benefits and challenges of collaborative R&D

Collaboration among government, academic, and industrial organizations offers important benefits. Government support of industry R&D reduces the financial and technological risk for PV companies, thus encouraging companies to advance technologies that provide societal benefits. The pace of innovation can be increased by combining the knowledge and expertise of national laboratories, universities, and private companies. Solving generic industry problems, such as handling ultra-thin silicon wafers or reducing the thickness of thin-film layers, benefits large segments of the PV industry. Despite these advantages, there are significant barriers to collaboration.

Intellectual property (IP) concerns are a major barrier to collaboration and a major cause of subcontracting delays. A company's IP is vital to its competitiveness, so companies are reluctant to enter any relationship that could expose their IP to other companies or even to universities and the government. Lack of relevance is a barrier to solving generic industry problems collaboratively: Because PV manufacturers are always seeking a competitive edge, they have an incentive to use proprietary equipment to solve problems instead of choosing a widely available solution. Fluctuations in government funding are a barrier to the success of long-term efforts.

Understanding and overcoming these barriers to collaboration—through structuring the project appropriately and building strong relationships with participants—is key to establishing a successful cost-shared R&D project. For lessons learned and recommendations particularly relevant to the benefits and challenges of collaboration, see Topics 1, 3, 4, 7, and 13.

Address entire technology development process

Companies and technologies must progress through many steps from conception to commercialization, and each step presents challenges. Building a substantial base of fundamental knowledge about a technology through long-term applied research is vital to accelerating progress and preventing product failures, but it requires patience and consistent support. The transition to first-time manufacturing is one of the most difficult steps, and a number of PV companies have failed or been delayed for years trying to make the transition. After commercial manufacturing has begun, problems such as module reliability issues can plague product introduction. Even success has its drawbacks: Successful companies tend to favor low-risk replication of existing processes over adoption of new, unproven approaches, which slows the overall pace of technology advancement.

To facilitate the success of PV technology, a cost-shared R&D project should commit adequate resources to each step in the technology-development process. An important part of this is evaluating prospective participants to determine where they are in the process. Are they performing initial research on a promising idea? Are they in pilot production? Have they spent adequate time iteratively identifying problems, making improvements, and testing in pilot production to be ready for full-scale production? This analysis helps ensure that the right amount of funding is awarded to the right companies for the right type of work, e.g., large-scale manufacturing subcontracts should be awarded to companies with large-scale manufacturing capabilities, and applied R&D subcontracts should be awarded to emerging companies performing applied research.

Understanding the technology-development process helps project managers know when to be patient and continue support as companies take risks and tackle challenging steps. It also helps managers know when success should be expected and when failure should result in discontinuing support. For lessons learned and recommendations particularly relevant to addressing the entire technology-development process, see Topics 6, 8, 10, 11, and 12.

Project Descriptions

Photovoltaic Manufacturing Technology/PV Manufacturing R&D Project

In 1991, in response to the prospect of a vanishing domestic PV industry, DOE and NREL initiated a new project focused on improving PV manufacturing technology. The Photovoltaic Manufacturing Technology (PVMaT) project was initially envisioned as a 5-year, industry-government, cost-shared project with the goal of enhancing the U.S. PV industry's leadership in manufacturing and commercializing PV components and systems; the project's emphasis on process engineering and industrial engineering R&D was a significant departure from NREL's traditional focus on materials R&D. The project was extended beyond this initial plan, and eventually it was transformed into the PV Manufacturing R&D (PVMR&D) project.

The PVMaT/PVMR&D project has focused on four key areas (Witt et al. 1998, 1):

- Improving manufacturing processes and equipment
- Accelerating manufacturing cost reductions for PV modules, balance-of-systems components, and integrated systems
- Improving commercial product performance and reliability
- Laying the groundwork for substantial scale-up of U.S.-based PV manufacturing plant capacities.

Table 2 shows PVMaT/PVMR&D solicitations since 1991. Total project funding through FY2005 was $151.4 million in DOE funding and $137.5 million in industry funding.[1]

Table 2: PVMaT/PVMR&D Funding and Cost-Share, 1991-2005

Phase (Year)	Focus of Work	DOE Funds ($K)	Private Funds ($K)	Private Cost-Share
Phase 1 (1991)	Problem Identification	1,053	0	0.0%
Phase 2A (1992)	Process Specific Manufacturing	30,738	21,316	40.9%
Phase 2B (1993)	Process Specific Manufacturing	13,384	14,557	52.1%
Phase 3A (1993)	Generic/Teamed Research	2,220	752	25.3%
Phase 4A1 (1994)	Product-Driven Systems & Components	5,343	1,812	25.3%

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[1] Industry cost-sharing in the PVMaT/PVMR&D project is measured in person-hours (design and testing) and materials; it does not include capital equipment purchases.

Phase 4A2 (1994)	Product-Driven Module Manufacturing	14,349	10,167	41.5%
Phase 5A1 (1998)	Product-Driven Systems & Components	4,261	4,700	52.5%
Phase 5A2 (1998)	Product-Driven Module Manufacturing	26,451	20,689	43.9%
IDIP - BOS (2001)	In-Line Diagnostic and Intelligent Processing - Balance of Systems	3,553	3,708	51.1%
IDIP - MOD (2001)	In-Line Diagnostic and Intelligent Processing - Module Manufacturing	23,352	30,426	56.6%
YDR - BOS (2004)	Module and Component Yield, Durability, and Reliability - Balance of Systems	2,996	5,326	64.0%
YDR - MOD (2004)	Module and Component Yield, Durability, and Reliability - Module Manufacturing *	23,677	23,998	50.3%
	Total	151,377	137,451	47.6%

*Funding estimated from amounts negotiated for completion.

The PVMaT/PVMR&D project played an important role in helping U.S. PV manufacturers reduce costs, expand production, and remain competitive in a rapidly growing global PV market during the 1990s and into the new century. For example, as shown in Figure 1, the 14 PVMaT/PVMR&D participants with active production lines in 2005 realized significant cost reductions during the 1990s and into the new century. Their weighted-average cost for manufacturing PV modules (in 2005 dollars) declined by 54%, from roughly $6 per Wp in 1992, to $2.75 per Wp in 2005. In addition, their manufacturing capacity increased by more than a factor of 17, from 14 MW in 1992 to 250 MW in 2005. As shown in Figure 1, the most rapid cost reductions occurred between 1992 and 1997. During this period, participating companies were able to take advantage of low-hanging fruit with respect to manufacturing R&D.

The PVMaT/PVMR&D project has also enabled a number of PV companies to make technological advances that helped them attract private capital. For example, AstroPower received a series of PVMaT/PVMR&D subcontracts during the 1990s that advanced its Silicon-Film PV technology to the point where it was first able to attract venture capital funds and then able to launch a successful IPO in 1998.[2] Another example of successfully attracting private capital is Evergreen Solar, a PVMaT/PVMR&D partner with four projects since 1994 to advance its String Ribbon™ manufacturing process. Thanks, in part, to the PVMaT/PVMR&D subcontracts accelerating the advancement of its manufacturing processes, Evergreen announced in March 2006 that, in the previous 4 months, it had secured contracts and orders totaling $380 million over the next 4 years (Evergreen Solar 2006).

The PVMaT/PVMR&D project has been considered, within DOE and by members of the U.S. PV industry, one of DOE's most successful collaborative R&D projects (Brown et al. 2005; Herwig 1996; NREL 1999). Of the 61 projects to date, approximately three quarters have resulted in success in the form of cost reductions, increased output, improved efficiencies, etc.

