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PV Manufacturing R&D Project Status and Accomplishments under "In-Line Diagnostics and Intelligent Processing" and "Yield, Durability and Reliability"

Preprint

Conference Paper
NREL/CP-520-39904
May 2006

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Presented at the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion (WCPEC-4)
Waikoloa, Hawaii
May 7–12, 2006

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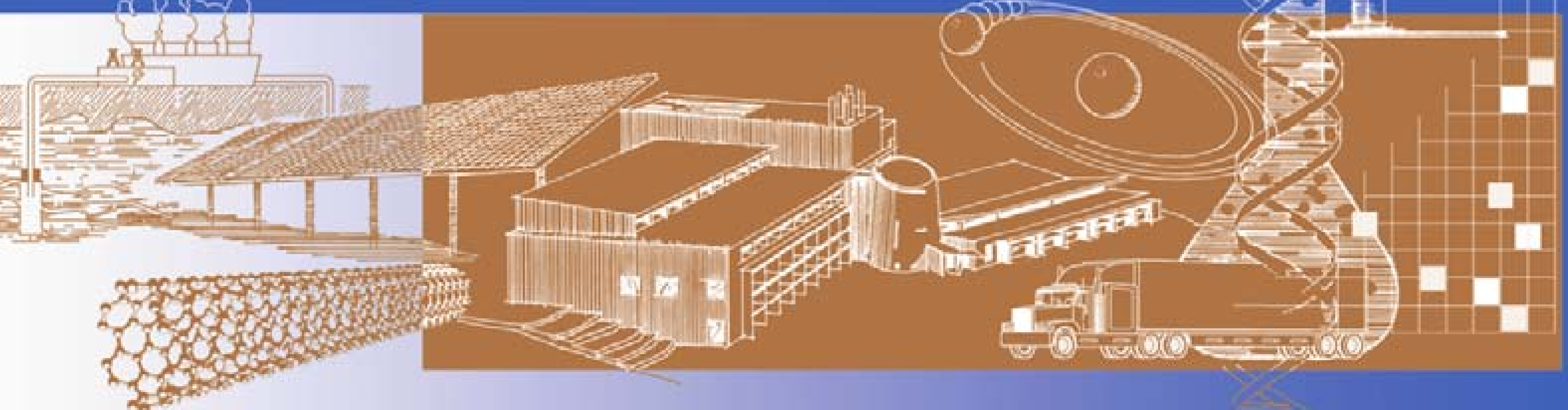

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PV MANUFACTURING R&D PROJECT STATUS AND ACCOMPLISHMENTS UNDER "IN-LINE DIAGNOSTICS AND INTELLIGENT PROCESSING" AND "YIELD, DURABILITY AND RELIABILITY"*

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ABSTRACT

The PV Manufacturing R&D (PVMR&D) Project conducts cost-shared research and development programs with U.S. PV industry partners. There are currently two active industry partnership activities. "In-line Diagnostics and Intelligent Processing," launched in 2002, supports development of new in-line diagnostics and monitoring with real-time feedback for optimal process control and increased yield in the fabrication of PV modules, systems, and other system components. "Yield, Durability and Reliability," launched in late 2004, supports enhancement of PV module, system component, and complete system reliability in high-volume manufacturing. A second key undertaking of the PVMR&D Project is the collection and analysis of module production cost-capacity metrics for the U.S. PV industry. In the period from 1992 through 2005, the average module manufacturing cost in 2005 dollars fell 54% (5.7% annualized) to $2.74/Wp, and the capacity increased 18.6-fold (25% annualized) to 253 MW/yr. An experience curve analysis gives progress ratios of 87% and 81%, respectively, for U.S. silicon and thin-film module production.

INTRODUCTION

The PV Manufacturing R&D (PVMR&D) Project conducts cost-shared research and development programs with U.S. PV industry partners. The goals of this partnership are to accelerate manufacturing cost reductions for PV modules, balance-of-systems components, and integrated systems; improve performance and reliability of commercial products; improve U.S. PV industry module manufacturing processes and equipment; and develop manufacturing technology to enhance investment opportunities for scale-up of U.S. PV manufacturing capacity. The Project monitors progress toward these goals by gathering data on U.S. PV manufacturing cost, and production capacity and level.

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There are currently two active industry partnership activities. "In-line Diagnostics and Intelligent Processing (IDIP)" supports development of new in-line diagnostics and monitoring with real-time feedback for optimal process control and increased yield in the fabrication of PV modules, systems, and other system components. This activity was launched in 2002 and currently has four active subcontracts. "Yield, Durability and Reliability (YDR)," supports enhancement of PV modules, system components, and complete system reliability in high-volume manufacturing. The first subcontracts in this activity were launched in late 2004 and the final ones in April 2006, for a total of 11 subcontracts, itemized below.

