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The Future of Photovoltaic Energy Conversion in Developing Countries

Steve Hogan

Solar Energy Research Institute
A Division of Midwest Research Institute

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PREFACE

This report is the result of information compiled for a chapter in the National Academy of Sciences' sequel to Energy for Rural Development. The author is indebted to the organizations and individuals who supplied information used in this report. A special thanks is due to Rick Adcock and Kay Firor of SERI for their reviews of this report and helpful discussions.

Steve Hogan
Photovoltaic Research Branch

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

Sigurd Wagner, Chief
Photovoltaic Research Branch

Donald Feucht, Manager
Photovoltaics Division

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SUMMARY

Recent studies reveal that photovoltaic energy conversion will be economically viable for usage in developing countries. This report presents an overview of programs designed to lower the costs of such conversion systems. Government goals are reviewed, as well as application projects relative to rural usage. A summary of the state-of-the-art in both advanced research and commercially available technology is presented. It is concluded that with the range of the work being done, such systems wil be viable for many rural applications within 5 years.

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INTRODUCTION

1.1 ECONOMIC AND SOCIAL IMPLICATIONS OF PHOTOVOLTAICS IN DEVELOPING COUNTRIES

In the four years since the appearance of the National Academy of Sciences publication Energy for Rural Development, advancements in the field of photovoltaic devices and system applications have been encouraging. Unlike many other projections about technological advances, expected pricing and efficiency goals for photovoltaics have been met and, in many cases, exceeded. The industry is beginning to mature, and a glance at the number of companies currently manufacturing either cells or systems (Appendix A) reflects this increase over its status in 1976. Photovoltaic energy conversion still represents one of the neatest and most aesthetically pleasing schemes for the application of solar energy, and it is no longer the solar technology farthest from feasible widespread application in developing nations.

Worldwide activities in the research and development of photovoltaic devices (solar cells) have increased dramatically. The money spent on this increase, while insignificant compared to money spent on nonrenewable resources, reflects the added importance that technologically developed countries are attaching to the development of renewable energy resources. Fabrication of photovoltaic devices requires technological expertise and sophisticated equipment; hence, the industry remains restricted to industrialized countries. However, manufacturers must be aware that the production volumes needed to further reduce manufacturing costs may initially come from energy demands of developing countries (DCs).

The photovoltaic system, with its high reliability and low maintenance requirements, could be more economically attractive than other energy sources in the rural areas of DCs. In addition, policy makers realize that a transfer of technology eventually must occur. This transfer initially will require that local residents be trained in site preparation, foundation fabrication, and routine maintenance (module washing, battery water filling, etc.). As production volumes increase, encapsulation techniques also would be transferred, and cell production could be moved to locales with adequate fabrication-site potential. However, DCs must engage in extensive international trade to attain their first systems and, therefore, international assistance may be required to take the first steps toward energy independence and a better standard of living for people of developing nations.

Demonstration projects of rural village electrification by photovoltaic systems illustrate the importance of DC applications. These applications have increased in complexity from powering educational television sets in remote areas, through the powering of water pumps for potable water, to current projects in Mali, Upper Volta, Saudi Arabia, and the Southwest United States that attempt to satisfy total power needs of isolated villages. These latter projects should provide important background information about technical aspects (reliability, maintenance, lifetime, etc.) and socioeconomic effects of rural electrification by photovoltaic systems. Although these socioeconomic effects will probably not be different from those encountered with any other method of village electrification, it is imperative to establish baseline studies identifying potential problems as soon as possible.

Some form of communication should be established and maintained between representatives of DCs and fabricators of photovoltaic systems, so that suppliers will know the villagers' actual needs. A clearinghouse such as the United Nations might help develop such a communications channel. Again, a major consideration in photovoltaic electrification is the availability of money to purchase systems. Many developing countries, particularly non-oil producers, are hard-pressed to engage in international trade to pay for photovoltaic systems. International organizations (such as the World Bank) or helping organizations (such as AID) might be of assistance in the purchase of initial systems. As cottage industries are established, a national economic infrastructure can lead to international trade. Educational and technological transfers are equally as important as the transfer of hardware from developed countries to developing ones, if DCs are to become self-reliant and establish their own economic infrastructures.

1.2 PHOTOVOLTAICS TECHNOLOGY: THE STATE OF THE ART

The technology available for terrestrial photovoltaic systems has been expanded greatly in the last four years. This expansion has not affected materials used (silicon is still the workhorse of solar cell modules), but changes have occurred in techniques of manufacturing and prices have subsequently declined. Most governments are establishing programs to meet lower price goals for these silicon-based modules. The U.S. goals, more aggressive than most, call for the 1986 price of photovoltaic modules to be $\$700/kW_p$* at a production level of 500 MW_p. The present quotations of \$7 to $\$10/W_p$, with an estimated 1979 production of over 1 MW_p, fall in line with the U.S. goals monitored by the Department of Energy (DOE). Again, the success of such programs depends on capturing markets in rural areas of DCs where photovoltaic systems can compete economically with conventional power sources.

Technological developments, either anticipated or in progress, lead to further price reductions. Ongoing research in single-crystal silicon and ribbon- or web-grown silicon, including new or improved processing techniques, strongly suggests that near-term price goals for silicon photovoltaic modules of $\$2.80/W_p$ by 1982 will be met. Current economic analysis indicates that meeting this goal will facilitate significant market penetration into rural applications. These analyses are based on a comparison of energy costs per kWh for diesel generators, present utility-grid line extensions, and installation of photovoltaic modules. Every application and locale must be examined on an individual basis, however, to assure economic viability. While an application in a remote village in Africa may be competitive now, a similar application in India may not be, because of differences in diesel fuel prices and annual insolation levels, for example. These analyses show that an advantage to PV systems is their modular nature. Systems that can be tailored easily to an initial application, and just as easily expanded as power demands increase, are still being designed and developed.

Technologies using elements other than silicon are also nearing commercialization. These technologies (such as thin-film CdS-based systems or GaAs concentrator systems) may eventually prove advantageous in rural DC applications. Substantial price reductions are probable, and new technologies could go well below established price goals for silicon. These are infant technologies, compared with the silicon-based systems, however, and will require at least four to five years in the market to establish their reliability and durability—aspects that silicon systems are now only beginning to evidence.

Some materials undergoing worldwide research and development are even further from commercialization. This research covers both new techniques and new materials for solar cell fabrication, and represents revolutionary rather than evolutionary changes in photovoltaic device de-

*All quotations of future cost goals are in 1980 constant dollars.

signs. Advanced techniques include new methods of depositing very thin films of materials on cells to reduce waste and costs, and utilizing low-cost fabrication processes such as spraying or screen-printing the different materials of a photovoltaic device. Many of these techniques are not energy-intensive, nor do they require advanced technological capabilities. Therefore, they represent technologies that easily could be transferred to DCs.

New materials research focuses on such diverse materials as CdTe, $Zn_3 P_2$, and others. While all are probably capable of adequate efficiency (i.e., greater than 10% efficiency) and low cost, perhaps the most promising of the new materials is amorphous silicon. The sources of this material are abundant, indicating the potential for a low-cost photovoltaic structure. Researchers are actively involved in use of this material, but more needs to be done to understand the physics of amorphous silicon cells and improve their efficiency (presently 3% to 5%). It is hoped that developments coming out of advanced research laboratories will enable manufacturers to produce photovoltaic modules in the 1990s costing from $150 to $400/kW_p$.

A field of increasing importance, and one that has been neglected for several years, is the work being done on the balance of system (BOS) of a photovoltaic installation. BOS represents the entire system except for the photovoltaic modules, and includes structures, power conditioners, and storage. Work is being done to develop new low-cost support structures, increase efficiencies of power converters, and lower the costs of storage (as well as to examine new storage techniques, such as flywheels). As these programs advance, the prices of complete systems will drop and system reliability will improve. Present lifetime expectations are 20 years for modules, 10 to 12 years for power converters, and 8 to 10 years for storage (if batteries are used). The cost of systems without storage could reach approximately $2/W_p$ by 1986.

Research and development must continue if costs are to drop so photovoltaic systems will be more affordable to DCs. Development of electric devices tailored to loading of photovoltaic systems has been neglected and should escalate. Again, each application requires a site-specific analysis, and present manufacturers must make sure that these analyses are carried out to facilitate reliable and successful photovoltaic system implementation.

SECTION 2.0

INFORMATION TRANSFER AND GOVERNMENT GOALS

2.1 INFORMATION TRANSFER

Information on photovoltaic devices has increased over the last several years. Several books on both system and device engineering are available [1,2,3], numerous tutorial articles and reviews have appeared [4,5,6], and conferences covering a wide variety of materials have been held [7,8,9]. Such information enables policy makers to know about current system designs and device research trends. This is important to governments of developing countries, and makes it possible for them to converse knowledgeably with photovoltaic system manufacturers.

Information transfer in the opposite direction, enlightening system manufacturers to the needs of the people of DCs, has begun only recently. Studies by such groups as the Worldwatch Institute [10], Massachusetts Institute of Technology Lincoln Lab (MITLL) [11,12], and the World Meteorological Organization (WMO) [13] have become available recently. These studies reveal the importance of solar energy usage (and, in some cases, photovoltaic conversion) to future capabilities and possibilities of DCs. The studies point out that investments in nonrenewable energy sources over the next 20 years by DCs would be clearly a mistake and that in order to develop an economic infrastructure with growth potential, it is important to begin investing in renewable energy sources now.

2.2 GOVERNMENT GOALS

This anticipated investment in renewable energy sources and the remote nature of applications suggest that DCs will provide the initial impetus for photovoltaic industry growth. A study by the BDM Corporation [14] indicates that water pumping applications alone will provide a potential market of 400,000 units of less than 5 hp each by 1986. These applications for photovoltaic conversion can represent the earliest economic "break-even" market. Within the United States, this potential market is evidenced by DOE's establishment of a comprehensive plan to initiate an international dialogue on photovoltaic trade. Additionally, international manufacturers are scrambling to establish their expertise in rural photovoltaic system development. These manufacturers are being both assisted and prodded by government programs and pricing goals to accelerate the marketing of photovoltaic systems.