Additional information on the PVMaT/PVMR&D project is available on the project Web site www.nrel.gov/ncpv/pv_manufacturing.

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[2] AstroPower was unable to move its Silicon-Film PV technology into production before it declared bankruptcy in 2003. GE Energy, however, bought AstroPower in early 2004 and is still pursuing the Silicon-Film technology (under a new PVMR&D contract).

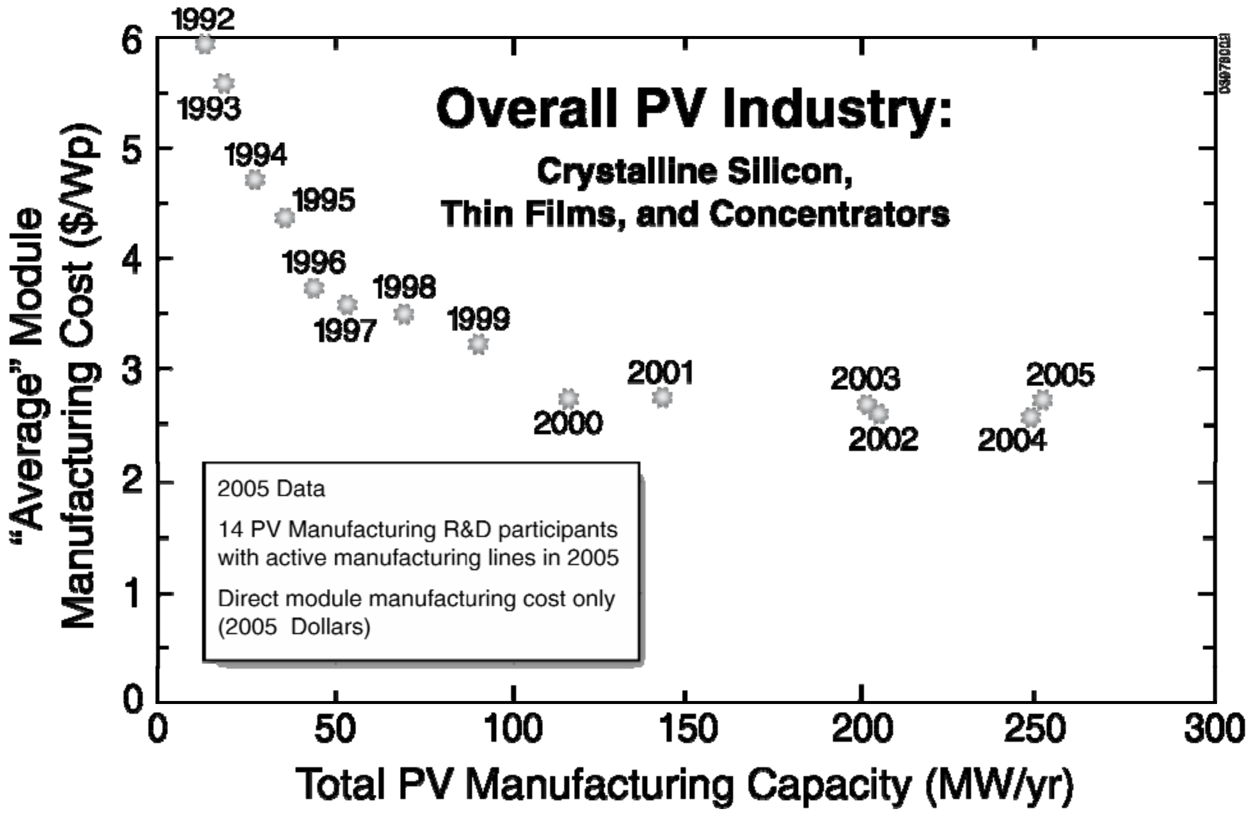

Figure 1: PVMaT/PVMR&D Cost-Capacity Data (1992-2005)

Thin-Film PV Partnership Project

The Thin-Film PV Partnership project was initiated between 1992 and 1994 as an expansion of previous thin-film PV work conducted by the Solar Energy Research Institute/NREL since 1978. The goal of this cost-shared project is to facilitate the widespread market penetration of a range of thin-film technologies, including amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CIS).

The project encourages collaboration among industry, national laboratories, and universities through its national teams (Table 3). Teams—typically made up of 5-10 NREL researchers, 15-25 university scientists, and 10-20 industry scientists and technologists—meet regularly (about every 9 months) to organize collaborative research activities. Typically, industry team members lead the process, with NREL functioning primarily in a monitoring role for immediate issues and adding mid- and long-term perspective for others.

Table 3: Thin-Film PV Partnership Project National Team Tasks

National Team	Major Tasks
CIS	Improved junctions, non-CdS junctions, molybdenum issues, transients, thinner layers
a-Si	Improved efficiencies, improved stability, low-band-gap alternative alloys, higher deposition rates
CdTe	Contacts, thin CdS (improved efficiencies), understanding degradation mechanisms, thinner layers, higher voltage cells
Environment, Safety, and Health	Module recycling, in-plant use and disposal of materials, obtaining EPA toxicity characteristic leaching procedure certification for CdTe and CIS modules
Module Reliability	Water vapor ingress, edge sealing, tin oxide peeling, glass breakage, barrier layers, accelerated testing, testing outdoors in extreme climates

Source: Zweibel (1997); NREL (2000).

The Thin-Film PV Partnership project's budget between 1994 and 1999 was $102 million in DOE funding ($20 million annually) and $30 million in industry funding ($6 million annually). Between 2000 and 2006, the budget decreased to $75 million in DOE funding ($12.5 million annually) and $25 million in industry funding ($4.2 million annually). Funding has been directed to cost-shared subcontracts with "technology partners"—companies working to bring thin-film technologies from the prototype to pilot production phase of development and then to successful first-time manufacturing. Funding has also been directed to cost-shared subcontracts with "R&D partners," which include NREL, universities, and companies solving more fundamental and mid-term (3-10 years) problems that would not be tackled by companies working on immediate scale-up issues (e.g., materials stability issues, innovative device designs, and new film formation processes). Funding R&D partners also allows start-up companies, which might not yet be poised for actual manufacturing, to enter the field.

The Thin-Film PV Partnership project has contributed to increases in the efficiencies of laboratory cells and large-area modules and has helped a number of companies move new PV technologies from the laboratory into pilot production and then first-time, commercially successful manufacturing. Several thin-film companies have shared R&D 100 Awards with the Thin-Film PV Partnership. Two technology partners, Uni-Solar (a-Si) and First Solar (CdTe), are now considered world leaders in their technologies in terms of conversion efficiencies and production. These companies have experienced rapid production growth in the past several years (Figure 2) and, with their sister companies in CIS, provide a solid basis for the rapid growth of thin-film technologies in the future.

