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PV MANUFACTURING R&D PROJECT STATUS & ACCOMPLISHMENTS UNDER "IN-LINE DIAGNOSTICS & INTELLIGENT PROCESSING"

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ABSTRACT

In 1991, the U.S. Department of Energy (DOE), National Renewable Energy Laboratory, and Sandia National Laboratories embarked on a research partnership with the U.S. photovoltaic (PV) industry by cost-sharing industry-based R&D efforts.[1] The PV Manufacturing R&D (PVMR&D) Project, an extension of the earlier PV Manufacturing Technology (PVMaT) Project, aims at streamlining and improving the current PV manufacturing technology to enable U.S. manufacturers to compete in the global marketplace. Currently, PVMR&D has ten active subcontracts with manufacturers working in several facets of the U.S. PV industry; four subcontracts were completed within the past year.

BACKGROUND

The PV Manufacturing R&D (PVMR&D) Project is a partnership with the U.S. photovoltaic (PV) industry in cost-shared manufacturing research and development activities. The overriding PVMR&D mission is directed at facilitating R&D to improve PV manufacturing processes and equipment; accelerate manufacturing cost reductions for PV modules, balance-of-systems components, and integrated systems; increase commercial product performance and reliability; and enhance the investment opportunities for substantially scaling up U.S. manufacturing capacity and increasing U.S. market share. Progress toward achieving these objectives is tracked by analyzing the trends in direct module manufacturing costs, existing PV production capacity, and estimated cost savings.

A sampling of the achievements under the current "In-Line Diagnostics and Intelligent Processing" (IDIP) procurement includes the development of an innovative wafer molding manufacturing process, the implementation of in-situ measurements of individual cells in a triple junction during deposition, and the fabrication of sloped, insulated tiles for PV systems integration. Future work in PVMR&D will be focused on improvements related to yield, durability, and reliability.

PROJECT IMPACT

As part of its mission, PVMR&D is tasked with facilitating manufacturing cost reductions and significant production capacity scale-up. To track progress toward these goals, PVMR&D collaborates with its industry partners to compile a database of both historical and projected values for manufacturing cost and capacity figures, as well as estimated cost savings directly related to project participation.

Cost-Capacity Achievements

The overriding goals of PVMR&D are directed at accelerating manufacturing cost reductions and enhancing the investment opportunities for substantially scaling up U.S. manufacturing capacity. Figure 1 shows continued progress toward meeting these goals: total PV manufacturing capacity increased from 14 MW at the project's inception to 201 MW at the close of 2003, while direct manufacturing costs, in 2003 constant dollars, decreased from $5.55 to $2.49 over the same time period.

In this context, direct manufacturing costs is defined as those costs directly associated with module production and do not include research, sales, marketing, or general administrative expenses. The cost shown here are calculated as a weighted average based on manufacturing capacity. Production capacity represents the potential production if operating at full capacity.

Recapture of R&D Funding for PV Manufacturing R&D

PVMR&D module manufacturing partners have provided the Project with manufacturing cost reductions that can be directly attributed to the efforts completed

