NASA Technical Memorandum 79097

PHOTOVOLTAIC POWER SYSTEMS FOR RURAL AREAS OF DEVELOPING COUNTRIES

(NASA-TM-79097) PHOTOVOLTAIC POWER SYSTEMS FOR RURAL AREAS OF DEVELOPING COUNTRIES (NASA) 19 p HC A02/MF A01 CSCL 10A

N79-15411

Unclas
G3/44 43369

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TECHNICAL PAPER to be presented at the
International Seminar on Solar Energy
sponsored by the United Nations in collaboration
with the Government of Japan
Tokyo, Japan, February 5-10, 1979

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ABSTRACT

Photovoltaic (PV) applications for rural areas of under-developed countries are discussed in relation to PV system technology, reliability, and present and projected cost. The information presented is derived mainly from NASA, Lewis Research Center experience with PV systems deployed with a variety of users for applications relevant to LDCs. A detailed description of two village power systems is included. Energy cost comparisons are presented for PV systems versus alternative energy sources. It is concluded, based on present PV system technology, reliability and cost that photovoltaics provides a realistic energy option for LDCs in both the near- and far-term.

INTRODUCTION

The importance of energy to the economy of nations has been underscored repeatedly in recent years. For none is energy of greater consequence, though, than for the people of the developing countries. Over one-third the population of the world is at, or slightly above, a subsistence level of energy consumption, i.e., 8.5×10^6 Btu per year per capita or about 10% of the per capita consumption of western European countries (ref. 1). Further, consumption at the subsistence level is mainly in the form of non-commercial "fuels" (e.g., wood, crop residues, and animal wastes and human and animal labor) with an energy utilization efficiency of about one-fifth that for commercial fuel (ref. 2). Thus, the effective per capita energy consumption, adjusted to reflect "useful work," is in reality about 2% that in western Europe.

Such levels of energy consumption are characteristic of poverty at the absolute level, where life is at the margin of physical existence. In human terms it means high infant mortality, low life expectancy, illiteracy, chronic malnutrition, and for millions of infants less protein than is sufficient to permit optimum development of the brain (ref. 3). Such are the grim realities behind the abstract numbers.

Tragically, the future may promise no better for citizens of the poorest nations. A recent study of energy needs in developing countries, prepared for the U.S. Agency for International Development (ref. 1), projected the following scenario. By the turn of the century, if traditional modes of development continue (i.e., capital and energy intensive approaches patterned after the industrialized nations), oil consumption in the non-OPEC LDCs will grow steadily to become comparable to present-day U.S. consumption. In the same period world petroleum production will peak leading to competition for supply and rapid increase in price. The combination of increased costs for oil imports and debt service payments will leave many LDCs with a declining ability to exploit indigenous hydrocarbon resources, or to stimulate general economic growth. Consequently, "a large fraction of the 3-4 billion LDC rural population in the year 2000 will not be able to raise their energy usage above subsistence level."

There is probably no one answer for the energy dilemma of the poorest nations; rather, a mix of mutually supporting technical, institutional and developmental approaches will be required. Among the technical approaches which could ameliorate the present situation, and avert a possibly dire future, is the more extensive use of renewable energy resources, specifically solar. In this regard, the direct conversion of solar energy to electricity by means of solar cells is of great interest. Of all the solar technologies, photovoltaic (solar cell) power systems appear to have the most flexibility for meeting a large variety of the small-scale, decentralized energy needs of rural areas in underdeveloped countries. It has been acknowledged that photovoltaic systems have many desirable features: modularity (therefore scalable in size); no moving parts; low maintenance; and a potentially long life. On the other hand, uncertainty has been expressed concerning capital (or first) costs and system reliability.

From 1958 to recent years the major application of solar cells has been in space where it is the power system of choice, supplying watts to several kilowatts of power to hundreds of spacecraft. In the 1960s, Japan successfully employed solar cells in a number of instrument, communication, and navigational aid applications; total peak power employed in all applications to 1976 was 22 kW (ref. 4). From the early 1970s, U.S. firms began marketing photovoltaic power systems for communications, instrument, and corrosion protection applications. By 1975 the annual terrestrial solar cell production in the U.S. was about 100 kW peak. Production has approximately doubled each succeeding year, partly under the impetus of the newly created national photovoltaic program and partly as a result of an expanding commercial applications market. In this same period, 1975-78, solar cell module price has dropped from about \$35/Watt peak to \$13/Watt peak, both in 1978 dollars.

The purpose of this paper is to discuss (1) photovoltaic applications for rural areas of underdeveloped countries, (2) the status of photovoltaic system technology, (3) reliability, and (4) present and projected system costs. Understandably, for proprietary reasons, detailed information from commercial organizations on applications, systems and cost is not generally available. Therefore, the material presented here is drawn almost exclusively from the many and varied terrestrial photovoltaic systems developed by the NASA Lewis Research Center (LeRC) since 1970. The bulk of this application development was carried out as part of the Department of Energy (DOE) Photovoltaic Tests and Applications Project, managed by LeRC.

It is hoped that this paper will further the understanding of development planners, public administrators, and donor agencies concerning this potentially consequential energy option.

APPLICATIONS

From the user's point of view, a solar photovoltaic (PV) power system is not an end in itself; it only provides an enabling commodity, namely, electricity. Based on the user's needs, the electricity can be employed to power a host of services. For purposes of organization we can arrange these services into application categories. One such category is water pumping. Applications can be subdivided by use. In the case of water pumping, for example, the subdivisions might be potable water and crop irrigation. For each application there is an associated device or mechanism, the electrically powered "load," which provides the desired service. Referring to the water pumping example, the "load" would be an electric motor/pump assembly.