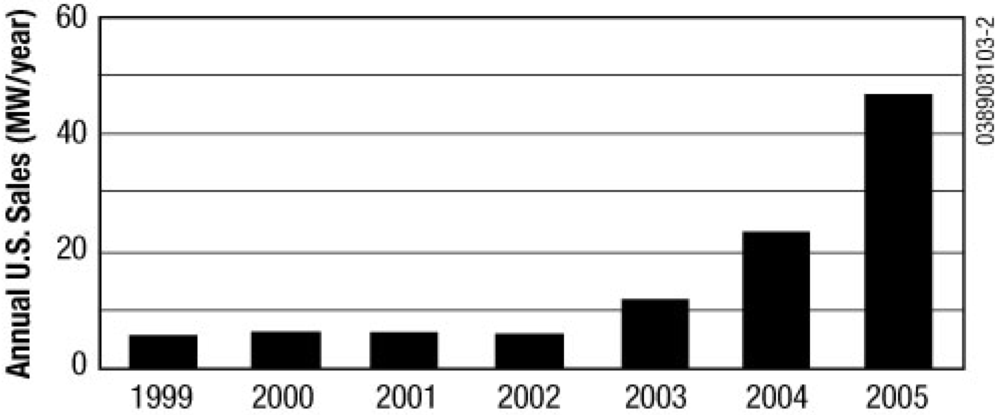

Figure 2: Historical Sales of Thin-Film PV Modules Made in the United States

More information on the Thin-Film PV Partnership project is available on the project Web site www.nrel.gov/ncpv/thin_film.

Lessons Learned

1. Public-Private Cost Sharing

Context

Developing innovative technologies such as PV involves taking financial and technological risks. To help share the risk of R&D between the public and private sectors, a critically important shift took place during the 1980s, from cost-plus contracting to cost-shared contracting. With the approval of the Technology Innovation Act of 1980 (also known as the Stevenson-Wydler Act) and the Patent and Trademark Amendments Act of 1980 (also known as the Bayh-Dole Act), the foundation for cost-sharing was laid. During the past 20 years, the use of cost-sharing, when engaging the private sector in R&D, has become fairly standard practice.

Lessons Learned

The following lessons about public-private cost-sharing have come out of the PVMaT/PVMR&D project:

- Large companies that cannot afford to cost-share 50% or more for large-dollar-value manufacturing R&D subcontracts do not have the resources to sustain expansion in capacity and competitiveness.[3]
- Smaller, less-mature companies may not be able to cost-share as much—a 30% cost-share for a smaller-dollar-value subcontract is reasonable for proven technologies. As these companies mature, it is reasonable to expect them to cost-share 50% for smaller-dollar-value subcontracts.
- Many companies are reluctant to implement new manufacturing processes, but an industry-government partnership can help make implementing new technologies a priority. For example, Solarex (now BP Solar) was reluctant to implement wire saws during the early 1990s, until it signed a PVMaT/PVMR&D subcontract—and key personnel argue that it might still be using the old technology were it not for involvement in the project. Today, this improvement saves BP Solar millions of dollars per year, and wire-saw use has spread broadly to other PV companies and other parts of the semiconductor industry.

The following lessons about public-private cost-sharing have come out of the Thin-Film PV Partnership project:

- Larger, private companies have a greater ability to cost-share, although their willingness to cost-share depends on the level of risk. For technology partnerships—aimed at bringing technologies from the prototype to pilot production phase and then to first-time manufacturing—cost-sharing at 40% is reasonable. For higher-risk R&D partnerships—aimed at solving more fundamental and mid-term (3-10 years) problems that would not be tackled by companies working on immediate scale-up issues (e.g., materials stability, innovative device designs)—cost-sharing at 20% is reasonable. (Because these technologies are still on the emerging-technology improvement curve, they involve higher risks than technologies in the PVMaT/PVMR&D project; therefore, it is reasonable for the government to pay a larger share of the total cost.)
- Smaller, private companies may not be able to cost-share as much. For technology partnerships, cost-sharing at 20% is reasonable, and, for R&D partnerships, 10% is reasonable.
- Universities present unique partnership opportunities, allowing companies to build long-term relationships and undertake riskier projects. If a university is involved in the R&D, cost-sharing can be waived for that portion of the contract (up to 10% of the total).
- Setting aside 20% of each project's budget for collaborative work allows for shared research and lessons learned on top-priority items that the entire industry faces, while preserving the majority of the funds for work on proprietary research. This collaborative work builds a common awareness: university and laboratory researchers understand what industry needs, and industry understands

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[3] For the purposes of DOE R&D subcontracting, "large" companies are defined as those having more than 500 employees and "small" companies as having 500 or fewer employees. However, this cost-sharing guidance is tied more to the financial and organizational capacity of the companies than to their size under these official definitions.

what these researchers can do for them. One recent example of this approach being used successfully is the development of thinner copper indium diselenide (CIS) thin-film layers. For years, CIS layers have been made 3-μm thick, even though it is known that thinner layers would be effective; companies continued to use the 3-μm thickness due to inertia in changing processes. Recent skyrocketing indium prices make thinner layers desirable. The Thin-Film PV Partnership's National CIS Team—seven companies, 10 universities, and NREL—explored thinner cell technologies and helped companies transition to the use of thinner CIS layers. After 1 year of collaborative research, CIS layer thickness has been reduced to 1-1.5 μm, resulting in large material and processing savings for CIS PV companies such as Shell Solar Industries, Energy Photovoltaics, Global Solar Energy, and International Solar Electric Technology. The next step is reducing thickness to 0.3 μm.

Recommendations

A. **Institute a multi-tiered cost-share program.** The program should account for size of the company, type of institution, type of technology, and work performed. It makes sense for the government to pay a larger share for higher-risk activities.
B. **Include universities.** Universities should be included in partnerships when possible. To encourage engagement of universities by industry, the cost-sharing requirement for the portion of a project's budget directed to universities should be reduced or waived.
C. **Include national laboratories.** Expand this structure to include national labs in R&D collaboration.
D. **Include a specific budget set-aside for team partnerships.** This allows lessons learned to be shared and increases industry-wide benefits.

2. Project Proposal Evaluation Panel Composition

Context

Evaluating project proposals and making awards requires establishing some sort of selection panel. The effectiveness of this process is related to the perceived or actual independence, objectivity, and expertise of the panel members. The composition of the panel has implications for the effectiveness and credibility of the selection process.

Lessons Learned

The following lessons have proven important to maintaining credibility of the industry-government-university collaborations through the PVMaT/PVMR&D project:

- From the beginning, project proposals were evaluated using independent panels with experts from the public and private sectors. To ensure there were no conflicts of interest, no evaluation panel experts were chosen who had current ties to the PV industry. Although day-to-day project management was carried out by a team of R&D specialists at DOE headquarters, NREL, and Sandia National Laboratories, the panels had real control over the allocation of project resources.
- Typically, the evaluation panels included one person from NREL and one person from Sandia on a panel of 12 or more individuals. These panels were designed to have a heavy industry representation to ensure their credibility with industry. The limited number of government managers on the panels has been challenging at times because the project managers must be willing to risk losing some control over the process.
- Participants had a broad mix of expertise (e.g., manufacturing, utility, and investment banking) in the semiconductor and (formerly) PV industries to provide a broad view of the market. Although broad representation on the panels has worked well, it has been a challenge to maintain a good mix of people because of the limited pool of potential participants (i.e. people with relevant PV knowledge who are not currently tied to the PV industry).