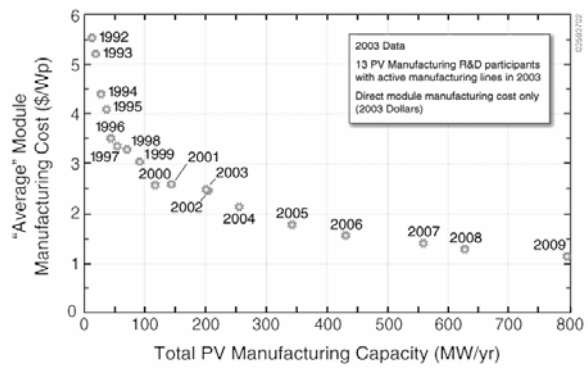

Fig. 1. U.S. PV manufacturing cost-capacity for 2003

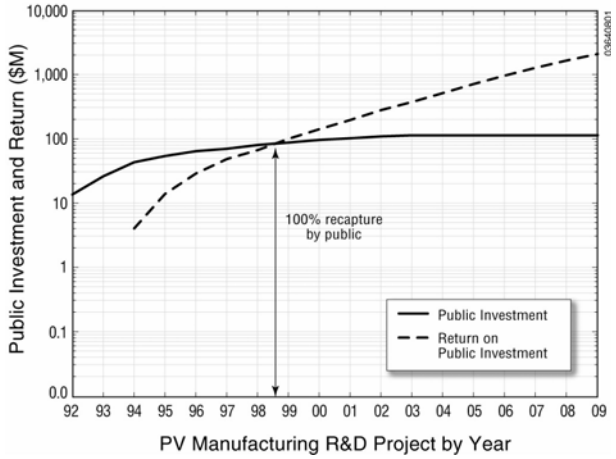

Fig. 2. Recapture of public investment in PVMR&D

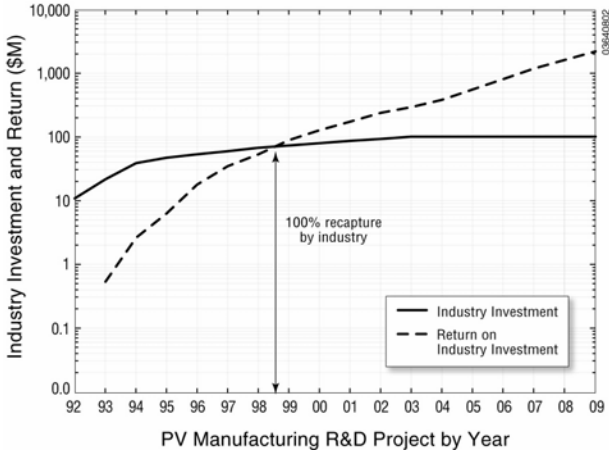

Fig. 3. Recapture of industry investment in PVMR&D

under their cost-shared subcontracts. In addition to the raw cost-savings data, manufacturers have also provided information related to how those cost reductions will be allocated. The recapture of the money invested by both the U.S. DOE and the companies themselves can be determined by analyzing how much of the cost reductions will be passed on to consumers through lower prices and how much will be retained by the company as increased profits, debt reduction, or capital investment.

Figures 2 and 3 show the recapture of public and industry investment, respectively. This analysis shows that the public and industry both recaptured funds by mid-1998, including all investments through 2003.

IN-LINE DIAGNOSTICS & INTELLIGENT PROCESSING

In 2001, PVMR&D launched IDIP solicitation with the goal of improving process control on current production technology. Under this procurement, PVMR&D awarded a total of fourteen subcontracts, ten of which are ongoing to date. The work to be performed under these subcontracts represents a broad range of activities throughout the PV industry, from encapsulant development to wafer fabrication to complete system integration.

Module Manufacturing & Support

AstroPower, Inc., focused efforts on improvements to its Silicon-Film products and associated manufacturing line. Under its recently completed PVMR&D subcontract, "High Volume Manufacturing of Silicon-Film Solar Cells and Modules," AstroPower developed a breakthrough wafer-molding process to increase silicon utilization and throughput. Previously using a continuous-sheet method, AstroPower recently implemented a process that produces individually molded wafers, thus drastically reducing waste. This process alone has reduced the amount of silicon feedstock used per wafer by 30%, significantly accelerating manufacturing cost reductions for AstroPower's APx-8 cell. Considerable gains in yield and efficiency have resulted from implementing this process.

Under the PVMR&D subcontract, "Large-Scale PV Module Manufacturing Using Ultra-Thin Polycrystalline Silicon Solar Cells," BP Solar is developing a process to produce and handle silicon wafers 100-µm thick on 290-µm centers.[2] This effort includes the development of models to explore changes to device parameters, an examination of cutting media, as well as the development of processes and equipment for demounting and subsequent handling of very thin silicon wafers. BP Solar proposes to use thinner wafers to reduce silicon consumption and cost.

Energy Conversion Devices, Inc. (ECD), has continued to advance the amorphous silicon (a-Si) manufacturing technology of lower-tier subcontractor United Solar Ovonic. Under the "Implementation of a Comprehensive On-Line Close-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production" subcontract, ECD developed a comprehensive set of diagnostic systems that provide continuous online quality monitoring for each cell in the triple junction device, closed-loop thickness control systems for the ZnO and ITO deposition processes, and plasma monitoring systems to optimize the deposition process.[3] Using this foundation, ECD is now developing systems for continuous online optimization and closed loop control of the a-Si thickness and properties.