Listed in Table 1 are several major photovoltaic applications and uses pertinent to rural areas of underdeveloped countries. The PV system power level associated with typical uses is also displayed. In estimating power level, a solar insolation factor was used representative of insolation found in countries lying between 30° N and 30° S latitude, namely, one watt (peak) = 1.6 kWH (electric)/year. Actual load performance data was employed.

In practice, users may desire a group of services at a single location. For this instance it is usually desirable to employ one system to power several discrete loads. We therefore have defined a category called "cluster" applications. Examples of these are village power and medical services applications. A village power application using a centrally located power system might include any or all of the following services: potable water pumping, food preservation, grain milling, home lighting, educational TV. A medical services application, likewise, might include drug and vaccine preservation, potable water pumping, and work area lighting.

Since 1970 the LeRC has been actively engaged in developing "standalone" PV systems for near-term, cost-effective applications. In all cases, these systems were installed in rural or remote areas and turned over to the user for operation and maintenance. A summary of the applica-

TABLE 1. - PHOTOVOLTAIC APPLICATIONS IN RURAL AREAS OF LDCs

APPLICATION CATEGORY	TYPICAL USES	PV SYSTEM POWER REQUIREMENTS
WATER PUMPING	POTABLE WATER	$0.08\ W_p/\ell^a$/DAY
	IRRIGATION	$85\ W_p/HA\text{-}MM^b$/DAY
REFRIGERATION	FOOD PRESERVATION	$100\ W_p$ PER 5 CU. FT. REFRIG.
	DRUG & VACCINE PRESERVATION	
LIGHTING	HOMES	$16\ W_p$ PER 20 W FL. LAMP[c]
	WORK AREAS	
COMMUNICATIONS	EDUCATIONAL TV	$40\ W_p$/TV SET[d]
FOOD PREPARATION	MILLING	$3.5\ W_p$/KG FLOUR/DAY
	DECORTICATION	
COTTAGE INDUSTRY	METAL OR WOOD FORMING	$2.0\ kW_p$/1 HP MOTOR[e]

[a]30M TOTAL DYNAMIC HEAD.

[b]FOR 5M HEAD; 60% FIELD EFFICIENCY.

[c]AVERAGE USE 2 HOURS PER NIGHT.

[d]32 WATT TV SET, 4 HOURS OPERATION/DAY.

[e]8 HOURS OPERATION/DAY.

TABLE 2. - NASA LEWIS RESEARCH CENTER PHOTOVOLTAIC APPLICATION SUMMARY

SINGLE APPLICATIONS	USE	USER	DATE OPERATIONAL	LOCATION	POWER LEVEL, W_p
COMMUNICATIONS	EDUCATIONAL TV	GOVT. INDIA	JULY 1976	1) AHMEDABAD, INDIA 2) SAMBALPUR, INDIA	55 55
*REFRIGERATION	FOOD PRESERVATION	NAT. PARK SER.	JUNE 1976	ISLE RUYALE, MI	220
*REFRIGERATION	MEDICAL	VILLAGE RESIDENTS PAPAGO TRIBE	JULY 1976	SIL NAKYA, AZ	330
*INSTRUMENT	WEATHER DATA	NAT. WEATHER SER.	APR-SEPT 1977	1) NEW MEXICO; 2) NEW YORK; 3) HAWAII; 4) ALASKA; 5) MAINE; 6) FLORIDA	75-150
*HIGHWAY	DUST STORM WARNING SIGN	DEPT. TRANS-AZ	APRIL 1977	CASA GRANDE, AZ	116
*INSTRUMENT	INSECT SURVEY TRAPS	DEPT. AGRIC.	MAY 1977	COLLEGE STATION, TX	23 & 163
*REFRIGERATION	WATER COOLER	INTERAGENCY VISITOR CENTER	OCTOBER 1977	LONE PINE, CA	446
CLUSTER APPLICATIONS					
*FIRE LOOKOUT	2-WAY RADIO, REFRIGERATOR, LIGHTING, POTABLE WATER	FOREST SERVICE	OCTOBER 1976	1) PILOT PEAK, CA 2) ANTELOPE PEAK, CA	294 294
*VILLAGE POWER	POTABLE WATER, LIGHTING, REFRIGERATION, WASHING MACHINE, SEWING MACHINE	VILLAGE RESIDENTS PAPAGO TRIBE	DECEMBER 1978	SCHUCHULI, AZ	3500
**VILLAGE POWER	POTABLE WATER, GRAIN MILLING	VILLAGE RESIDENTS	FEBRUARY 1979	TANGAYE, UPPER VOLTA, AFRICA	1800

* PART OF DOE TESTS AND APPLICATIONS PROJECT, MANAGED BY LeRC

** SPONSORED BY U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT tions deployed is given in Table 2. Although some of these applications are not of direct interest for rural areas of developing countries, e.g., instrument and highway applications, the majority constitute a sizeable body of relevant application experience germane to the needs of underdeveloped countries.

All systems installed are operating, except for three short-term demonstrations - the two India Educational TV units and the seasonally used refrigerator at Isle Royale - and one weather data station which was washed to sea during a severe storm in the winter of 1978.

