OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

FAIR USE POLICY

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

19244

United Nations Industrial Development Organization

Distr.
LIMITED

ID/WG.519/7(SPEC.)
14 October 1991

ORIGINAL: ENGLISH

Expert Group Meeting on
Processing and Application of
New Materials

Vienna, Austria, 4-6 November 1991

PHOTOVOLTAIC SOLAR ENERGY DEVICES: MATERIALS RESEARCH AND APPLICATIONS*

Prepared by

B. L. Sopori**

* The views expressed in the document are those of the author and do not necessarily reflect the views of the Secretariat of UNIDO. Mention of the names of firms and commercial products does not imply endorsement by the United Nations Industrial Development Organization (UNIDO). This document has not been edited.

** National Renewable Energy Laboratory, Golden, CO 80401, U. S. A.

V.91-29727

ABSTRACT

Research in solar cells spans over a variety of materials systems including Si, GaAs, GaInP, InP, CdTe, $CuInSe_2$ and α-Si. The device designs for solar cells have now been well established and have been applied to fabricate high efficiency laboratory devices on high quality materials. For example, single junction silicon solar cells with best efficiency of 22.4% under 1-sun illumination, and 29% under concentrated sunlight have been fabricated. Likewise, GaAs based cells with efficiency greater than 30% under 1-sun have been demonstrated. Thin film polycrystalline solar cells are now considered potential low-cost technologies for photovoltaic modules. Commercially, photovoltaic modules based on crystalline silicon, polycrystalline silicon, amorphous silicon, and gallium arsenide are available for a variety of applications. The performance of commercial solar cells is primarily limited by their material quality. Hence there is considerable emphasis within the materials research program to develop technologies that can produce high quality materials at lower costs which, in turn, can allow photovoltaic energy to be produced at costs comparable to that from the other energy sources.

This talk will review material requirements for high efficiency photovoltaic devices and discuss current research directions and identify critical areas which must be developed in the near future for commercial use of photovoltaic systems. A discussion of various everyday-life applications of photovoltaic technology will be presented. We will discuss particular needs in the developing countries for photovoltaic power systems.

INTRODUCTION

It is recognized that in order to meet the energy demands of 1990's and beyond, the new sources of energy have to be explored. It is expected that nearly 600 GW of new generating capacity may be needed worldwide between now and year 2000 (1-3). The estimated need for the new generating capacity in the U.S is expected to be 100GW. The developing countries are expected to require about 350 GW of capacity with India and China accounting for over 50% of this increase. Although it appears that much of these needs can be met by thermal generation using gas fired plants (35%), coal(19%), nuclear(15%), hydroelectric(5%) and others, there are increasing demands that the environmental issues associated with these sources of energy be considered. The general trends are expected to be: to switch from fossil fuel to use of low carbon dioxide releasing fuels such as methane, increased use of wind and geothermal energy, increase in the use of solar thermal energy, and increased use of solar electric in suitable applications. Concomitantly, there is considerable emphasis towards developing renewable, non-fossil fuel based energy generating systems which include solar, wind, geothermal, biomass and other renewables.

Use of solar energy is becoming particularly attractive as the demands on energy consumption in the world increase and as the "true costs" of the conventional sources of energy are being recognized. These true costs take into account costs of waste disposal, impact on the environment and safety. Clearly, conversion of solar light into electricity, i.e. Photovoltaics (PV), could be a viable option if the cost of PV energy can be lowered to level of conventional energy costs. During the past decade photovoltaic (PV) power technology has experienced considerable gains both in performance improvement and the cost reductions. In this presentation we will focus on the emerging technologies of photovoltaics. This paper will address the issues related conversion of solar light into electricity and its applications for near-term and long term markets, with an emphasis on the potential in developing countries.

PHOTOVOLTAIC POWER SYSTEMS

Photovoltaic devices and power systems offer some unique advantages that place them in favorable position for many applications ranging from small power devices such as watches and calculators, to utility power systems. These are: modularity, scalability and environmental compatibility.