Energy Photovoltaics, Inc. (EPV), achieved milestones related to productivity improvement and the stabilization of PV module power output under its subcontract, "Productivity Enhancement for Manufacturing of Amorphous Silicon PV Modules." Through this work, EPV substantially improved the automated RF matching network by implementing active feedback capabilities to continuously tune conditions during deposition. In addition, EPV worked to improve the uniformity by employing an optimal combination of process conditions and improvements in the deposition systems.

Evergreen Solar, Inc., recently completed the second phase of its subcontract, "Innovative Approaches to Low-Cost Module Manufacturing of String Ribbon Si PV Modules." During this subcontract, Evergreen has developed a means of growing two silicon ribbons from a single crucible.[4] This breakthrough technology enabled Evergreen to double silicon manufacturing capacity without requiring additional production space. Evergreen

focused on improving this dual-ribbon growth technique to bring this technology into the production line. Implementation of this silicon growth technique resulted in significant cost reductions due to increased production scale and savings on consumable goods. To date, Evergreen has demonstrated a 14.6% cell made from the dual-ribbon material.

Under the "Trajectory Oriented and Fault Tolerant Based Intelligent Process Control for Flexible CIGS PV Module Manufacturing" subcontract, ITN Energy Systems, Inc., in collaboration with Global Solar Energy (GSE), has developed trajectory-oriented predictive/control models, fault-tolerance control, control platforms, and in-situ sensors for implementation on GSE's CIGS production line.[5] To date, ITN's focus on CIGS processing has led to physics-based and empirical models of CIGS deposition, as well as the application of model-based control for CIGS processing and predictive models for constructing new evaporation sources. Process improvements resulted in significant increases in CIGS uniformity, yield, throughput, and thickness control, including a 71% reduction in copper variability. Further developments include in-situ sensor development and the potential for enhanced process status monitoring and control of all deposition processes.

RWE Schott Solar, Inc. (RSSI), focused on improving the manufacturing processes for its edge-defined film-fed growth (EFG) ribbon technology to boost yield, quality, process control, and throughput. RSSI is developing Statistical Process Control (SPC) techniques and a Computer Maintenance Management System (CMMS) under its current PV Manufacturing R&D subcontract, “EFG Technology and Diagnostics R&D for Large-Scale PV Manufacturing.”[6] To date, RSSI has developed and installed the CMMS, enabling routine use of high-level SPC on equipment performance throughout all three areas of wafer, cell, and module manufacturing. These developments support RSSI in capacity scale-up for both wafer and cell production.

Under its “Development of an In-line Minority-Carrier Monitoring Tool for Process Control During Fabrication of Crystalline Silicon Solar Cells” subcontract, Sinton Consulting, Inc., implemented improvements for its in-line minority-carrier monitoring tool.[7] The instrument uses quasi-steady-state photoconductance measurements to predict final cell efficiencies. When incorporated into the production setting, this tool has the potential to significantly decrease manufacturing costs as lower efficiency materials can be removed from production during early processing stages. Due to the 0.4-s measurement time, the tool has a capacity of 30 MW per year. In addition, Sinton has also designed a variety of tool configurations, enabling users to measure both boules and wafers.

During the "PV Manufacturing R&D - Integrated CIS Thin-Film Manufacturing Infrastructure" subcontract, Shell Solar Industries, Inc. continued advancement of CIS production through development of high-throughput CIS absorber formation reactors and implementation of associated safety infrastructure, XRF measurement for process feedback, bar-code scribed serial numbers, and intelligent processing functions for production.[8] This work addressed multiple production bottlenecks, thereby exercising the overall process at higher production rates and laying the groundwork for evaluation of near- and long-term manufacturing scale-up.

Specialized Technology Resources, Inc. (STR), is collaborating with U.S.-based PV manufacturers to develop and complete qualification testing on an expanded line of high-performance, engineered encapsulation for constructing PV modules under a subcontract entitled, “Development of New Low-Cost, High-Performance, PV Module Encapsulant/Packaging Materials.”[9] To date, STR has evaluated PV manufacturer input, identified formulation strategies, and developed analytical models, all of which have contributed to the manufacture of new encapsulants. The company improved the performance of the new Super Fast Cure and Flame Retardant EVA encapsulants and scheduled lamination trials and IEC qualification testing.

