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Status and Recent Progress in Photovoltaic Manufacturing in the USA

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STATUS AND RECENT PROGRESS IN PHOTOVOLTAIC MANUFACTURING IN THE USA

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ABSTRACT

This paper describes the present status of photovoltaic technology and recent manufacturing progress obtained through the U.S. Department of Energy's Photovoltaic Manufacturing Technology Project (PVMaT). Although barriers to the widespread use of photovoltaics—a clean and renewable energy—continue to exist, many of these barriers are cost-related and can be addressed through further research on existing approaches. Important areas for development are new materials, improved manufacturing processes, more efficient conversion of sunlight to electricity, and ensured long-term reliability. Improvements in these areas can be expected to lead to lowering of system costs and, ultimately, of energy cost. Specific improvements in manufacturing processes by individual PVMaT participants are described.

INTRODUCTION

The study of photovoltaic (PV) technology has been a significant R&D area in the United States for about the past 25 years. At first, many people thought the ultimate areas of application would be large terrestrial installations similar in size to conventional power-generation facilities. However, during this time, smaller terrestrial applications have also become important, both as an initial market for PV systems and, in their own right, as new, essential applications (e.g., power supplies for telephones along highways, portable road signs, remote monitoring and communication systems, and individual residences). And although the advances in the technology have been noteworthy, barriers still exist to the widespread use of this relatively clean and renewable energy. Many of these barriers are cost-related and can be addressed through further research on existing approaches. Important areas for further development are new materials, improved manufacturing processes, more efficient conversion of sunlight to electricity, and ensured long-term reliability. Improvements in any of these areas can be expected to lead to lowering of system costs and, ultimately, of energy cost. This paper describes the present status of PV technology and some of the recent progress obtained through the U.S. Department of Energy's Photovoltaic Manufacturing Technology Project (PVMaT).

PHOTOVOLTAIC TECHNOLOGY STATUS

Technology status for a developing technology like PV is characterized by the technical capabilities of the particular type of technology in terms of conversion efficiencies, as well as the production capacity and product cost. Cell and module conversion efficiencies are given below for various PV technologies. Also given in this section are collective historical data regarding the module cost and production capacity for participants in PVMaT. Information across the industry can also be found in various publications (see, for example, Maycock, 2000).

Cell and Module Conversion Efficiencies

For this discussion, PV technologies have been divided into three main areas: flat-plate-crystalline silicon, flat-plate thin films, and concentrator (Witt, 2000). Flat-plate technologies include thick cells of crystalline silicon (from both ingot and sheet-growth techniques) and thin-films (for this discussion, less than 100 micrometers) of various materials, usually deposited by some type of vapor deposition or by electrodeposition. Present thin-film approaches generally do not allow conversion efficiencies as high as those demonstrated by crystalline silicon modules. But thin-film cells require only 1/10 to 1/100 of the expensive semiconductor material as that required by crystalline silicon for equal collection areas. Primary materials under study for thin-film application include amorphous silicon, copper indium diselenide, and cadmium telluride. With concentrators, an additional tradeoff is practiced whereby portions of the more expensive semiconductor material in the system are replaced with a system of lenses or reflectors that can be made from less expensive material. This replacement may, however, be at the expense of overall system efficiency, and thus, one should consider each system as a whole in evaluating its benefits.

Table 1 presents cell and module conversion efficiencies (percentage of sunlight converted to electricity under standard conditions) for both ingot- and non-ingot-based crystalline silicon technologies. Although there are specific areas for improvement associated with each of the crystalline silicon sub-technologies, general research areas that apply to crystalline silicon include: a) manufacturing yield and throughput, b) impurity/defect gettering and passivation, c) low-cost, high-efficiency processes, d) environmentally benign processing and waste-stream reduction, e) manufacturing automation and module packaging for 30-year life, f) thinner wafers and associated handling, g) wire-saw slurry recycling (ingots only), and h) new processes to produce “solar-grade silicon.”

