SERI/TP-211-3401
UC Category: 270
DE88001197

Overview of the U.S. Experience with Photovoltaics in Developing Countries

T. Surek
Solar Energy Research Institute
G.J. Jones
Sandia National Laboratories, Albuquerque
R.H. Annan
U.S. Department of Energy

September 1988

Presented at the International Workshop on Renewable Energy in Developing Countries
Kiryat Anavim, Israel
June 12-17, 1988

Prepared under Task No. PV840101

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A02

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications, which are generally available in most libraries: *Energy Research Abstracts, (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

OVERVIEW OF THE U.S. EXPERIENCE WITH PHOTOVOLTAICS IN DEVELOPING COUNTRIES

T. Surek
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

G. J. Jones
Sandia National Laboratories
Division 6223, P.O. Box 5800
Albuquerque, NM 87185

R. H. Annan
U.S. Department of Energy
PV Technology Division
Washington, DC 20585

ABSTRACT

Recent advances in photovoltaic technology, the result of a U. S. Department of Energy program in partnership with industry, universities, and utilities, are described. An overview is given of the current and projected markets for photovoltaics. The discussion of the technology and markets sets the stage for the primary subject matter of the paper, which is the discussion of the U. S. experience with photovoltaics in developing countries. Thousands of photovoltaic systems worldwide are providing reliable, cost-effective electrical energy in remote applications such as telecommunications, water pumping, and vaccine refrigeration.

1. INTRODUCTION

The modern era of photovoltaics (PV) -- the direct conversion of sunlight into electricity -- began in the mid-1950's with the discovery of the silicon solar cell at Bell Laboratories. The potentials of the technology were realized from the outset: PV could provide electric power worldwide with no cost for fuel, no pollution or other environmental effects, and simple, relatively maintenance-free operation at remote locations. The modularity of the technology -- systems can be built in sizes from a few watts to many megawatts -- was seen to be a further advantage for these applications. In spite of its potential, the use of PV was relegated to providing power to space satellites through the early 1970's as a result of its high cost, and the low cost and easy availability of fossil fuels. The oil embargo of 1973 changed the perception of photovoltaic technology, and marked the beginning of a concerted effort, in the U. S. as well as the rest of the world, to reduce the cost of PV for terrestrial applications. The U. S. Department of Energy's (DOE) National Photovoltaics Program was born from this crisis; the Program's aim is to develop PV technology which can produce economically competitive electric power in utility-scale applications in the U. S. In the short time since its beginning, the Program has made tremendous strides in increasing the efficiency and improving the reliability of PV modules, and decreasing the cost of PV-produced electricity.

It is a recognized fact that the bulk of the world's increasing energy demands in the next couple of decades will come from developing countries. This is based on the reality that the majority of the earth's population, several billions of people, live today without the benefits of electric power, and the attendant benefits it provides through improved productivity and economy, and improved social conditions (health and welfare, education, etc.). The growth rate in energy markets is 9 to 10 % per year in developing countries versus only 2 to 3 % in the developed world. This raises the question as to how the developing countries are going to meet such huge energy demands in order to achieve the minimum objectives of their economic and social development programs. Thousands of PV systems worldwide are providing part of the answer to this question: modules are generating power in small remote, grid-independent applications such as telecommunications, water pumping and vaccine refrigeration. In all these applications PV is **today's economical power option of choice** when the full lifecycle costs and benefits of the PV system (e. g., reliability) are considered.

This paper reviews the recent advances in PV technology which have occurred under the DOE Program. A short overview of PV markets, both current and projected, is also given. The discussion of the technology and markets is necessary to set the stage for the primary subject matter of the paper which is the U. S. experience of using PV systems in developing countries in a variety of remote, stand-alone applications which are cost-effective today. The conclusions reached from these applications, and the expectations and impacts of future technology advances are discussed.

2. U.S. PHOTOVOLTAIC PROGRAM

Developing cost-competitive photovoltaic power for utility-scale applications is a goal of both the U. S. government and industries. Over the last 11 years, the U. S. government has invested more than $800 million in photovoltaics -- much of it on long-range, high-risk research and development. The private sector -- both PV industry and electric utilities -- has invested hundreds of millions of its own dollars, emphasizing near-term PV technology development and commercialization. The vast expertise of our universities is tapped through subcontracts and collaborative research. Government, industry, and academia are pulling together as a team to find the technical solutions required to establish photovoltaics as a competitive energy supply option. This investment of funds and people has paid off: the cost of PV-supplied power, without storage, has decreased some forty-fold over the past 11 years to about 30 cents per kilowatt-hour today; the expected lifetime of commercial,

Table 1:
FEDERAL/INDUSTRY LONG-TERM (YEAR 2000) TECHNICAL GOALS (1986 DOLLARS)
Based on a levelized electricity cost-target of 6 cents/kWh

	Flat-Plate Systems	Concentrator Systems
Module Efficiency at 25°C (in %)	15 - 20	25 - 30
Module Cost (in $/square meter)	45 - 80	60 - 100
Balance-of-Systems Costs		
-- area-related (in $/square meter)	50 - 100*	125
-- power-related (in $/kW)	150	150
System Life Expectancy (in years)	30	30

* Balance-of-system costs vary depending upon the type of flat-plate system (fixed, one-axis, or two-axis tracking)

FEDERAL/INDUSTRY NEAR-TERM (EARLY 1990s) TECHNICAL GOALS (1986 DOLLARS)
Based on a levelized electricity cost-target of 12 cents/kWh

	Flat-Plate Systems	Concentrator Systems
Module Efficiency at 25°C (in %)	10 - 20	15 - 25
Module Cost (in $/square meter)	90 - 240	110 - 275

flat-plate crystalline silicon modules has increased to 20 years or more; efficiencies of silicon solar cells have doubled; and new photovoltaic materials and device configurations have evolved which have the potential for much lower costs and/or greater efficiencies than the conventional silicon technology.

The U. S. Department of Energy's (DOE) **National Photovoltaics Program: Five Year Research Plan, 1987-1991** [1] describes an aggressive research program in photovoltaic materials, devices, modules, and systems to establish the technology base for cost-competitive photovoltaic electricity. In the long term (year 2000 and beyond), the goal is to achieve photovoltaic-generated electricity produced at a 30-year levelized cost of 6 cents per kilowatt-hour. In the near term (early 1990-s), the Program intends to gain the technology improvements needed to produce electricity at 12 cents per kilowatt-hour. The Program is pursuing parallel development paths toward these goals, including flat-plate thin films, flat-plate crystalline silicon, and concentrating collectors. Table 1 shows the respective goals for flat-plate and concentrator systems in terms of module efficiency and cost as well as goals for the other system parameters. The Program is under the direction of the Photovoltaic Energy Technology Division of DOE, with the research activities performed and managed by the Solar Energy Research Institute (SERI) and Sandia National Laboratories. Program implementation is based on partnerships among the federal government, private industries, universities, and electric utilities.

In spite of decreasing federal budgets in recent years, the technology has continued to make significant advances. Improvements in materials and processing, solar cell design, and cell fabrication techniques have led to new records in cell efficiencies in nearly all material areas. Advancements in module efficiency, cost and reliability have resulted in a growing list of U. S. utilities that are testing photovoltaics. The continuing successes may be attributed to three factors: the strength of the technology; the health and aggressiveness of the industry, as exemplified by cost-sharing of research programs; and the cost competitiveness of the product in an increasing number of applications. In the following, we review the recent advances and major research directions in each of the PV technologies of interest: crystalline silicon, amorphous silicon, polycrystalline thin films, high efficiency (III-V) materials, and concentrator cells. Summaries of the technical accomplishments are given in the various annual Program documents [2,3].