The following lessons about project proposal evaluation have come out of the Thin-Film PV Partnership project:

- The partnership emphasized up-to-date knowledge on emerging PV technologies in choosing its selection panels. This in-depth expertise was necessary to fully understand the intricacies of an emerging technology such as thin-films. Also, panel members immersed in emerging technologies were less likely to favor well-established technology options, thus opening up a wider variety of emerging technologies for consideration.
- Project selection comprised two stages. First, projects were evaluated for their technical merit, independent of technology type; this allowed various technologies to advance to the next stage. A typical technical evaluation panel consisted of approximately 85% NREL personnel and 15% representatives from outside organizations such as the Electric Power Research Institute and the U.S. Department of Commerce. Second, projects were evaluated for their value to the program; different technologies were compared and prioritized with respect to how well they met project goals. A typical programmatic evaluation panel consisted of approximately 50% NREL personnel, 33% DOE personnel, and 17% representatives from outside organizations.

Recommendations

A. **Understand the trade-offs in choosing a selection panel.** Panels chosen for objectivity, independence, and avoiding potential conflicts of interest add credibility and enhance broad stakeholder buy-in; but they could lack current, in-depth technological expertise or favor more mature technologies. Panels chosen for expertise enable deep technological evaluations and open the field to emerging technologies but could result in a narrow perspective or increased subjectivity.
B. **Consider the project type.** Independent panels representing a wide spectrum of industry (knowledgeable about, but not directly tied, to the PV industry) might be appropriate for projects focusing on more mature technologies. Highly expert panels immersed in the technologies in question might be appropriate for projects focusing on emerging technologies.
C. **Use your judgment.** There is no simple formula for choosing a selection panel. The panel should represent a range of views without losing sight of the goals of the project.

3. Intellectual Property and Collaboration

Context

Intellectual property is vital to PV companies and is a central issue in cost-shared R&D projects. Companies want to protect their IP from all other companies—and even from universities and the government—which has a major effect on the steps necessary for placing cost-shared subcontracts and on the collaborative R&D relationships that PV companies are willing to enter.

Lessons Learned

The following lessons about IP and collaboration have come out of the PVMaT/PVMR&D and Thin-Film PV Partnership projects:

- Private companies can be reluctant to engage in “deep” collaborations/sharing arrangements—which could potentially expose their IP—with other companies. For example, in 1993, the PVMaT/PVMR&D project issued the solicitation “Problem Solving: Teamed Research on Generic Problems.” The goal was to create industry teams to address shared manufacturing problems. However, a true teamed approach, with companies collaborating together, never materialized. Ultimately, Spire Corporation developed automated solar cell assembly equipment and processes, and Springborn Laboratories developed encapsulant technologies. Collaboration was limited to these products and processes being tested in the factories of PV manufacturers.
- More open collaboration among large companies is possible when the large companies agree to work together on a small problem and share information only about that problem.
- Subcontracts increasingly have become focused on IP issues. In the beginning of the PVMaT/PVMR&D project, smaller companies, with small production and profits, were less concerned about IP. Virtually same-day turnaround for signing subcontracts or letter subcontracts was possible. Today, because of IP concerns, subcontracts can take up to 5 months to sign in extreme cases. PV

companies have become larger and more sophisticated and have teams of lawyers to isolate them from other companies and the government.
- Companies are very reluctant to sign over or disclose proprietary information to government/laboratory personnel. For example, one PVMaT/PVMR&D subcontractor would not disclose adequate information about its IP to NREL's patent counsel to have the IP protected in the subcontract. The process dragged on until the subcontractor eventually disclosed the information, greatly extending the subcontract process.
- Companies can be reluctant to share information with national laboratories for several reasons: Employees can leave the laboratory to join a private PV company; IP from one subcontract could accidentally become mixed with other IP in Cooperative Research and Development Agreements (CRADAs) and Work for Others (WFOs) agreements; and national laboratories have a mandate to seek private investment for spin-offs and licenses.
- Companies can be reluctant to share information with universities because they see university personnel as potential employees for start-up PV companies (i.e. competitors), and they see universities as wanting to spin-off start-up companies themselves.

Recommendations

A. **Make it worthwhile.** To interest companies in partnership with the government, make them feel the support is in their best interest. Retaining IP rights is vital to PV companies.

B. **Address individual concerns.** Find out what issues related to collaboration and sharing are most important to each individual company and address these issues on an individual basis.

C. **Reduce the need for competitors to share.** One way to reduce the need to share and minimize IP issues is to establish a vertically integrated structure supporting the needs of a single PV manufacturer with lower-tier subcontracts—with the PV manufacturer in charge. For another approach to sharing, see Recommendation 1D.

4. Contracting Delays

Context

Changes in the PV industry happen quickly. When a manufacturing problem is identified, it must be addressed rapidly. However, slow subcontracting processes result in lengthy delays—sometimes years—between when a problem is identified and when it is addressed with the help of government support.

Lessons Learned

The following lessons about contracting delays have come out of the PVMaT/PVMR&D project:

- Fifteen years ago, subcontract procurement, evaluation, negotiation, and signing could be completed within 6 months. The subcontracting process has become increasingly complicated over the years. Additional DOE requirements have resulted in additional subcontracting steps, such as the pre-board review and audit review. This complexity has added time to the subcontracting process, which can now take up to 2 years in a few extreme cases.
- Time required to place a subcontract is related to the value, and the resulting complexity, of the subcontract: A $2 million subcontract takes much longer to place than a $100,000 subcontract. More people are involved, more reviews are required, and lawyers scrutinize IP issues more closely—all of these cause delays.
- Addressing IP issues early in the subcontracting process can save time. For example, when a company identifies at the outset that it will be using IP developed at its own expense during the subcontract, NREL's legal department can undertake the necessary procedures to have that IP protected simultaneously with the rest of the subcontracting process, adding no time to the process. If the company does not identify its IP until the end of the subcontracting process, the legal procedures extend the process. Also, when companies do not read (or do not have their lawyers read) the entire subcontract and appendices at the outset, the subcontracting process can be extended when, at the time of signing the subcontract, the companies discover provisions they had not been aware of.

- In the past, a process called “letter subcontracts” was often used to expedite project work. A letter subcontract included a draft statement of work and award amount and allowed the subcontractor to begin working before the official, “definitized” contract was signed. This decreased the time between when a problem was identified and when work to solve it began. Use of letter subcontracts has fallen out of favor in recent years, resulting in delayed start of work.

Recommendations

A. **Place subcontracts quickly.** The longer work takes to begin, the less valuable it is. DOE should aim to complete source selection within 6 months, and then complete subcontracting within 4 months after sources are selected. This way, work to solve a problem begins 10 months after the problem is identified.

B. **Streamline processes.** To meet the timeframe above, streamline source selection and subcontracting processes. One important strategy is to address IP issues up front, instead of allowing them to become obstacles at the end of the subcontracting process.

5. Scale of Contracts

Context

As with R&D groups at companies, a critical mass is necessary to keep government-funded PV R&D productive. Too much money can result in funds being wasted on projects that are lower on the priority list just because more important ones are not yet up to speed. Too little money can result in only some related tasks making progress, resulting in a lack of input to other critical tasks when it is needed (i.e. progress is not optimized).

