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PHOTOVOLTAICS OVERVIEW

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ABSTRACT

This paper first discusses some of the basic concepts underlying photovoltaic system operation including the photovoltaic effect, reponse to solar radiation, cell materials, efficiency, operating characteristics and manufacturing processes. System components are considered next, including stationary and tracking flat-plate arrays, concentrating arrays, storage and power conditioning equipment. Both stand-alone and grid-connected applications are discussed and the paper concludes with a brief look at industry trends and prospects.

FUNDAMENTALS

Background

In 1960, photovoltaic cells were essentially hand-made, cost approximately $1000 per watt of power and were used almost exclusively for space applications. In 1970, cells were manufactured in batch processes, cost approximately $100 per watt, were primarily used in space applications but were making an entry into remote applications. In 1980, larger quantities of cells were produced in larger batch processes, cost approximately $10 per watt, saw significant terrestial applications (primarily stand-alone, remote devices) and began to be used for grid-connected residential applications. Today we are on the threshold of continuous process manufacturing and cells are being purchased (in large orders) for approximately $5 per watt. There are several thousand (mostly very small) residential systems and one (1 MW) central power station in operation and two under development--all in California. In addition, there is a rapidly growing market for photovoltaic consumer products such as watches, calculators, radios, televisions, battery chargers, etc., that is primarily being met by the Japanese.

Photovoltaic Effect

Photovoltaic cells are devices which convert light into electricity. Because the source of light (or radiation) is usually the sun, they are often referred to as solar cells. The word photovoltaic comes from "photo," meaning light, and "voltaic," for voltage. The output of a photovoltaic cell (or a connected array of cells) is direct current electricity.

The direct energy conversion of light to electricity is referred to as the photovoltaic effect and was first reported in 1839 by a Frenchman named Becquerel, who observed a difference in electric potential between two electrodes immersed in an electrolyte that varied with light intensity. Although there were many significant historical developments between 1839 and the present, most discussions of photovoltaics and the modern silicon cell date back to 1954 and work done at Bell Labs.

The Sun as a Source of Power

Although artificial light can be used to power photovoltaic devices, their value lies in their ability to utilize free and renewable sunshine. A photovoltaic device in earth orbit that maintains normal incidence to the sun's rays receives approximately a constant rate of energy. This amount, called the solar constant, is 1.353 kW/m^2 (428 Btu/hr. ft^2).

The solar constant and the associated solar radiation spectrum immediately outside the earth's atmosphere is determined solely by the nature of the radiating source (i.e., the sun) and the distance between the earth and sun. Because there are no effects due to air attenuation, this condition is referred to as air mass zero (AM0).

Terrestial applications of photovoltaic (or any solar) devices are complicated by two factors: 1) the earth's rotation about its axis and 2) atmospheric effects. The earth's rotation produces hourly variations in power intensities at a given location on the ground and completely shades the device during nighttime hours. In addition, a device located in the northern hemisphere receives more energy during the summer than in the winter, thus giving rise to seasonal variations in power intensities.

The presence of the atmosphere and associated climatic effects both attenuate and change the nature of the resource. The combination of reflection, absorption (filtering), refraction and scattering results in highly dynamic radiation at a given location on the earth's surface. Because of cloud cover and scattering of sunlight, the radiation received at a point is made up of both direct (or beam) sunlight and diffuse (or scattered) sunlight. This distinction is important because both concentrating and tracking flat-plate devices rely on their ability to focus direct sunlight. There is a considerable regional variation in the amount of direct radiation received, with the desert southwest receiving the most. Consequently, many of the initial applications of concentrating and tracking flat-plate devices have been located in California, Arizona and New Mexico.

Air mass, defined as $1/\cos\theta$ (where θ is the angle between the sun and directly overhead) is a useful quantity in dealing with atmospheric effects. It indicates the relative distance that light must travel through the atmosphere to a given location. Air mass one (AM1) is a reference condition and corresponds to the sun being directly overhead. The spectral distribution of sunlight can be plotted for various air mass values, thus providing a useful indication of atmospheric attenuation effects.

The results of rotational and atmospheric effects at various locations has led to essentially two types of radiation data--hourly and average daily.

Typical meteorological year (TMY) data is hourly solar radiation data based on statistical analysis of several years of measurements and is available for 235 cities from the National Climatic Center. Hourly data is used with the more sophisticated computer simulation programs.

The second type of solar radiation data, average daily, is useful for predicting long-term performance and for economic analysis. It is available from the Solar Energy Research Institute (Insolation Data Manual).