In the United States, DOE has set target prices for photovoltaic modules (in quantities of tens of kilowatts) to decrease to \$2.80/W by 1982, 70¢/W by 1986, and 15¢ to 50¢/W by 1990. A yearly budget of well over \$100 million is being projected over the next 8 years [15] to meet those goals, representing the most aggressive and comprehensive program toward furthering the development of photovoltaic energy conversion so far undertaken by any country. More details about the programs will be given later in this report.

The United States is by no means the only government establishing cost goals and providing money for photovoltaic device development [8,16]. In France, the Commissariat a l'Energie Solaire (COMES) has established price goals of \$1.60 to \$2.50/W by 1985. COMES and the Centre National de la Recherche Scientifique are spending between \$4 million and \$5 million each in programs for photovoltaic devices and systems research. In West Germany, the prospect of developing export potential stimulated the Ministry for Research and Technology to establish an eight-year, \$76 million program to perfect a photovoltaic system utilizing polycrystalline silicon. The program goal is to develop arrays cheaper than \$2.40/W by 1985. Both Italy and Great Britain have smaller, established programs in photovoltaic research. The European Economic Community (EEC) has announced planned expenditures of over \$23 million in the next four years for photovoltaic system development, and a major goal of the EEC is to construct several generating plants of 300-400 kW each. Japan established the multibillion-dollar Sunshine Project in 1974 to develop a strong photovoltaic device manufacturing base by 1985. India, meanwhile, has established a goal of \$2.80/W by 1985, a price considered to be the threshold for economic rural water pumping in India. Development efforts and economic goals of the Soviet Union have not been publicized, but an excellent review of programs under way is given in an article by Palz [17]. In addition to all of these programs, private industries are spending millions of dollars on research and development. This money represents confidence in the future of photovoltaic power generation, encouraging optimism about the future availability of this energy source for DCs.

SECTION 3.0

RURAL PHOTOVOLTAIC APPLICATIONS

Demonstration projects that place photovoltaic power sources in remote villages are important to electrification plans of developing countries. The systems in Upper Volta, Mali, the Southwestern United States, and Saudi Arabia are offspring of initial tests and applications of photovoltaic systems which were located typically in remote settings where they provided power for such loads as ocean buoys, forest fire lookout towers, and remote communication links. Projects that are either in various planning or implementation stages will be discussed here.

3.1 REMOTE COMMUNICATIONS

3.1.1 Educational Television Sets in Niger and the Ivory Coast

One of the first applications geared toward DC applications was a system of over 4000 photovoltaic-powered educational television sets (ETVs) established in 1975 in Niger and the Ivory Coast [18]. The French government successfully demonstrated this system, designed to educate the rural villagers on a 4-hour-per-day basis, and expansion is anticipated. An Ivory Coast firm expects production of ETVs in the next decade to exceed 13,000 photovoltaic-powered sets [19]. A World Bank estimate projected a worldwide demand of 10 MW for ETVs by the early 1980s, and concluded that photovoltaic-powered sets presently have an economic advantage over alternate systems [20]. These systems have proven to be reliable.

3.1.2 Telecommunications in Mexico

Another remote telecommunications application has been successfully demonstrated since 1977 by the Mexican government. The project, utilizing 36 W of photovoltaic power, operates a rural telephone station. It is unique, in that all components of the system were designed and produced in Mexican laboratories. A solar cell pilot production line is being set up to produce 20 kW per year [21], and it is anticipated that 70 more stations will be installed in rural applications.

3.2 WATER PUMPING AND IRRIGATION

3.2.1 25-kW Irrigation System in Mead, Nebraska

A 25-kW irrigation system, larger than most rural applications, has provided important baseline information about silicon module reliability and system design. The project, sponsored by DOE and located in Mead, Nebraska, has shown a module failure rate of 2% [22] in 2 years and has provided important statistical information on such aspects as soiling and cleaning [23]. The system has been running for 2 years with less down-time than the local utility. Figure 3-1 is a view of the Mead system and associated support structures. Further U.S. water pumping applications have been identified and analyzed as well [24].

3.2.2 Rural Water-Pumping Applications in the Republic of Mali

The Republic of Mali has at least five photovoltaic systems presently in use, initiated and installed largely with French assistance, that are used primarily for water-pumping in rural areas (see Fig. 3-2). Figure 3-3 presents a view of a 16-kW system being installed at a hospital in San. This system will provide power for water pumping, drug and medicine refrigeration, and lighting and cooling in the operating

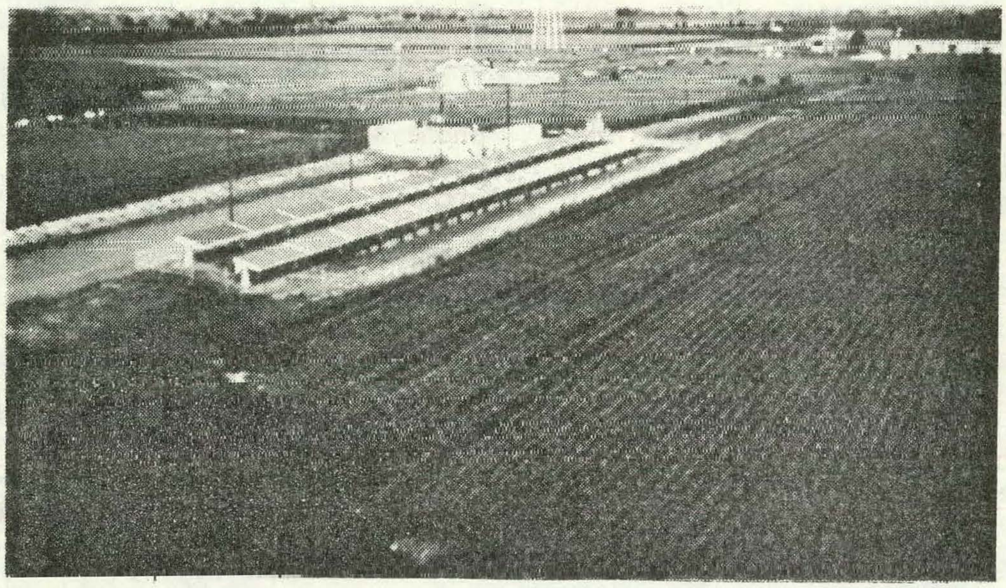


Figure 3-1. 25-kW_p photovoltaic-powered irrigation system at Mead, Nebraska.

rooms. A program financed by AID and administered by the Solar Energy Research Institute (SERI) will install four more water-pumping stations in four regions. The 2-kW photovoltaic array-powered stations will also feature 20 to 30 m^3 of water storage, and are a part of a complete pumping system offered by Guinard of France. No electric storage is planned for the systems; Peace Corps volunteers will install them.

Educating villagers to operate systems properly and consideration of the unique characteristics of each village must accompany technology transfers. One problem with the remote pumping systems in Mali arose because the villagers lacked the training necessary to operate them. The people of the village, accustomed to getting their drinking water after dinner, could not understand why the water tap did not work in the evening and so thought the system was not worthwhile. Proper training will help alleviate such problems in the future.

3.2.3 Feasibility Studies

A study pertinent to DC water-pumping applications has been conducted by NASA Lewis Research Center (LeRC), one of the world's leading centers for research in photovoltaic applications for rural areas. The results of the LeRC study state that, under present cost goals, a utility line grid extension of greater than 5 to 7 miles makes consideration of the use of photovoltaic systems a practical alternative. The study also projects a 6 GW_p market in foreign water-pumping applications, and concludes that significant market penetration will occur in 1981 or 1982 as the systems become economically feasible. It also cautions that a four-year lead time is necessary to evaluate and test planned systems, and that development of those systems will be paced by costs, government attitudes, and choice of sources of funding [25].

Several other papers also present prospects of photovoltaic power for pumping

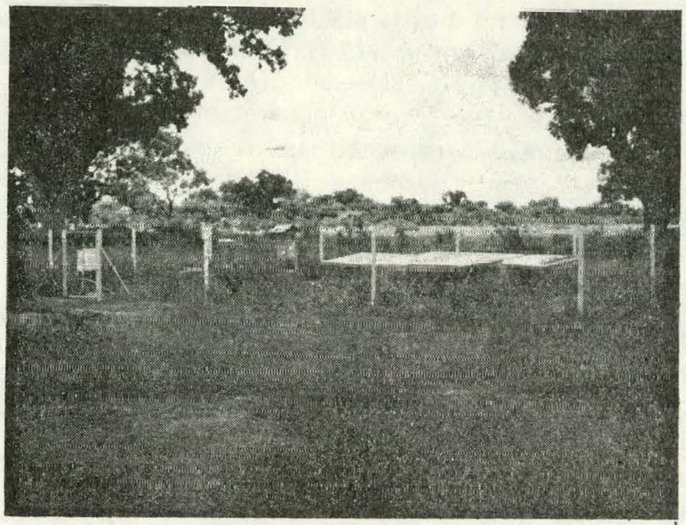
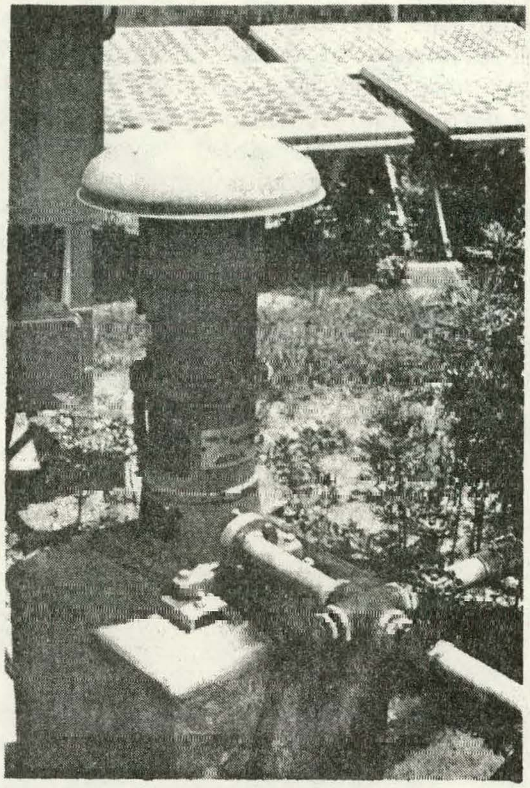


Figure 3-2. Remote photovoltaic-powered water pump in Mali (courtesy of Dr. W. Mackie).