Lessons Learned

The following lessons about scale of contracts have come out of the PVMaT/PVMR&D and Thin-Film PV Partnership projects:

- The PVMaT/PVMR&D project had six large solicitations from 1992-2004. In 1992 and 1993, large subcontracts received approximately $4 million of government funds over 3 years. Large subcontracts received approximately $3 million of government funding over 3 years in 1994 and again in 1998, 2001, and 2004. These amounts are in nominal dollars. As a result, companies with increasingly large and expensive-to-solve problems have been asked to address these problems with less funding over time in real terms.
- From the PVMaT/PVMR&D experience, it is more beneficial to distribute larger awards to a smaller number of capable subcontractors than to distribute smaller awards to a larger number of subcontractors that includes less capable companies. Typically, for the PVMaT/PVMR&D project, the bottom 60% of proposals received are not worth investing in, the top 40% are good ideas, and it is best to fund the top third. Funding less-capable companies increases the chances of those companies—and, thus, the subcontracted R&D—failing to fully capitalize on the investment. Entech and Photovoltaics International (PVI) are examples of small companies that successfully completed their subcontracts but failed to capitalize on their success. Entech, a small concentrator company, cut its production cost in half, increased its production capacity 100-fold (by outsourcing component manufacturing), and increased efficiency. However, its sales of terrestrial PV never took off, and much of its business transitioned to space-based PV. PVI manufactured concentrator modules from extruded plastic components. It implemented a several-megawatt production line before being purchased by an energy company, which eventually decided to focus on wind power and dropped its PV program—PVI subsequently disappeared.
- It is important to develop less-mature PV companies and emerging technologies but not by funding them to perform tasks for which they are not yet capable.
- From the Thin-Film PV Partnership experience, the risk calculation is different for emerging vs. more mature companies/technologies. Because each emerging company/technology has a higher individual chance of failing than a more mature company/technology, an emerging technology R&D project’s overall risk can be reduced by funding a larger number of companies and technologies, i.e.

"not putting all your eggs in one basket." Some companies and technologies will fail, but the project will succeed on the strength of the innovative companies and technologies that succeed. Moreover, some PV companies might be doing well with a less capable technology, whereas other companies with excellent technologies might not yet be succeeding; thus, it is important to support companies not only for what they are, but also for what they can become.

Recommendations

A. **Select the best proposals every time.** From the PVMaT/PVMR&D experience, select only the highest-ranked proposals for each subcontract. Completely re-compete subcontracts each time they are up for renewal. Objectively compare the merits of proposals from past subcontractors and emerging companies.

B. **Make awards based on risk/reward profiles.** For more mature companies/technologies, make awards to a small number of capable companies, so risk of a company failing is low and funds are sufficient for companies to accomplish their goals. For emerging companies/technologies, spread funding around to decrease overall project risk and increase the potential for innovation. As emerging companies/technologies transition to become more mature companies/technologies and expectations of success increase, funding strategies can change correspondingly from more companies funded at a smaller dollar amount and lower cost-share to fewer companies funded at a higher dollar amount and higher cost share.

C. **Make appropriate awards.** Too much money leads to waste, and too little money leads to substandard results. Focus on determining the amount of money each company needs to accomplish its mission and ensuring the resulting award is adequate. From the PVMaT/PVMR&D experience, the best way to determine appropriate funding is via consensus of the project selection panel; it is better to rely on expert judgment than on formulas.

6. Company Maturity, Stage of Development, and Iterative Processes

Context

Choosing the right company for the right job is essential to a successful subcontracted R&D project. PV companies vary greatly in their level of maturity and the stage of development of their products and manufacturing processes. To be successful, products and processes must progress through an iterative cycle of improvements before attaining full-scale production. When making award decisions, it is essential to identify where potential companies and their technologies are on the spectrum of maturity.

Lessons Learned

The following lessons about company maturity, stage of development, and iterative processes have come out of the PVMaT/PVMR&D and Thin-Film Partnership projects:

- Just because a PV company has a good idea for a product does not mean production can be scaled-up immediately. Problems in the manufacturing process are identified during pilot production. These problems lead to improvements in the process, which create other problems, necessitating additional improvements, etc., in an iterative process. There are no shortcuts—every company must go through these iterations before achieving large-scale manufacturing. Moreover, achieving pilot production does not ensure a company will ever achieve full-scale production.
- Companies in large-scale production understand their products. Companies performing applied research on their products or processes without experience in pilot-scale production, e.g., trying to understand the underlying mechanism of their solar cells, are typically not ready for full-scale production. Applied research is another part of the iterative manufacturing process. A company performs applied research, starts a small pilot manufacturing line, discovers problems, and starts more applied research. Skipping the necessary steps results in sub-par products being put on the market too quickly, potentially giving the entire PV industry a black eye.
- First-time manufacturing plants can take as much as three times as long to reach their rated production capacity as plants built as duplicates or expansions of existing technologies. If products and processes are well established, replication and expansion are relatively easy, and plants reach

full production quickly; for example, a company with 100-MW production has a relatively easy time expanding to 200 MW. Making a larger jump, e.g., from 10 to 100 MW, typically results in plants with numerous makeshift solutions and a longer time to full production. However, once all manufacturing issues are fully ironed out, replication/expansion at the new scale is much easier.
- Emerging companies and companies with emerging or immature technologies are often overly optimistic, e.g., regarding future costs and manufacturing capacities. An overabundance of optimism often means the company does not fully understand its problems yet. More mature companies understand their problems better and, thus, tend to be more realistic in their self-assessments.

Recommendations

A. **Set reasonable targets.** When awarding a subcontract involving significant scale-up, select companies that already have adequate production to enable the scale-up. Do not expect a company with a product in pilot production to scale-up from 1 to 500 MW in 3 years. This magnitude of scale-up is more realistic in three 3-year phases, for example: 1) from 1 to 10 MW, 2) from 10 to 100 MW, and 3) from 100 to 500 MW.

B. **Understand the maturity of companies and products.** Award subcontracts based on the maturity of the company and product: award large-scale manufacturing subcontracts to companies with large-scale manufacturing capabilities; award applied R&D subcontracts to emerging companies performing applied research; but do not confuse the two. Market share and production volume are the best measures of company maturity. For example, Specialized Technology Resources (STR) is a relatively small company in terms of employees and factory size, but it produces about 80% of the EVA used in PV modules—the market has decided that STR is “mature.” For PV module manufacturers, production capacity (MW) is the best measure of maturity.

C. **View highly optimistic claims with healthy skepticism.** Although optimism is good—without it, companies would not start their ventures in the first place—subcontract selection should place higher value on proven experience.

D. **Evaluate past performance of previous awardees**. It is important to include a review of performance on previous subcontracts when evaluating new proposals from previous awardees.

7. Addressing Common Problems across Companies

Context

There are problems that affect the entire PV industry, the solution to which benefits the entire industry. The recent silicon feedstock issue is an example of such a generic problem. The feedstock issue is not only about supply, but also about cost. One approach companies are taking to be competitive is to make silicon wafers thinner and larger, requiring a new generation of equipment capable of handling these fragile wafers at an ever-increasing throughput. Another approach is for silicon suppliers to make purified, low-cost silicon specifically for solar applications. The challenge is how to effectively employ government support to solve generic problems such as this.

Lessons Learned

The following lessons about addressing common problems across companies have come out of the PVMaT/PVMR&D and Thin-Film PV Partnership projects:

- It is difficult, but important, to find ways to support solutions to generic PV industry problems. If a problem is solved for only one company, IP issues arise that limit the benefit to the industry as a whole.
- One way to mitigate effects of IP issues is to fund manufacturing equipment manufacturers to solve common industry problems, e.g., a manufacturer produces equipment for handling large, thin wafers, and then sells the equipment to multiple PV manufacturers. However, PV manufacturers are always seeking a competitive advantage, giving them an incentive to develop proprietary equipment. The key is to keep equipment manufacturers tied in with the PV manufacturers so that when the equipment is produced, the PV manufacturers buy it. One example of a PVMaT/PVMR&D project resulting in a product used by multiple PV manufacturers is an in-line diagnostics subcontract awarded to Sinton

Consulting in 2001. Sinton developed an instrument that measures silicon at an early stage in the PV manufacturing process, providing information that helps companies ensure quality, reduce waste, and monitor solar cell costs. The instrument entered the market in 2005 and received an R&D 100 Award that year; today, it and similar Sinton instruments that incorporate advances made under the subcontract are used by 30 cell manufacturers and 44 universities and national laboratories.