The photovoltaic systems are all solid-state systems which convert sunlight to dc power. Typically a PV power system may consist of arrays of photovoltaic modules to generate the power, the power conditioning unit that may include regulators, dc-to-ac converters and other power control devices, and the load. The PV modules for terrestrial power generating systems are of two types: flat plate and concentrator systems. The flat plate modules normally operate at one sun illumination conditions and are placed at a fixed location with an inclination that maximizes the incoming flux (insolation). In some newer designs, the flat-plate systems may be also be designed for low concentrations, typically 10X. A flat-plate system has no moving parts, thus offering very high reliability. The concentrator systems, by their design must track the sun in order to focus energy on the photo-electric converter cell. Even in the concentrator systems involving tracking, a high degree of reliability is expected. In fact, the photovoltaic systems are designed for a 20-year life expectancy. This simple operation ensures low operating and maintenance costs.

Another feature of PV power is the ease of scalability, allowing power systems to be readily deployed in different sizes, with short construction times. This permits larger systems to be assembled from smaller modules. Hence, experience, test information, and economic data obtained from modular segments can easily be translated to large systems. Perhaps the most attractive feature of PV systems is the environmental compatibility. In a PV power system no pollutants are released during its operation, posing no threat to the global warming, no fuel is consumed during operation, and the systems are "quiet". Thus, the impact on the environment is minimal. This is also true for fabrication of PV modules because the existing semiconductor industry has already established ways of affluent disposal that do not threaten the environment.

The primary component of a photovoltaic system is the energy delivering photovoltaic module or a string of modules. Each of the modules is typically standardized for specific system applications. For example, a system for 12 volt battery-charging application may deliver a 14-16 volts at the peak input power, i.e. with the highest available intensity of the sun, whereas a module for utility power application might be rated at 48 volts. Each module has two-dimensional array of solar cells, encapsulated within the module to protect it from environment such as moisture, snow, hail, rain, wind etc. The PV modules utilize series-parallel arrangement of solar cells to match the output currents and voltages to the desired load conditions.

At this time the PV technology is not cost-competitive with other sources of electricity for utility market. However, as the module efficiencies improve and the production levels (MW/year) increase , the PV energy costs are expected to reduce. The cost of a PV module that can deliver certain energy is also related to the efficiency of the module. Figure 1 shows the module costs ($\$/m^2$) as a function of levelized electricity costs and various efficiencies for (a) fixed-place, and (b) concentrator systems (4). The cost target for the PV generated electricity is established using estimates of the conventional fuel and the capacity of the photovoltaic units it can displace, and is constant at $0.06/kWh in 1986 $U.S. However, there are already many other applications where PV can provide electricity in a cost-effective manner. These are discussed in a later section.

PHOTOVOLTAIC DEVICES

It has been well recognized that semiconductors like GaAs, CdTe and Si are among the most suitable materials for efficient photovoltaic conversion of solar energy. These choices are based on the appropriateness of their band gaps to match the solar spectrum. Recently, InP has been added to this list because its high radiation resistance which makes it well suited for space applications. During the past decade several cell designs have emerged and many techniques for cell fabrication have been well developed. GaAs and Si have received particular attention because of already existing high levels of processing technologies. Advances in these technologies have also made it possible to design and fabricate multijunction (MJ) cells. Furthermore, there has been increasing emphasis on developing polycrystalline thin films, of which the most promising appear to be CdTe and $CuInSe_2$. Another material system that has resulted in commercial modules is based on amorphous silicon.

In recent years there have been many advances in the photovoltaic devices which has led to fabrication of highly efficient solar cells and developed a commercial market for a variety of applications. The laboratory demonstration of high efficiency devices is indicative of the fact that a great deal of knowledge has been acquired to design such high efficiency devices. The current technology, although far from being cost-effective in many applications, already has markets where photovoltaics can offer economic viability. However, much of the future efforts need to be diverted for commercialization of the PV technology so as to lower the module costs. One of the main approaches to accomplish cost reduction is to develop materials technologies that can produce uniform, large-area photovoltaic devices of high material quality. The material technologies are particularly important in thin-film based systems where traditional distinction of material costs and process costs essentially disappear.