Crystalline silicon has been the workhorse of the PV industry to date with the bulk of the PV power modules used made from single or polycrystalline silicon materials. Silicon is one of the best understood materials, with a technology base rooted in the semiconductor industry. Yet, in the past two years, major breakthroughs have been made in the laboratory with efficiencies of 21 to 22% achieved by several researchers. The translation of these high efficiencies to low-cost silicon materials, using low-cost cell fabrication processes, constitutes much of the current program activity. In addition, efforts are going into lowering the material costs by growing thin sheets (or ribbons) of silicon directly from the melt, and thus eliminating the cost and attendant material waste of slicing an ingot, and growing a thin film of polycrystalline silicon on a low-cost substrate. The latter approach has recently resulted in a 12.6% efficient laboratory solar cell. The research is expected to improve the cost-effectiveness of today's products, leading to crystalline silicon modules which are available at less than $2 per peak watt in the near future.

The advent of **amorphous silicon** (a-Si) photovoltaics has been one of the most exciting areas in the field. Fifteen years ago, the material was merely a laboratory curiosity; today, it has a large segment of the PV market, mostly in low-power consumer applications. The advantages of this technology are: low silicon material usage (about 1/300th of that for crystalline silicon); the ability to deposit the a-Si films on low-cost substrates such as glass, steel or plastic by scalable deposition processes; and the ability to fabricate entire modules, with interconnected solar cells, at once during film deposition. A range of applications other than PV (such as xerography and thin-film transistors) has spurred a large investment in a-Si by the private sector. Solar cell efficiencies in the laboratory have reached 11 to 12% for single-junction cells and over 13% for multijunction cells. (The latter device consists of two or more solar cells which are stacked on top of each other -- either mechanically or monolithically -- to provide a more efficient use of the sun's spectrum.) Submodules, about 1 square foot in area, are in the 8 to 10% range, while large-area modules, 3 or 4 square feet, are now produced at 6% efficiency. The state-of-the-art in module size is a 4 ft. x 4 ft. module. The trend in the technology is toward the multijunction devices, both for higher efficiencies and for improved stability. This requires research on amorphous silicon materials which are alloyed with germanium, carbon or other elements. The expectations are that 15% multijunction module efficiencies can be achieved at costs which are a fraction of today's crystalline silicon module costs.

A related area to amorphous silicon is that of **polycrystalline thin films** -- primarily copper indium diselenide ($CuInSe_2$) and cadmium telluride (CdTe). These materials are very effective in absorbing sunlight, so very little material is required (typically 1 to 2 microns). The films can be deposited by a variety of potentially low-cost methods on inexpensive substrates such as glass. The range of efficiencies achieved is similar to a-Si (11% for laboratory cells), yet these materials have received far less attention to date. Another important result is that these thin-film materials have been shown to be very stable in laboratory tests. Efficiencies of submodules are above 9% for $CuInSe_2$ and above 6% for CdTe -- the latter result is on one of the first submodules of this size produced in the U. S. The research trend in polycrystalline thin films is also toward the higher efficiency multijunction cells, aimed at producing module efficiencies in the 15 to 20% range. This requires development of alloy materials, such as $CuInSe_2$ alloyed with gallium or sulfur, and CdTe alloyed with magnesium, zinc, manganese or mercury. One can also combine two types of materials in a multijunction cell. For example, the combination of an a-Si top cell and a $CuInSe_2$ bottom cell, in a four-terminal device, has led to a greater than 10% efficient submodule of nearly 1 square foot area. Increasing investments in the U. S. private sector in polycrystalline thin films are likely to result in the emergence of these materials as commercial PV products in the near future.

High efficiency materials, such as gallium arsenide (GaAs), are formed from elements in columns III and V of the periodic table. The approach here is to develop cells which may be somewhat more expensive, but produce more power per unit area because of their higher efficiency. Such trade-offs in cost/efficiency form the basis of the DOE Program (see Table 1). Efficiencies of 23.7% were realized recently in GaAs, while a novel thin-film approach, which uses only a few microns of GaAs by "cleaving" the film from a reusable GaAs substrate, has resulted in a laboratory efficiency of 22.4%. Efficiencies of 35 to 40%, under concentrated sunlight, may be achieved with multijunction cells using III-V alloy materials, such as AlGaAs and GaInAs. A two-stack cell of AlGaAs and GaAs was measured recently to be 23.9% efficient under one-sun illumination. Research in the area of high efficiency cells is centered on the development of the exacting crystal growth processes needed to produce high quality materials.

The approach of **concentrator cells** is based on the combination of a small-area (and relatively expensive) solar cell with low-cost lenses and systems which concentrate sunlight onto the cell. The multijunction III-V cells described above hold the promise of very high efficiencies in this approach. The recent excitement has been the achievement of greater than 28% efficiencies in single-junction Si and GaAs concentrator cell in the laboratory. The former was demonstrated at a concentration of 140 suns, while the latter was achieved at 400 suns. The GaAs device was 27.5% efficient at 1000 suns concentration. Module-ready Si cells of up to 24% efficiency (at 150 suns) have been fabricated and tested in concentrating modules. These results, as well as developments in the concentrating modules themselves (e. g., low-cost Fresnel concentrator lenses, prismatic cell covers which improve light input into the cells, improved module reliabilities, etc.), have created a resurgence of interest in concentrating collectors among the PV industry and utilities. One of the largest PV concentrator systems in the world, a 300-kilowatt system, is currently under construction in Austin, Texas in a jointly-funded project by DOE.

In addition to the materials and devices, and module research efforts described above, the DOE program supports research on PV systems. The goal of the **systems development** effort is to establish the system and balance-of-system technology base and transfer it to industry. An important activity in this area is the Design Assistance Center (DAC) at the Sandia National Laboratories. The goal of the DAC is to accelerate the acceptance of PV worldwide by assisting industry in educating the user about the benefits and use of the technology. The DAC does this through consultation, design summary documents, and workshops. The DAC also provides design assistance to a variety of utility, private, and federal projects in the U. S. and abroad. During 1987, the DAC has worked with over 100 users worldwide on PV systems ranging in size from less than 100 watts to 300 kilowatts. The DAC has also played a key role in many of the PV system activities in developing countries described in this paper.

A continuing effort in **systems evaluation** is aimed at determining system reliability and performance through the maintenance of a field-performance data base in cooperation with private system operators. The Program's long-term commitment to reliability research is validating the dependability of photovoltaic systems under actual operating conditions. Our recent findings lead to several significant conclusions: the overall consistency of energy production data shows that performance degradation in modules over time has been minimal and that many early system problems have been overcome; system performance is well understood and can be accurately modeled, effectively ensuring the quality of new designs; typical failure rates of crystalline silicon PV modules average well below one-half of 1% per year; and current operation and maintenance costs for large systems (of 25 kW or more) are about 0.5 cents per kWh, which compares favorably with all other energy supply technologies.