SUBCONTRACTOR ACTIVITIES

Subcontracts are selected by competitive procurements. The two procurements currently active are described below.

In-line Diagnostics and Intelligent Processing (IDIP)

The IDIP procurement is directed at improvements in module manufacturing processes; system and manufacturing flexibility; and balance-of-system development. These subcontracts emphasize new and improved in-line diagnostics and monitoring with real-time feedback for optimal process control and increased yield in the fabrication of PV modules, systems, and other system components. Subcontracts active as of April 2006 are listed in Table I.

Yield, Durability and Reliability (YDR)

The YDR procurement is directed at enhancing module, system-component, and complete-system reliability. Focus areas for these goals are improvement of module-manufacturing processes; system and system-component packaging, integration, manufacturing, and assembly; product manufacturing flexibility; and balance-

Table I. IDIP subcontractors during FY 2006, listed in alphabetical order by company name.

Subcontractor	Title of Subcontract
BP Solar International, Inc.	*Large-Scale PV Manufacturing Using Ultra-Thin Polycrystalline Silicon Solar Cells
Energy Conversion Devices, Inc.	Implementation of a Comprehensive On-Line Closed-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production
Evergreen Solar, Inc.	*Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules
ITN Energy Systems	*Trajectory-Oriented and Fault Tolerant Based Intelligent Process Control for Flexible CIGS PV Module Manufacturing
Schott Applied Power, Inc.	Plug and Play Components for Building-Integrated PV Systems
Schott Solar, Inc.	*EFG Technology and Diagnostics R&D for Large-Scale Manufacturing
Specialized Technology Resources, Inc.	Development of New Low-Cost, High-Performance, PV Module Encapsulant/Packaging Materials
Spire Corporation	Development of Automated Production Line Processes for Solar Brightfield Modules

*Research completed as of April 2006.

of-systems development. The YDR subcontracts are shown in Table II.

Table II. YDR subcontractors, listed in alphabetical order by company name.

Subcontractor	Title of Subcontract
BP Solar International, Inc	Development of Large High-Voltage PV Modules with Improved Reliability and Lower Cost
Dow Corning Corporation	High Performance Packaging Solutions for Low Cost, Reliable PV Modules
Evergreen Solar	Low-Cost Manufacturing of High-Efficiency, High-Reliability String Ribbon Si PV Modules
First Solar, LLC	Implementation of Reliable Manufacturing of Higher Efficiency First Solar Modules
GE Energy	Solar Cell Design for Manufacturability
PowerLight Corporation	Accelerating PV Cost Effectiveness Through Systems Design, Engineering, and Quality Assurance
Schott Solar, Inc.	High Performance Multicrystalline Modules and Products
Shell Solar Industries	Photovoltaic Module Manufacturing Technology
Shingleton Design	One-Axis Trackers - Improved Reliability, Durability, Performance, and Cost Reduction
SunPower Corporation	Automated Manufacturing of High Efficiency Modules
Xantrex Technology	Advanced, High Reliability, System Integrated 500kW Photovoltaic Inverter Development

Selected Highlights of Subcontractor Activities

BP Solar developed a process to use thinner wafers to decrease Si consumption and cost. For this effort they completed process equipment specifications for sawing, demounting, and handling 100 µm wafers cut on 290 µm centers, and reduced wafer thickness in production from 250 to 220 µm. They have also introduced lead-free interconnects on all BP Solar multicrystalline Si modules, and new junction boxes on all commercial products.

Dow Corning Corporation is developing prototype encapsulant materials with fast lamination speed, 20% faster than typical EVA lamination times, and the potential for non-laminator assembly methods such as pinch rollers. They have completed initial prototype laminations to determine minimum thicknesses for the adhesive and encapsulant layers by demonstrating bubble-free laminates and suitable samples for cut and voltage break-through testing.

Energy Conversion Devices has completed testing of an on-line PV capacitive diagnostic system to stabilize and optimize a-Si deposition, improving both solar cell efficiency and production yield. They have also developed optical reflection spectrometers for online QA/QC and closed-loop control of film thickness and cross-web uniformity of several of the critical layers in their cell structure.

Evergreen Solar has designed and bench-tested a new in-situ ribbon cutting apparatus for their string ribbon® Si-based PV modules. Because of the success of tests, implementation of a pilot phase has been accelerated. A move to thinner 170 µm wafers is under development, focusing on process yield improvement in the glass etch, decal application, and tabbing and stringing steps.

First Solar is currently ramping up activity on their subcontract, which will develop advanced front contact window layers, an enhanced semiconductor vapor transport deposition system, and improved post-deposition processing.

GE Energy is currently ramping up activity on their subcontract, which will develop a set of improvements to their silicon-film cells and also a low-cost silicon-film module.

