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April 1980

The Future of Photovoltaic Energy Conversion in Developing Countries

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MASTER

SERI

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Operated for the
U.S. Department of Energy
under Contract No. EG-77-C-01-4042

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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 \$3.00
Printed Copy \$ 5.25

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SERI/TP-611-407
UC CATEGORY: UC-63

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DEVELOPING COUNTRIES

STEVE HOGAN

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PREPARED UNDER TASK NO. 3221.30

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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.

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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 will be viable for many rural applications within 5 years.

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SECTION 1.0

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 non-renewable 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_3P_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.

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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 à 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 gov-

ernment. 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 m³ 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-m³ 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 m³/h to the 41.6 m³ 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-m³ 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 contain-

ing 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 manu-

facturers 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 cm³ 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- μ m-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 cm²/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 cm²/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-cm² 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	0.214 \$/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

^aThis 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-cm² 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.

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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 structure 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/Cu₂S 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/m² [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 representa-

tive, 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
Aerospatiale 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

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 neue 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

Compagnie Industrielle des Piles
Electriques (CIPEL)
Division des Produits Industriels
125 rue du President Wilson
92302 LeVallois Perret
FRANCE

Contronic Peer-G, Cruse
Postfach 605, 344
2000 Hamburg 60
FEDERAL REPUBLIC OF GERMANY
040/44 09 59

Contronic Solar-Electronic
Bornstrasse 32
2000 Hamburg 13
FEDERAL REPUBLIC OF GERMANY

Crystal Systems, Inc.
Shetland Industrial Park
35 Congress St.
Salem, MA 01970
(617) 745-0088

Dow Chemical USA
FP&S/TS&D, Lab 3, 2020 Dow Center
Midland, MI 48640
(517) 636-1000

Dow Corning Corp., Solar Energy
2200 West Salzburg Rd., Box 1767
Midland, MI 48640
(517) 496-4000

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

Solar Cell Array Field
Electric Batteries

Novelty Items
Solar Cell Array Field

Novelty Items
Solar Cell Array Field

Solar Cells

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

Solar Cell Protective Coating
Collector Insulation
Solar Cell Materials
Special Insulating Units
Silicone Sealants and Adhesives
Silicone Heat Transfer Fluids

Ecotronics, Inc.
7745 East Redfield Rd.
Scottsdale, AZ 85260
(602) 948-8003

ELMEG GmbH, Abt. ESOTRON
Rudigerstrasse 12
5300 Bonn 2
FEDERAL REPUBLIC OF GERMANY

Ferranti GmbH
Widenmayerstrasse 5
8000 Munchen 22
FEDERAL REPUBLIC OF GERMANY
089/29 38 71

Ferranti Ltd., Electronic Components
Division
Gem Hill Chadderton
Oldham
Lancashire OL9 8NP
UNITED KINGDOM

France Photon
BP 119
Usine des Agriers
16004 Angouleme Cedex
FRANCE
(45) 62.41.11, Telex 790244

Free Energy Systems, Inc.
Price & Pine Streets
Holmes, PA 19043
(215) 583-4780

General Electric Co.,
Space Div.
P. O. Box 13601
Philadelphia, PA 19101
(215) 962-2112

Gould, Inc., Gould Laboratories
540 East 105th St.
Cleveland, OH 44108
(216) 851-5500

Protective Coatings
Plastic Sheets and Films

Microprocessors
Proportional Controls
Power Conditioning Equipment
Solar Cells

Novelty Items

Solar Cell Module
Solar Cells
Solar Cell Array Field

Solar Cell Array Field
Solar Cells
Solar Cell Protective Coating

Solar Cell Array
Solar Cells

Solar Cell Module
Solar Cell Protective Coating
Solar Cell Array Field

Solar Cell Panels
Solar Cell Module
Solar Cell Array Field
Heat Pumps
V-Trough Concentrating Collectors
Evacuated Tube Collectors
Large Wind Turbine Generator Systems

Electric Batteries
Solar Cell System Components
Heat Pipe Heat Exchangers

Grumman International, Inc.
64-65 Grosvenor St.
London W1X 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

Hierwi 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

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

Leroy-Somer
Boulevard Marcellin Leroy
16004 Angoulême
FRANCE

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

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

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

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

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

Solar Cells
Space Power Satellite Systems

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

Solar Cell Array Field
Wind Energy Conversion Systems

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

Solar Cell Power Generation

Solar Cell Power Generation

Martin-Marietta Aerospace
12250 S. Hwy. 75, Box 179
Denver, CO 80201
(303) 973-3000

McGraw-Edison Company,
Power Systems Div.
P. O. Box 28
Bloomfield, NJ 07003
(201) 751-3700