- From the Thin-Film PV Partnership experience, another approach is to involve organizations such as universities, national laboratories, and small companies in studying a generic problem via small, applied research contracts. The result could be a technology that is licensed to industry or, more often, a "proof of concept" that encourages others to work independently toward a proven goal; for example, if a university were able to prove the effectiveness of a 0.3-µm-thick CIS cell, companies—, knowing this goal is achievable—would devise their own ways to implement it.

Recommendations

A. **Address generic problems.** Solving generic PV problems boosts much of the industry.

B. **Develop new strategies.** It is difficult to address generic problems in a meaningful way without running into problems of relevance (PV manufacturers do not buy the generic solution) or IP (PV manufacturers opt for proprietary solutions to their problems and do not want to share). New strategies should be developed to make generic solutions acceptable to industry, based on the specific concerns of and relationships among key industry players.

8. Link between Applied R&D and Technology Development

Context

Developing very-low-cost thin-film PV requires achieving module costs similar to those of expensive carpets (about $50/m^2) but with semiconductor technologies made at high performance in areas of many square miles per year. Thin-films, which appear to have this potential, are outside the mainstream of semiconductor knowledge. Unlike crystalline silicon, for which an enormous amount of knowledge has been accumulated (e.g., models, process experience, and degradation mechanisms), thin-film materials have not been used in other electronic devices and thus, until now, a substantial thin-film "knowledge base" has not accumulated. As a result, working with thin-films is less predictable and riskier. The success of thin-film PV depends on the parallel development of a solid knowledge base synchronized with rapid technological advances. Without such parallel progress, success is likely to be very risky owing to possible failure at key transitions (e.g., manufacturing scale-up or initial outdoor reliability).

Lessons Learned

The following lessons about the link between applied R&D and technology development have come out of the Thin-Film PV Partnership project:

- Each PV technology has a different set of challenges and possible approaches to success. Among the thin-films, three technologies have stood the test of time: amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CIS). Of these, a-Si had the best knowledge base; the others lacked such a base almost entirely. Thus, it was extremely difficult to develop CdTe and CIS except in an empirical manner, i.e. based on educated trial and error. Although progress has been rapid at the device level (to reach cell efficiencies greater than 15%), the greatest problem with the lack of a knowledge base has been replicating and scaling-up these lab-based successes, in particular during the transition to first-time manufacturing and then in terms of initial outdoor reliability. Not knowing the key parameters of a device (doping, impurities, defects, grain boundary effects, thermal sensitivities, etc.) makes it difficult to identify processing zones and to tune processes to simultaneously achieve high efficiency, high yields, and high reliability. Thus, without fundamental understanding of the underlying science, one often encounters unexplained processing variations.
- Scale-up is challenging because it means taking devices and processes that were successful at 1 cm^2 size, making large prototype modules (a 10^4-fold size increase), and then manufacturing them in adequate volume to test yield and throughput issues (another 10^5-fold size increase per year to reach 10 MWp). Accomplishing this kind of scale-up without an adequate knowledge base would be almost

miraculous. From a practical standpoint, it is high risk and prone to failure because corporate resources are usually stretched thin during this transition.

- Introducing new thin-film module designs into the marketplace is challenging in terms of electrical and physical performance. Modules are meant to last 30 years. Yet, accelerated tests for proving 30-year durability are inherently difficult, if not impossible, to develop. Instead, prototype modules must be tested as early as possible outdoors and in controlled indoor tests. The lack of a sufficient knowledge base means that potential device-level degradation mechanisms are not well understood, their evolution with time outdoors cannot be predicted, and tests cannot be tailored to diagnose them. While having a solid knowledge base does not eliminate these problems completely, it can help to minimize their effects.
- Parallel efforts in applied research and technology development reduce the risk of failures in module manufacturing scale-up and initial outdoor reliability.
- Building a knowledge base (e.g., through research on fundamental material properties) is a long—and, at times, tedious—process that offers little immediate reward. To support this type of effort, funding agencies and researchers must recognize its importance and have the patience to follow through in the long term.

Recommendations

A. **Support parallel applied R&D and technology development efforts.** Technological progress is possible without an adequate knowledge base, but in key transitions such as first-time manufacturing and initial product introduction, a lack of knowledge can destroy a company or even a technology. To avoid this, it is important to fund R&D on the materials and devices underlying each emerging technology in parallel to funding module development.

B. **Commit to building a knowledge base for the long term.** Recognize the importance of acquiring fundamental knowledge and make this effort a priority. Provide patient, consistent support to universities (which have graduate students well suited to this type of work) and national laboratories in performing the research.

9. Limitations of Cost and Performance Projections

Context

Project managers are continually updating their understanding of PV module cost and performance assessments and are often asked to make judgments based on such assessments, which impact funding priorities.

Lessons Learned

The following lessons about the limitations of cost and performance projections have come out of the Thin-Film PV Partnership and PVMaT/PVMR&D projects:

- The success of PV depends in large part on the efficiency, cost, and reliability of candidate module technologies. Yet understanding how these attributes will change in the future is difficult, in particular because it depends on the success of ongoing and future R&D. The range of inputs and projections can be very large; for example, a recently developed Thin-Film PV Partnership cost model contains approximately 80 inputs. In this model, the input with the most impact on end-use electricity cost is module efficiency, followed by encapsulation cost, processing cost, and semiconductor material cost. However, there is too much uncertainty in factors such as these to project future costs with precision; thus, the inputs and, ultimately, the outputs are inherently influenced by the biases of the parties making the assessments. For example, past assessments by various bodies found that some technologies that are considered viable today (e.g., CdTe and CIS) were unworthy of funding. Embedded biases can easily overcome facts or perspectives when so much of the assessment process is based on opinion (e.g., opinions about doubling efficiencies or reducing costs by a factor of 5). Even if an objective approach can be assumed, the range of possible outcomes is wide, depending on whether R&D is fully successful and what device and process compromises must be made to achieve successful, high-yield manufacturing.