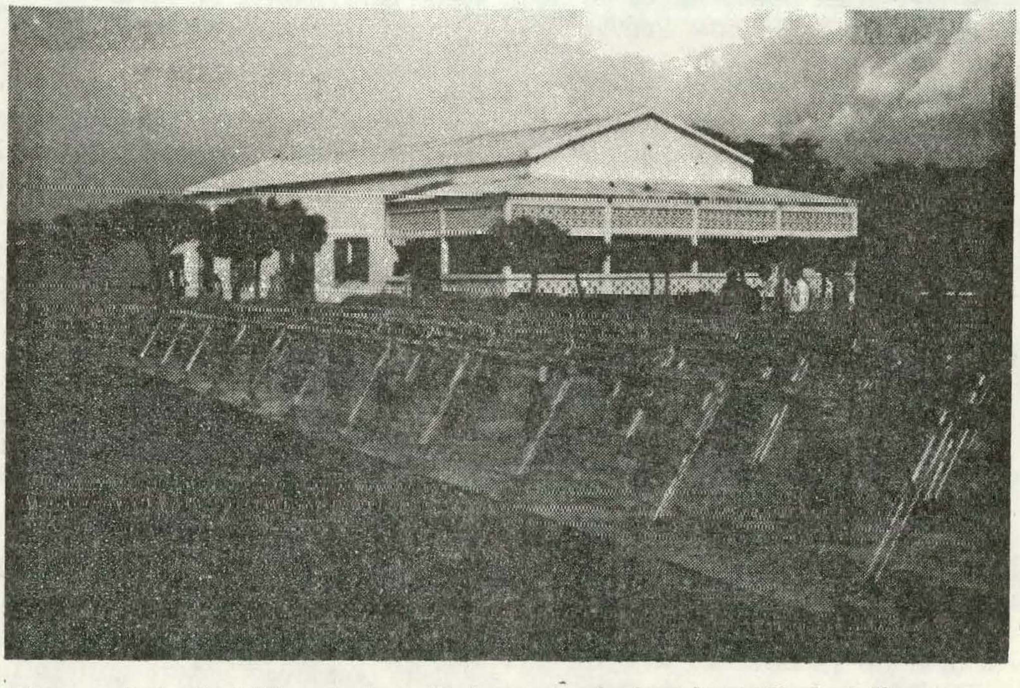


Figure 3-3. 16-kW_p photovoltaic array being installed at the hospital in San, Mali (courtesy of Dr. W. Mackie).

applications in rural areas. The first, a brief overview of details from the 1978 Solar Energy Congress in New Delhi, estimates that photovoltaic systems will be competitive with diesel systems by 1983 [26]. The second paper gives a more thorough comparison of photovoltaic power versus diesel power for water pumping in rural India. This analysis concludes that the photovoltaic source is economically viable at a cost of \$3.50/W_p for irrigation and \$6/W_p for drinking water [27], a price that will soon be available. Another paper, presented at the World Meteorological Organization Conference on Solar Energy [28], describes a photovoltaic pumping system in Corsica, specifying the components used and providing a test sequence for evaluation.

3.3 PHOTOVOLTAIC STAND-ALONE VILLAGE POWER SYSTEMS

More complex photovoltaic systems to meet the entire electrical power needs of a village also are being designed. Previously referenced reports [12,14] give projected photovoltaic system sizing for typical villages in Upper Volta and India. Both reports estimate that a 10-kW_p system is necessary to meet the initial total demand of a typical village of 500 people. These demands would include such items as a potable water supply, irrigation, ETVs, school/shop lighting, milling, refrigeration, and site-specific cottage industrial applications.

Another LeRC paper discusses the utilization of photovoltaic power systems in 19 DCs. The paper concludes that those systems can presently operate at an energy cost of \$1.60 to \$2.20/kWh [29] and that this cost will be reduced to 25¢ to 50¢/kWh by 1983-85, when economic viability is attained. The paper also points out that the modularity of photovoltaic systems helps to overcome the problem of initial high capital outlays for unused central-station capacities.

Two other LeRC studies examined market potential and costs for village power systems. The first estimates a potential of 10 GW_p for foreign market applications in village power, with an average usage of 24 W_p per person. It concludes that, if DOE price goals are met, a potential of 20 GW_p could be required by the year 2000 [30]. The second study involved a detailed analysis of energy costs for photovoltaic systems versus diesel and utility extension [31]. This analysis is presented graphically in Figs. 3-4 and 3-5. As can be seen from the graphs, photovoltaic systems are presently competitive in applications requiring less than 5000 kWh/yr, and by 1981 will be competitive for many larger applications.

3.3.1 1.8-kW_p System in Tangaye, Upper Volta

LeRC has successfully implemented two photovoltaic stand-alone village power systems [31,32]. The first of these two systems was installed on March 1, 1979, in Tangaye, Upper Volta. The project, sponsored by AID, is designed to study the social and economic effects of an electric-powered water pump and grain mill. This relieves the village women from their daily 1- to 2-hour routine of milling flour and lifting water by hand. Financial considerations limited the photovoltaic system size to a 1.8 kW_p, 120-V DC array, with 540 amp-h of battery storage. The villagers constructed a building to house the mill, power regulators, and storage batteries. Figure 3-6 shows the installed system.

Initial sizing estimates for water requirements of 500 ℓ/day and for grain milling of 320 kg/day for over 600 families were used to procure the system components. A 1-hp commercial burr mill, with a 120-V DC motor, is being used that has a milling capacity of 45 to 135 kg/h. Two 20-W fluorescent bulbs are also powered in the milling room. The water pump, with a 1/4-hp 120-V DC motor, can deliver

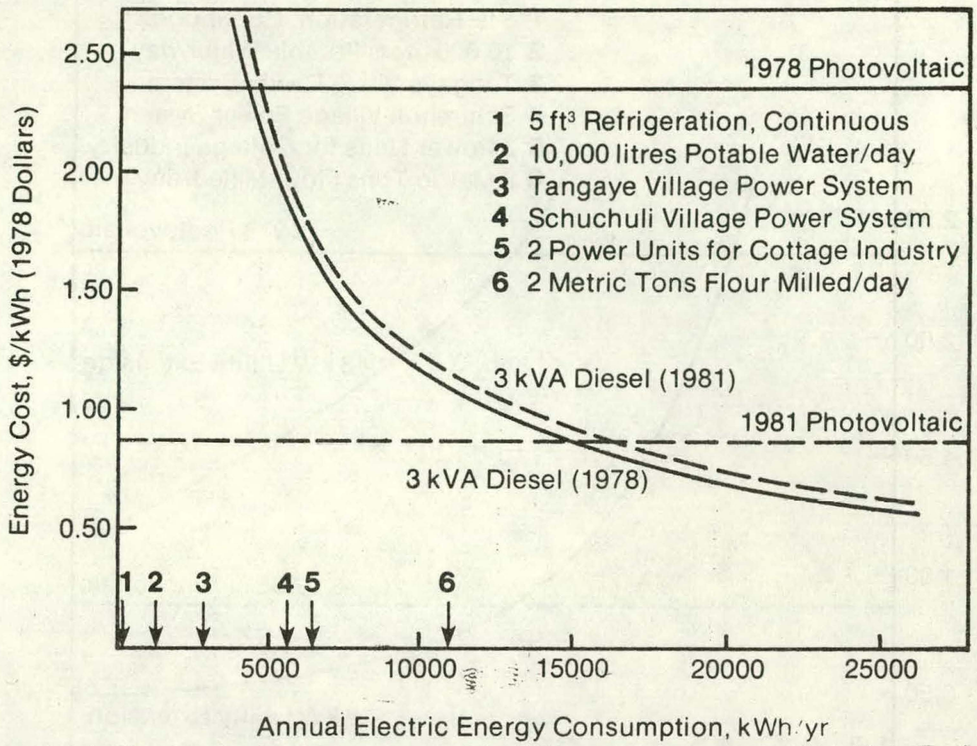


Figure 3-4. Photovoltaic and diesel energy cost comparisons [Ref. 31].

1457 ℓ/h at a dynamic head of 28 m. The pump supplies water to a 6-m^3 storage tank and dispensing area near the milling building. Safety precautions include a fenced-in array area, enclosed water pump, underground cabling, under/over voltage protection, water level shut-off switches, and adequate education for villagers so they can safely operate the equipment.

Because the system has been installed recently, no socioeconomic impacts have yet been reported. These reports, when available, will constitute the beginning of the baseline information needed to fully understand the potential and ramifications of using photovoltaic power systems in DCs.

3.3.2 3.5-kW$_p$ System on the Papago Indian Reservation

The second stand-alone application successfully implemented by LeRC was the installation of a 3.5-kW$_p$, 120-V DC photovoltaic array in the village of Schuchuli. This village of about 100 people is located on the Papago Indian Reservation in southwestern Arizona, and needs a power supply for water pumping, lighting, refrigeration, and services for village housekeeping. The system, consisting of 24 photovoltaic panels that provide 120-V DC, was inaugurated in December 1978 after the hardware was designed and installed. DC systems were used exclusively, to avoid the power losses, cost, and additional complexities of the DC-AC inverters. Battery storage of 2380 amp-h capacity was incorporated to provide power at night or during low insolation periods. Portions of the array can automatically disconnect to prevent overcharging the batteries, and automatic load shedding prevents the batteries from excessive discharging.