The success of the PV Program would not be possible without the close collaboration of the PV industry, utilities, universities and the government. Cost-sharing research contracts with industry, sometimes under 50% cost-sharing arrangements, have infused nearly $7 million into the materials and devices research in 1987. More than 50 universities worked on research projects for the Program in 1987, receiving $6.7 million. The private sector has cost shared system experiments in joint projects with the government, and many utilities initiated their own joint projects with PV industry partners to examine some of the newly evolving module technologies in a utility setting. As the research identifies the most promising materials and processes, collaborations with industry will guide our efforts toward a cost-competitive product for electric utilities.

3. PHOTOVOLTAIC MARKETS

In order to view the U. S. involvement in photovoltaics in developing countries in the proper context, it is important to review briefly the recent history and current status of PV markets worldwide and the involvement of the U. S. PV industry in these markets. This will also provide a better appreciation of the wide range of applications of PV today. A detailed analysis of worldwide PV markets is given in reference 4. Several DOE Program documents review the U. S. experience with today's photovoltaic systems and describe potential market opportunities for photovoltaics [5,6].

Photovoltaics is now used in applications ranging in power from a few milliwatts to several megawatts, with many of the applications cost effective. The advent of the microelectronics industry has resulted in the use of many megawatts of PV in millions of calculators, watches, and other small devices. It is estimated that some 130 million units (small PV modules) were fabricated for the calculator market in 1987 [4]. As costs have improved, so have the number and sizes of the consumer products utilizing PV technology. Battery chargers, auxiliary power supplies, and emergency radio power sources are just some of the new applications of PV now being brought on the market. A garden light, produced by a U.S. a-Si manufacturer, was sold in some 160,000 units in 1987, with sales expected to triple this year [7].

The system and balance-of-system technologies have now matured to the point that the only technical obstacle to the eventual widespread utilization of PV in U.S. utility systems is collector (i.e., PV module) cost. However, the progress already made in this area has led many U.S. utilities, as well as third party investment groups, to begin to investigate large-scale photovoltaic systems today. Three megawatt size installations exist in the U.S.: the 1 MW plant at Hesperia, California (Arco Solar, Southern California Edison); the 2 MW plant in Sacramento, California (DOE, Sacramento Municipal Utility District); and the 6.5 MW plant in Carrisa Plains, California (Arco Solar, Pacific Gas and Electric). In addition, several utilities are looking at smaller-scale power for residential applications, as well as examining new technologies such as amorphous silicon. The conclusions reached by the utilities are very encouraging. The PV systems have proven to be extremely reliable; the plants deliver power, as expected, when the sun is shining. Operation and maintenance costs are comparable to conventional technologies. The power delivered by PV is an excellent match to the utility demand -- this feature of PV may make it attractive to many utilities well before the long-term cost goals are realized. From these large-scale installations, it is estimated that the cost of PV power today, without storage, is about 30 cents/kWh.

In between the consumer markets, where PV serves mostly as a convenient if not cost-effective source of power, and the utility-scale experimental systems, where the power delivered is not yet cost-competitive with other energy sources, exists the **real market for today's photovoltaics** -- the supply of power in remote, stand-alone applications.

Thousands of PV systems worldwide provide power to communications, water pumping, refrigeration, and other small-to-medium power uses. In this market segment, PV systems are not only economically viable but are the **preferred** choice over other alternatives, as discussed in detail in the next section. The cost of PV is not an impediment to the growth of these markets, rather the lack of awareness of the technology is what limits today's market size.

Figure 1 shows the historical trend in world PV markets over the past seven years. The figure identifies shipments by PV manufacturers in the U. S., Japan, and other countries (Europe and rest of the world). The total module shipments in 1987 were 28.6 MW [4], including 8.65 MW from the U. S., 12.45 MW from Japan, 4.7 MW from Europe, and 2.8 MW from the rest of the world. Several trends are apparent from the figure. First, the increasing share of Japan in the market is the result of their domination of the consumer product market. Module shipments from Japan actually decreased from 1986 to 1987 as a result of a saturation of the calculator market. Second, the U. S. share of the world market has decreased from about two-thirds in 1981 to less than one-third in 1987. However, if the consumer products are not considered (8.6 MW in 1987), the U. S. is the market leader in 1987 with about 8 MW of the remaining 20 MW of power products. Of this latter total, some 18.2 MW went into commercial products, with the remainder used in various government-funded projects. In terms of cell technology, flat-plate crystalline silicon (single crystal and cast polycrystal) modules suppiied 62.2% of the market (including well over 90% of the power products), and amorphous silicon accounted for 37.4%. The remaining 0.4% included minimal shipments of concentrator modules and flat-plate crystalline silicon modules based on silicon ribbon or sheet material. Concentrator modules, which in prior years had a much greater share of the market, are expected to increase in 1988 as a result of various projects coming on line (e.g., the DOE/Austin project).

It is instructive to consider the 18.2 MW of commercial products in 1987 further as about two-thirds of this total includes module shipments to developing countries. Following an analysis of the markets [4], we can identify three major sectors where essentially all PV systems in developing countries fall. These are: (1) Worldwide Communications and Signals (about 9 MW); (2) Worldwide PV/Diesel Commercial (about 5 MW); and (3) Worldwide Off-the-Grid Rural (about 4 MW).

Communications and remote signals (microwave repeaters, radio and TV transmission, telephone, government/military communications, etc.) constitute the largest PV business sector. Some 6 MW of PV modules were shipped to developing countries for this purpose in 1987, including about 3 MW from the U. S. The second largest business sector includes uses such as water pumping, cathodic protection, village power (tens of kW sizes), and vaccine refrigeration; about 80% of the 5 MW in 1987 were used in developing countries. The off-the-grid rural sector includes applications such as battery charging, home lighting,

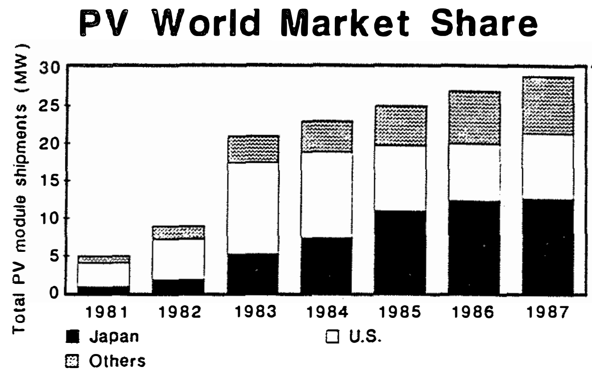

Fig. 1. Historical trend in world photovoltaic markets from 1981 to 1987.

power for radio and TV, and small-village power (up to a few kW). This market segment is widely dispersed, with some dozen countries each using about 200 to 300 kW in 1987. About 2 MW of the PV modules in this market sector were shipped to developing countries, including about 1 MW from U. S. suppliers.

Projections of future markets in photovoltaics depend on a variety of factors ranging from technical considerations (module costs and efficiencies realized by the various technologies) to economic variables (world oil prices, electricity prices) to social concerns (environmental issues, health concerns). The extent of U.S. government funding is seen to be a factor as well, as it may determine the rates at which the various technology options will transfer from the laboratory to the marketplace. For the stand-alone markets of interest in the developing countries, it is important to realize that the market size is not as much dependent on PV costs as it is on the ability to educate users and penetrate the application sectors where PV is cost-effective today. Based on the anticipated growing demand for the technology, a forecast [4] of annual module shipments is 30 to 35 MW by 1990, 60 to 100 MW by 1995, and 100 to 200 MW by the year 2000 in the three market sectors of interest to developing countries, identified earlier in this section. The total PV markets are estimated to be about three times these figures. Module selling prices are projected to be (in 1987 dollars per peak watt) $4.00 by 1990, $3.00-$3.50 by 1995 and $1.50-$2.00 by 2000. The higher ends of the market figures (and lower ends of the price figures) are seen to occur under favorable economic and social conditions (e.g., increasing oil prices, aggressive U. S. government program). The communications market sector is seen to continue to remain the major market, with the PV/diesel market increasing and eventually surpassing it. Applications in developing countries will continue to be the major part of these three market sectors.