- Bias in assessments can be mitigated by the composition of the selection panel and by what actions are taken based on the recommendations of the panel (see Lesson 2). From the PVMaT/PVMR&D experience, picking too few reviewers results in bias, and picking too many results in inability to reach consensus. PVMaT/PVMR&D panels had about 12 members who were instructed to be technology neutral, focusing only on goals such as increased capacity, decreased cost, and improved reliability. These panelists—who were chosen for their technical capabilities as well as their objectivity—were entrusted with determining the validity of cost and performance assessments and how to act on them. From the Thin-Film PV Partnership experience, a panel with members representing each technology has difficulty reaching decisions, whereas a panel with a dominant viewpoint or set of personalities creates the risk of bias resulting in potential errors. In this case, the effects of potential bias can be mitigated by the actions taken based on the recommendations; as noted in Lesson 5, funding a variety of technologies and companies reduces the overall risk of an emerging technology project. Technology evolution is a creative process, and, regardless of assessment results, no one can predict with certainty what technology will succeed in the future.
- Cost estimates can be used successfully for program guidance. An example is the move toward thinner layers in CIS and CdTe to reduce semiconductor materials costs, processing time/costs, maintenance costs, and energy costs (if efficiencies and yields can be maintained). Showing the community these potential savings motivated them to pursue this opportunity, and important progress has been made toward thinner layers (about a 50% reduction, with more progress ongoing; see Lesson 1).
- It is useful to understand PV module costs, and it can be easy to create ranges for such costs. However, closing those ranges to actual product attributes is the work of R&D and manufacturing—nothing else can do it—and that takes time and money.
- From the Thin-Film PV Partnership experience, the results of cost estimates can be used to establish funding priorities but must not be overused. Biased assessments must be avoided, or key opportunities could be lost. New technologies can be assessed to see whether they have the potential to compete with existing ones, using optimistic assumptions to avoid losing opportunities. The greatest value of cost assessments is in refining questions for research planning, not in making go/no-go decisions about funding. For that, a more intuitive approach using both cost estimates and insights into risks and pathways is more appropriate.

Recommendations

A. **Use cost assessments appropriately.** Perform cost assessments for module technologies and relate them to system cost to understand efficiency/cost tradeoffs. However, be careful in such assessments and do not overuse them. They are useful for refining questions about research directions within each technology, but there are potential pitfalls with using them for inter-technology comparisons. This recommendation is particularly applicable to emerging technologies such as thin-films, for which the uncertainty in assessments is larger. From the PVMaT/PVMR&D experience, assessments of more mature technologies (e.g., some crystalline silicon PV) involve less uncertainty because of these technologies' extensive track record of manufacturing and use.

B. **Mitigate bias through selection panel choices and actions taken based on recommendations.** The composition of the selection panel is important for mitigating bias in cost and performance assessments, as are the actions taken based on panel recommendations. A panel chosen for objectivity can be entrusted with interpreting the results of assessments. Because some bias in assessments is unavoidable, mitigate the effects of such bias by directing funds in such a way that a variety of technologies and companies are supported (in an emerging technology project).

10. The Difficulty of First-Time Manufacturing

Context

Along the path to success, after excellent cells and prototype modules have been made, the critical transition to first-time manufacturing often takes much more time than expected. In some cases, delays can extend up to 5 years, there can be multiple attempts and failures, and companies and technologies can falter or even disappear.

Lessons Learned

The following lessons about the difficulty of first-time manufacturing have come out of the Thin-Film PV Partnership project:

- Taking a new, unproven, often unique PV technology to successful commercial manufacturing is probably more challenging than any other aspect of PV module development and entails great technical and financial risk. The following are examples of setbacks: BP Solar in a-Si and CdTe (ended 2003), Golden Photon in CdTe (2001), First Solar in CdTe (major setback in 2001, overcome by 2004, now a great success), Boeing CIS (mid-1990s), Ametek CdTe (mid-1990s), and Glasstech Solar a-Si (mid-1990s). In addition, several CIS companies have remained in pilot production for more than 5 years or have not even made it to that point.
- Several times during periods of budget fluctuations, the Thin-Film PV Partnership considered major reductions in support of a-Si module development. These were based on assessments of the technologies' adequacy at the time—relatively high module costs and low efficiency. Yet a-Si recently experienced a great success in module development for flat, commercial rooftop applications using flexible modules (Uni-Solar). This is a major and rapidly growing market segment. The a-Si modules are attractive because they do not require expensive racks and they replace traditional roofs. Atypically high module costs and low module efficiencies (the primary evaluation metrics) for this technology had caused them to be misleadingly undervalued. Similarly, the slow progress of CIS into manufacturing has caused some to question the funding of this technology, despite the fact that it has the highest efficiency of any thin-film option, almost 20% at the cell level. Yet, recently, about 25 small companies have entered the CIS field worldwide, taking on this same transitional risk. Both of these examples represent opportunities that could be lost if program managers are too narrow in their willingness to see opportunities.
- Under the stress of tight funding situations, program managers might feel pressure to make simplistic decisions to relieve the stress quickly. For example, the Thin-Film PV Partnership has experienced pressure to cut funding for small companies that were not yet able to manufacture modules in favor of supporting companies with better short-term prospects. The partnership decided to not cut funding for these small companies, and now the companies are receiving venture capital and contributing to PV production.
- While success may take longer than originally anticipated, if successful at a reasonable scale, firms can build on this success and scale-up production rapidly. For example, two U.S. companies—First Solar in CdTe and Uni-Solar in a-Si—have achieved successful first-time manufacturing and are rapidly expanding production.
- Thin-Film PV Partnership management was originally unaware of the full spectrum of risks of transitioning to first-time manufacturing and underestimated the cost to overcome these risks and the delays implicit in them.

Recommendations

The following are ways to reduce the risk for PV companies making the transition to first-time manufacturing:

A. **Be adequately patient.** Patience with setbacks and continued support are justified if the technology is promising. However, the financial climate for PV today is different than in the past, which has implications for maintaining or discontinuing support of struggling companies. Private-sector funding of thin-film PV, virtually zero in the past, has grown considerably during the past few years. The availability of private funding enables DOE to leverage investments from the private sector, and increases the likelihood that DOE supported successes will successfully transition into full-scale production. However, it also reduces the need for DOE to be as patient with failure because government funding is no longer the only lifeline available for emerging companies. Other situations that might justify discontinuing support include projects that extend DOE's investment beyond a desirable timeframe, or the discovery of a flaw in a technology that shows the technology cannot meet program goals.

B. **Support risk-taking companies.** Recognize the risk companies are taking by making the transition to first-time manufacturing and support this leap.

C. **Support work that aids the transition.** Parallel R&D at national labs and universities can help PV companies make the transition to first-time manufacturing.

11. Module Reliability Problems during Introduction of Innovative Technologies

Context

Several thin-film companies—after making the difficult transition to full production capacity—failed during introduction of their module technologies, at least partially owing to serious reliability issues.

Lessons Learned

The following lessons about module reliability problems during introduction of innovative technologies have come out of the Thin-Film PV Partnership project:

- Device-level and module design- and packaging-level issues can exist with new technologies. For example, BP Solar's a-Si glass modules had high breakage rates that caused fires, and its pre-commercial CdTe modules had serious voltage degradation. Golden Photon experienced degradation of its CdTe modules.
- There is no simple way to ensure that all device- and module-level issues are overcome before product introduction.
- Cautious companies that emphasize reliability can succeed.
- The earliest possible recognition of device and module degradation mechanisms is essential for success.
- Although there is no certain way to determine all failure mechanisms in advance, aggressive indoor and outdoor testing can help to uncover such problems and, thus, minimize risk. First Solar experienced module failures initially but overcame them with a product delay, replacement of all failed modules, and progress in module stress testing to identify failure mechanisms.
- A variety of accelerated aging tests are used for PV (Table 4). There are also various needs for improving accelerated aging testing. The following are needs—identified in a recent industry/university/government/laboratory workshop—that apply to PV devices, modules, and systems:
    - Developing reliable, predictable correlations between highly accelerated lifetime tests (HALT) and real-world performance in the field
    - Managing the sensitivity about information on equipment failure, HALT testing, and proprietary information related to materials and methods
    - Understanding the true mechanisms and sources of failures and degradation and their relationship to what HALT measures
    - Providing deeper understanding beyond pass/fail modes of testing
    - Using real-world deployments to investigate PV successes and failures
    - Developing capabilities to test for multiple variable impacts, conditions more extreme than standard test conditions, and components as they exist in a system or subsystem