There are presently five kinds of loads on the system: lights in all the buildings, a

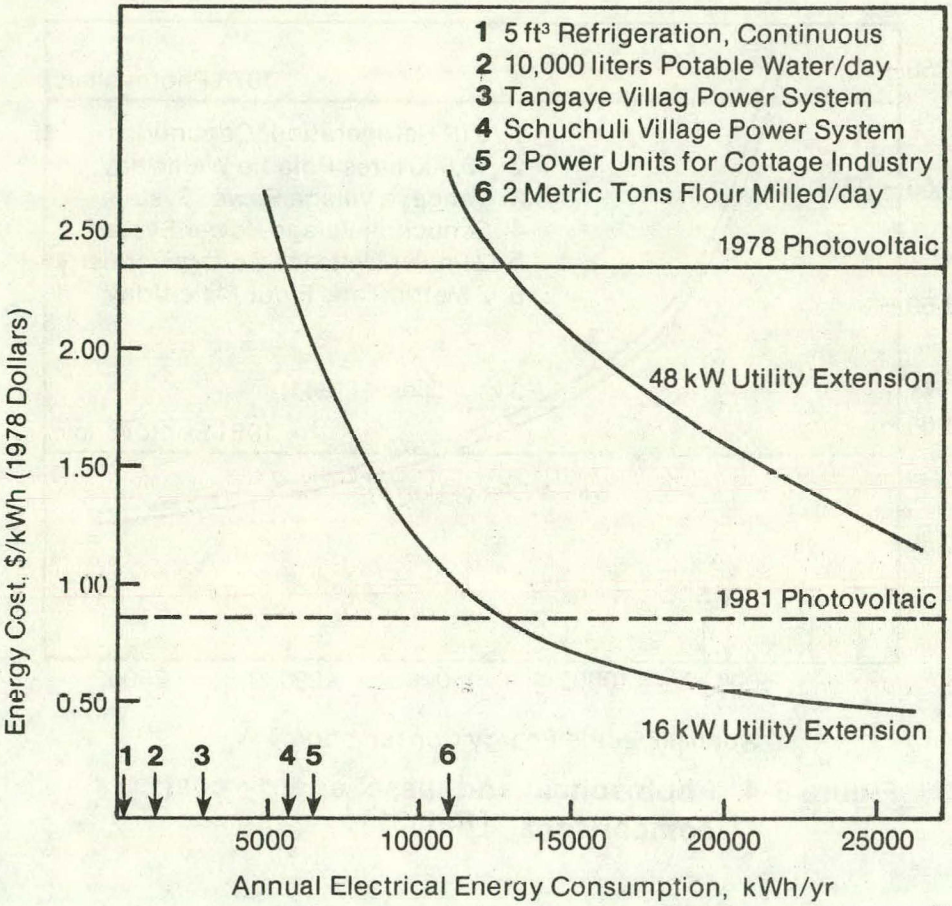


Figure 3-5. Photovoltaic and utility extension energy cost comparisons [Ref. 31].

water pump, refrigerators, a washing machine, and a sewing machine. The lighting consists of fifty-three 20-W, 120-V DC fluorescent lights in the houses, church, feast hall, electrical equipment building, and Domestic Services Building (DSB). The water pump is a 2-hp, 120-V DC motor-driven pump capable of supplying 4.2 m^3/h to the 41.6 m^3 storage tank and water distribution system. The refrigerators, washing machine, and sewing machine are located in the DSB, the center for village domestic activities.

Fifteen 0.13-m^3 refrigerators were custom designed to incorporate three refrigerators each into a single cabinet with a single compressor. The five compressors are located outside the DSB so that waste heat is not vented into the room containing the refrigerators. The washing machine is a standard wringer-type unit retrofitted with a 1/4-hp, 120-V DC motor. This type was chosen because its simplicity was preferred by the village women. The sewing machine is available commercially, and has a 1/8-hp, 120-V universal motor. Safety features are similar to those of the Tangaye project, with the exception that power is distributed through overhead lines installed by the Tribal Association. Figure 3-7 shows the installed system.

A social and economic impact assessment of the Schuchuli system has been carried out and reported [33]. Initial findings reveal that the photovoltaic-powered water pump has not changed the water usage of the villagers, since the pump was already

Figure 3-6. A view of the 1.8-kW$_p$ solar cell arrays (right center) in the village of Tangaye, Upper Volta, which power a water pump and a grain mill. The pump supplies the water dispensing tank (center). The grain mill, operated as a cooperative by the village, is located in the building behind the tank.

present (but powered by a diesel generator). However, a household monetary charge for diesel fuel is no longer required. The refrigerators have been very popular, with all but one family using them. Items stored in the refrigerators include milk, meat, juices, fruits, and vegetables—most of which require preparation before eating. At least one family is using a refrigerator to store medicine (in this case, insulin).

To date, the most successful item of electrification in Schuchuli is the washing machine, with 9 of the 11 households making use of it. The sewing machine has been a limited success, because sewing is commonly viewed as an optional household activity. The addition of lights has received favorable responses, with an average usage of 3.5 h/day. However, no major lifestyle changes have been observed, even though the use of refrigerators has permitted less frequent shopping trips to a large, substantially cheaper store that is farther away than the general store. The washing machine, too, has reduced the number of trips to the commercial laundromat, some 26 km away.

In open meetings, villagers have discussed the new system and, generally, their attitude is favorable. Some residents, however, expressed dissatisfaction with its limited capabilities, and there were some initial start-up problems because only some villagers had lights, because of a component supply problem. At present, the system does seem to adequately supply the basic electrical needs of the villagers, and represents a baseline system on which to model future rural electrification.

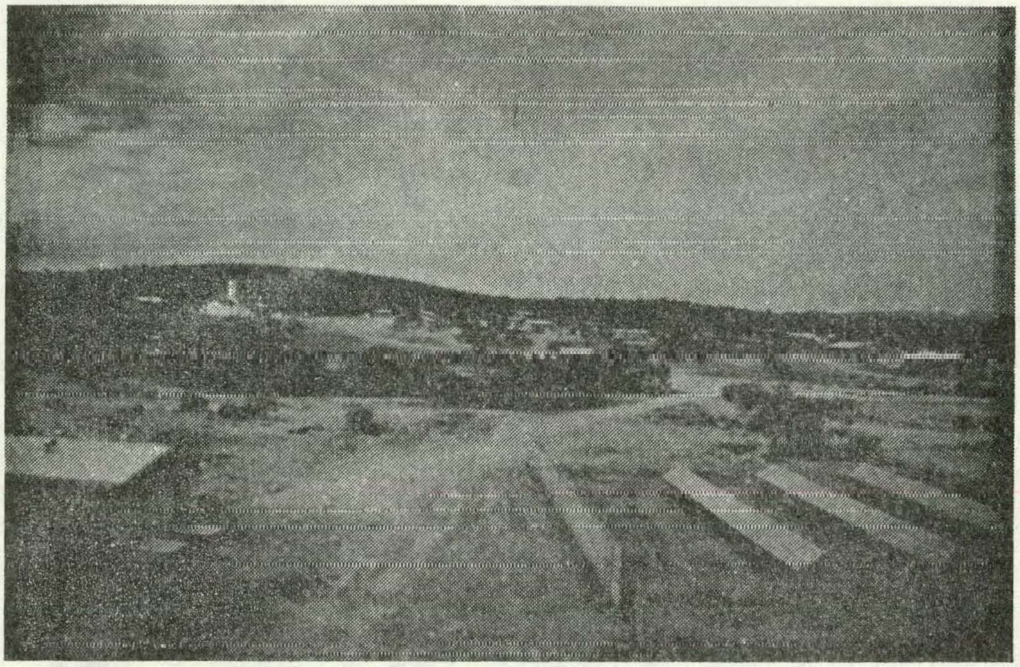


Figure 3-7. This is the world's first Solar Photovoltaic Village Power System. Power is generated by a 3.5-kW_p solar cell installation which converts visible sunlight directly into electricity.

3.3.3 350-kW_p System in Saudi Arabia

An example of a photovoltaic system being designed to supply a large amount of power is a joint Saudi Arabia-United States effort to establish a 350-kW_p system that will supply the electrical needs of Al-Jubailah in Saudi Arabia. This system, with complete electrical control and battery storage, will have a diesel generator backup to supply additional power needs. Although presently in the design stage, the system should be completed by 1983, with significant technological transfer playing an important role in the project.

SECTION 4.0

CURRENT TECHNOLOGY

All installed remote systems to date have utilized silicon-based solar cells and will continue to do so in the near future. Reliability data indicate a 2% failure rate after 2 years in application, with a 20-year potential lifetime. New technologies are emerging that will be cost-competitive with the previously mentioned price goals, making further applications in DCs possible.

4.1 LOW-COST SOLAR ARRAY PROJECT

The largest single program attempting to reduce costs on single-crystal silicon photovoltaic arrays is the DOE-sponsored Low-Cost Solar Array (LSA) Project administered by the Jet Propulsion Laboratory (JPL). The program is designed to achieve DOE goals of $2.80/W by 1982 and 70¢/W by 1986. The LSA project is divided into four tasks: polysilicon material production, formation of this polysilicon material into large single-crystal sheets, encapsulation, and production process and equipment. Associated support activities include engineering, operations, and project analysis and integration (PA&I). Progress to date will be reviewed in each of the four tasks, drawing from several sources [34,35,36].

The first task, polysilicon material production, is taking two major directions. First, a manufacturing process is being sought that will reduce the cost of the semiconductor-grade silicon (99.999% pure) currently used as the start material for silicon solar cells. The cost of this material is presently $70/kg, or roughly $3/W$_p$ in final form. To meet DOE cost targets, it is necessary to reduce the price to $14/kg by 1982. However, a more basic problem is the possibility of future shortages of polysilicon crystal. Major manufacturers of this vital component agree that a shortage will occur by 1982 if photovoltaic industry production levels continue to increase at their present rate. Corrective steps must be taken immediately if this shortage is to be avoided.

The second direction taken by outside contractors in the first task is the evaluation, definition, and production of solar-grade polysilicon. The purity of the semiconductor-grade material might not be critical, and evaluations are being undertaken to examine the effects of higher levels of impurities in the start material. Two contracts are designed to establish novel methods of producing the solar-grade material, and projected prices for these methods range from $6 to $9/kg.