CURRENT STATUS OF SOLAR CELLS

Since photovoltaics is still an emerging technology, its progress in the research side and in commercial production should be evaluated separately. In the research side, new cell designs and development of laboratory scale technologies for cell fabrication have permitted single crystal cells to reach performance approaching theoretical limits. For example best efficiencies reported in single junction cells of silicon, GaAs and InP, under one sun (AM1.5) illumination, are 22.3%, 25.0% and 20.4% respectively. Higher conversion efficiencies have been obtained for concentrated light. There has also been a rapid progress in the polycrystalline thin film cells. In particular CdTe and $CuInSe_2$ (CIS) have emerged as very promising materials with potential for low-cost fabrication technologies. Large-area (1 sq.ft) modules of CdTe have shown efficiencies upto 8.1%, whereas small area cells have shown efficiency of 13.4%. $CuInSe_2$ module, of 4 sq.ft aperture area, of 9.7% efficiency has been obtained.

Although solar cells based on a variety of different material systems are being fabricated in the laboratory, there are only three types of material based cells commercially manufactured. These are: crystalline and polycrystalline silicon, amorphous silicon, and gallium arsenide material system. On the commercial side the module costs of photovoltaic panels, primarily based on crystalline and α-Si, have come down to $4-$5 / Watt. In addition several new methods for material growth for Si and GaAs have been developed which have potential of meeting the cost goals for being competitive with other sources of energy.

A quest for developing even more efficient conversion devices has led to fabrication of multijunction (MJ) cells. Multijuction devices utilize spectral splitting between the cells so as to match the response of each cell with its illumination spectrum in order to obtain the optimal performance. This necessitates that the top cell be transparent to longer wavelength illumination used for the bottom cell(s). In general, it is believed that two junctions are required to derive sufficient benefit from the complexity of the structure. Two approaches employed in MJ configuration are: (1) Mechanically stacking and (2) Monolithic assembly. It has been determined that for the optimum performance the band-gaps of the top and the bottom semiconductors should be ~ 1.7ev and ~ 1.2 ev, respectively. Multijunction cells based on crystalline semiconductors have already demonstrated efficiencies exceeding 30% For example, mechanically stacked cells of GaAs/Si and GaAs/GaSb have shown efficiencies of 31% and 34% under one sun and concentrated illumination respectively. Likewise, monolithic multijunction cells of AlGaAs/GaAs and InGaP/GaAs of efficiencies 27.6 % and 27.3% respectively have also been fabricated.

SOLAR CELL DESIGNS

A typical solar cell consists of a PN junction illuminated to produce photovoltaic power. The parameters of such a device may be categorized into two groups: (1) Optical and (2) Electronic. The optical design involves development of methods that can effectively capture the incident broad-band optical flux and improve the flux distribution so as to create the most useful distribution of photo-generated carriers. The electronic design pertains to the most efficient collection of photo-generated carriers and minimization of carrier recombination in the bulk and at the surfaces of the cell.

The optical design involves several features that can allow improved light transmission into the cell. These features are:
a. Reduction in optical reflectance at the front surface of the cell. A conventional approach to accomplish this is by depositing single or two-layer anti-reflection coating(s). Design of such a coating for minimizing reflectance in certain wavelength region, is well known in optics; however, in a solar cell they are designed to optimize the short circuit current. Another approach applied to some solar cells involves using rough or textured surfaces to lower the surface reflectance. These approaches are extensively used in silicon solar cells since they can be produced by chemical etching . An added advantage of texturing is that it converts normally incident light to oblique incidence within the cell, which can lead to increased effective absorption and light trapping. Texturing has also been effectively used in α-Si and other polycrystalline thin films.

b. Application of light trapping for thin film silicon solar cells is expected to lead to very high efficiency solar cells even on low-quality material. Consequently, there is much interest in developing techniques for thin film silicon solar cells.

c. Another feature in optical design is minimization of the shadowing due to metal contacts. Typically a suitable grid design involves a compromise between the series resistance of the cell and the optical shadowing. Two approaches used to overcome this problem are the following. In one case the contacts (and the junction) are located on the back-side of the cell leaving the entire front surface for optical collection. This design requires that the minority carrier diffusion length in the base region be very large. The other approach is to employ a prismatic cover on the cell in a way that the cover deflects light above the metal grid into the open cell regions.