The U. S. interest in PV markets in developing countries is clear. These markets represent an opportunity for the U. S. PV industry to sell and develop products, increase production capacity, and maintain economic competitiveness with foreign suppliers. The U. S. PV industry is currently exporting over half of its total production: 4.5 MW out of 8.65 MW in 1987, essentially all to developing countries. Outside of consumer products, these markets represent the **fastest** growing markets for the U.S. PV companies and are being aggressively pursued. An additional area where U.S. industry has been successful is in marketing PV module production capability in developing countries. This includes everything from entire turn-key plants to parts of a process line such as cell fabrication or module lamination to testing equipment for cells and modules. It is estimated that over 7 MW of PV production-related equipment from the U. S. has been or is being installed in countries like China, India, Saudi Arabia and Yugoslavia among others, with many other deals currently in negotiations. Clearly, as the PV markets become more and more competitive in the developing countries, it is to their advantage to have the local capability to manufacture all or part of the PV systems to be used in the country.

The key to successful penetration of the overseas markets lies with the initiatives taken by the U.S. industry. This has been aided by the efforts of the Committee on Renewable Energy Commerce and Trade (CORECT). CORECT, a committee of 12 federal agencies mandated by Public Law and chaired by the DOE, works to facilitate the worldwide use of renewable energy technologies through a variety of information transfer and technical assistance activities. Providing technical education to the buyers and financing organizations, and export education and assistance to U.S. firms, are expected to lead to increased sales of U.S. renewable energy products in developing countries. Technical assistance for photovoltaic project feasibility, design, system procurement specifications, and training is available through Sandia's Design Assistance Center (DAC) described earlier.

As part of its efforts, CORECT (along with various federal, state, private and other organizations and agencies) sponsored the first **Photovoltaics: Investing in Development Conference**, organized by DOE, in May 1987 [8]. This conference was attended by over 75 decision-makers from over 30 countries, and it enabled the U.S. PV industry to demonstrate its products, representatives of the developing countries to express their needs for electric power, and the world finance community to understand the economics of photovoltaics. Over $1 million in U.S. industry sales has been reported to date as a direct result of this conference, and prospects for further sales are pending.

4. APPLICATIONS IN DEVELOPING COUNTRIES

The majority of photovoltaic systems sold today are designed to provide power to remote, grid-independent or stand-alone applications. If there is a current need for a reliable power source in a remote area, PV is probably the right choice. The site may be difficult to fuel, it may be impossible to guarantee local maintenance support, or extension of the utility grid may be too expensive to be practical. Most, if not all, of the electric power needs encountered in developing countries are characterized by these problems. Since PV systems avoid these problems, they are being used in thousands of remote applications -- today. Photovoltaics is the ideal power source for such applications since PV systems require no fuel, need little maintenance, have a proven record of high reliability, and are completely modular. PV systems can be sized to the specific load, whether it is a few watts or several kilowatts, matching the economic and energy needs of the user. This provides the user with flexibility in design that is not possible with conventional sources. In the following, we review briefly the features of stand-alone systems, examine the questions involved in determining cost-competitiveness of PV systems, and review the experience with PV systems in five remote application areas in developing countries: communications, water pumping, vaccine refrigeration, lighting and home power, and multi-use systems.

4.1 Stand-Alone Systems

Stand-alone systems are typically configured as shown in Fig.2; the simplest configuration consists of the array subsystem, the storage subsystem, and the load subsystem. The distinguishing characteristic of the stand-alone application is that it must meet all of the load with a near-unity availability, day and night, as needed. Therefore, all stand-alone systems employ some form of storage -- either electrical or product. If the system is a hybrid, involving other energy sources such as a back-up diesel, then this other source constitutes the fourth subsystem.

The design of the stand-alone system has been made relatively simple with the development of new design approaches. In all cases the first step is to characterize the application (e.g., peak/average power needed, local insolation levels and seasonal variations). The next step is to determine the criticality of the load; that is, the allowable period of time without energy (e.g., days or hours per year, on the average, that the system is not expected to deliver power). The latter term, in essence, identifies the system availability required. Once the characteristics of the application and the system availability requirements have been determined the actual design process begins.

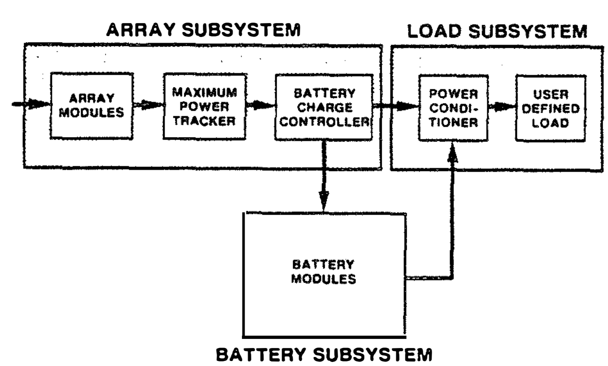

Fig. 2. Block diagram of a stand-alone photovoltaic system.

The first step is the match of the power conditioner or other power processing hardware to the load. Next, for a given system availability, one must select a set of battery capacity/array power values (from an infinite set which all give the same system availability) which are best suited and most economical for the application. The remaining steps involve selection of the actual hardware; several papers and reports describe the considerations involved in this process [9,10].

The PV stand-alone system has evolved into a commercial product of high reliability. It is easy to design, build, and use today; however, there will be further evolution in the future. Tomorrow's system will have more power processing and control hardware, greater load hardware acceptability, increased use of ac power, and lower costs.

4.2 Cost Effectiveness of PV

Stand-alone systems were the first applications of PV to achieve economic viability. There are two general classes of applications from an economic point of view. The first class is economical simply because there is no other reasonable alternative to meeting the load. Remote lighting systems and security systems are examples of such applications. For the cases of interest in developing countries, we deal with the second class of applications where PV systems are more cost effective than conventional sources on a **total cost/benefit** basis. Such cases include clear-cut situations such as diesel replacements, or cases where PV is cost effective based on the savings it allows in overall installation and operation costs.

The best approach to look at the cost effectiveness of PV versus an alternative is worth further discussion, as there are several ways to compare two or more purchase choices. The comparison of first costs may be appropriate if the choices have similar life-times, and operating and maintenance (O&M) costs. PV systems are usually not the choice on this cost basis. If one choice has significantly higher O&M costs, such as the cost of fuel, some form of lifecycle costing must be used. In this case, the cost of fuel and maintenance over the evaluation period must be brought back to the present time and added to the first costs to obtain a more equitable comparison. However, it is often forgotten that a comparison based on lifecycle costs can still be misleading since it implicitly assumes that both options have the same reliability. To correctly compare PV systems to alternate energy sources, one must include the cost of <u>not</u> meeting the load in the costed configuration. This total cost/benefit analysis allows the comparison of a high reliability PV system to a lower reliability conventional system. In essence, economic comparison on this latter basis considers not only the cost of having the system, but also the cost of <u>not</u> having the PV system. These points can be illustrated by considering the three main remote applications of PV systems.