The second task seeks to transform the polysilicon into large sheets of single-crystal material, reducing the cost (in 1980 $) from the present $3/W$_p$ to 94¢/W$_p$ by 1982. To do this, five areas of crystal growth and wafer formation are being examined. The first area is an examination of advanced Czochralski crystal growth, the method that has been used for years in the formation of single-crystal materials. The contracts are set up to determine ways of continually feeding molten silicon into the crucible from which the single-crystal silicon is grown. At present, ingots with a diameter of 15 cm are being grown from the continuous-feed system, and as much as 108 kg/crucible has been grown. The second area of examination is the development of cast ingots. One contractor has shown a cast ingot of 15 cm^3 and has fabricated cells with 15% efficiency after wafering and processing. The third area of examination is the wafering process. Advanced techniques of cutting the cylinders or cubes into the 100- to 200- μm-thick wafers used for the actual solar cells are being examined. One of these techniques involves the use of many blades or wires to make multiple cuts of the original ingot.

The fourth area of examination focuses on the shaped-ribbon process, a process that grows single crystals in a thin, continuous web, thereby eliminating the need to slice the ribbons into wafers as is normally done. One contractor has demonstrated separately: (1) 15-h operation of a 5-ribbon station (each ribbon 5 cm wide), (2) growth of a 10-cm-wide ribbon, (3) 11% efficiency of ribbon-grown cells, and (4) large grain structures. Another contractor has shown a 27.1 cm^2/min growth rate and has produced a 15%-efficient cell from its web-grown process. Still another contractor is examining a method of ribbon-to-ribbon (RTR) crystallization by creating single-crystal ribbon silicon from polycrystalline ribbons, and has achieved growth rates of 55 cm^2/min. Each of the ribbon techniques mentioned has yet to demonstrate adequate growth rates to meet the DOE cost goals, but holds promise of potentially lower costs than the Czochralski-grown wafers. The fifth area of low-cost growth-technique evaluation is a contract to produce thin coats of silicon on low-cost carbon-coated ceramic substrates by dipping the substrates into molten silicon. To date, a 5-cm by 40-cm cell has been produced, and a 2-cm^2 cell has been demonstrated to have an efficiency of over 10%. Figure 4-1 represents a comparison of different growth techniques, including a comparison of different technology skills required.

	CZ	FZ	Ribbon	Casting
Growth Rate (mm/min)	2	4	30	~6
Max. Width (mm)	150	100	100	~100
Throughput (gms/min)	80	70	2	~100
Crystal Structure	Single	Single	←Multi-Grained→	
Technology-Skill	High	Ex. High	High	Low
Sawing Required	Yes	Yes	No	Yes
Solar Cell Efficiency (%)	16	16	11	~11

Figure 4-1. Characteristics of various silicon growth techniques for Czochralski (CZ), float zone (FZ), ribbon, and casting growth (courtesy of T. Ciszek).

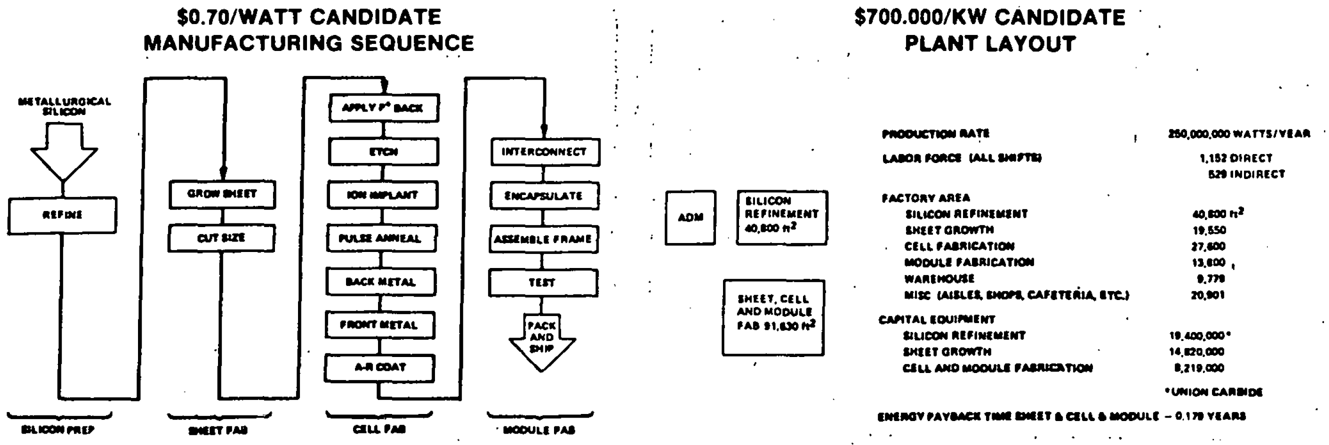


Figure 4-2. Possible module mass-production facility: (a) $0.70/W candidate manufacturing sequence; (b) $700/kW candidate plant layout.

The third task of the LSA program is to evaluate different cell encapsulant materials that have lifetimes of 20 years. At present, different glasses and polymers are being tested that might meet cost goals, and degradation models are being formulated.

The fourth task, that of evaluating the production process and equipment, has entered into a new phase. The task is designed to reduce the cost of producing finished modules from silicon wafers. Different junction formation techniques have been analyzed, including ion-implantation. Thick-film metallization systems have been reliably used in cell production and nine companies are under contract to propose future production facility models. Figure 4-2 represents a possible mass-production facility generated by the LSA program.

Again, there are three support areas of the LSA task: engineering, operations, and project analysis and integration (PA&I). The engineering area has included examination of reliability, wind load, soiling, module interconnects, stress, and other factors. The operations area oversees the activities of different DOE photovoltaic buys. Qualification testing and performance evaluation in 16 field test sites have been ongoing for several years, and will continue as DOE buys continue. The PA&I area includes economic analyses of present and future photovoltaic modules, and it has established a computer program that can evaluate candidate factories and different cell processing techniques.

The goals of the LSA project are summarized in Table 4-1. These are aggressive goals, but many manufacturers feel that a marketable price of $1.50/W_p$ is attainable by 1982. Similar goals are also envisioned by foreign governments, and single-crystal silicon photovoltaic technology is being actively developed in foreign countries. Two French organizations, the Centre de Recherches Nucleaires (CRN) and the Laboratoires d'Electronique et de Physique Appliquee (LPE), are looking at improved or low-cost diffusion techniques for single-crystal silicon. Most of the remaining industrialized countries are monitoring the single-crystal programs and preparing for eventual entry into the market.

Table 4-1. **LOW-COST SOLAR ARRAY PROJECT; PRELIMINARY 1982 TECHNICAL READINESS PRICE ALLOCATION GUIDELINES**

(1980 Dollars)

	Goals	
Silicon (Polycrystalline)	14 $/Kg	0.035-0.117[a] $/W$_p$
Sheet Alternatives:		
-Cz Ingot & Slicing	28.9 $/m^2 of wafer	0.204 $/W$_p$
-Hcm Ingot & Slicing	35 $/m^2 wafer	0.246 $/W$_p$
-EFG	24.2 $/m^2 wafer	0.314 $/W$_p$
-Web Dendritic	39.3 $/m^2 wafer	0.297 $/W$_p$
-SOC	20.3 $/m^2 wafer	0.196 $/W$_p$
Cell Fabrication	21 $/m^2 of cells	0.141-0.192[a] $/W$_p$
Encapsulation Materials	14 $/m^2 of module	0.098-0.139[a] $/W$_p$
Module Assembly	14 $/m^2	0.098-0.139[a] $/W$_p$
Module Totals		0.70 $/W$_p$

[a]This range is caused by the use of different sheet technologies.

4.2 MULTIGRAINED AND AMORPHOUS SILICON CELLS

Silicon solar-cell technology has also spawned the use of multigrained silicon and amorphous silicon. Multigrained (or polysilicon) cells have been shown to yield a high efficiency (11%) and have been moved from the lab to mass production by two companies. Heliotronic GmbH, a subsidiary of Wacker-Chemitronic GmbH in West Germany, is producing a cast polysilicon in brick form. With government support, Wacker has established a program with AEG-Telefunken in which Wacker supplies the polysilicon bricks and Telefunken produces the modules. The cells will cost less than the Czochralski-grown single-crystal cells because they require less energy in fabrication, and the process is more amenable to mass production with higher production rates. Field testing of arrays has begun, and results reinforce original estimates of module lifetimes. The other corporation looking into polysilicon cells is Semix, Inc., a subsidiary of Solarex Corp. in the United States. Semix is also forming the polysilicon in a cast brick. A production facility has been set up, and it is reported that Semix will be making a 15%-efficient cell, at $4 to $6/W$_p$, by mid-1980. Although efficiencies that high have yet to be approached, the price range is reasonable compared to single-crystal cell prices.

4.3 THIN-LAYER POLYSILICON CELLS

Development of thin-layer polysilicon cells is still in the research stage. The DOE lead center for solar research, the Solar Energy Research Institute (SERI) in Golden, Colorado, is sponsoring 17 contracts totaling $2.9 million. Effects of multicrystals are being examined, and methods for fabricating the material onto low-cost substrates are being developed. As part of the work, one university under contract has achieved 9.7% efficiency with a 9-cm^2 cell fabricated by growing the crystal onto a substrate of coarse-grained metallurgical-grade silicon. The growth was accomplished by a chemical vapor deposition (CVD) technique. Other institutions (or organizations) under contract are looking at degradation and stability, as well as theoretical modeling of currents across the many grains in the material. More research to improve grain size and passivate grain boundaries needs to be done before the thin-film polysilicon cells can become feasible even for cost estimates.

SECTION 5.0

ADVANCED RESEARCH

5.1 RESEARCH ON AMORPHOUS SILICON CELLS

Cells based on amorphous silicon-hydrogen alloys represent an even younger technology than thin-film silicon, yet hold great promise to eventually provide a very low-cost cell. A principal advantage is that amorphous silicon absorbs light 10 to 100 times better than single-crystal silicon. This means that a 1- μm-thick layer will be adequate to absorb the light; hence, the material saved from the normal solar cells of 100- to 200- μm thickness will be significant. The cell structure, however, has only been capable of 6% efficiency on a very small device size, with 3% efficiency more typical for normal device sizes. DOE (through SERI) is devoting almost $3 million in 17 contracts to attain a reproducible efficiency of near 10%.