The electronic design of the cell emerges from the requirements of maximization of the photo-generated current and minimization of the dark current. These requirements are such that many of them complement each other. For a given semiconductor the electronic parameters for high efficiency design require: (1) low bulk recombination, (2) low carrier recombination at each interface, (3) reduced metal/semiconductor contact area. In addition , the emitter design must minimize the injection component of the cell dark current.

MATERIALS RESEARCH

In order to lower the cost of PV modules, the materials research is pursued along two approaches: (1) Utilize lower cost materials and processing techniques to produce PV modules with conversion efficiencies lower than obtainable from best devices, and (2) Utilize highest quality crystalline semiconductors to obtain highest efficiency cells so that over-all module cost of $/W can be reduced. In the former case it is expected that the lower cost of PV panels deploying low-cost polycrystalline materials (in thin film form) will allow significant cost reductions. The latter approach recognizes that improving the device efficiency can have a major impact on the over-all system cost (see Figure 1).

The solar cell materials research extends over many material systems and emphasizes the following major aspects:
A. To lower the materials costs
B. Improve material quality
C. Improve capability for fabrication of large area cell

The specific issues that address these aspects are different for different materials. It is instructive to consider each material.

Silicon is the most extensively used electronic material which is primarily used in micro-electronic. For these applications, silicon is available in many categories which are of different purity and crystal perfection. Traditionally the highest quality material is obtained by float zone (FZ) technique. However, more common variety is grown by Czochralski (CZ) method. Silicon has been, and continues to be, the primary material for solar cells. Because of its importance in the electronics industry, the electrical, optical, chemical and physical properties of silicon are better known and understood than any other semiconductor. Furthermore, solar cell industry is able to utilize this wealth of knowledge for the fabrication of high efficiency devices. Concomitantly, silicon solar cells have led to the basic cell designs which are applied to other material systems.

Single crystal silicon has produced cells with efficiencies reaching near theoretical limits. The highest efficiency devices have been fabricated on float zone material of high purity and with a low density of crystal defects. Solar cells fabricated on CZ substrates have significantly lower efficiencies. Currently, attempts are being made to "upgrade" Czochralski silicon during solar cell processing and develop cell designs which are more tolerant to material quality. While these attempts are proving to be quite successful, both FZ and CZ substrates remain to be too expensive for flatplate terrestrial applications. However, such devices can meet the cost objectives for concentrator applications. Currently, there are attempts made to grow CZ wafers of lower purity and at higher speeds to lower the substrate costs.

A recent approach for reducing the cost of silicon substrates has been to grow polycrystalline material. This has been accomplished in two ways. In one case a square shaped polycrystalline ingot is cast by a rapid directional solidification. The cast ingot has large grains and the grain growth is nearly columnar. The ingot is then sawed into square wafers. In the other approach silicon ribbons are grown in the sheet form which are typically 200 µm to 250 µm thick. These substrates offer an advantage since they do not require any sawing. Polycrystalline substrates are now commonly used for commercial solar cell production. It is expected that the cost of polycrystalline substrate will be significantly lower than that of the single crystal substrates.

The major research areas that can help increase the commercial potential of silicon based photovoltaic systems are related to development of post-growth processes that can improve the material quality of commercial silicon substrates. Currently the research under US Department of Energy program addresses the issues of basic electronic mechanisms that can getter impurities, annihilate defects and passivates impurities and defects so as to ameliorate their influence on the device performance.

GaAs based devices have been fabricated in many configurations using different substrates as well as separable films. These include GaAs/GaAs, GaAs/Ge, GaAs/Si. The cell structures are grown by Metalorganic Chemical Vapor Deposition (MOCVD) and Molecular Beam Epitaxy (MBE). Major research efforts are directed towards improving the uniformity of growth on large areas, utilizing lower-cost substrates and over-all cost reduction of the process for cell fabrication.

Amorphous silicon solar cells are used in a variety of low-power consumer applications which is a well-suited market for this material. Its use in power applications has been hampered by the photo-induced degradation (Staebler-Wronski effect). The primary area of materials research in α-Si is to determine mechanisms of photo-induced degradation. The various sources affecting instability of amorphous silicon have been identified; these include photons, high energy particles, quenching at high temperatures, applied bias voltage, and current injection. Currently, some progress has been demonstrated in overcoming some of these limitations by improved device design. In particular,thin multijunction a-Si alloy devices have proven to have lower light-induced degradation than single junction devices.