The telecommunications case is probably the simplest example to consider. In general, the capital cost of the PV system will exceed that of its competition. For a remote site, there will be little difference in installation costs. If only these first costs are considered, then the PV system might seem unattractive. However, when refueling and scheduled maintenance are considered, then a more equitable lifecycle cost is obtained and the PV system will usually turn out to be more cost effective. In addition, most alternatives to PV have significantly lower reliability. Therefore, one must include the cost of down-time, the value of lost communications, and the cost of unscheduled maintenance. In some remote applications, the cost of a single unscheduled maintenance can exceed the cost of the entire energy system. These last costs constitute the costs incurred by <u>not</u> using photovoltaics.

The situation is more dramatic in the case of water pumping. Here the PV system may be more cost effective even on a first cost basis, since the modularity of the technology allows it to be sized to the load, resulting in PV modules that represent only a fraction of the total system cost. The photovoltaic system usually includes storage (potable and livestock), while some of the alternatives such as handpumps are supply on demand. As with the telecommunications example, a basic lifecycle analysis including only fuel and scheduled maintenance usually results in a lower cost for the PV system. However, limiting the analysis to just these terms can underestimate the benefits of photovoltaics. For example, a single well with a handpump will not be able to supply the needed water for typical village sizes if the well depth is moderate-to-deep. Comparing a handpump to PV in these cases requires that the cost of drilling another well be included. In many cases, diesels are used to pump water although they are grossly oversized for the job. The high pump rates can result in premature well silting, while the cycling of the diesel can increase maintenance. Finally, there is the basic question of reliability. Not only must the true availability of the alternative be considered, but also the impact of the lack of water on the health and economics of the user. This problem is increased in those cases where no storage is provided.

In the case of vaccine refrigeration, the PV system again might seem unattractive on a first cost only basis. When viewed using a basic lifecycle analysis, which includes the cost of fuel and its delivery, the PV systems are seen to be very competitive. However, the true value of PV in this case comes from its reliability. The vaccines being stored are a very high value item, both in terms of purchase cost and potential health cost savings. The loss of these vaccines can constitute an expense far exceeding the initial cost of the PV system. In at least one country the availability of kerosene refrigeration systems has been reported at under 50%. This has resulted in thousands of dollars worth of lost vaccine. Harder to estimate are the costs to the country in terms of increased rural health care, infant mortality, and loss of villager confidence in the medical teams. The total of these impacts constitute the cost of <u>not</u> using photovoltaics.

The cost effectiveness of PV systems versus an alternative can be illustrated in more quantitative terms. Figure 3 shows the results of a detailed economic analysis [11,12] based on experiences with over 2700 systems in 45 countries covering five application categories: water pumping, communications, vaccine refrigeration, lighting and home power, and multi-use systems. Examples of these applications will be described in the next section. The analysis summarized in the figure was based on an investigation of system cost and actual field experience. The figure shows the range of sizes and loads for which photovoltaic systems (at about $8 per peak watt module cost) are the least-cost option. The "break-even-range" depicts the load range where either PV or the alternative could be the least-cost option depending on the parameter values selected.

For water pumping, PV bridges the gap between the handpump, which is suitable for low flows from shallow wells, and the small diesel generator. The PV system saves the cost of additional wells needed for the handpumped system at higher flows and deeper wells, and avoids the extremely poor match between the diesel and the moderate village water supply needs. In a recent in-depth study of PV, handpumps, and diesel for rural water supply, Cabraal [13] makes an even stronger conclusion. Photovoltaics is found to be economic against both diesel and handpumps for villages of 300 to 2000 persons and water depths of 20 to 40 meters. Even the initial cost of the PV system is found to be less than comparable handpump systems on a per capita basis due to the requirement for additional boreholes for handpump systems. Photovoltaic lighting systems have been found to have payback times of as little as eighteen months when compared to kerosene and other fuels. There are commercial enterprises already in place in several countries to supply individuals with PV lighting systems. Similar situations exist for other stand-alone applications.

For stand-alone applications with large energy demands, a PV/storage system by itself may be uneconomical. However, by combining the PV system with a back-up energy source, such as a diesel or gasoline generator, system economics can be improved. Such PV/fossil hybrid systems are being used, but their design requires detailed modeling to determine the optimal mix of PV and back-up energy. Reliability data and O&M costs need to be included in the design process. Detailed analysis indicates that hybrid systems can economically displace up to 90% of the diesel fuel use [14].

Future stand-alone applications are not anticipated to change dramatically from today's options. As PV module costs decrease and operating costs of other energy options increase, the economic viability limits of PV systems are expected to expand greatly for all stand-alone applications.

4.3 Applications Experience

The key finding of the study [11,12] cited above is that PV systems have been well accepted by the users based on their reli-

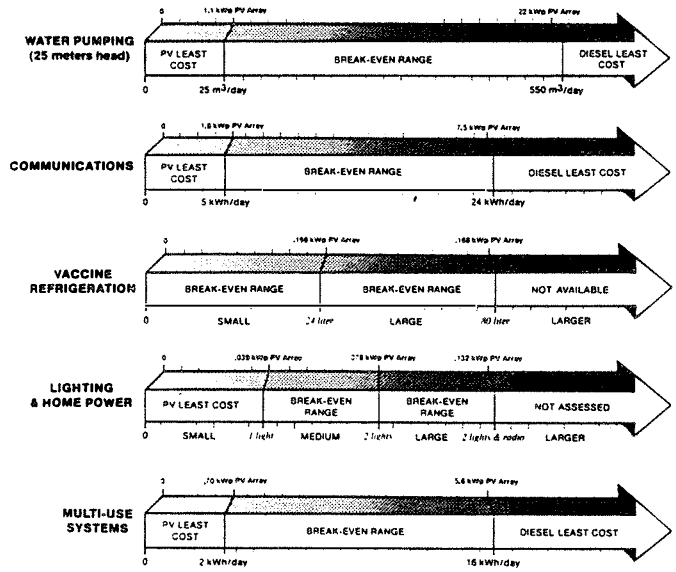

Fig. 3. Financial viability limits for photovoltaics in five application areas in developing countries based on detailed economic analysis of the experiences with over 2700 systems in 45 countries.

ability, independence from fuel, and minimal maintenance requirements. The PV modules were found to be reliable, and, although the performance of power conditioning and end-use equipment was somewhat less than the PV modules, careful selection of field-proven components should ensure successful system operation. The major limitations to implementing PV systems in developing countries were found to be institutional support and the lack of long-term financing. This section reviews some of the applications experience for photovoltaics in developing countries by citing examples of specific applications in each of the five categories examined in the recent study [11,12]. These examples are not meant to serve as the totality of the U.S. experience with PV systems in developing countries, but are used to illustrate the application of the technology in cost-effective ways and to draw some general conclusions from the experiences.