The amount of terrestial power received on a properly tilted surface on a clear day is approximately 1 kW/m^2, which is referred to as 1-sun. Note that it is considerably less than the solar constant (1.353 kW/m^2). This is indicative of the attenuating nature of the atmosphere. If we have 1 kW/m^2 of sunlight for 1-hour, we receive 1 kwh/m^2 of energy. For a typical day in the sunbelt, we receive about 5-5.5 kwh/m^2 per day, which is equivalent to saying we receive 5-5.5 peak sun hours per day.

Cell Materials

A variety of semiconductor materials are used in fabricating photovoltaic cells and modules. These include single crystal silicon, polycrystalline silicon, amorphous silicon and a large number of advanced technology materials--most notably cadmium sulfide and gallium-arsenide. Only single crystal and polycrystalline silicon cells will be discussed in this report because of their advanced stage of development.

Polysilicon is the feedstock for the production of high quality single crystal silicon sheet. Currently, polysilicon costs about $60 to $70 per kilogram. The national goal is to reduce this cost by about a factor of three by 1990.

Modules and Arrays

A typical solar cell produces approximately 0.5 volt and a current that depends strongly on the intensity of the sunlight. In order to get more useable values of voltage and current, solar cells are connected in series to increase voltage, and the series of cells are connected in parallel to increase current output. Twenty to sixty or more cells are packaged together with a tranparent cover (usually glass) and a water-tight seal to form a module or panel. In turn, these modules are wired together in a series - parallel combination that best meets the needs of the application.

Operating Charactersistics

The most important performance parameter for a photovoltaic module is its current-voltage (or I-V) characteristic. For given insolation, the operating voltage and current vary with load. Current will vary from zero (corresponding to infinite load or open circuit) to a maximum, called I_{sc} (corresponding to zero load or short circuit). The maximum operating voltage, V_{oc}, corresponds to open circuit conditions and the minimum voltage is zero at the short circuit condition. Thus I_{sc} and V_{oc} are two limiting parameters that are used to characterize a photovoltaic module for a given amount of insolation.

The maximum power point is the desired operating point for a PV-array (or module or cell) and corresponds to the current and voltage on the I-V curve which produces maximum power.

The fill factor is an operating characteristic which indicates the performance quality of a module. It is the ratio of the maximum power and the product of I_{sc} and V_{oc}.

The operating temperatures of solar cells are important in that high operating temperatures have a negative effect on both power output and long-term durability. The nominal operating cell temperature (NOCT) is the temperature that a cell would operate at under standard conditions.

Commercially available silicon cells have efficiencies as high as 15 percent. Laboratory efficiencies of over 20 percent have been achieved. Considerable research is in progress to improve efficiency, verify performance, lower production costs and increase reliability and durability.

MANUFACTURING OF CRYSTALLINE SILICON CELLS

Czochralski Process

The standard method of growing single crystal silicon from a molten bath is called the Czochralski process. A relatively small amount of polysilicon is placed in a crucible in a vacuum furnace to produce a silicon melt. A solid single crystal seed is lowered into the bath, rotated slowly and pulled upward. The molten silicon adheres to the seed and solidifies as it is drawn out, forming a cylindrical ingot. The crystalline structure of the grown ingot conforms to that of the seed material.

The pure silicon ingots are generally 8 cm in diameter and 75 cm in length. The ingots are sliced into very thin wafers, losing about half of the valuable silicon in the process.

In order to improve the prospects for Czochralski cells, larger ingots (say 15 cm diameter, 150 kg) need to be grown per unit of time and improved multi-slicing techniques must be developed.

Edge-Defined Film-Fed Growth Technique

This process, being developed by Mobil Solar Energy Corp., uses the growth of single crystal ribbons to make cells. A die is partially immersed in molten silicon and capillary action causes the silicon to rise and form a solid ribbon in the die. The ribbon is continuously withdrawn and wrapped on drums.

For the future, machines must be developed which can produce multiple ribbons (say ten per machine) at a more rapid rate. Ribbons have the advantages of not wasting material in the slicing process and of packing the rectangular modules much more densely than the circular cells.

Dendritic Web Process

Westinghouse is developing relatively high efficiency single crystal cells (i.e., 15 to 16 percent) using a ribbon process that utilizes surface tension properties rather than capillarity. Two dendrites are lowered into molten silicon and withrawn producing a superior ribbon material with controllable thickness and uniformity.

Automated machines that can continuously produce ribbon at high production rates must be developed.

Heat Exchange Method (HEM)

The heat exchange method, being developed by Crystal Systems, Inc., uses a casting process which produces a square ingot of crystalline silicon. The ingot is mostly single crystal except near the edges. The ingot is sliced into square wafers that allow for densely packed modules. Average cell efficiencies of about 11 percent have been produced, with some cells reaching efficiencies as high as 15 percent.