Table 1. Conversion Efficiencies for Crystalline Silicon PV

Material	Cell (%)	Module (%)
Float-Zone	24-25	21-23
Czochralski	22-24	15-18
Cast Polysilicon	18-20	14-15
EFG Ribbon	14-15	11-13
Dendritic Web	15-17	14
String Ribbon	14-15	12
Thick-Silicon Substrate	16-17	10

Table 2 presents conversion efficiencies for thin-film cells and modules. As in crystalline silicon, manufacturing throughput and yield and improved conversion efficiency are primary concerns for all thin films, with special attention to reducing the gap between laboratory cell efficiencies and production module efficiencies. Specific amorphous silicon research is directed to the following areas: a) novel growth techniques that allow higher growth rates and better materials and b) improved fundamental understanding with the goal of improved material stability and long-term field performance. Current cadmium telluride R&D includes work addressing the issues of: a) improved film deposition, b) better contacting techniques for extracting electrical power from the cells, and c) low-cost module packaging for long-term reliability. Current R&D areas for copper indium diselenide are: a) scalability of production processes, b) new deposition techniques and materials that lend themselves to lower-temperature and non-vacuum approaches, and c) improved understanding of the device physics at the active semiconductor junction.

Table 2. Conversion Efficiencies for Thin-Film PV

Material	Cell (%)	Module (%)
Amorphous Si	12-13	7-8
CdTe	15-16	8-9
$CuInSe_2$ (CIS)	18-19	10-12

Concentrator technologies are generally of two types: low concentration (usually 10 to 20X), which uses line or one-dimensional focus, and high concentration (usually 100 to 1000X), which uses point or two-dimensional focus. Table 3 presents cell conversion efficiencies for various materials that lend themselves well to the somewhat higher module operating temperatures often found in concentrator systems. Note that the efficiencies are reported at particular concentration ratios because the efficiencies are a function of measurement conditions, including light intensity. Module efficiencies are in the range of 15% to 17% for the Si-based systems, with prototypes of more than 20%. Modules using GaAs cells have efficiencies of more than 24%.

Table 3. Cell Efficiencies for Concentrator Systems

Material	Concentration Factor	Efficiency (%)
Si	<400	27
GaAs	<1000	28
$GaInP_2/GaAs$	1	30.3
$GaInP_2/GaAs$	180	30.2
$GaInP_2/GaAs/Ge$	50	32.3

General issues for concentrator systems include the structural characteristics of the system that lend themselves to larger applications and, hence, make the highly visible and currently more-prevalent small-application market less useful to concentrators in terms of establishing market position. A second concern is that concentrator systems use essentially only direct radiation, and therefore, their areas of best application require high-intensity sunlight, such as the Southwest United States. Areas of R&D that are important for concentrators include, as in flat-plate PV, manufacturing yield and throughput and higher conversion efficiency to reduce ultimate energy cost. In addition, concentrators can benefit from improved cell materials and structures. Higher efficiencies are expected from multijunction structures, such as the 2- and 3-junction devices shown in Table 3, and 4-junction devices under development. Novel concentrating techniques may also ultimately be incorporated into successful concentrator systems.

Module Manufacturing Costs and Capacities

PV module costs are usually given in "dollars per watt," with the watt value defined in terms of the module power rating under specific conditions. Figure 1 shows total manufacturing capacity versus average direct costs for modules manufactured by participants in the PVMaT Project. The plot is based on 1999 data from 12 industrial participants, each of which has active production lines. The "average module manufacturing cost" is a weighted average based on the manufacturing capacity of each of these participants. As seen for the 12 manufacturers, PV manufacturing capacity has increased by more than a factor of seven since 1992, from 13.6 to 99.3 megawatts. Additionally, the weighted-average cost for manufacturing PV modules has been reduced by 36%, from $4.23 to $2.73 per peak watt. Projections through 2005 indicate a steady decline, to an average module manufacturing cost of $1.16 per peak watt at just over 865 megawatts of capacity.