Water pumping is an increasingly important remote energy need. The goal of sufficient supplies of clean water is a major goal of all nations, and many worldwide organizations such as the World Health Organization (WHO) and the United Nations. In a cooperative effort with the World Bank and the government of Bolivia, the U. S. DOE recently installed three small pumping systems for potable water supply in the altiplano region of Bolivia near Lake Titicaca. The systems have operated reliably since their installation in August 1986, requiring no maintenance. The systems (see Fig. 4) use submerged, centrifugal pump/motor combinations. The photovoltaic arrays, ranging from 160 to 320 watts, represent only a small fraction of the total system cost; the pump, plumbing, and storage represent the major cost. A typical

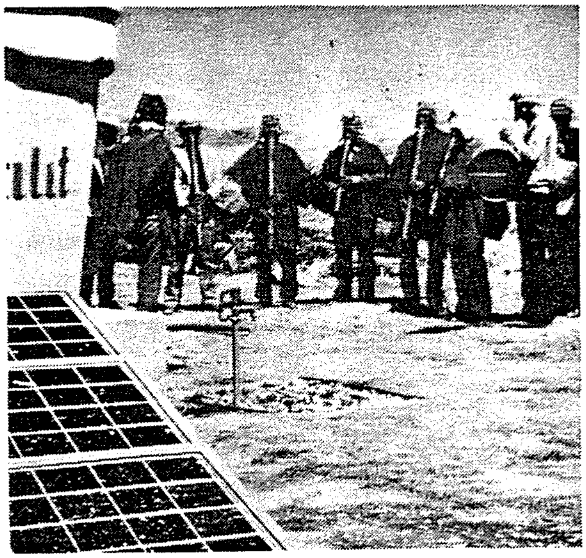

Fig. 4. Photovoltaic water pumping system installed at Sanka Jahuira, Bolivia in August 1986.

Fig. 5. Irrigation of one hectare of fruit trees in Tunisia using a 1500 watt photovoltaic system.

breakdown of costs is given in Table 2 [15]. The acceptance of the PV systems by the users was immediate, resulting in a usage which has rapidly increased to two times that originally anticipated. For deeper wells, a jackpump is often better suited to the task, and there are numerous PV-powered jackpumps in operation throughout the world.

In addition to supplying potable water, numerous PV systems are used to supply water for livestock and for crop irrigation (see Fig.5). Use of PV systems in such cases often results in increased overall productivity if the alternate means is either human or animal power. By replacing human power, the PV system allows the worker to engage in other productive crop or income-producing activities. Replacement of animal power can avoid the animal product loss often associated with the use of farm animals for labor.

The studies [11,12] of PV-powered water pumping systems have shown that their overall viability is a function of factors, both technical and institutional, which are not related to PV module performance. Successful systems have incorporated careful selection of pumps, motors, and controls. The availability and proper use of credible data on solar resources and well yield characteristics have helped to avoid significantly oversized and undersized systems. Effective training of local personnel corrects misconceived user expectations and reduces system downtime.

Table 2: COST SUMMARY FOR PV WATER PUMPING

PV modules (160 W)	$ 960
Hardware (submersible pump/dc motor, structure, cabling, etc.)	2200
Installation	270
Water tanks (6 cubic meters for 3 days storage)	2000
Shipping	70
TOTAL COST	$5500

As with water pumping, there is a growing worldwide interest in extending health care to everyone. The World Health Organization's Extended Program for Immunization has the eradication of polio and other preventable diseases as its near-term goal. To achieve this goal, energy must be available to rural health clinics throughout the world, especially for **vaccine refrigeration.** Photovoltaics, with its characteristics of high reliability and unattended operation, is ideally suited to these applications. The WHO has approved PV/battery-powered refrigeration systems (e.g., Fig. 6) for vaccine storage. The U.S. DOE has recently completed the initial phases of a cooperative effort with the Organization of American States and the Pan American Health Organization resulting in installation of two vaccine refrigerator systems each in El Salvador, Guatemala, and Honduras (see Fig. 7).

The power needs of such vaccine refrigeration systems are typically small, about 100 to 200 watts. This allows the collectors to be easily mounted on the roof of a health clinic or on the adjacent grounds. The low dc voltage makes the systems safe even if one comes in contact with the connections. These systems have been made more attractive by the availability of new no-maintenance, lower-cost batteries. A typical breakdown of the costs for a PV vaccine refrigeration system is shown in Table 3 [15]. The extra first costs for the PV modules and batteries are more than made up by the uncertainties of fuel supply for kerosene or propane powered units, the complex temperature control

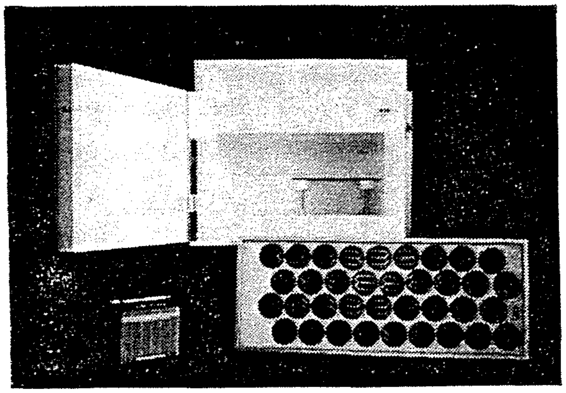

Fig. 6. Photovoltaic vaccine refrigeration system includes refrigerator, PV module, battery, and voltage regulator.

procedures needed with the latter units and the frequent maintenance. Also, the real cost of a vaccine storage failure is not just confined to the lost vaccines. There is a direct people cost in terms of poorer health, increased infant mortality, and disease. A recent study adds further credibility to PV-powered versus kerosene refrigerators. The viability of many vaccines is dependent on maintaining the temperature between 4 and 8°C. Kerosene refrigerators do not have thermostats, which necessitates complex daily maintenance procedures and adjustments of several kerosene burner parameters by trained personnel. The study confirms that PV systems have much to offer in simplifying maintenance needs.

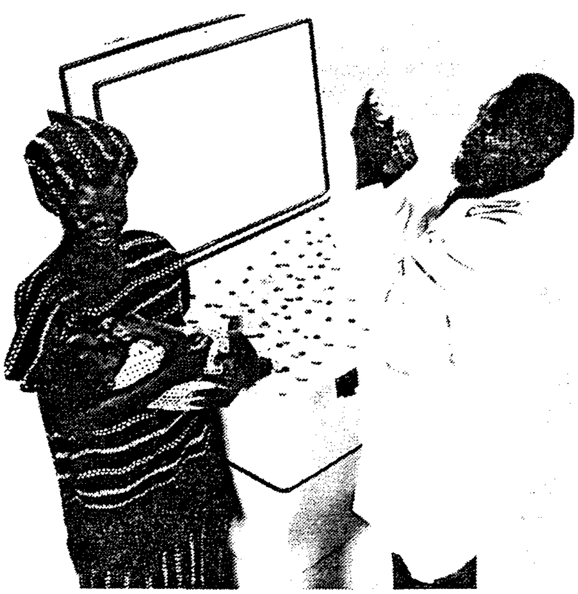

Fig. 7. Vaccine refrigeration is one of the most valued applications of PV in developing countries. Six systems were recently installed in Central America.

Table 3:
COST SUMMARY FOR PV VACCINE REFRIGERATION

PV modules (160 W)	$ 960
Hardware (4 cubic feet refrigerator, structure, battery housing, etc.)	970
Installation	200
Batteries (6kWh for 6 days storage)	300
Shipping	70
TOTAL COST	$2500

Institutional support is critical to the success of PV-powered vaccine refrigeration systems. Effective training must be conducted so users understand the operating principles of the system, the consequences of overloading, and the required maintenance procedures. Also, complete coordination with end-user organizations results in an understanding of the particular vaccination program and leads to more efficient and appropriate system designs. Knowledge of load power consumption under field conditions and availability of credible solar resource data are also important requirements for system design.