Larger ingots possessing more than 90 percent single crystal material must be produced in the future for this process to approach acceptable costs.

Silicon on Ceramic (SOC) Process

Honeywell is developing the SOC process to produce large grained, polycrystalline sheet silicon. The process uses ceramic substrates to support growth of silicon from the melt. A carbon wetting agent coats the ceramic substrate which is exposed to molten silicon as it moves past a fused-silica trough. The molten silicon solidifies into a layer on the ceramic material. Efficiencies of about 10 percent have been achieved. Continuous processing at high rates and higher efficiences are required for future marketability.

ARRAY TYPES

There are two basic types of arrays: flat-plate and concentrating. Flat-plate arrays utilize both diffuse and direct sunlight and can operate in either a fixed orientation or in a sun-tracking mode. For most applications, flat-plate arrays are fixed in orientation with the exception being central power station production of electricity in the southwest U.S.

Photovoltaic concentrators use only direct (beam) radiation and require sun-tracking. Because of the high temperatures resulting from concentration, they are cooled--either passively or actively.

Photovoltaic concentrator technology can be broadly divided into two classes: baseline PV concentrators and advanced PV concentrators. Baseline concentrators use planar-junction silicon cells and either linear (25 to 75x concentration ratios) or point-focus (50 to 250x concentration ratios) Fresnel lenses. Maximum annual efficiencies are about 15 percent

Advanced concentrators use more exotic cell materials such as Aluminum-Gallium-Arsenide or non-planar silicon cells or multiple junction devices. Concentration ratios are from 500 to 1000 x. They use point-focus Fresnel lenses, domed or curved facet, often with secondary focusing. The goal is to achieve annual conversion efficiencies of greater than 20 percent.

SYSTEM COMPONENTS

Storage

Batteries have been used as the principal means of electric energy storage for photovoltaic systems. Lead-acid batteries are the most commonly used type, but nickel-cadmium batteries have also been used. The more promising of the new battery systems include zinc-chlorine, sodium sulfur and lithium-iron sulfide. In order to provide storage at an attractive price, the cost of batteries must decrease by a factor of three and the discharge life must be increased from about 1500 to 3000 cycles.

Other storage options include pumped water, compressed air, flywheel and thermal storage.

Power Conditioning

For simple systems with direct current loads and battery storage, the only type of control that is required is voltage regulation. However, an inverter is required for any system producing an alternating current output. The inverter may be self-commutated or, if grid-connected, line-commutated. The inverter simply converts from direct to alternating current. The quality of the ac-signal produced is important in that poor signal quality may be unacceptable on the utility grid and may also cause damage to equipment. Consequently, harmonic distortion is often an important consideration in selecting an inverter. New inverters have decreased the total harmonic distortion by an order of magnitude over their predecessors and high quality signals are easily obtainable (i.e., less than 2 percent THD). Cost of these inverters, however, must be reduced by a factor of 2 to 3.

STAND-ALONE APPLICATIONS

In addition to space vehicles and satellites, stand-alone applications of photovoltaics include remote telecommunications systems, transportation aids and warning signals, buoys and other navigational devices, cathodic (corrosion) protection of bridges and pipelines, remote sensing stations, water pumping and irrigation, small systems for cabins and homes, battery chargers and various consumer products, and village power systems. These systems have proven to be extremely reliable. Usually they have some form of storage and/or backup energy supply. Battery storage is most common for smaller systems and diesel generators often provide backup for larger stand-alone systems.

There are many small lightweight portable photovoltaic devices that operate at power levels usually less than 100 watts. These include digital watches, clocks, radios, televisions, caboose lights for trains, portable military communications systems and small battery chargers.

GRID-CONNECTED RESIDENTIAL APPLICATIONS

In contrast with stand-alone systems which are often remote and for which it is usually impractical or uneconomic to tie into the utility, grid-connected photovoltaic systems must compete directly with conventionally produced electricity. The combination of high photovoltaic system costs and relatively low costs for competing resources make residential applications uneconomical at present. However, there are good indications that significant reduction in PV-systems costs are imminent as larger scale production facilities come on line.

Residential Systems Research Needs

Assuming that the cost of residential photovoltaic systems will decrease significantly during the 1980s, the following research needs must be addressed to adequately prepare for their commercialization:

- o The solar (and hence photovoltaic) resource must be well defined at various locations throughout the U.S. using long-term monitoring.
- o The performance, reliability and durability of residential photovoltaic systems must be evaluated using both controlled laboratory and field experiments.
- o Various modules, mounting strategies and power conditioning equipment must be evaluated under controlled test conditions.
- o Failure mechanisms in subsystems and components must be identified, verified and reported to manufacturers.
- o Safety, maintenance and reliability requirements for photovoltaic systems operating in a grid-interactive mode must be established.
- o Analytical models must be validated and improved by comparing results with measured data.
- o Residential building designs that increase the direct utilization of PV-generated power must be developed.

