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Terrestrial Photovoltaics Technologies – Recent Progress in Manufacturing R&D

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C.E. Witt, T. Surek, R.L. Mitchell,
M. Symko-Davies, and H.P. Thomas

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TERRESTRIAL PHOTOVOLTAIC TECHNOLOGIES – RECENT PROGRESS IN MANUFACTURING R&D

C. Edwin Witt
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, Colorado 80401
Phone: 303-384-6402, Fax: 303-384-6490

Thomas Surek
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, Colorado 80401

Richard L. Mitchell
National Renewable Energy Laboratory, 1617 Cole Blvd.
Golden, Colorado 80401

Martha Symko-Davies
National Renewable Energy Laboratory, 1617 Cole Blvd.
Golden, Colorado 80401

Holly P. Thomas
National Renewable Energy Laboratory, 1617 Cole Blvd
Golden, Colorado 80401

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ABSTRACT

This paper describes photovoltaics (PV) as used for energy generation in terrestrial applications. A brief historical perspective of PV development is provided. Solar-to-electricity conversion efficiencies for various photovoltaic materials are presented, as well as expectations for further material improvements. Recent progress in reducing manufacturing costs through process R&D and product improvements are described. Applications that are most suitable for the different technologies are discussed. Finally, manufacturing capacities and current and projected module manufacturing costs are presented.

INTRODUCTION

A photovoltaic (PV) cell is a semiconductor device that converts sunlight directly into electricity through the Photovoltaic Effect. PV systems (or sometimes just photovoltaics) generally consist of several or many PV cells (usually grouped and packaged into sets of cells called modules), power-conditioning equipment that processes the resulting power into a desirable form for applications, energy-storage equipment if desired, and, sometimes integral support structures. This paper describes the status of present terrestrial PV technologies, recent manufacturing research and development in PV, and some of the many terrestrial applications to which this relatively new technology has been applied. PV module manufacturing capacities and associated costs are also discussed.

PRESENT STATUS OF PHOTOVOLTAIC TECHNOLOGIES

Early R&D work in photovoltaics took place in the 1950s and 1960s and was directed toward developing power sources for satellites (Komp, 1984; Perlin, 1999). Only during about the last 25 years (i.e., since the mid-1970's energy crisis) has R&D been directed to developing PV for the large-scale power production usually associated with terrestrial applications. In the process, 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, etc.). The most important remaining developments for PV terrestrial applications are the lowering of system costs and, ultimately, energy cost through the use of new materials, improved manufacturing processes, more efficient conversion of sunlight to electricity, and ensured long-term reliability.

Photovoltaic technologies can be divided into two main areas: flat-plate and concentrator. In the flat-plate technologies, semiconductor material is used to cover as much area as possible on a flat plate, while practicing tradeoffs between material cost and conversion efficiency of light into electrical power. 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.

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 using a type of vapor deposition or 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 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.

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. Crystalline Silicon PV Conversion Efficiencies (%)

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. Thin-Film PV Conversion Efficiencies (%)

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 the efficiencies are reported at particular concentration ratios since 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 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.

In 1999, the total amount of PV cells/modules shipped, was about 200 megawatts (Maycock, 2000). This number, which represents power generation capability, is based on conditions of approximately one kilowatt of energy falling on one square meter of module surface, plus several other specific conditions relating to environment, such as temperature. The manufacturers then specify a power rating for their cells/module based on its output capability under the specified conditions. If we assume 10% conversion efficiency as the average for these modules, we can estimate the total surface area of the modules produced in 1999 as a little less than 1.5 square kilometers. Approximately 83% of the terrestrial PV cells/modules sold in 1999 were based on crystalline silicon of some form. Nearly one-half of the thin-film products shipped were for indoor use (e.g., watches and calculators). Concentrators accounted for less than 1% of the cells/modules shipped in 1999.

RECENT IMPROVEMENTS IN MANUFACTURING PROCESS

The following are some of the recent R&D advances resulting from a major federal government/industry partnership known as the Photovoltaic Manufacturing Technology Project (PVMaT). PVMaT is administered through the Department of Energy and its federal laboratories, the National Renewable Energy Laboratory and Sandia National Laboratories and has existed since initial U.S. Congressional funding in 1991. The R&D is cost-shared by DOE and the individual industry participants performing the activity. The work described is not inclusive of all the types of activity performed either by industry as a whole or even 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), Witt (1998), and Witt (1999).

ASE Americas Inc. is working on improvements in process integration and in the implementation of Statistical Process Control and data systems. Improvements are directed at reducing yield losses in areas of electrical and mechanical performance and reducing chemical waste. This effort includes work in laser-cutting technology to increase speed for cutting wafers and R&D to ensure a stronger edge-defined, film-fed growth (EFG) wafer and improve cell processing to achieve 15% solar cell efficiencies. They have successfully deployed new high-speed lasers and nozzle designs on a laser wafer-cutting system with the potential to decrease cutting labor costs by 75% and capital costs by a factor of two. Also, they have designed, constructed, and tested a 50-cm-diameter, EFG cylinder crystal growth system to successfully produce thin cylinders up to 1.2 meters in length and down to 100 microns in wall thickness.

AstroPower, Inc., is improving their flexible manufacturing system for Silicon-Film™ solar cells. During the past year, they have extended their continuous processing from Silicon-Film™ sheet fabrication to solar cell fabrication steps. Their goals are to achieve large-area (900-cm^2), 12%-efficient (10.8-W) solar cells. Recently, they have fabricated cells processed with in-line water-based cleaning, completed construction and evaluation of a prototype in-line surface etch system, designed and purchased a prototype in-line diffusion-oxide etch system for Silicon-Film™ plank processing, and designed a prototype process for production of PV-grade silicon from metallurgical-grade silicon.