Many semiconductors suitable for PV conversion have high optical absorption and, hence, can be used in thin film form. These include : a-Si, $CuInSe_2$ and CdTe. Solar cells based on thin film technology can offer the advantage of low material cost as well as monolithic fabrication of cells. In addition it is expected that large-area depositions will reduce fabrication costs.

$CuInSe_2$ based PV devices typically use CdS/CIS or ZnO/CdS/CIS configurations. One of the processes for deposition of CIS consists of depositing individual layers of In and Cu (sometimes Ga is also Included) onto a metallized glass substrate and then subjecting this structure to a selenization process. Such a process consists of heating the structure (380 - 450°C) in a Se-rich environment such as H_2 Se-Ar gas mixture. The research efforts are directed to understand stoichiometry, microstructure such as phase separation, chemical nature at grain boundaries, and defects in the material.

CdTe is a promising polycrystalline solar cell material which has already produced small-area cells with efficiency in excess of 12%. A number of techniques are used to grow materials for various layers of the cells. These include spraying, solution growth, sputtering, and electrochemical depositions. The major research issues are: interface effects such as at CdS/CdTe, material purity and capability for uniform large-area growth.

PHOTOVOLTAIC POWER SYSTEMS: APPLICATIONS

Photovoltaic systems are already being used economically for a variety of remote power applications in the U.S and worldwide. The current PV sales have reached to over 40 MW per year and the industry continues to expand. In the future, PV must progress through a series of expanding markets, beginning with high value, smaller applications, and finally arrive at bulk power applications when PV costs have declined and the larger manufacturing capabilities are realized. Various markets for PV applications may be categorized as:

Consumer Market: A well established small market for PV is portable consumer products such as pocket calculator, radios, watches, and patio lights. Although newer applications are being introduced which include automotive applications e.g. car fans, wind shield defrosters, battery chargers etc., these applications do not comprise sufficient energy as a significant use of PV. However, such applications are clearly cost-effective.

Remote power applications: The remote power applications comprise applications in the areas which are not connected to a central power grid. Currently the remote power applications are the major terrestrial use of PV systems. Examples are: water pumps for irrigation and live stock, signal lights along railroad tracks, mountain-top communication stations. Solar powered water pumps are attractive applications for PV because the demand for delivered water is less constrained by the intermittent nature of the solar power, and water pumping is often needed far from existing power lines.

Utility market: Air conditioning is a rapidly growing market in the U.S and many tropical countries. Meeting this demand with the centrally generated power is very expensive because of the high capital cost and operating expenses needed to meet short term peak demands. Solar energy provides natural match between the air conditioning demand and availability of solar insolation. Use of PV as peak power generator can compete with other means of providing for peak loads viz. solar thermal and natural gas. PV can also be used on-site to run air conditioners specially designed using high efficiency brushless or reactance dC motors driving a conventional compressor. These could be used in conjunction with attic fans and room fans. Likewise, PV driven motors can be used to pump heat exchanger fluids in a home hot-water system or for a pool heater.

CONCLUSION

Photovoltaic power systems offer many advantages for such applications as peak-load generation in the utility systems, remote applications in the regions that are not connected to utility grids, and in many consumer applications. At present the PV generated energy can be cost-effective only for remote and consumer applications. However, as the PV module efficiencies increase above 15% and as the production costs decrease, PV energy will find acceptance in the utility market. In order to accomplish this objective, emphasis must be placed on developing material and process technologies which can be commercially used to lower the PV module costs. The general directions of research needed for various solar cell material systems are identified in this paper.

Photovoltaic power can be particularly valuable in developing countries where the new energy needs are estimated to be very high in 1990's and beyond. Figure 2 shows word-wide estimated requirements of the new generating capacities. It is estimated that developing countries alone will require about 350 GW of capacity in next 10 years. The remote power requirements of the most unelectrified rural communities are huge, and can be met, in part, by the PV power.