RELIABILITY

The silicon solar cell, a product of the well-developed semiconductor industry, is a highly reliable and stable device when protected from the environment. Photovoltaic systems have proven extremely reliable for onboard power for spacecraft for over 20 years. Terrestrial solar cells are similar in many respects to space cells, except that they are manufactured using lower cost techniques and are encapsulated differently to protect them from earth environment.

Silicon solar cell modules incorporated in systems listed in Table 2 have accumulated over 623 module-years operation time. There have been only four module failures. To date, then, this experience indicates a module failure rate of only 0.0064/yr.

System reliability is strongly dependent on system design and the selection and assembly of the components, i.e., modules, batteries, controls, regulators, structure, and wiring. Operating experience from the variety of geographically dispersed applications listed in Table 2 indicates excellent system reliability. Only one component (non-module) failure was observed in the score of systems deployed to date; this involved a defective voltage regulator which was readily replaced.

In this regard it can be noted that a manufacturer of remote instrument equipment reports (ref. 5) that some customers now specify photovoltaic power for outdoor instrument systems, even for sites where power is available from utility lines. This is because these customers have found the outage rate greater for utility power than for photovoltaic systems.

SYSTEMS

A PV power system typically consists of a solar cell array, energy storage, and regulation and control devices. The solar cell array structure serves as a means of integrating the relatively small, low power, low voltage module[1] into a usable assembly. It mechanically supports the

[1] Basic building block: contains a number of solar cells electrically connected and encapsulated in a supporting frame.

modules and provides routing and attachment points for the wire harness which connects modules and collects power from the array. Energy storage typically consists of a number of lead-acid cells connected in series and/or parallel to provide the desired voltage. Sufficient storage capacity must be provided to meet specific load requirements and to account for diurnal and seasonal variations in solar insolation. Voltage regulation is provided to protect the batteries from over-charge and excessive discharge and to protect the loads from voltage extremes.

Basically, a PV system for single application use is relatively simple from a technical point of view, consisting of the three elements described above. Cluster applications, because of additional control features often required to properly manage the multiple loads, may have an added element of complexity.

For purposes of exposition, two representative village applications will be discussed below. One, Schuchuli (Arizona, U.S.), includes water pumping, lighting, refrigeration and housekeeping services. The other, Tangaye (Upper Volta, Africa), includes water pumping and food preparation.

Schuchuli Village Power System

The village of Schuchuli is located on the western edge of the 2,750,000 acre Papago Indian Reservation in southwestern Arizona. The village's 15 families (95 people) are 27 km (17 miles) from the nearest available electric utility power. The villager's diet has been tied to traditional (i.e., non-refrigerated) methods of food storage and preparation and includes items such a chili, beans, tortillas and commercially available non-perishable vegetables and canned foods. Cattle raising and wild game hunting provide an occasional supplemental source of food. Until the advent of the PV power system, water was provided by a diesel-powered pump; kerosene lamps and candles provided lighting in the homes.

On December 16, 1978, the world's first Village Photovoltaic Power System began operation, providing the residents of Schuchuli with the following services: electric power for potable water pumping; lights in the homes and community buildings; family refrigerators; and a communal washing machine and sewing machine.

The Schuchuli Village Photovoltaic Power System consists of a 3.5kW, 120 volt, DC PV array, 2380 ampere-hours of battery storage, controls, regulator and instrumentation, and an overhead electrical distribution network. The batteries and controls are located in an electrical equipment building (EEB) as indicated in the block diagram of Figure 1.

The system is all DC to avoid the losses associated with commercially available DC/AC inverters and to maximize system efficiency. The

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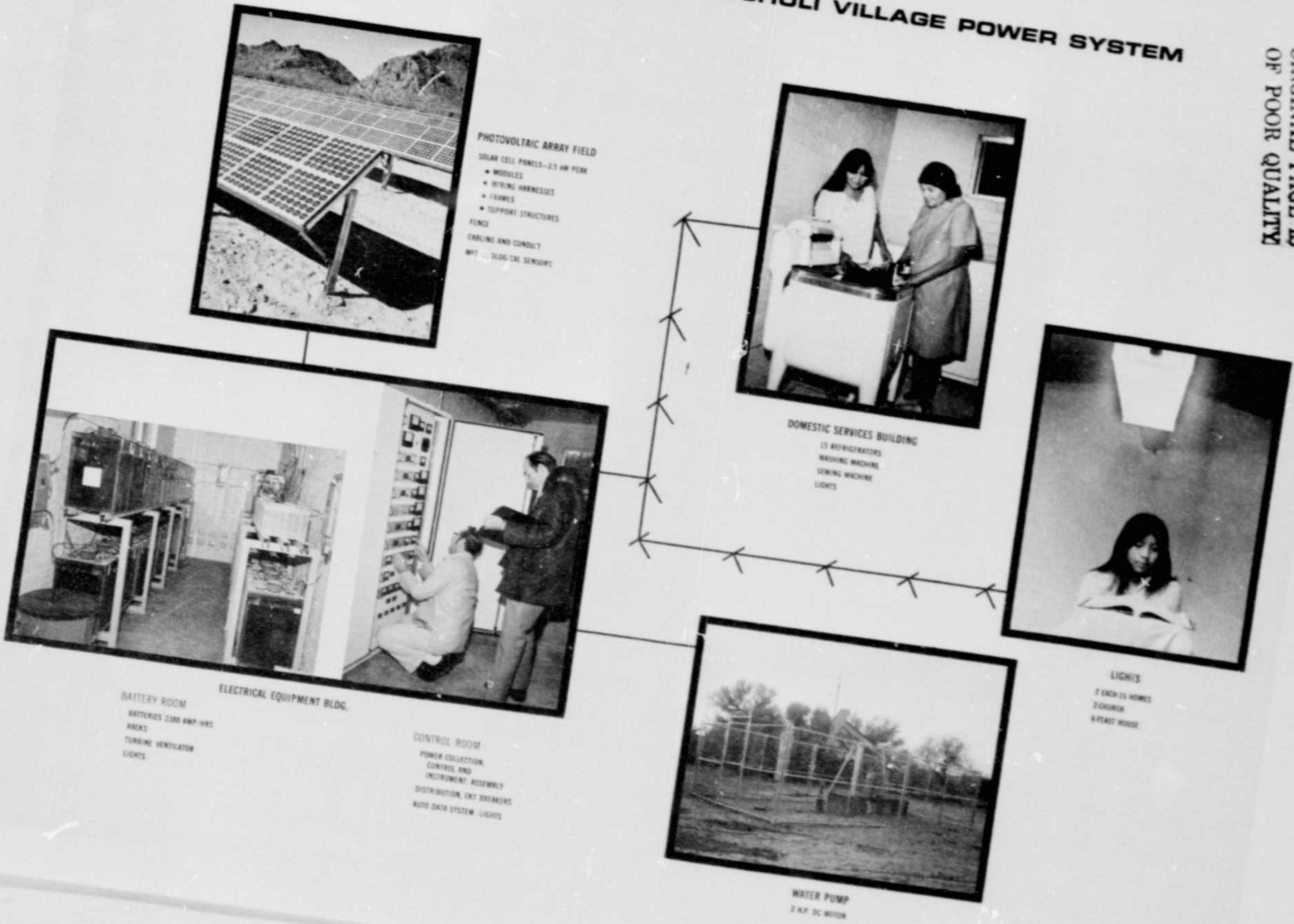
FIGURE 1 - BLOCK DIAGRAM OF SCHUCHULI VILLAGE POWER SYSTEM