Evergreen Solar, Inc. is improving their string-ribbon crystal-growth process by reducing labor and material costs and capital costs of additional furnaces, and by increased automation and efficiency. Accomplishments include the development of a new string material and edge meniscus control (patent filed), reduced consumable costs, and the design and construction of a lower cost, automated crystal-growth machine. Results of all these are a 200% increase in run length, a 5% increase in cell efficiency (relative), a 20% improvement in total factory yield, a 60% reduction in consumable costs, and a 20% (projected) reduction in new furnace costs.

PowerLight Corporation produces a PV system that mounts PV modules (crystalline or thin-film) on a 3-inch-thick styrofoam board coated with a proprietary cementitious coating. The system can be mounted on any flat roof and installed with flat or sloped PV tiles. PowerLight is boosting their PV manufacturing capability by improving the sequential integration of semi-automated and automated component stations in the existing manufacturing line for their PowerGuard® rooftop product. They have reported achieving a reduction from $5.80/W to $4.80/W total costs for installed PV systems of 250 kW or larger. In addition, during this same period of time, they have increased their production capacity from 5 to 20 MW per year.

Siemens Solar Industries is concentrating their research on the development and integration of new optimized cell fabrication processes into their manufacturing line for the production of 17%-efficient, 125 micron-thick cells. They are also developing large-area cell production capability for 200-mm-diameter, 4.5-W prototype solar cells and low-cost prototype modules. To date, they have completed development of a pilot crystal-growth process for quality ingots to be sliced into 150-micron wafers and then processed into 125-micron cells, completed the development of an auto-boating process for 150-micron wafers, demonstrated prototype 125-micron 16%-efficient solar cells, and completed the development of a pilot process for fabricating 125-micron-thick, back surface field (BSF) solar cells. They have also demonstrated the ingot growth of 200-mm-diameter Czochralski (Cz) silicon and initiated the development of a 200-mm-diameter cell fabrication process.

Spire Corporation is addressing automated photovoltaic module assembly. They are developing a series of automated, flexible systems, including 1) an integrated module-edge processing system, combining automated edge trimming, edge sealing, and framing processes, 2) an automated junction-box installation system, 3) a final module test system combining high-voltage isolation testing and performance testing in a SPI-SUN SIMULATOR™, and 4) an automated buffer storage system. The systems will be capable of assembling modules made with either crystalline-silicon solar cells or thin-film solar-cell laminates. Spire has developed the module buffer storage system with a conveyor load/unload. It is called the SPI-BUFFER™ 350. Modules are stacked vertically on a cart for mobility and high storage density. This system has a conveyor speed of 20 cm/s, a storage capacity for modules up to 102 cm x 162 cm, and a storage depth of 51 cm. Spire has also developed a system, the SPI-MODULE QA™ 350, for transporting, probing, and testing modules for electrical isolation, ground continuity, and performance (current-voltage measurement). Both of these developments were demonstrated to the PV industry in June 1999.

APPLICATIONS

PV systems may be used for almost any situation requiring electrical power. Systems may be designed to be either tied to or independent of the utility grid. They may or may not possess energy storage capability. The power conditioning associated with the system can scan a broad spectrum of sophistication and is determined by the ultimate requirement in terms of D.C. or A.C. purity. The size of the application may vary from milliwatts (as in a calculator) to kilowatts (as in grid-tied, commercial-roof mounted generating stations) or megawatts and larger (as envisioned with central-station generating systems). Consequently the list of applications is long and includes rural applications such as electric fences, water pumping for livestock, and irrigation; remote applications such as village power, telecommunications, and signaling; and grid-connected power generation on commercial and residential buildings. The size and penetration of specific application-related markets will depend on costs. Consequently, the following section presents some historical data on module manufacturing costs and a related factor, manufacturing capacity – both existing and projected. Obviously, the relation between module manufacturing costs and systems prices will depend upon many factors such as the system components, dealer mark-up, etc. Such analysis is beyond the scope of this paper. For information on system specifics, the reader can contact PV manufacturers directly. A list of manufacturers can be found in "United States Renewable Energy Manufacturers & Service Providers," a document published by the International Programs Office at the National Renewable Energy Laboratory (1999).

MODULE MANUFACTURING CAPACITIES AND MANUFACTURING COSTS

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 Program. 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.

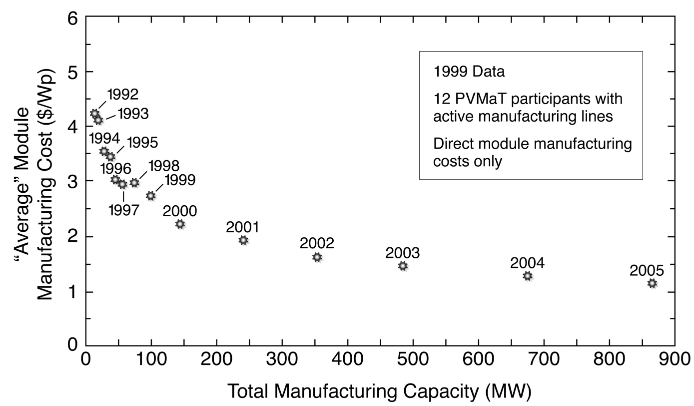

Figure 1. PVMaT Manufacturing Cost/Capacity

CONCLUSIONS

Significant manufacturing R&D advancements in photovoltaics have been made in the last 10 years. During this period, the cost of manufacturing PV modules has also been reduced. As a result, new applications and markets are being penetrated by PV systems. We now see a developing renewable energy technology that provides the promise of a secure and unlimited power source. Free-market parameters will determine the ultimate success of this technology, and continued R&D improvements are expected to further enhance PV potential.

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