REFERENCES

1. E. A. Moore and G. Smith, Capital Expenditures for Electric Power in the Developing World,the World Bank, Feb. 1990.
2. DOE, National Energy Strategy, First Edition, 1991/1992, Feb.1991.
3. EIA, International Energy Outlook: Projections to 2000.
4. U. S. Department of Energy Five Year Research Plan, 1987-1991, Photovoltaics: USA's Energy Opportunity, 1987.

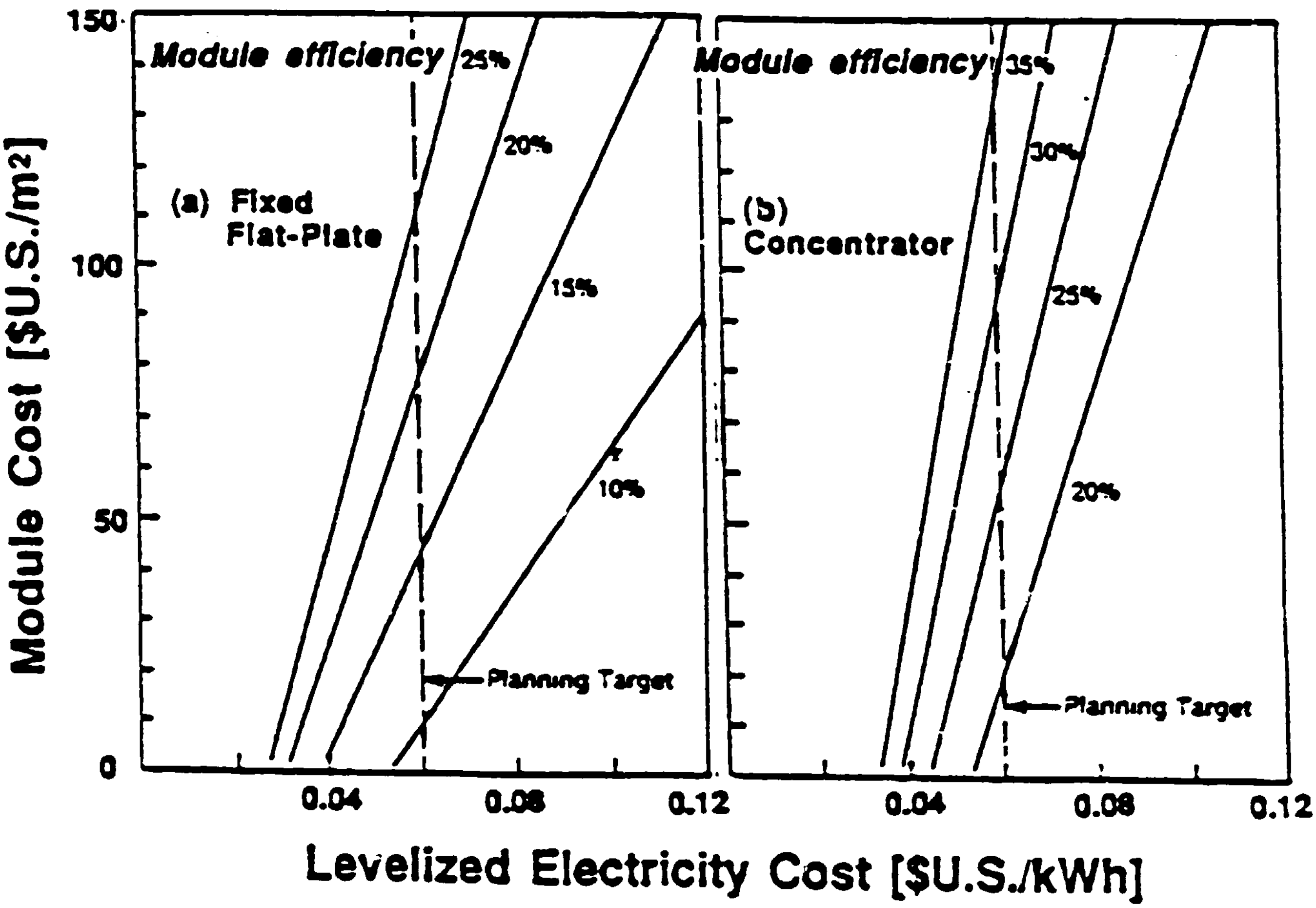

Figure 1. Cost analysis for photvoltaic flat-plate and concentrator modules.