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syst m voltage was set at 120 volts to limit distribution line losses and to enable use of commercially available DC switches and DC appliance motors. The load devices were individually selected on the basis of energy efficiency.

System design, exclusive of the overhead distribution network, was performed by LeRC. The overhead distribution network was designed by the Papago Tribal Utility Authority. A brief description of the major system components and features follows.

A 2 HP permanent magnet 120 VDC motor powers a jack pump which delivers approximately 4165 liter/hour (1100 gal/hour) into the village water distribution system which includes a 41,635 liter (11,000 gallon) storage tank located approximately 365 m (1200 feet) from the well. A control system limits pumping to daylight hours roughly centered about mid-day, except for emergency situations.

A total of 47, 20 watt/120 VDC fluorescent lights are installed in the village. The lights employ a special design 120 VDC/23 kHz inverter-ballast which enables the lamp to produce the same number of lumens as a 120 VAC/60 Hz ballast.

A total of 15, 0.13 m^3 (4.7-cubic-foot) refrigerators (with a small freezing compartment) are installed in the domestic services building. These refrigerators are of a custom design developed by a manufacturer of marine refrigerators and are completely insulated with a minimum of 3 inches of polyurethane foam. Each has an automatic door closer and a key lock. Three refrigerators are assembled as a unit and powered from a single compressor with a 1/8 HP 120 VDC permanent magnet motor. The manufacturer reports that the duty cycle should be about 25% "on" in a 43C (110F) ambient environment based on test results from a similar unit.

A standard wringer-type washer was retrofitted with a 1/4 HP permanent magnet 120 VDC motor. A wringer-type washer was selected for overall simplicity and to reduce water consumption. The washer is connected to a cumulative timer which allows up to 12 hours per day of washer operating time. At 1/2 hour/load, this provides for washing approximately 1.75 loads/person/week.

A commercially available sewing machine with a 1/8 HP, 120 V universal motor was also installed in the domestic services building.

A LeRC-developed computerized system simulation program was used to determine PV array size and battery capacity. A composite hourly load profile for each month was used in the sizing calculation as was a 20% degradation of PV array output due to dirt accumulation and potential PV module encapsulant darkening, and a ±20% variation of insolation from average values. Worst case battery depth-of-discharge was calculated to be 60%.

The PV array consists of 24, 1.22m-by-2.44m (4 ft.-by-8 ft.) panels. Each panel contains 8 modules connected in series to make up a 120 VDC series string. The panels are arranged in 3 rows of 8 and are located in a 21.3m-by-30.5m (70 ft.-by-100 ft.) fenced area. Panel frame and support structure are designed to withstand 161 km/hr (100 MPH) wind loads and are fabricated from commercially available hardware.

The battery consists of 52, 2380-ampere-hour capacity cells connected in series with a parallel arrangement of 4 pilot cells for load management. One pilot cell has a 1055-ampere-hour capacity and the other 3 have 310-ampere-hour capacities. All capacities are at a 500-hour, 25C (77F) discharge rate. The cells were designed for operation with PV systems and have lead-calcium plates capable of deep discharge cycle operation. The batteries are housed in a separate, vented room in the electrical equipment building.

Because of unknowns in the use of the loads and variations in insolation, a load management subsystem was incorporated into the design to (1) protect the batteries from excessive discharge and potential damage, and (2) to maintain operation of the more critical loads at the expense of less critical loads. The load management subsystem sequentially disconnects loads as the battery capacity decreases to preset levels.