Japanese laboratories have become very active in the development of amorphous silicon cells, and 4.3% efficiencies have been reported by Sanyo. It is anticipated that Sanyo will be using amorphous devices in its consumer products by fall 1980, due in part to the good conversion efficiency of these devices under fluorescent illumination. Great Britain is also actively pursuing the amorphous silicon fields at both Dundee University and the University of Sheffield. Dundee University has reported a laboratory cell efficiency of almost 5%.

5.2 RESEARCH ON OTHER MATERIALS

There are materials other than silicon that can be used for photovoltaic devices (much of this information was drawn from a SERI conference [37]). Cadmium sulphide (CdS) in conjunction with cuprous sulphide (Cu_2S) has been used for over 10 years for photovoltaic conversion. Figure 5-1 shows two typical configurations of the cell. The normal method of fabrication is to deposit the CdS by evaporation, in a vacuum, onto a zinc-coated sheet of copper substrate. The Cu_2S is formed on top of the CdS layer, classically by dipping the substrate into a solution of CuCl but more recently by planar methods such as evaporation. A gold grid is placed over the front and the entire assembly is encapsulated to be watertight. Theoretical efficiencies of 16% have been calculated, but only a 9.1% conversion efficiency has been reported, with practical limits felt to be just over 10%. This cell is a leading contender in the effort to reach thin-film DOE cost goals of 15¢ to 40¢/W_p by 1990.

Two of the most exciting new prospects in material fabrication are screen printing and spray deposition. The screen-printed cell, a very inexpensive process amenable to mass production, has recently emerged from the Matsushita Labs in Japan. The cell stucture is CdS/CdTe with all the components screen-printed, and reported efficiencies of over 8% have prompted DOE to encourage research activities in the United States on this process as well as on the spray deposition technique. The spray process is also a low-cost technique in which the CdS is sprayed onto the substrate and heated to form the active layer. Such a process is currently being used in a preproduction phase by Photon Power, Inc.

The second material that has achieved commercial feasibility is gallium arsenide (GaAs). Like silicon, this material is single-crystal, but it is capable of higher conversion efficiencies than silicon and is much more costly to process. For this purpose, it is being considered for applica-

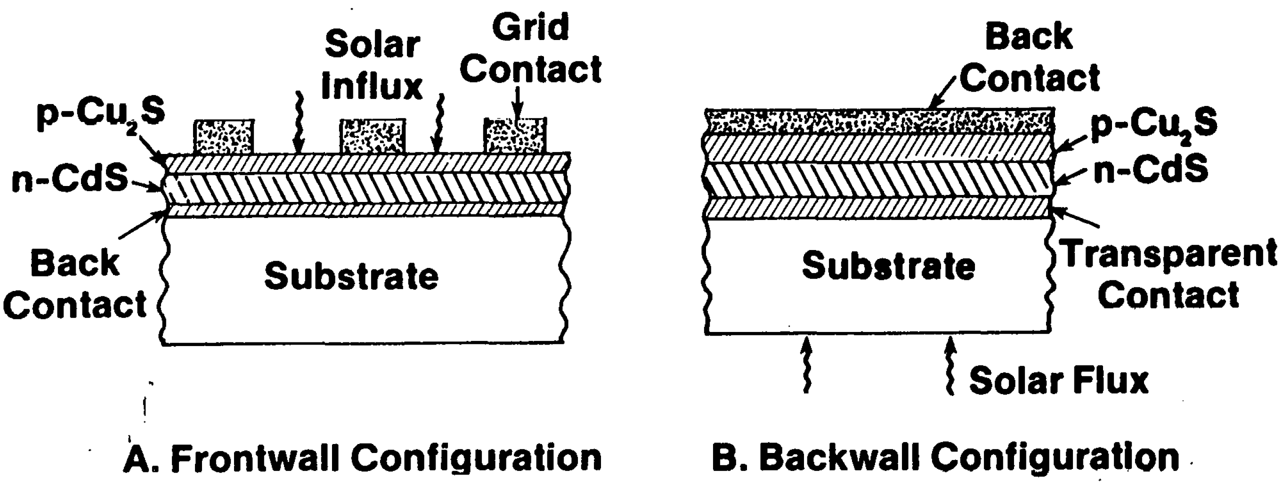


Figure 5-1. General configurations of the CdS/Cu_2S solar cells (courtesy of S. Deb).

tions where concentrated sunlight is used. The single-crystal GaAs has achieved efficiencies of 25% at concentrations of 500x to 2000x. This compares to silicon efficiencies of 20% in concentrations of 200x to 1000x. Special tandem cells have achieved 31% efficiency, but operation was at 2000x in a laboratory environment. It is anticipated that concentrators will not be used extensively in DCs because of the increased system complexity required to track the sun (as opposed to the stationary flat-plate modules).* Therefore, of greater significance to flat-plate technology (and to DCs) is the research being conducted to develop thin-film and amorphous GaAs. The thin-film (or polycrystalline) GaAs effort has achieved 6% to 8% efficiencies.

5.3 ADVANCED MATERIALS RESEARCH

The importance of innovative concepts in materials and cell design is apparent from the amount of money and effort being channeled into relevant research. In the United States alone, over $6 million is being spent on development of new materials and technologies. At a recent Advanced Research and Development meeting, it was noted that the material of future significance in photovoltaic conversion may not even be known at the present. This emphasized the need for strong ongoing activities in basic research and the importance of continued receptiveness to unconventional ideas.

With the necessity to conduct advanced research in mind, work is being supported in areas such as electrochemical photovoltaic cells. Other potentially advanced materials being studied include cadmium telluride, indium phosphide, cuprous oxide, polyacetylene, zinc phosphide, cuprous selenide, and a variety of lesser known materials. The research is being monitored by SERI, under DOE funding. Research on promising materials such as cadmium telluride continues also in France, Japan, West Germany, and through EC, while the Battelle Institute in Frankfurt has reported a cadmium selenide cell with 5% efficiency and hopes soon to achieve 10% efficiency.

*However, a recent announcement indicates that a concentrator system will be used for the Saudi Arabian project described previously.

SECTION 6.0

SYSTEMS RESEARCH

Recently, price goals for photovoltaic systems were added to U.S. cost goals, indicating the increased importance of taking into account the balance of system (BOS) in the design of cost-effective total photovoltaic systems. As noted, the BOS comprises all of the photovoltaic system components except the modules. It includes the area preparational activities (site preparation, array foundations, field wiring, installation of modules), the power conditioning apparatus (regulators, inverters, instrumentation, safety switchgear), the energy storage device, and all surrounding items (such as necessary buildings). Present capital costs of the BOS items vary with size but are around $35/m^2 [38], while the additional electronic equipment ranges from $6 to $20/W, based on a recent manufacturers' survey. The established goals are for system prices (including photovoltaic modules) to be $6 to $13/W by 1982 and $1.60 to $2.20/W by 1986. The eventual goal is to reduce the system's cost to $1.10 to $1.30/W by the year 2000.

DOE has given Sandia Laboratories the responsibility to manage aggressive programs concentrating on the BOS aspects, and several projects are under way to this end. One project involves analyzing low-cost support structures and their reliability and durability under different load conditions, such as wind or seismic variations. Sandia is also pursuing the development of inverter and power equipment that more closely matches the photovoltaic array—thereby maximizing power output from the system. A wide variety of cost analyses are being done, mostly along the lines of life-cycle costs.

The main area of concern, however, was expressed recently by a representative of a photovoltaic array and system manufacturer [39]. According to the representative, reliability is still the key to photovoltaic system success, especially when competing with the diesel generator in rural areas. The work being done on the BOS components must also make reliability a major concern, because the entire system must be as reliable as the cells to achieve this success.

Energy-storage methods associated with current photovoltaic systems still need technological improvements. Presently, only lead-acid batteries are suitable for photovoltaic outputs, but these batteries are inconvenient because they have only a 5- to 7-year lifetime. Research continues on both advanced battery technology and alternate storage mechanisms, but even if a major breakthrough occurs today, it will still be at least five years before mass utilization can take place.

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SECTION 7.0

CONCLUSION

In summary, several points become clear. First, a great deal of optimism about the future of photovoltaic power sources, especially for DCs, exists in private, industrial, and government sectors. This optimism may be fueled by the knowledge that an investment in nonrenewable energy resources is equivalent to throwing gasoline on a fire in an attempt to extinguish it. Photovoltaic systems represent the most direct method of energy conversion and will be a major source of energy, worldwide, by the year 2000.

Second, the utilization of photovoltaic systems is economically viable now in certain applications and locations. As the prices for arrays drop below $\$2/W_p$ by 1984, the workable applications will increase dramatically, so that by 1988 the feasibility of photovoltaic systems in rural areas will be almost universal. Baseline studies, similar to those being conducted by NASA Lewis Research Center, must be initiated now to prevent unnecessary delays or problems during the incorporation of PV systems into energy requirements of DCs.

Third, to effect a successful implementation, manufacturers must establish communications with those who know the energy needs of the people of DCs. Every supportive mechanism must be examined by the manufacturers to simplify the introduction of electrical power to villages starving for it and to thereby tap the estimated 1000-MW market that exists in DCs. The transfer of technological information is also imperative and cannot be neglected. Manufacturers must be able to look at each new application separately, and not try to force one mass-produced but incompatible system on every application.

Finally, economic assistance will have to be provided from some outside source to begin initial energy developments in DCs. It is unlikely that DCs will be able to establish their own power generation networks (through photovoltaic or any other systems) until they can manage international trade developed on a sound economic infrastructure.

The future of photovoltaic systems for DCs looks bright, especially with the proper assistance. The next five years will be crucial for establishing the baseline for applications. It is therefore important to examine future potentials closely and to pursue a course best suited not only for the people of developing countries, but also for the entire world.