Table 4: Current Status—PV Module Accelerated Aging Tests

Thermal cycle with current flow, 200+ cycles, -40°C to +90°C
Damp heat exposure, 1,000+ hours, +85°C, 85% RH
Humidity-freeze cycling, 10-50+ cycles, -40°C to +85°C, 85% RH
Hail impact, 1" diameter, 23 m/s
Qualification test sequence (IEC 61215 or 61646)
Surface cut, 45° cut (UL-1703) evaluation by wet hi-pot
ASTM: G154 70°C, >1,000 hours; B117 5% salt solution, 35°C, 96-hour cycle 48-hour wet, 48-hour dry (salt/fog); D903 180° peel strength; D1002 shear test single-lap-joint

Dynamic and static mechanical loading: Static load, 50-90 lb/ft^2, 1-hour application to each side, 2 cycles
Unique tests for flexible modules to capture coiling, flexing, and forming characteristics
Rigid Modules: vibration tests for shipping, dynamic load testing, static load testing, non-uniform wind loading, dynamic testing in wind tunnels, exterior temperature testing, current based TC50 and HF10, voltage bias
Flexible Modules: heat/humidity/sunlight/high voltage, delamination test TCOD 15, solder bond failure (initial and 5-hour @ 165°C)

Recommendations

A. **Test early.** Incorporate device and module testing as early as possible, and even in parallel with the development of new module technologies. Use existing accelerated aging tests and support improvement of testing methods and correlation of testing with real-world performance of PV devices, modules, and systems.
B. **Expect problems.** Expect and plan for early reliability problems.
C. **Be patient.** Exercise patience while reliability issues are overcome.

12. Reluctance of Successful Companies to Adopt Innovative Approaches

Context

The difficulty of establishing the manufacturing approach for a new technology—and the high payoff of replicating manufacturing rather than redesigning and re-proving it—make successful manufacturers slow to adopt new device designs and processing approaches. This can keep industry from reaping the rewards of new technology and slow the pace of PV module and system price reductions.

Lessons Learned

The following lesson about the reluctance of successful companies to adopt innovative approaches has come out of the Thin-Film PV Partnership project:

- Although it is essential to support companies through the transition to manufacturing and beyond, in terms of incremental process and device optimization, more substantial progress (at higher risk) can come from new companies that adopt more aggressive processes and device alterations. In addition to accelerating the progress of innovation, new companies add pressure to existing ones, forcing them out of their financial comfort zone. This can lead to a faster, widespread reduction in module and system prices (e.g., the reaction of crystalline silicon PV companies and system integrators to the advent of commercial thin-films).

Recommendations

A. **Support aggressive companies.** Continue to seed and support aggressive PV companies, especially those that adopt innovative new technologies (if these are judged likely to succeed). These types of companies are most readily differentiated from incremental-change-type companies by their stage of product development—they typically have a new product in a pre-manufacturing/pre-commercial stage, whereas incremental-change companies are typically cloning existing commercial products and processes with only minor changes.
B. **Set aggressive goals.** Another way to encourage aggressive technology development, even in more mature companies, is to set aggressive performance and cost targets. If the targets represent a major leap beyond a company's current product, the company will have to do more than rely on incremental change to achieve them.

13. Budget Adequacy

Context

Developing a new PV technology takes a long time, and progress to first-time production is unpredictable. Annual federal budget cycles and major program redirections can seriously impact success. Several times during the development of thin-films, budgets changed by more than 20% in 1 year, leading to cancellation and reduction of many research activities.

Lessons Learned

The following lessons about budget adequacy have come out of the Thin-Film PV Partnership project:

- Technology development in thin-films is very challenging, arguably below critical mass in terms of funding, and vulnerable to budget fluctuations.
- For a technology such as thin-films to be commercialized successfully, a combination of several technological aspects—including materials, device designs, processes, and module design and packaging—must be developed. To do this, each individual aspect within the combination must be funded adequately. If even one aspect is underfunded—and, thus, underdeveloped, the product is not prepared for manufacturing or reliable deployment.
- Consistent programmatic support within a complex management system like the DOE/NREL/Sandia system is nearly impossible, no matter how well intentioned the management is.
- At times of federal budget stresses, decisions that are made based on organizational rather than programmatic priorities can have serious impacts on technology progress.
- The progress of thin-films in the United States has been affected negatively by budget problems of three kinds: lack of funds, rapid reductions in funds, and premature phase-out of funds. In the past 5 years, the Thin-Film PV Partnership project has twice been subject to 20% budget cuts. In response, the project made the following adjustments:
  - An entire technological approach, single-junction thin-film silicon, was cut. This was felt to be a longer-term technology with no obvious advantage and was sacrificed to preserve other technologies that were more promising and likely to come to fruition in the nearer term.
  - Activities that were building the thin-film “knowledge base” (see Lesson 8) were cut in favor of keeping leading technology partners at nearly full funding. These partners were about to become successful, and stopping funds at this stage could have been catastrophic. First Solar and Uni-Solar were supported and subsequently did achieve success.

Recommendations

A. **Minimize budget impacts.** Develop clear priorities for programmatic decisions and search for ways to minimize annual or sudden budget changes.

B. **Allow for planning.** When budgets are radically altered, develop the best possible perspective about choices so that adequate planning can occur.

C. **Forward fund when possible.** If a subcontract starts in the middle of the fiscal year, obtain funding for a full 12 months, using the carryover to fund the subcontract into the next fiscal year. This provides time to obtain additional funding in the next fiscal year before the already-secured funds run out. Although DOE and Congress frown on carryover, it can protect a program.

D. **Stretch underfunded subcontracts.** If, for example, 10 months of funding are received for 12 months of work, extend the subcontract into the next fiscal year and reduce the monthly level of research effort/funding burn rate. Assuming funds are secured in the new fiscal year, this allows the project to be completed (although it takes longer) instead of losing any of its facets.

E. **Fund all aspects of a technology.** Support of a company must be sustained as the company develops each aspect of its technology. Failure to fund even one aspect of the technology (e.g., materials R&D or device design) can result in failure of the product.

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13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT** *(Maximum 200 Words)*

As the U.S. Department of Energy’s (DOE’s) Solar Energy Technologies Program initiates new cost-shared solar energy R&D under the Solar America Initiative (SAI), it is useful to analyze the experience gained from cost-shared R&D projects that have been funded through the program to date. This report summarizes lessons learned from two DOE-sponsored photovoltaic (PV) projects: the Photovoltaic Manufacturing Technology/PV Manufacturing R&D (PVMaT/PVMR&D) project and the Thin-Film PV Partnership project. During the past 10-15 years, these two projects have invested roughly $330 million of government resources in cost-shared R&D and leveraged another $190 million in private-sector PV R&D investments. Following a description of key findings and brief descriptions of the PVMaT/PVMR&D and Thin-Film PV Partnership projects, this report presents lessons learned from the projects.

15. **SUBJECT TERMS**

solar energy; Solar America Initiative; SAI; Solar Energy Technologies Program; Photovoltaic Manufacturing Technology/PV Manufacturing R&D; Thin-Film PV Partnership project; PVMaT/PVMR&D; PV; photovoltaics; energy use; Robert Margolis; Rick Mitchell; Ken Zweibel

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