At 50% depth-of-discharge, the washing and sewing machines are disconnected, at 60% the lights are disconnected, at 70% the water pump motor is disconnected, and finally at 80% depth-of-discharge the refrigerators are disconnected. As the batteries are recharged, loads are sequentially reconnected into the system in reverse order. The four pilot cells provide a method for sensing the depth-of-discharge of the 2380-ampere-hour cells.

System voltage is regulated by array string switching. There are relays (one per string) which connect the array strings to the main bus or open circuit the strings through a field-programmable drum relay. The drum relay is commanded to increase or decrease the number of connected strings by a controller which senses system voltage. This same drum relay is also used for the load management subsystem.

Under- and over-voltage protection is provided in addition to system voltage regulation. If system voltage exceeds the maximum allowable value, the PV array is disconnected. If system voltage drops below the minimum allowable, the loads are disconnected. Alarm lights are provided for these conditions.

Since the Schuchuli village PV power system is the first of its kind, it is completely instrumented to obtain a substantial amount of basic engineering data. There are two independent instrumentation subsystems; a panel meter subsystem and an automatic cassette data recorder. The panel meters are read daily by a village resident who is trained to take readings and to recognize anomalous operation. Measurements are also recorded hourly by the automatic data system. The cassettes and the panel meter data are mailed to LeRC weekly for analysis.

An overhead distribution network was installed by the Papago Tribal Utility Authority and generally follows the water distribution line, thus establishing a utility corridor around the village. The 120 VDC distribution system consists of two circuits with two No. 1 ACSR bare aluminum conductors each and a grounded fifth wire which acts as an electrostatic grid. One of the two distribution circuits provides power for all appliances in the domestic services building. The other circuit provides power for lights in all the other buildings.

The photovoltaic system design and installation conforms to National Electrical Codes and OSHA Safety Regulations and specifications. Additional safety features are: a 1.8m (6 ft.)-high chain-link fence with a locked gate surrounding the array field, warning signs; and enclosed pump.

Tangaye Village Power System

The West African village of Tangaye, Upper Volta, is located about 190 km east of Ouagadougou, the capital city. The main occupations of its 2700 inhabitants are farming and cattle-raising and the main food crops are sorghum and millet. The men of the village perform the farming chores while women are responsible for all aspects of family care. This includes a number of laborious and time-consuming tasks such as drawing of water and preparing of daily meals. Food preparation, for example, involves the pounding of grain, the primary source of food, into a coarse flour using a large wooden mortar and pestle. Finer flour is obtained by stone grinding the grain by hand. This arduous task alone generally occupies about two hours per day.

As part of a project sponsored by the U.S. Agency for International Development (AID) entitled, "Studies of Energy Needs in the Food System," a photovoltaic system powering a grain mill and water pump is currently being installed in the village. Operation is scheduled to begin in mid-February 1979.

The system consists of a 1.8 kW (peak), 120 VDC PV array, 540-ampere-hours of battery storage, regulator, controls, and instrumentation designed by LeRC. The PV array, located in a fenced-in area, provides power via underground cable to a control cabinet located in a nearby mill/battery building as shown in the artist's rendering, Figure 2. Storage batteries are located in one room of the building; the mill and control cabinet are in the other. An underground cable carries power from the control cabinet to the water pump. A water storage tank and dispensing facility are located near the well. The tank was designed by LeRC and procured and installed by Upper Volta AID Mission personnel. The mill/battery building was built by the men of Tangaye.