Utility Research Needs

Important utility concerns that need to be addressed include:

- o Fault protection and safety.
- o Current and voltage harmonics and overall signal quality at the inverter output.
- o Voltage regulation and reactive power compensation.
- o Isolated operation (or islanding) of multiple PV-systems on a given feeder line.

Residential Experiment Stations

To address many of the research needs of the previous two sections, the U.S. Department of Energy, in conjunction with Sandia National Laboratories (Albuquerque), has funded the operation of three photovoltaic residential experiment stations (RES).

The Southwest RES is located in Las Cruces, New Mexico and is operated by the New Mexico Solar Energy Institute. Eight prototype systems are currently in operation in order to evaluate performance in an extremely hot, dry and high insolation environment.

The Northeast RES in Concord, Massachusetts is operated by the Massachusetts Institute of Technology Energy Laboratory. Five prototypes are evaluating performance in an environment typical of northeast and midwest climates.

The Southeast RES was recently established in Cape Canaveral, Florida and is operated by the Florida Solar Energy Center. In addition to a full-scale photovoltaic house and a flexible subsystem test facility, five prototypes will be constructed over the next two years to evaluate performance in a warm, humid, ocean-salt environment that experiences numerous summer thunderstorms. Georgia Institute of Technology is a partner in the SE RES project and is responsible for monitoring nine photovoltaic systems throughout the region. In addition, Georgia Tech is leading utilities-related research efforts. Other important participants in this project include the Alabama Solar Energy Center, Georgia Power Company, Tennessee Valley Authority, Southern Company Services, Inc., Florida Power and Light Company, Florida Power Corporation, Tampa Electric Company and Jacksonville Electric Authority.

CENTRAL POWER STATIONS

Three utility companies are vigorously pursuing photovoltaic central power stations. Southern California Edison recently dedicated a 1 MW flat-plate two-axis tracking facility in the California desert. In addition, the Sacramento Municipal Utilities District and the Pacific Gas and Electric Company are both developing large (i.e., 1 MW or greater) central systems.

PHOTOVOLTAIC MARKETS

Total worldwide shipments of photovoltaic modules in 1982 are estimated at approximately 9 (peak) megawatts. The U.S. controls about 60 percent of this market, Europe 19 percent, Japan 19 percent, and others 2 percent. This includes flat-plate modules, concentrators and consumer products. For 1983, it is projected that over 14 megawatts will be sold.

At the February 1983 Photovoltaics Program Review Meeting, the U.S. Department of Energy offered the following conclusions concerning industry and product trends:

- The volume of sales continued to increase in 1982 with a 53 percent increase over 1981 despite poor economic conditons.
- Prices, particularly of larger purchases, continued to decline. The $5 per peak watt price barrier was broken.
- Japanese companies became active competitors in traditional market segments and currently dominate the consumer products market.
- The U.S. photovoltaic industry is still not profitable, but 1983 is expected to be a good year.
- The industry attracted considerable risk capital in 1982, even though it was a recession year.
- Many new small manufacturing companies were formed overseas.
- Second generation Fresnel lens will be introduced in 1983.
- The durability of modules continues to improve as does module efficiency. Module efficiencies of 9.5 percent are common and 11 percent are readily available.

In summary, photovoltaics technology is rapidly advancing along many fronts and future prospects for a properous photovoltaics industry are very good.

REFERENCES

1. Backus, C.E., Photovoltaic Technology Assessment, Solar Technology Assessment Project, Florida Solar Energy Center, Cape Canaveral, FL, April 1981.

2. Boes, E.C., Photovoltaic Concentrator Technology Development, presented to the Solar Research and Development Panel, Energy Research Advisory Board, Albuquerque, NM, July 13, 1982.

3. Designing Small Photovoltaic Power Systems, Second Revised Printing, Monegon Publication No. M111, Monegon, Ltd., Gaithersburg, MD, February 1982.

4. Green, M.A., *Solar Cells*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1982.

5. Krantz, A.D., Industry Trends, Photovoltaics Program Annual Review, Arlington, VA, February 15-16, 1983.

6. Maycock, P.D., DOE Program Review Special, Photovoltaic News, Alexandria, VA, February 15-16, 1983.

7. Maycock, P.D. and Stirewalt, E.N., *Photovoltaics*, Brick House Publishing Co., Andover, MA, 1981.

8. Research Plan, Photovoltaic Southeast Residential Experiment Station, Florida Solar Energy Center and Georiga Institute of Technology, Cape Canaveral, FL, December 10, 1982.