ITN Energy Systems has implemented improved process controls and fault-tolerance procedures on the Global Solar production line, resulting in an 85% increase in yield and a 13% increase in cell efficiency.

PowerLight has improved their PowerGuard product manufacturing, including a reduction in the cost of the mortar coating of the foam backer-boards, as a result of input from accelerated testing. They have completed design of a prototype foamless PV roof tile and implemented production of PowerGuard tiles for customers without the need for added insulation.

Schott Applied Power has developed a new design for a free-standing mounting system bracket, allowing the module to be completely free to rotate to shallower angles in response to wind forces and to prevent it from over-rotation; this design has been rigorously validated, including wind tunnel testing on scale-model array design.

Schott Solar has raised the production yield for their EFG (Edge-defined Film-fed Growth) wafers, demonstrating high-yield processes for 250-µm EFG wafers, implementing a higher cutting speed laser (+60%), and cutting cycle time reduction (~20%). They have integrated diagnostic equipment and statistical methods for high-speed monitoring of wafers, cells, and processes in their 60-MW manufacturing facility, resulting in a 15% increase in wafer and cell operational throughput.

Shell Solar has introduced a thin 125 µm wafer-cutting wire to their pilot production mode, giving an increase of almost 8% in watts out per kg of silicon input for a significant cost improvement and demonstrating a production increase of over 6% for over 500 saw runs.

SunPower Corporation, a new member of the PV Manufacturing R&D Project, introduced an antireflective glass to their module design, resulting in a module with a 223 W power output and a corresponding 17.9% total-area efficiency, as verified by NREL. SunPower also developed and successfully tested a lead-free interconnect system, finding an additional benefit of increased resistance to fatigue failure.

Specialized Technology Resources Inc. developed a new thin-film encapsulant formulation which is thinner and has improved glass adhesion.

Spire Corporation built and tested an automated module lay-up process system for large-area modules, as well as a robotic string busing system, which automatically connects solar cell strings together and installs bypass diodes in the cell circuit before lamination. They also demonstrated a method for forming shallow, fine-pitch corrugations in copper ribbon to relieve stress and maintain high yield in the cell string soldering process.

Xantrex Technology is currently ramping up activity on their subcontract, which will develop the architecture, system components, software, and control circuits for a 500-kW system-integrated PV inverter.

PROGRESS IN MANUFACTURING COST, CAPACITY AND PRODUCTION LEVEL

To track the progress of these activities in meeting the project objectives, and to monitor the state of U.S. PV manufacturing as a whole, the PVMR&D Project annually gathers data from a variety of industry contributors. The data aggregate a significant majority of the U.S. PV industry on manufacturing cost ($/Wp) and production capacity (Wp/yr). Other company cost centers or costs not directly related to manufacturing, such as marketing, administration and sales, are excluded. Cost data include all manufacturing costs and manufacturing-related overhead costs associated with the actual manufacturing of modules and cells/wafers. The cost values represent the actual cost of producing modules at each year's specific capacity level.

Production *capacity* data represent the actual capacity of the manufacturing facility, as determined by the rate-limiting processes. Regularly scheduled maintenance and down time are included, assuming a fully staffed production line. Production *level* data represent the actual megawatts of modules produced on the production/pilot lines, including cells/wafers and modules that were not used for sale but were of product quality. Finally, projections five years into the future were solicited from the contributors for cost/capacity/production.

Figure 1 shows the progress in combined crystalline-Si/thin films/concentrator module manufacturing production cost vs. capacity from 1992 to 2005, as well as the projections to 2010. From 1992 to 2005, the average module manufacturing cost decreased 54% to $2.74/Wp (in 2005 dollars), an average 5.7%/year decrease, while the production capacity increased 18.6-fold to 253 MW, an average 25%/year increase. These numbers represent a slight slowdown in cost decrease and capacity increase reported previously [1] for the 1992-2003 data set. This change is attributable to a recent temporary shortage in silicon feedstock as discussed further below.

Figure 2 shows the production levels and manufacturing plant utilization (production/capacity) over the same time period, for both thin-film and silicon

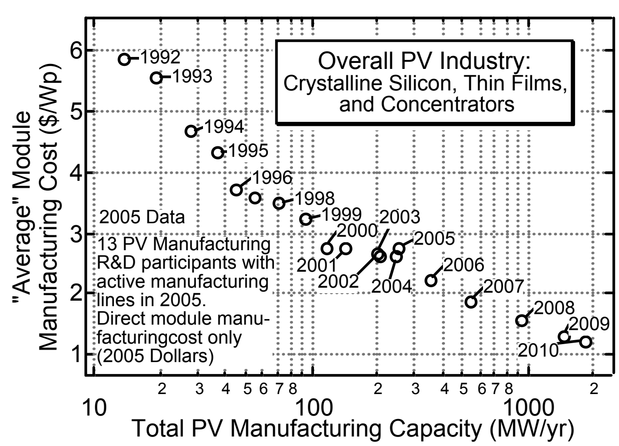

Fig. 1. U.S. PV module manufacturing cost vs. capacity.

modules. Also shown is the fraction of production due to x-Si vs. thin films. The manufacturing plant utilization for Si modules have to date been quite stable from year to year, while thin-film manufacturing plant utilization has fluctuated much more. There was a pause in the growth of Si production in 2003-2005, attributable to a silicon feedstock shortage. This growth pause is projected to continue into 2006, but a return to normal growth is anticipated in 2007.