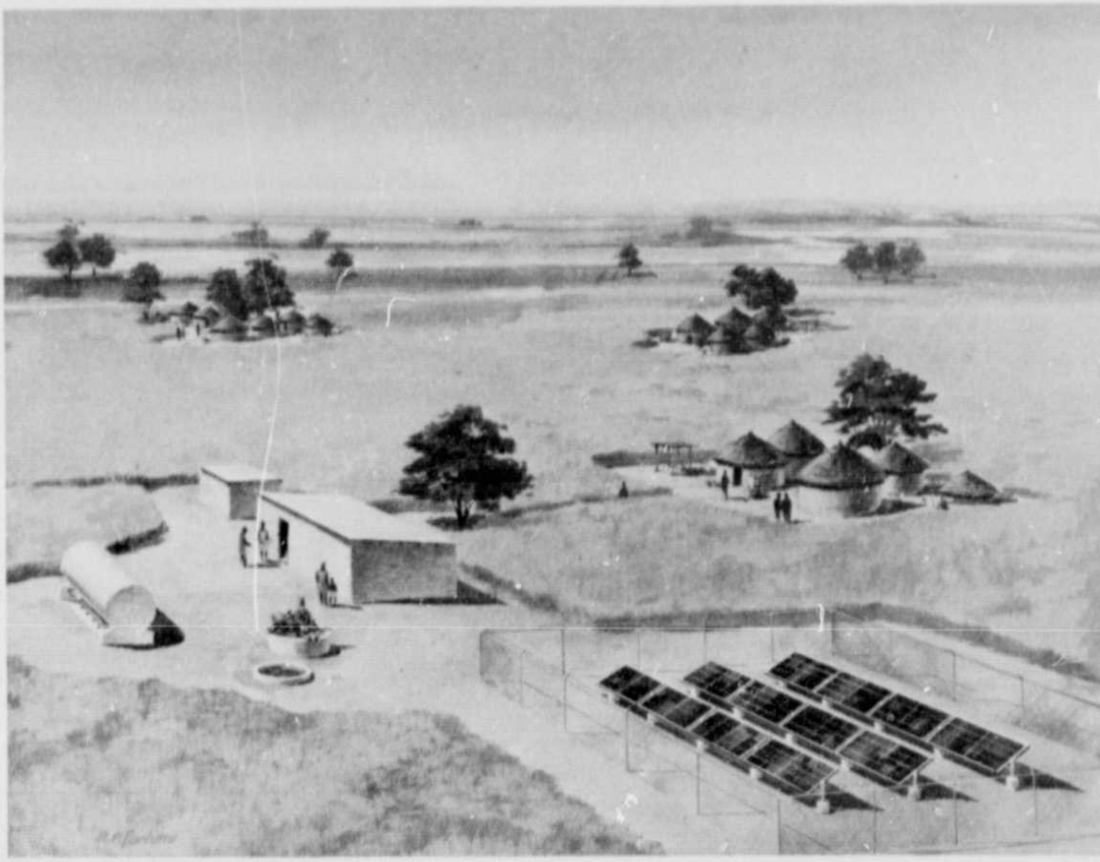


Figure 2 - Artist's Concept of Photovoltaic Power System in Tangaye, Upper Volta

System size was established based on limitations of available funding and site specific details obtained during a visit in February 1978. The water pumping was set at 5000 liters/day based on the measured recovery rate of the well. A mill was selected to provide approximately 320 kg/day of finely ground grain, enough to meet the daily requirements of about 640 families.

The system loads consist of a commercial burr mill using a 1 HP 120 VDC motor and a positive displacement water pump with a 1/4 HP 120 VDC motor. The pump is capable of delivering 1457 liters/hour at a total dynamic head of 28 meters (92 feet). The mill has a manufacturer's rated capacity of 45 to 136 kg/hr depending on the material being ground.

The procedure used for PV array and battery sizing was the same as described previously in the section on Schuchuli. According to the computations, the battery maximum depth-of-discharge should be about 30%.

The 1.8 kW (peak) 120 VDC PV array consists of 12 series strings of 8 modules each. The modules are assembled into 12, 1.22m-by-2.44m (4 ft.-by-8 ft.) panels (each containing 8 modules wired as 1 series string). The panels are arranged in 3 rows of 4 panels each and are located within a fenced area of $256m^2$ ($2755 ft^2$). Array tilt angle is 11° from the horizontal year around. The panel frame and support structure are designed to withstand 161 km/hr (100 MPH) wind loads and are fabricated from commercially available hardware. A separate 74 watt 12 VDC panel and a 100-ampere-hour battery will provide power for instrumentation and controls.

The battery for the 120 VDC system consists of 55, 540-ampere-hour cells designed specifically for PV systems operation. The battery cells are mounted on two single-tier racks located in a separate vented room of the milling building.

The system utilizes three control subsystems: system voltage and battery charge regulation, pump controls (tank and well water level sensors), and mill operating timer control. System voltage and battery charge regulation are accomplished by array string switching. The pump controls consist of a water level sensor in the water storage tank to stop and start the pump and a water level sensor in the well to stop the pump when the well water level drops below the pump intake. The mill control consists of a timer which will allow the mill to be operated for an accumulated time of 8 hours/day.

In addition to system voltage regulation, under- and over-voltage protection is provided identical to that of the Schuchuli system.

The system contains two types of instrumentation - panel meters and an automatic data logger. Data from these instruments are to be read and recorded daily by the mill operator. The data tapes are to be forwarded to LeRC for reduction and analysis.

Safety features incorporated in the design of the Tangaye system are similar to those described previously for Schuchuli.

COSTS

Photovoltaic system costs are commonly divided into costs associated with (1) the photovoltaic module, and (2) the balance-of-system (BOS). The module is the smallest, electrically interconnected, environmentally protected assembly of solar cells: the basic building block of the solar array. The BOS is composed of the following items:[1]

[1]Excluded are shipping, electric power distribution lines, and loads powered by the system.

o Array, Structure, and Site Preparation: module mounting frames; frame supports and foundations; security and safety equipment; site clearing, leveling, drainage;

o Electrical: wiring, interconnects; control circuits/instruments; load management circuits; voltage regulation, power conditioning; enclosure or building;

o Storage: batteries; racks and venting equipment; enclosure or building;

o Installation and Checkout

o Other: system sizing and design; module test and inspection; packaging and freight preparation; maintenance equipment.

Module Cost

Based on the May 1978 U.S. General Services Administration (GSA) price schedule, module costs for kilowatt quantities ranged from \$14.70 to \$18.30/Wp.[1] For tens of kilowatts quantity in 1978, the DOE block purchases were about \$13/Wp (1978 dollars). The DOE module cost projection, in 1978 dollars, is as follows: 1979, \$9/Wp; 1980, \$5/Wp, 1981, \$2.45/Wp; 1986, \$.61/Wp.

BOS Cost

Current BOS cost can be ascertained by examining the costs of recently installed photovoltaic systems. The following information is derived from a detailed cost analysis (refs. 6 and 7) of the systems listed in Table 2, except for the short-term India Educational TV units and the Isle Royale refrigerator. The analysis indicates that BOS costs over the range of PV system power from about 0.4 to 4 kWp, are 57% to 46% of the total installed system cost. As a check on the cost analyses, three commercial manufacturers of photovoltaic systems were surveyed to obtain BOS costs for a nominal 2 kWp system. The costs were found to be in agreement with those of the above analysis. It was concluded that for recently deployed photovoltaic systems the BOS costs fall in the range of \$11 to \$17/Wp (1978 dollars).