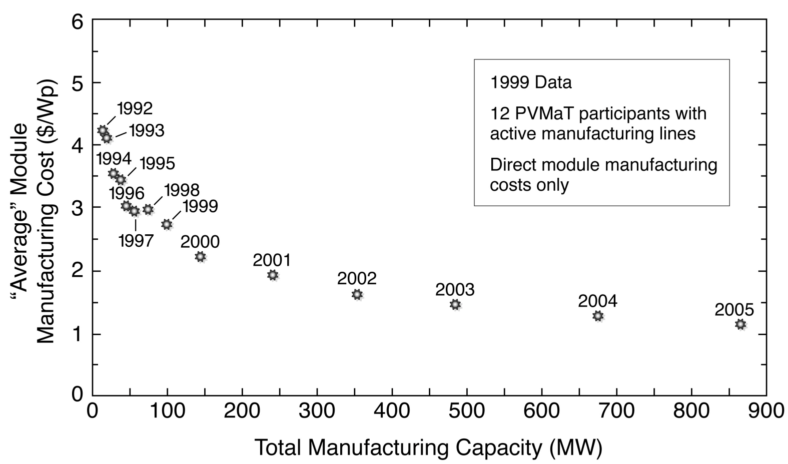

Figure 1. PVMaT Manufacturing Cost/Capacity

RECENT PROGRESS IN MANUFACTURING PROCESSES

The following are some of the recent manufacturing R&D advances resulting from PVMaT. The work described is not inclusive of all the types of activity performed either by industry as a whole or even by just the PVMaT participants. However, the accomplishments presented here represent some of the more significant recent manufacturing advances. Additional information on these technologies can be found in Mitchell (1998), Thomas (1998), and Witt (1998, 1999).

Module Manufacturing Processes

Each manufacturer of solar-electric modules has a unique approach to producing high-performance, competitively priced products. Under PVMaT contracts, manufacturers work to improve their own processes and technologies.

Crystalline Silicon Modules

ASE Americas cuts wafers from silicon material produced in the unique edge-defined, film-fed growth (EFG) system, which produces a thin-walled cylinder of crystalline silicon material that is cut into wafers for cell and module manufacture. In FY 2000, the company integrated high-speed lasers into the wafer-cutting stage of production. Faster cutting can decrease labor costs by 75% and reduce the capital costs of production by 50%.

BP Solar is working to reduce the costs of producing its polycrystalline silicon PV modules and to increase the capacity of its manufacturing plant. The company incorporated the recycling of SiC and oil, and it is using a recently developed optimized wire-saw process. BP Solar has also begun environmental testing of the cells resulting from a new ultrasonic doper and a silicon-nitride deposition system. This past year, the company also studied methods for detecting cracks in wafers and finished cells, analyzed ways to reduce the cost of consumables by at least $0.05/wafer, developed a prototype ultrasonic doper, selected a candidate method for in-line, non-destructive testing of cell interconnects, and selected two candidate fast-cure encapsulant formulations for environmental and outdoor testing.

Evergreen Solar, Inc., produces silicon material called string ribbon to make PV modules. In a continuous process, each machine grows a single ribbon 24 hours a day. For its 10-MW plant, Evergreen plans to install 120 of the new machines it developed in FY 2000. The new machine includes an automatic system to measure ribbon thickness, an algorithm for controlling the thickness, and improvements to the furnace design. The machine can produce material 8 cm wide 30% faster than before. The company developed a new string material and edge-meniscus control method and applied for patent protection of these innovations. These changes in manufacturing have increased run length by 200%, increased cell efficiency by 5%, improved factory yield by 20%, reduced costs of consumables by 60%, and reduced the cost of the new furnace by a projected 20%.