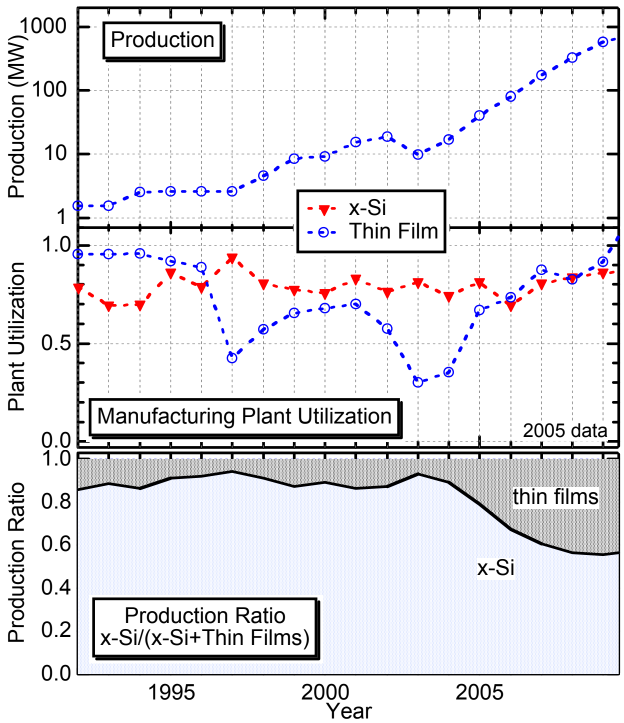

Fig. 2. Manufacturing production levels, plant utilization (production/capacity), and production ratio for crystalline silicon and thin-film PV.

The relationship between production level and cost is shown in Fig. 3 in the form of "experience curves." In this analysis, the dependence of cost upon *cumulative production* (i.e. "experience") is considered. It is often observed empirically that cost decreases according to an inverse exponent of the cumulative production. The value of the exponent determines the "progress ratio," the fraction by which the cost falls for each doubling in cumulative production. Figure 3 shows that over the 1992-2003 period, silicon module production cost has followed a fairly stable learning curve with an 87% progress ratio. In 2004-2005 the cost actually rose, attributable to the silicon feedstock shortage as previously noted. This rise in cost is projected to be only a temporary anomaly, and the overall trend of costs falling with a roughly 87% progress ratio is forecast to continue through 2010. For thin-film production, the data are less well described by a learning curve due to an anomalous rise in costs in 2001-2003 due to redesigns of the modules during that time period. The fit to a learning curve is shown in Fig. 3 as the dashed line, with a progress ratio of 81% from 1992 to 2010.

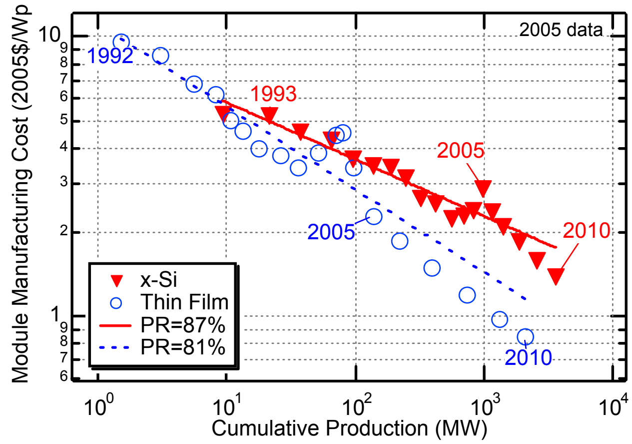

Fig. 3. Experience curve plot of module cost vs. cumulative production for x-Si and thin-film modules. The solid line represents a progress ratio=87% fit to the 1992-2003 x-Si data.

ACKNOWLEDGMENTS

This work is supported or funded under DOE Contract No. DE-AC36-99GO10337. The core of the PV Manufacturing R&D Project is the participation of the industry partners. We are especially grateful to the companies for providing their production cost-capacity data to the industry survey presented here. We also thank S. Pedigo and A. Hicks for their many contributions to the Project.

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