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SECTION 8.0

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APPENDIX A

TERRESTRIAL PHOTOVOLTAIC SYSTEM AND COMPONENT MANUFACTURERS

This list was compiled by the Information Systems Division of the Solar Energy Research Institute, Golden, Colo., and includes manufacturers known to be (or soon to be) producing and marketing photovoltaic components and, in some instances, complete systems. Every attempt was made to compile as complete a listing as possible; however, some manufacturers may have been inadvertently left off. It therefore represents the best information available to the panel at this time.

PHOTOVOLTAIC MANUFACTURERS

Company Name	Product(s)
Acurex Corporation, Alternate Energy Div. 485 Clyde Ave. Mountain View, CA 94042 (415) 964-3200	Domestic Hot Water/Space Heating/Cooling Systems Steam Supply Systems Decentralized Power Plants Data Acquisition Systems Process Hot Water Systems Irrigation Systems Parabolic Trough Collectors Concentrator Solar Cell Assembly
Acrimpianti Via Bergano, 21 20135 Milano ITALY (02) 5497, Telex 33211	Solar Cell Power Generation
Aerospatialo 37 Boulevard de Montmorency 75781 Paris Cedex 16 FRANCE 524 43 21	Flywheels/Inertial Systems Heliostats Solar Cell Array Tower Focus Power Plant Components
Aidco Maine Corp. Orr's Island, ME 04066 (207) 833-6700	Swimming Pool Heating Systems Domestic Hot Water Systems Space Heating Systems Solar Cell Array Field Decentralized Power Plants Thermal Collector Subsystems Process Heat Systems Greenhouses Wind Turbine Generator Systems Ethanol Plant Equipment Biomass Conversion Systems Solar Ponds
Amalgamated Wireless Australia Ltd. P. O. Box 96 North Ryde, New South Wales 2113 AUSTRALIA	
Ansaldo, Electric Systems Div. Via Pacinotti, 20 16151 Sampierdarena, Genova ITALY 010-4103, Telex 27006	Tower Focus Power Plants Dispersed Solar Electric Power Plants Domestic Hot Water Systems Solar Cell Array Field

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Applied Solar Energy Corp. (formerly Optical Coating Lab, Inc.) 15251 East Don Julian Rd. City of Industry, CA 91746 (213) 968-6581	Solar Cell Module Silicon Solar Cells
Arthur D. Little, Inc. 25 Acorn Park Cambridge, MA 02140 (617) 864-5770	Photoelectric Solar Energy Satellite Systems Solar Cell Array Field
Automatic Power, Inc. 213 Hutcheson St. Houston, TX 77023 (713) 228-5208	Wind Machine Generators Dual Blade Wind Machines Small Wind Turbine Generator Systems Towers Wind Turbine Blades Controllers Solar Cell Array Solar Cell Module
AEG-Telefunken Raumfahrttechnik und neve Technologien Industriestrasse 29 2000 Wedel, Holstein FEDERAL REPUBLIC OF GERMANY 04103/7021, TWX 2189520	Solar Cell Module Solar Cell Array Field
ARCO Solar, Inc. 20554 Plummer St. Chatsworth, CA 91311 (213) 998-0667	Solar Cells Solar Cell Protective Coating Solar Cell Array Solar Cell Module
C and D Batteries 3043 Walton Rd. Plymouth Meeting, PA 19462 (215) 828-9000	Electric Batteries
Centre National d'Etudes des Telecommunications (CNET) 38-40 rue de General Leclerc 92131 Issy Les Moulineaux FRANCE 331 638 4839	Solar Cell Array Field Wind Turbine Generator Systems
Christeva Sonnenenergietechnik GmbH Sommerstrasse 20 8021 Sauerlach FEDERAL REPUBLIC OF GERMANY 08104/16 44	Storage Tanks Solar Cell Array Field Flat Plate Collectors, Liquid

Columbia Chase Corp. Solar Energy 55 High St. Holbrook, MA 02343 (617) 767-0513	Swimming Pool Heating Systems Solar Cells Solar Cell Array Field Do-It-Yourself Domestic Hot Water Systems Domestic Hot Water Systems, Liquid Absorbers, Copper Flat Plate Collectors, Liquid Housing/Framing
Compagnie Industrielle des Piles Electriques (CIPEL) Division des Produits Industriels 125 rue du President Wilson 92302 LeVallois Perret FRANCE	Solar Cell Array Field Electric Batteries
Contronic Peer-G, Cruse Postfach 605, 344 2000 Hamburg 60 FEDERAL REPUBLIC OF GERMANY 040/44 09 59	Novelty Items Solar Cell Array Field
Contronic Solar-Electronic Bornstrasse 32 2000 Hamburg 13 FEDERAL REPUBLIC OF GERMANY	Novelty Items Solar Cell Array Field
Crystal Systems, Inc. Shetland Industrial Park 35 Congress St. Salem, MA 01970 (617) 745-0088	Solar Cells
Dow Chemical USA FP&S/TS&D, Lab 3, 2020 Dow Center Midland, MI 48640 (517) 636-1000	Latent Heat Storage Modules Pipe Insulation Collector Insulation Vapor Barriers Neoprene Sealants and Adhesives Plastic Sheets and Films Protective Coatings Solar Cell Materials Solar Cell Protective Coating Silicone Sealants and Adhesives Anti-Freeze Eutectic Salts
Dow Corning Corp., Solar Energy 2200 West Salzburg Rd., Box 1767 Midland, MI 48640 (517) 496-4000	Solar Cell Protective Coating Collector Insulation Solar Cell Materials Special Insulating Units Silicone Sealants and Adhesives Silicone Heat Transfer Fluids

	Protective Coatings Plastic Sheets and Films
Ecotronics, Inc. 7745 East Redfield Rd. Scottsdale, AZ 85260 (602) 948-8003	Microprocessors Proportional Controls Power Conditioning Equipment Solar Cells
ELMEG GmbH, Abt. ESOTRON Rudigerstrasse 12 5300 Bonn 2 FEDERAL REPUBLIC OF GERMANY	Novelty Items
Ferranti GmbH Widenmayerstrasse 5 8000 Munchen 22 FEDERAL REPUBLIC OF GERMANY 089/29 38 71	Solar Cell Module Solar Cells Solar Cell Array Field
Ferranti Ltd., Electronic Components Division Gem Hill Chadderton Oldham Lancashire OL9 8NP UNITED KINGDOM	Solar Cell Array Field Solar Cells Solar Cell Protective Coating
France Photon BP 119 Usine des Agriers 16004 Angouleme Cedex FRANCE (45) 62.41.11, Telex 790244	Solar Cell Array Solar Cells
Free Energy Systems, Inc. Price & Pine Streets Holmes, PA 19043 (215) 583-4780	Solar Cell Module Solar Cell Protective Coating Solar Cell Array Field
General Electric Co., Space Div. P. O. Box 13601 Philadelphia, PA 19101 (215) 962-2112	Solar Cell Panels Solar Cell Module Solar Cell Array Field Heat Pumps V-Trough Concentrating Collectors Evacuated Tube Collectors Large Wind Turbine Generator Systems
Gould, Inc., Gould Laboratories 540 East 105th St. Cleveland, OH 44108 (216) 851-5500	Electric Batteries Solar Cell System Components Heat Pipe Heat Exchangers

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Grumman International, Inc. 64-65 Grosvenor St. London WiX DB UNITED KINGDOM 016293847	Solar Cell Power Generation
Herrmann Helfried Postfach 1450 8998 Lindenberg FEDERAL REPUBLIC OF GERMANY 0838/28 82	Solar Cell Power Generation
Herwi Solar GmbH Am Stein 7 8755 Alzenau FEDERAL REPUBLIC OF GERMANY 06023/52 35u. 09372/55 62	Solar Cells
International Rectifier, Semiconductor Div. 233 Kansas St. El Segundo, CA 90245 (213) 322-3331	Solar Cell Module Silicon Solar Cells
International Research and Dev. Fossway Newcastle upon Tyne UNITED KINGDOM 650451	Solar Cells
International Solar Leasing Co. 7010 Convoy Ct. San Diego, CA 92111 (714) 560-9173	
InterTechnology/Solar Corp. 276 Broadview Ave. Warrenton, VA 22186 (703) 347-9500	Heat Pump Systems, Water-To-Air Compound Parabolic Concentrators Domestic Hot Water Systems, Liquid Flat Plate Collectors, Liquid Parabolic Trough Collectors Support Systems Swimming Pool Heating Systems Sealants, Adhesives, and Gaskets Space Heating Systems, Liquid Solar Assisted Heat Pump Systems Domestic Hot Water/Space Heating/Cooling Systems Process Hot Water Systems Energy Management Systems Air-To-Water Heat Pumps Water-To-Water Heat Pumps Special Insulating Units Solar Cell Array Field

Solar Cell Module
Concentrator Solar Cell Assembly
Wood Burning Tools/Fireplace Accessories
Gasification Systems
Organic Decomposition Systems
Liquefaction Systems
Conversion Plants
Educational Aids

(R.T.C.) La Radiotechnique-Competec
130, Avenue Ledru Rollin
75540 Paris Cedex 11
FRANCE
347 69 30

Solar Cells
Space Power Satellite Systems

Leroy-Somer
Boulevard Marcellin Leroy
16004 Angouleme
FRANCE

Heat Pumps
Educational Aids
Vertical Axis Wind Machines
Small Hydropower Systems
Solar Cell Array Field

Leroy-Somer
156, rue de l Universite
75007 Paris
FRANCE
551 55 59

Solar Cell Array Field
Wind Energy Conversion Systems

Leybald-Heraeus GmbH & Co. KG
Postfach 549, Wilhelm-Rohn-Strasse 25
6450 Hanau 1
FEDERAL REPUBLIC OF GERMANY
06181/364-1, TWX 4-184-741

Lockheed Missiles & Space Co., Inc.
1111 Lockheed Way
Sunnyvale, CA 94088
(408) 742-4321

Solar Cells
Ocean Thermal Gradient Systems
Electric Batteries
Domestic Hot Water/Space Heating/
Cooling Systems
Microprocessors
Closed-Cycle Ocean Technology Systems