Significant reduction of BOS costs will not be easy. Costs are spread among several major and disparate elements. Thus, the cost reduction of items in any one BOS element will not markedly reduce the total BOS cost. Also, the BOS is composed of materials and parts which are products of relatively mature technology and production. Further, possible cost

[1]Module peak power, as determined for 60C (140F) cell temperature, 100 mW/ cm^2 solar insolation, AM1, measured at 15.8 volts.

reduction approaches involving greater module conversion efficiency as well as increased BOS standardization do not unequivocally assure large BOS cost reduction, since trade-offs are involved in most instances. In view of these factors we have made a conservative projection of BOS cost (1978 dollars) as follows: 1979, $12/Wp, 1980, $10/Wp; 1981, $8/Wp; 1986, $5/Wp.

Energy Cost

Photovoltaic. - The installed photovoltaic system costs, projected to 1986, for 600 to 10,000 peak watt systems are calculated from module and BOS cost estimates given in the preceeding section. For completeness the calculation includes a levelized annual replacement and maintenance cost conservatively estimated to be about 15% of the annual capital cost. The following assumptions were made: (1) annual energy output per peak watt, 1.6 kWH; (2) annual interest rate, 10% (ref. 8); and (3) system life, 20 years. The results are displayed in Table 3 as Levelized Annual Costs and Energy Cost, $/kWH.

TABLE 3. - INSTALLED PHOTOVOLTAIC SYSTEM COST PROJECTIONS

(1978 $ U.S. PER PEAK WATT)

YEAR	MODULE COST	BOS COST	TOTAL FIRST COST	LEVELIZED ANNUAL CAPITAL COST	LEVELIZED ANNUAL REPLACEMENT AND MAINTENANCE	ENERGY COST, $/KWH
1978	13.00	15.00	28.00	3.29	.44	2.33
1979	9.00	12.00	21.00	2.46	.31	1.73
1980	5.00	10.00	15.00	1.76	.23	1.24
1981	2.45	8.00	10.45	1.22	.17	.86
1986	.61	5.00	5.61	.66	.10	.47

Alternative Power Sources

For purposes of comparison the cost of alternative power sources, namely, diesel/electric and utility powerline extension, are considered.

Diesel/electric. - It is frequently stated that diesel generators offer a reliable source of electricity and that the initial cost is very low for demands less than 10 kW. To ascertain actual cost experience, a survey was made of several suppliers. This survey indicates that costs, less shipping, ranged from $2700 for a 3 KVA generator to $5500 for a 10 KVA generator, plus $1000 for installation. The cost per kilowatt of capacity installed thus ranges from $1200 per kW to $650 per kW. (Most applications discussed herein require 3 KVA continuous power, or less.) Further, the yearly maintenance costs equal or exceed the initial costs of the diesel generators, based on the recommended maintenance schedule. Also, experience in the U.S., where fuel is relatively cheap, indicates that for diesel generators run at maximum capacity annual fuel costs equal or exceed first cost of the generator. Lastly, it is recommended practice to provide a second diesel generator on-site as a back-up, to insure power availability.

Consideration of only the initial cost of a diesel generator can be quite misleading. Rather it is necessary to consider the levelized annual cost for the generator, operation and maintenance. In calculating energy costs, the following assumptions are made: (1) 1978 fuel cost, $2/gal. (based on recent cost in Ouagadougou, Upper Volta); (2) system life, 5 years; (3) annual interest rate, 10%; (4) fuel escalation of 7% per annum.

Powerline extension. - For calculation of cost of extending a line from an existing transmission line to the point of use, the following assumptions are made: (1) line costs, $4000/km (ref. 9); (2) electric energy cost, $.10/kWH; and (3) annual interest rate, 10%.

Cost Comparisons

Figure 3 shows energy cost versus annual energy consumption for a photovoltaic system and a 3 KVA diesel in 1978 and 1981. Superimposed on the plot are the annual energy consumption for several applications relevant to needs in rural areas of underdeveloped countries. The cost breakeven point for photovoltaics is 4200 kWH and 17,000 kWH annual energy consumption, respectively, in 1978 and 1981.

Figure 4 provides as energy cost versus annual energy consumption for photovoltaics versus powerline extension, in 1978 and 1981. Energy consumption of characteristic applications are superimposed on the plot. The cost breakeven point for photovoltaics is 5400 kWH and 12,000 kWH for 16 and 48 km line extension, respectively, in 1978; and 17,000 kWH and >25,000 kWH for 16 and 48 km extension, respectively, in 1981.

CONCLUDING REMARKS

Experience with installed PV systems, which are currently powering a variety of services for users in rural or remote areas, confirms that PV systems can provide a viable approach to meet many of the basic energy needs in underdeveloped countries. PV system technical development is mature, reflected in the exclusive use of commercially available hardware for the systems described here. PV system reliability, based on evidence accumulated to date, appears to be satisfactory. PV system energy cost, today, is competitive with alternative power sources for applications requiring an energy consumption of 5000 kWH/year or less. Within this range

FIGURE 3.