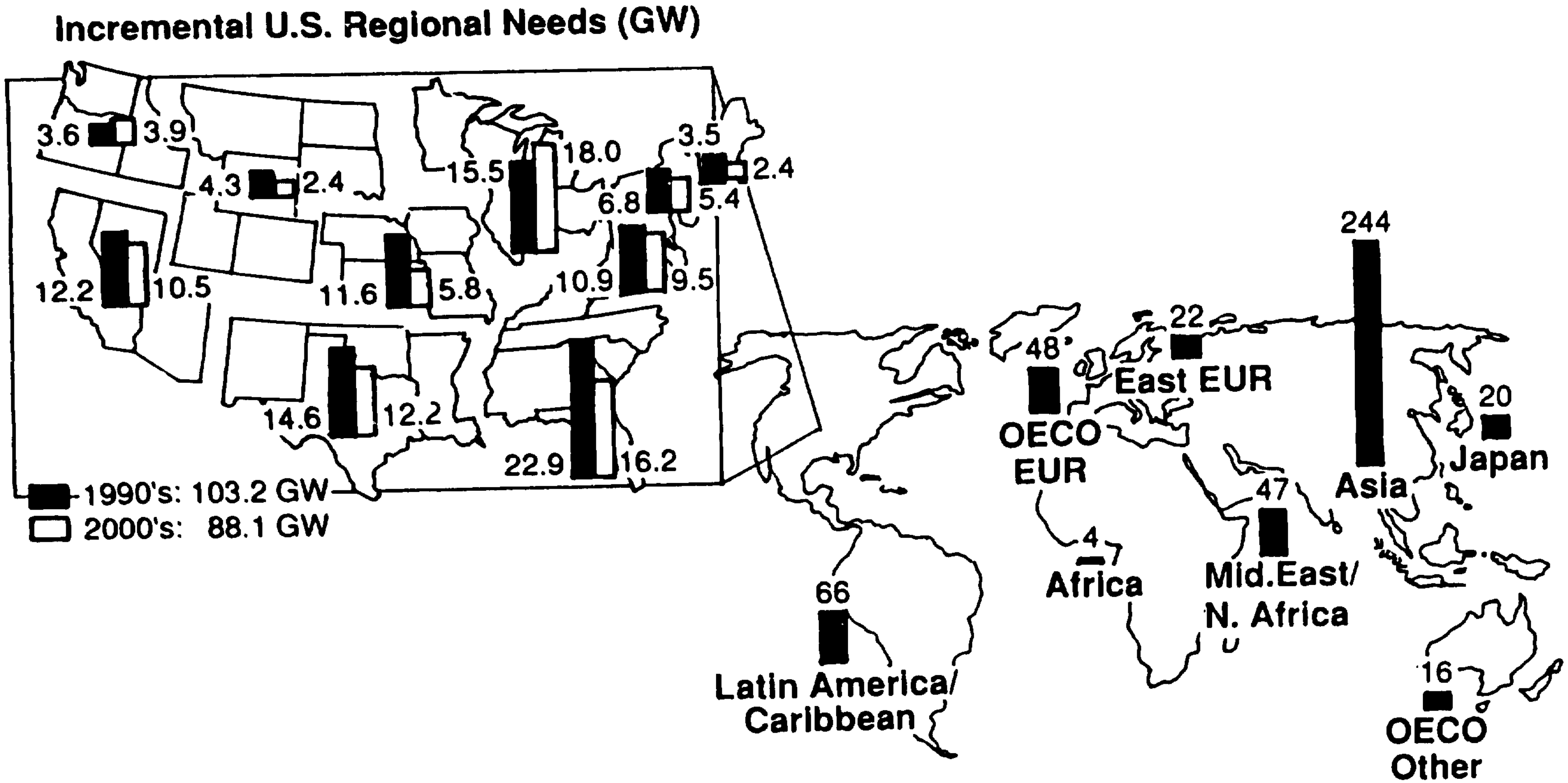

Figure 2. Worldwide estimated power capacity needs