Lucas Electrical Ltd.
(Pes Division)
Great Hampton St.
Birmingham, B18 6AH
UNITED KINGDOM
0212365050

Solar Cell Power Generation

Lucas Industries Australia,
Batteries Div.
1156 Nepean Hwy.
Cheltenham, Victoria 3192
AUSTRALIA

Solar Cell Power Generation

Martin-Marietta Aerospace 12250 S. Hwy. 75, Box 179 Denver, CO 80201 (303) 973-3000	Tower Focus Power Plants Concentrator Solar Cell Assembly
McGraw-Edison Company, Power Systems Div. P. O. Box 28 Bloomfield, NJ 07003 (201) 751-3700	Solar Cell Module
Megatech Corp. 29 Cook St. Billerica, MA 01821 (617) 273-1900	Educational Aids Solar Cell Array Field Software
Mobil Tyco Solar Energy Corp. 16 Hickory Dr. Waltham, MA 02154 (617) 890-0909	Concentrator Solar Cell Assembly Solar Cell Module Solar Cells Solar Cell Array Field Silicon Solar Cells
Monsanto Industrial Chemicals Co. 800 North Lindbergh Blvd. St. Louis, MO 63166 (314) 694-2153	Greenhouses Special Insulating Units Plastic Sheets and Films Silicon Solar Cells Coolants
Motorola Semi-Conducteur S.A. 126 Chemin Canto, La Quzeto 3100 Toulouse Houtgar FRANCE	Solar Cell Module Solar Cells Solar Cell Array Field
Motorola, Inc., Semiconductor Group 5005 East McDowell Rd. P. O. Box 20924 Phoenix, AZ 85036 (602) 244-5511	Collector Support Subsystems Power Conditioning Equipment Solar Cell Array Solar Cell Module Silicon Solar Cells
N. V. Philips' Gloeilampenfabrieken Bldg. Tam Eindhoven NETHERLANDS (040) 782302	Solar Cell Panels Solar Cell Module Solar Cell Array Field
National Semiconductors, Ltd. 331 Cornelia St. Plattsburgh, NY 12901 (518) 561-3160	Silicon Solar Cells

Officine Galileo S. p. A., ESO (Solar Energy Dept.) Via Carlo Bini, 44 Firenze ITALY 055-47961	Tower Focus Plants Solar Cell Array Field
Philips 161 Starts St. South Melbourne, Victoria AUSTRALIA	
Philips GmbH, Unternehmensbereich Licht und Anlagen-Energie-Systeme Monckebergstrasse 7 2000 Hamburg 1 FEDERAL REPUBLIC OF GERMANY 040/3297-1, TWX 2-161587	Heat Pumps Evacuated Tube Concentrating Collectors Solar Cell Array Field
Philips Mexicana, S. A. de C. V., Division Energia Solar Durango 167 Mexico 1, D. F. MEXICO (905) 511-8050, (905) 525-1540	
Pompes Guinard 179 Boulevard Saint Denis 92400 Courbevoie FRANCE 788 50 52	Solar Cell Array Field
Pompes Gutnard Etablissements 179, Boulevard Saint Denis 92400 Courbevoie Haut-sen FRANCE 788 46 00	Solar Cell System Components
Rucker GmbH, UB Solartechnik Postfach 1232 5210 Troisdorf 1 FEDERAL REPUBLIC OF GERMANY 02241/740 31, TWX 889442	Solar Cell Power Generation
Semicon, Inc. 10 North Ave. Burlington, MA 01803 (617) 272-9015	Silicon Solar Cells
Sensor Technology, Inc. 21012 Lassen St. Chatsworth, CA 91311 (213) 882-4100	Solar Cell Panels Solar Cell Module Silicon Solar Cells Solar Cell Array Field

Siemens AG Postfach 103 8000 Munich 1 FEDERAL REPUBLIC OF GERMANY	Solar Cell Module Silicon Solar Cells
Silicon Material, Inc. 341 Moffett Blvd. Mountain View, CA 94043 (415) 965-9890	Solar Cell Module Silicon Solar Cells
Silicon Sensors, Inc. Solar Systems Div. Highway 18 East Dodgeville, WI 53533 (608) 935-2707	Cadmium Sulfide Solar Cells Selenium Solar Cells Solar Cell Array Field Silicon Solar Cells Solar Cell Module Radiation Measurement Devices
Siltec Corp. 3717 Haven Ave. Menlo Park, CA 94025 (415) 365-8600	Solar Cells
Societe des Applications de Helioenergie (SAHEL) 50, Rue J. P. Timbaud BP 301 92402 Courbevoie Cedex Paris FRANCE	
Solar Energy Products, Inc. 1208 NW 8th Ave. Gainsville, FL 32601 (904) 377-6527	Roll Bond Heat Exchangers Steel Tanks Back-Up Water Heaters Pumps Differential Controls Flat Plate Collectors, Liquid Support Systems Solar Cell Module Absorption Cooling Systems Domestic Hot Water Systems, Liquid Heat Pump Systems, Water-To-Air Domestic Hot Water/Space Heating/ Cooling Systems Swimming Pool Heating Systems
Solar Power Corp. 20 Cabot Rd. Woburn, MA 01801 (617) 935-4600	Power Conditioning Equipment Solar Cell Panels Solar Cell Module Silicon Solar Cells Solar Cell Array Field

Solar Power Ltd. 101-111 Strand London WC2R OAA UNITED KINGDOM 018368918	Solar Cell Power Generation
Solarex Corp. 1335 Piccard Dr. Rockville, MD 20850 (301) 948-0202	Blowers Educational Aids Tracking Devices Housing/Framing Anti-Reflective Glazing Coatings Novelty Items Solar Cell Panels Solar Cell Module Silicon Solar Cells Solar Cell Array Field
Solec International, Inc. 12533 Chadron Ave. Hawthorne, CA 90250 (213) 970-0065	Concentrator Solar Cell Assembly Solar Cell Module Solar Cells Novelty Items Parabolic Trough Collectors Solar Cell Array Field Active-Passive Hybrid Systems
Solectro Thermo, Inc. 1934 Lakeview Ave. Dracut, MA 01826 (617) 957-0028	Point Focusing Collectors Concentrator Solar Cell Assembly Active-Passive Hybrid Systems Nontracking Concentrating Collectors
Solenergy Corp. 23 North Ave. Wakefield, MA 01880 (617) 246-1855	Solar Cell Protective Coating Solar Cell Panels Solar Cell Module Power Conditioning Equipment
Sollos, Inc. 2231 Carmelina Ave. Los Angeles, CA 90064 (213) 820-5181	Solar Cell Array Field Solar Cells Solar Cell Module
Spectrolab 12500 Gladstone Ave. Sylmar, CA 91342 (213) 365-4611	Solar Simulators Solar Cell Panels Concentrator Solar Cell Assembly Solar Cell Array Solar Cell Module Silicon Solar Cells Solar Cell Array Field
Spectrolab 34-40 Clayton Rd. North Clayton, Victoria 3168 AUSTRALIA	

Spire Corp. Patriots Park Bedford, MA 01730 (617) 275-6000	Solar Cells Gallium Arsenide Solar Cells Silicon Solar Cells Solar Cell Protective Coating Solar Cell Array Solar Cell Module
Sun Tap, Inc. P.O. Box 754 Arlington Heights, IL 60006 (312) 255-5654	Power Conditioning Equipment Solar Cell Array Field
Sun Trac Corp. 540 Zenith Dr. Glenview, IL 60025 (312) 299-1080	Solar Cell Array Field Solar Cell Module Concentrator Solar Cell Assembly
SES, Inc. Tralee Industrial Park Newark, DE 19711 (302) 731-0990	Solar Cell Array Field Solar Cell Protective Coating Solar Cell Panels Solar Cell Module Cadmium Sulfide Solar Cells
Technidyne Associates 58-06 69th Pl. Maspeth, NY 11378 (212) 424-8448	Linear Focusing Collectors Decentralized Power Plants Solar Cell Array Field Window Unit Collectors
Termomeccanica Via del Molo, 1 19100 La Spezia ITALY 0187-503151, Telex 27171	Solar Cell Power Generation
Thermo Electron Corp. 101 First Ave. Waltham, MA 02154 (617) 890-8700	Irrigation Systems Rankine Cycle Engines Total Energy Systems Solar Cell Array Field
Thomson-CSF 173 Boulevard Haussmann 75008 Paris FRANCE Telex 204780	Solar Cell System Components
Tideland Signal Corp. 4310 Directors Row Houston, TX 77052 (713) 681-6101	Solar Cell Array Solar Cell Protective Coating Power Conditioning Equipment Solar Cell Array Field Solar Cell Module

Uce, Inc. 24 Fitch St. East Norwalk, CT 06855 (203) 838-7509	Solar Cell Array Field
Vactec, Inc. 2423 Northline Ind. Blvd. Maryland Heights, MO 63043 (314) 872-8300	Radiation Measurement Devices Solar Cell Module Selenium Solar Cells Silicon Solar Cells
Valvo GmbH Postfach 106.323 2000 Hamburg 1 FEDERAL REPUBLIC OF GERMANY	Solar Cell Array Field Electric Batteries
Varian Associates 611 Hansen Way Palo Alto, CA 94303 (415) 493-4000	Concentrator Solar Cell Assembly Gallium Arsenide Solar Cells
Wacker-Chemitronic Gesellschaft für Elektronik-Grundstoffe MbH Postfach 1140 8263 Burghausen FEDERAL REPUBLIC OF GERMANY 08677/831, TWX 05/6923	Silicon Solar Cells
Westinghouse Electric Corp. Advanced Energy Systems Div. P. O. Box 10864 Pittsburgh, PA 15236 (412) 892-5600	Tower Focus Power Plants Closed-Cycle Ocean Technology Systems Concrete Tanks Large Wind Turbine Generator Systems Heat Pump Systems, Air-To-Air Cooling Systems Space Heating Systems Solar Cell Systems Components Solar Cell Array Field Total Energy Systems Heliostats

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