Most of the PV modules manufactured by Siemens Solar Industries are made with Czochralski (Cz) crystalline silicon. The company is working to produce solar cells that are thinner and larger in surface area and that have back-surface field (BSF) processes to increase efficiency. These changes should reduce module manufacturing costs by 30%. To produce the new 17%-efficient thin cells, the company has developed a pilot crystal growth process for silicon ingots that will be sliced into 150-micron-thick wafers and then processed into 125-micron-thick cells. Siemens has also developed a pilot process for fabricating the thin cells so that they have a BSF. In FY 2000, the company demonstrated prototype 125-micron-thick cells that were 16.5% efficient. To produce larger-area cells, Siemens grew a 200-mm-diameter ingot and developed a new fabrication process for 200-mm cells.

Thin-Film Modules
AstroPower, Inc., produces solar cells from sheets of Silicon-Film™ material. This large-area sheet material is produced in a continuous manner that could be compatible with in-line processing. In FY 2000, the company continued its progress toward eliminating all batch process steps, from material growth to solar cell fabrication. The company fabricated cells processed with an in-line water-based cleaning system. It evaluated a prototype in-line chemical etching system to prepare the silicon surface prior to the diffusion step and to remove post-diffusion oxides. AstroPower designed and purchased a prototype in-line diffusion-oxide etch system for processing Silicon-Film™ sheets. Continuous, in-line processing will increase production speed and reduce costs.

Energy Conversion Devices, Inc. (ECD), works with United Solar Systems Corporation to improve the continuous manufacture of a-Si alloy PV modules in the United Solar manufacturing plant. ECD designed, fabricated, and installed a new substrate heating system in United Solar's 5-MW production facility, to decrease production downtime. Other ECD improvements include on-line diagnostic systems, a new process for depositing the back-reflector layer, improved cathode hardware, and new technology for changing substrate rolls. These improvements will be incorporated into equipment for United Solar's 25-MW production facility and should reduce module costs by 25% to 30% and increase manufacturing capacity 60% over 1997 levels.

First Solar, LLC, continued its work on its CdTe thin-film module manufacturing processes. The company adopted a new Underwriters Laboratories (UL)-listed mounting method and developed a new "cord-plate" contact termination method, replacing potted polyurethane termination "pigtails." Testing was completed for an improved module lamination process and a high-throughput solar finishing line that will be used in the First Solar production line. Another production-line improvement is an automated, single-laser scribing system that is up to 10 times faster and shows a 15-fold improvement in registration of consecutive laser-scribe lines over existing systems. First Solar's improved modules passed UL 1703 qualification testing.

Global Solar Energy, LLC, worked to increase the throughput of their manufacturing processes for CIGS thin-film PV modules. A new high-speed scribing process in its manufacturing equipment demonstrated robust and repeatable scribing. Engineers completed analyses and installed production equipment to integrate industrial ink-jet hardware and accomplish high CIS deposition rates. An alternative back-contact material and process for deposition on flexible polymer and stainless-steel substrates increased productivity without reducing product performance.

Spire Corporation sells production equipment for crystalline silicon or thin-film PV module manufacturers. It is developing automated systems that process the edge of modules, install junction boxes, test final modules, and store modules between processing steps. In FY 2000, Spire demonstrated the SPI-BUFFER™ 350, which stacks modules on a cart where they can be stored safely and moved to the next step on the production line. This buffer storage compensates for the batched steps of PV module manufacture. Spire also introduced the SPI-MODULE QA™ 350, a system for transporting, probing, and testing modules for electrical isolation, ground continuity, and performance in the form of current-voltage measurements.

Balance-of-System Components and System Manufacturing Processes
A program of research partnerships to improve manufacturing of the balance-of-system (BOS) components and complete design of solar-electric systems began in 1995. Research aims to develop innovative, low-cost, high-return, high-impact PV products. The work addressed improvements to components such as inverters, efficient integration of components into the system, improvement in the design of systems, and processes to produce cheaper solar-grade silicon for module production.