Under the “Development of Automated Production Line Processes for Solar Brightfield Module” subcontract, Spire Corporation designed a large-area, 800-W module for utility-scale PV arrays and began development work for the manufacturing equipment required to implement an automated production line for such modules.[10] As part of this effort, Spire recently completed fabricating and testing a full-scale prototype automated string inspection system for solar cells. The inspection system is capable of detecting large, visible defects, as well as imperceptible microcracks. This detection method, when incorporated into a production line, has the potential to decrease current labor hours spent performing visual inspections and to increase module yields by removing damaged cells from production at an earlier stage. The implementation of this automated string inspection system has the potential to accelerate manufacturing cost reductions and to increase commercial production reliability.

Balance of Systems & System Integration

PowerLight Corporation has made many improvements to the production of PowerGuard tiles during the “PowerGuard Lean Manufacturing” subcontract. Most significantly, the development of two new tile designs greatly improved the manufacturability of PowerGuard, creating the potential for drastic reductions in cost.[11] Additionally, the production launch of the Gen II sloped tile proved the manufacturing advantages of a continuous flow process and the benefit of applying lean manufacturing techniques to PowerGuard production. The Gen II flat tile shows great promise for taking advantage of the improvements gained from lean techniques. Under its subcontract, PowerLight has been able to make significant progress in reducing the cost of integrated PV systems.

Over the course of the "Plug and Play Components for Building-Integrated Systems" subcontract, RWE Schott Solar, Inc. (RSSI), is enhancing its systems for mounting and wiring PV arrays on both flat and pitched roofs, in addition to developing a 300-W AC module.[12] A novel grid-interconnection device for residential PV applications has also been prototyped. A major accomplishment of this effort has been the development of the company's new free-standing system for mounting large PV arrays on flat-roof buildings, allowing for penetrationless installation.

Efforts on the AC-module design to date have resulted in the determination of the preliminary specifications for the SunSine AC module and the design of the inverter packaging and integration with the PV module.

Xantrex Technology recently completed the work effort under its PVMR&D subcontract, "PV Inverter Products Manufacturing and Design Improvement for Cost Reduction and Performance Enhancements." In the first phase of this subcontract, Xantrex developed the hardware for three advanced, high-impact PV inverter products for grid-tied applications.[13] The weight, size, cost, and conversion losses of these new inverters were reduced by nearly 50% compared to current technology. In addition, the effort resulted in cost-reduced, higher-reliability, high-impact, PV products to market by improving development, procurement, and manufacturing efficiencies of the Xantrex inverter products.

YIELD, DURABILITY & RELIABILITY

The FY2003 procurement, "PV Manufacturing R&D—Large-Scale Module and Component Yield, Durability, and Reliability," is a continuation of the PV Manufacturing R&D Project, which focuses on further accelerating the PVMaT achievements and is designed to be impartial to various PV technologies and manufacturing approaches. The goals are to improve PV manufacturing processes and products while reducing costs, provide a technology foundation that supports significant manufacturing scale-up (500 MW total U.S. capacity), and position the U.S. industry to meet rapidly emerging large-scale deployment and other markets.

In response to the solicitation, the U.S. PV industry submitted an unprecedented 29 Letters of Interest (LOI): nine addressed non-module aspects of PV systems component manufacturing processes under Category A, "PV System and Component Technology," whereas the remaining twenty primarily addressed aspects of module manufacturing processes under Category B, "PV Module Manufacturing Technology." Upon review, seventeen of the LOIs were determined to be within the competitive range. Negotiations are underway with potential subcontractors under this procurement.

CONCLUSIONS

To date, PVMR&D has made substantial contributions to the U.S. PV manufacturing industry through cost-shared research efforts. Based on an analysis of the current trends in PV manufacturing, PVMR&D is facilitating research activities that result in cost savings for both the consumer and manufacturer, as demonstrated by both the recapture analysis and demonstrated cost reductions. The current IDIP subcontracts have resulted in improved manufacturing methods throughout the U.S. PV sector.

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