The first applications to turn to PV systems were not water pumping or health care, but rather those applications requiring an extremely reliable power source in isolated locations. This is certainly true for the **telecommunications** industry, and has resulted in the widespread use of PV systems to power microwave repeaters and regional telephone systems. As discussed above, this market sector for PV power modules is the largest in both developing and developed countries, with about 10,000 new installations per year currently. System sizes range from relatively large (few kW) telecommunications systems operated by governments or private companies to small (one-module, one-battery) radio systems used in health-care communications networks (see Fig. 8). In Colombia, for example, some 10,300 PV systems with over 540 kW total capacity are supplying communications, signaling, and other small power needs; ten years ago, some 90% of the 6500 villages with 100 or more inhabitants lacked telecommunications [16]. With refueling and maintenance at the remote locations very expensive for conventional diesel systems (even in North America, see Fig. 9), many countries (e.g., Telecom Australia) have turned to photovoltaics to power their remote communications networks. There are abundant examples from developing countries as well [11]. In remote signalling, there are thousands of navigation aids (see Fig. 10) all over the world powered by PV today, with thousands more added every year. The U. S. Coast Guard has increased the number of PV-powered navigational aids to 12,000 in 1987. Previously these types of applications used primary batteries which needed to be replaced on a periodic basis, making operation extremely expensive. Photovoltaics eliminates this cost allowing more systems to be deployed.

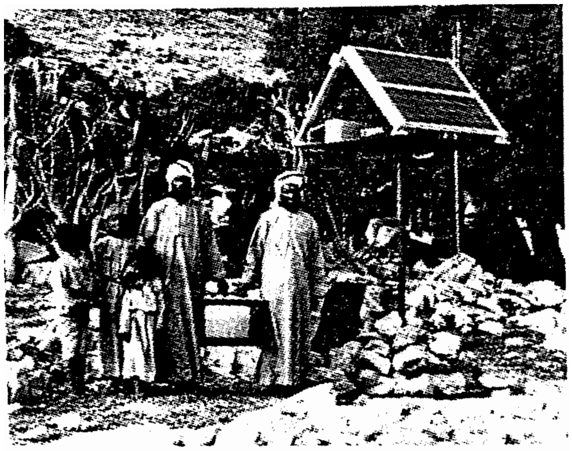

Fig. 8. Photovoltaic telecommunication system provides power for television and receiving equipment in a remote area of Oman.

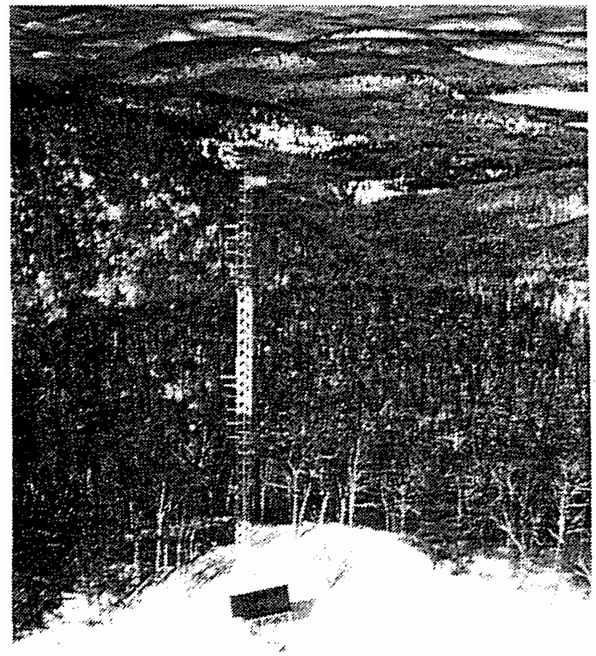

Fig. 9. Power for telecommunications and remote signals constitutes the largest market sector for PV power modules today. Photo shows radio communications in Northern Canada.

The overall reliability of PV-powered communications systems is dependent on selecting charge controllers and load equipment that have been field proven under the appropriate (sometimes harsh) environmental conditions. This requirement is not unique to PV, but applies to conventional systems as well. Advancements in electronics and system design have reduced the power requirements considerably over the years -- systems requiring 500 continuous watts in 1970 require less than 100 watts today. A major cost-driver (as well as reliability concern) in these systems is the battery. Because batteries are the only component requiring maintenance, user awareness of the state-of-charge and electrolyte level is important to ensure maximum battery life and reliability. The use of low-maintenence (e.g., sealed) and deep-discharge batteries is preferred.

Photovoltaic power for area **lighting and home power** systems is emerging as a significant technology in the developing world. Applications involve one-to-two module systems (tens of watts) used in individual households (to power lights, radio, television, refrigerators, etc.) as well as systems used to provide area lighting for community and security purposes. The predecessors of the PV systems have been kerosene, candles and primary batteries lighting from these sources was often expensive and of poor quality. A prime example of the PV experience in this area is that in French Polynesia and Tahiti. The South Pacific Institute for Renewable Energy (SPIRE) has installed nearly 2500 systems spread over 23 islands. (Of the total population of 180,000 people, some 40,000 live on outer islands separated by hundreds of miles of water, making fuel delivery very difficult and expensive.) The newer systems use 400 watts of PV modules, 425 ampere-hours lead-acid battery storage, a battery charge regulator designed by SPIRE, and strictly dc loads for lighting, refrigeration, and communications. Individual rather than centralized systems with distribution are preferred for two reasons: first, to encourage energy conservation by the individual users; and second, to have a degree of redundancy for small, isolated communities in case of system failure. Direct subsidies or loans from the government have encouraged the users to install the PV systems. The overall impact of PV has been to improve the quality of life and productivity in these countries through improved social activities, education, and communications.

The most important technical factor in the successful use of PV-powered lighting and home power systems is the selection of field-proven, reliable charge controllers. The availability and distribution of spare parts for the load and power conditioning equipment is a basic infrastructural need that must be met to ensure successful widespread system implementation.

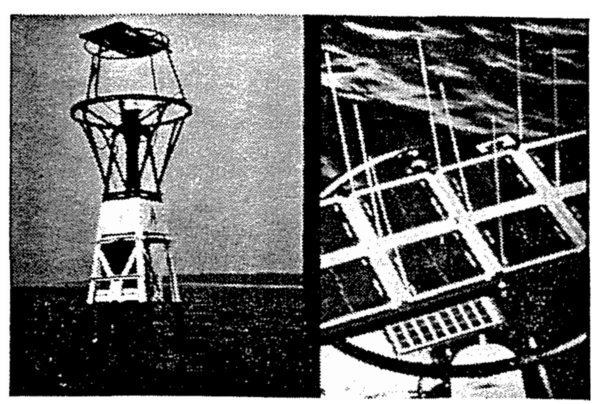

Fig. 10. Thousands of navigation aids are powered most cost-effectively by photovoltaics all over the world today.