Applied Power Corporation (APC) (formerly Ascension Technology) manufactures an ac solar-electric module that makes PV truly modular and simplifies installation of systems that are fully compatible with ac appliances and with the utility grid. In FY 2000, the first prototype SunSine® AC module delivered to NREL for outdoor testing showed that inverter efficiency met the project target of 91%. Refining the product's design, the company designed, built prototypes, and began production of a die-cast aluminum enclosure. APC filed two patent applications, one relating to the design of the die-cast enclosure, and the other to the power electronics design and a factory calibration procedure. APC also improved the reliability of its ac modules by incorporating its proprietary Zero Voltage Switching soft-switching into the SunSine® inverter. The company reduced production costs by cutting the number of parts by 57%. To make components smaller, APC reduced the footprint area of the inverter by 45%. The SunSine® AC 325 module passed FCC tests of electromagnetic emissions and underwent the PV Program's Highly Accelerated Life Testing. Near the end of FY 2000, APC began production of 110 units of this new version of its AC module. Of these, 28 were installed at the University of Texas, Houston Science Center.

Crystal Systems Incorporated has developed an effective and simple approach to removing impurities from inexpensive metallurgical-grade silicon to make it comparable to commercially available metallurgical-grade silicon. In FY 2000, the company conducted refining experiments that produced charges to 150 kg. Hot loading procedures for adding feedstock to molten silicon were developed and demonstrated for charges up to 300 kg. With an appropriate crucible, charge sizes up to 500 kg can be refined using the current heat-exchange method (HEM) furnace. Impurities have been removed to acceptable levels so that the approach is consistent with producing solar-grade silicon at a production cost of less than $20/kg.

PowerLight Corporation produces PowerGuard® tiles for rooftop solar-electric systems. The company's process mounts PV modules (crystalline silicon or thin-film) on 3-inch-thick boards of extruded polystyrene foam covered with a cementlike coating. In FY 2000, PowerLight increased production from 200 to 400 tiles per day. The company improved handling and application of the cement coating by designing a new hopper that included pneumatic mixing, easy cleaning, and an electronic motion-control circuit, and it eliminated the need to handle laminates twice by integrating a spacer attachment process into the production line. Other improvements include incorporating electronic sensors to monitor and control steps in the process line, better edge trimmers, and a better hydraulic tool for moving finished tiles to pallets for shipment. In FY 2000, the company estimated an overall cost reduction per board-foot of tile of nearly 60% compared with costs in 1999. PowerLight has increased production capacity from 5 MW to 20 MW per year.

Utility Power Group is completing a factory-assembled PV array, and Trace Engineering is developing companion 12-kW power conversion and energy storage units. The power conversion unit can operate in a grid-tied or stand-alone configuration when coupled with the 13-kW/h capacity energy storage unit. This fully integrated residential PV system will incorporate advanced power management and storage. UPG's PV array design can accommodate PV modules from several different manufacturers, either framed or frameless. Its design uses bolts and a rail assembly to attach the factory-assembled panels to the roof. In a test for planned projects for the Sacramento Municipal Utility District, UPG reported that a crew of two installed 1 kW of PV on a test roof in less than 1 hour.

CONCLUSIONS

Data from 12 PV manufacturers, which participate in PVMaT, show PV manufacturing capacity has increased by more than a factor of seven since 1992, from 13.6 to 99.3 megawatts. Additionally, the weighted-average cost for manufacturing PV modules has been reduced by 36%, from $4.23 to $2.73 per peak watt. Projections through 2005 indicate a steady decline, to an average module manufacturing cost of $1.16 per peak watt at just over 865 megawatts of capacity for these companies. Specific R&D performed by these companies addresses a broad spectrum of problems that have contributed to the existing cost barrier that is preventing the widespread use of PV. Further manufacturing R&D is expected to provide both additional improvements in product quality and reduced cost.

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