Megatech Corp.
29 Cook St.
Billerica, MA 01821
(617) 273-1900

Mobil Tyco Solar Energy Corp.
16 Hickory Dr.
Waltham, MA 02154
(617) 890-0909

Monsanto Industrial Chemicals Co.
800 North Lindbergh Blvd.
St. Louis, MO 63166
(314) 694-2153

Motorola Semi-Conducteur S.A.
126 Chemin Canto, La Quzeto
3100 Toulouse
Houtgar
FRANCE

Motorola, Inc., Semiconductor Group
5005 East McDowell Rd.
P. O. Box 20924
Phoenix, AZ 85036
(602) 244-5511

N. V. Philips' Gloeilampenfabrieken
Bldg. Tam
Eindhoven
NETHERLANDS
(040) 782302

National Semiconductors, Ltd.
331 Cornelia St.
Plattsburgh, NY 12901
(518) 561-3160

Tower Focus Power Plants
Concentrator Solar Cell Assembly

Solar Cell Module

Educational Aids
Solar Cell Array Field
Software

Concentrator Solar Cell Assembly
Solar Cell Module
Solar Cells
Solar Cell Array Field
Silicon Solar Cells

Greenhouses
Special Insulating Units
Plastic Sheets and Films
Silicon Solar Cells
Coolants

Solar Cell Module
Solar Cells
Solar Cell Array Field

Collector Support Subsystems
Power Conditioning Equipment
Solar Cell Array
Solar Cell Module
Silicon Solar Cells

Solar Cell Panels
Solar Cell Module
Solar Cell Array Field

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.
Gainesville, 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

Solarex Corp.
1335 Piccard Dr.
Rockville, MD 20850
(301) 948-0202

Solec International, Inc.
12533 Chadron Ave.
Hawthorne, CA 90250
(213) 970-0065

Solectro Thermo, Inc.
1934 Lakeview Ave.
Dracut, MA 01826
(617) 957-0028

Solenergy Corp.
23 North Ave.
Wakefield, MA 01880
(617) 246-1855

Sollos, Inc.
2231 Carmelina Ave.
Los Angeles, CA 90064
(213) 820-5181

Spectrolab
12500 Gladstone Ave.
Sylmar, CA 91342
(213) 365-4611

Spectrolab
34-40 Clayton Rd.
North Clayton, Victoria 3168
AUSTRALIA

Solar Cell Power Generation

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

Concentrator Solar Cell Assembly
Solar Cell Module
Solar Cells
Novelty Items
Parabolic Trough Collectors
Solar Cell Array Field
Active-Passive Hybrid Systems

Point Focusing Collectors
Concentrator Solar Cell Assembly
Active-Passive Hybrid Systems
Nontracking Concentrating Collectors

Solar Cell Protective Coating
Solar Cell Panels
Solar Cell Module
Power Conditioning Equipment

Solar Cell Array Field
Solar Cells
Solar Cell Module

Solar Simulators
Solar Cell Panels
Concentrator Solar Cell Assembly
Solar Cell Array
Solar Cell Module
Silicon Solar Cells
Solar Cell Array Field

Spire Corp.
Patriots Park
Bedford, MA 01730
(617) 275-6000

Sun Tap, Inc.
P.O. Box 754
Arlington Heights, IL 60006
(312) 255-5654

Sun Trac Corp.
540 Zenith Dr.
Glenview, IL 60025
(312) 299-1080

SES, Inc.
Tralee Industrial Park
Newark, DE 19711
(302) 731-0990

Technidyne Associates
58-06 69th Pl.
Maspeth, NY 11378
(212) 424-8448

Termomeccanica
Via del Molo, 1
19100 La Spezia
ITALY
0187-503151, Telex 27171

Thermo Electron Corp.
101 First Ave.
Waltham, MA 02154
(617) 890-8700

Thomson-CSF
173 Boulevard Haussmann
75008 Paris
FRANCE
Telex 204780

Tideland Signal Corp.
4310 Directors Row
Houston, TX 77052
(713) 681-6101

Solar Cells
Gallium Arsenide Solar Cells
Silicon Solar Cells
Solar Cell Protective Coating
Solar Cell Array
Solar Cell Module

Power Conditioning Equipment
Solar Cell Array Field

Solar Cell Array Field
Solar Cell Module
Concentrator Solar Cell Assembly

Solar Cell Array Field
Solar Cell Protective Coating
Solar Cell Panels
Solar Cell Module
Cadmium Sulfide Solar Cells

Linear Focusing Collectors
Decentralized Power Plants
Solar Cell Array Field
Window Unit Collectors

Solar Cell Power Generation

Irrigation Systems
Rankine Cycle Engines
Total Energy Systems
Solar Cell Array Field

Solar Cell System Components

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

SERIO