Multi-use systems are considered an important application for PV because of the large number of unelectrified villages in locations remote from the grid in all developing countries. Of some 560,000 villages in India, for example, only 17% are electrified; some 350,000 of these villages have less than 500 inhabitants. Two types of systems are included here: mini-utility systems (which include centralized generation and a distribution network to the whole community); and dispersed load centers (which are designed to power a variety of loads at the site of application). Typical system sizes are up to 5 kW for dispersed and up to about 30 kW for centralized applications (see examples in Figs. 11 and 12, respectively). One of the policy decisions, in fact, concerns whether centralized or dispersed systems are preferred in a given situation. There are numerous multi-use PV systems in existance in developing countries (in Africa, Asia, and Central and South America) for rural electrification and village power -- most of these systems (as other energy generating systems) are financed by governments and international organizations. Key factors in the viability of PV-powered multi-use systems were determined to be [11,12]: the reliability and complexity of power conditioning equipment; and the infrastructure for system management. Effective local management is clearly very important; a sense of local "ownership" results in a commitment to system success, ensuring an adequate supply of spare parts and availability of technical support. As these systems get larger, effective management (both technical and administrative) will become even more critical.

5. CONCLUSIONS

Research progress in photovoltaics is leading to new efficiency records in all material areas, and the transfer of new technology from the laboratory to the marketplace. Photovoltaic modules today are more efficient, more reliable and less costly than they were a few years ago. This is the result of an aggressive, goal-oriented U.S. government program in partnership with industry, universities, and utilities, with the ultimate aim to produce cost-effective PV electricity in U.S. utility markets. From a number of successful, megawatt-size utility experiments, it can be concluded that the acceptance of photovoltaics by utilities is a virtual certainty -- the only remaining technical obstacle is the cost of the PV modules.

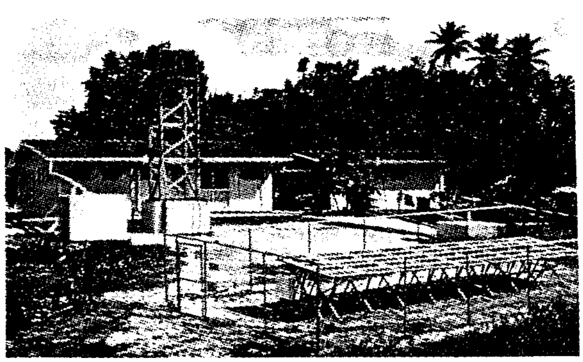

Fig. 11. The Waramuri Health Station in rural Guyana receives electrical power from a 1.5 kW photovoltaic system.

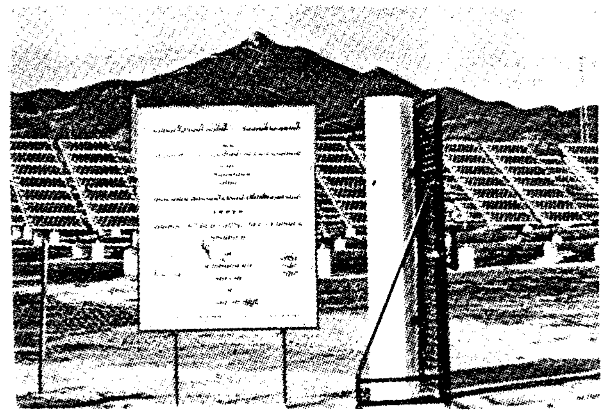

Fig. 12. A 25 kW village power system in Tunisia provides power for water pumping, agricultural tasks, and household needs. This is a jointly funded project by the Republic of Tunisia and the United States.

After three decades of research and development, photovoltaic technology has reached the status of being "appropriate" for vast numbers of applications -- today. It is "appropriate" in that it is the most economical, reliable, and available energy source for the whole spectrum of remote applications. Photovoltaics offers the promise of improving the quality of life for billions of people -- bringing them the benefits of safe, economical, and reliable electric power on a scale suited to their needs and economy. Achieving that promise requires education of the users, but not because the technology is complex. Rather, education is necessary because the technology is new and somewhat "mysterious"; there is no noise, moving parts, or pollution. The U. S. experience with photovoltaics in developing countries has shown that the overall weak link in implementing these systems is institutional support. Because PV is a relatively new technology, there is no established infrastructure to support training, maintenance, and repair. Education of the users, governments, and financing organizations should enhance the acceptability of the technology and lead to the development of the needed infrastructure. The experience with thousands of PV systems has also shown that today's PV systems are already accepted because of their reliability, independence from fuel, and minimal maintenance requirements. In many of these remote, stand-alone applications, photovoltaics is today's power option of choice on a total cost/benefit basis. Continued advances in PV technology -- and the expected reductions in module costs -- should lead to ever-increasing applications in both the developing and developed world.

ACKNOWLEDGMENTS

The work performed at the Solar Energy Research Institute and Sandia National Laboratories was supported by the U. S. Department of Energy under Contract Nos. DE-AC02-83CH10093 and DE-AC04-76DP00789, respectively.

REFERENCES*

[1] U. S. Department of Energy, "National Photovoltaics Program: Five Year Research Plan, 1987-1991", DOE/CH10093-7, May 1987.

[2] U. S. Department of Energy, "Photovoltaic Energy Systems: Program Summary, FY 1987", DOE/CH/10093-H4, February 1988.

[3] U. S. Department of Energy, "National Photovoltaics Program: 1987 Program Review", DOE/CH10093-21, April 1988.

[4] P. D. Maycock, "Photovoltaic Technology, Performance, Cost and Market Forecast to 2000", PV Energy Systems, Inc., Casanova, Virginia 22017.

[5] Sandia National Laboratories, "Today's Photovoltaic Systems: An Evaluation of Their Performance", SAND87-2585, 1987.

[6] Sandia National Laboratories, "Photovoltaics for Military Applications", SAND87-7016, January 1988. Work performed by Meridian Corporation.

[7] Chronar Corporation, private communication.

[8] U. S. Department of Energy, "Presentations of the Photovoltaics: Investing in Development Conference", May 4-6, 1987, New Orleans, LA.

[9] G. J. Jones, et al.,"Terrestrial Photovoltaic Power Technology", Proceedings of the 19th IEEE PV Specialists Conference (IEEE, New York, 1987) p. 25.

[10] R. N. Chapman, "Sizing Handbook for Stand-Alone Photovoltaic/Storage Systems", SAND87-1087 (Sandia National 1987).

[11] D. Eskenazi, et al., "Evaluation of International Photovoltaic Projects", SAND85-7018/1 and 2 (Sandia National Laboratories, September 1986). Work performed by Meridian Corporation.

[12] D. Eskenazi, et al., "Evaluation of International Photovoltaic Projects", Proceedings of the 19th IEEE PV Specialists Conference (IEEE, New York, 1987) p. 1339.

[13] A. Cabraal, et al., "A Comparative Assessment of Photovoltaics, Handpumps and Diesels for Rural Water Supply", SAND87-7015 (Sandia National Laboratories, November 1987). Work performed by Meridian Corporation.

[14] G. J. Jones and R. N. Chapman, "Photovoltaic/Diesel Hybrid Systems: The Design Process", Proceedings of the 19th IEEE PV Specialists Conference (IEEE, New York, 1987) p. 1024.

[15] H. N. Post and M. G. Thomas, "Photovoltaic Systems for Current and Future Applications", accepted for publication in Solar Energy.

[16] H. Rodriguez, "PV for Communication: Linking Distant Parts of Colombia by Radio and Television", in reference 8, page VII-9.

* The various U. S. Department of Energy and Sandia National Laboratories reports cited are available from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springsield, VA 22161.