PHOTOVOLTAIC & DIESEL

ENERGY COST COMPARISONS

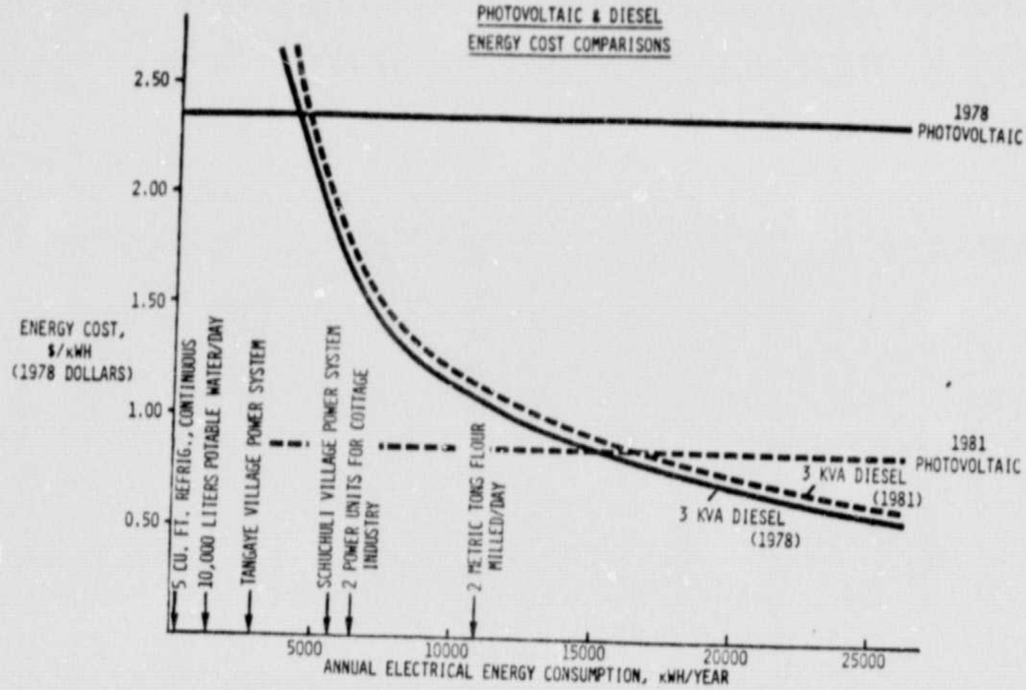
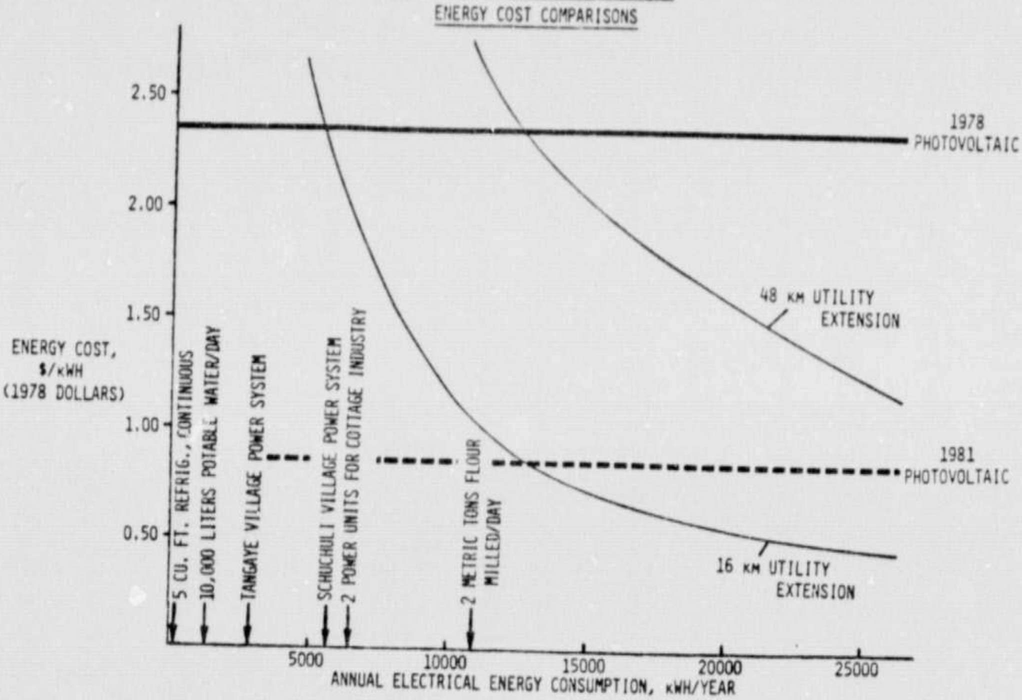


FIGURE 4.

PHOTOVOLTAIC & UTILITY EXTENSION

ENERGY COST COMPARISONS



of annual energy consumption lie many important applications relevant to rural areas of underdeveloped countries, see Figures 3 and 4 for examples. Over the next several years it may be anticipated that PV system energy cost will continue to drop steadily, approaching $.50/kWH by 1986. At that time it is likely that PV systems will be the least expensive source for all decentralized electrical generation in underdeveloped countries.

Inherent modularity permits PV systems to closely match a user's discrete needs for electrical power, from watts to tens of kilowatts or more. Likewise, because of modularity, increments of power may be added as future needs dictate and resources allow. This stepwise, incremental option associated with photovoltaics is in sharp contrast with the requirements associated with central generation schemes.

We conclude that photovoltaics must now be viewed as a realistic energy alternative for developing countries. PV power systems hold promise of aiding current programs for improving quality of life and increasing economic opportunity for rural populations. And, in the long pull, PV power systems promise a renewable energy resource which could markedly lessen dependence on imported fuels.

REFERENCES

1. Energy Needs, Uses and Resources in Developing Countries. P. F. Palmedo, et al., BNL 50784, March 1978.

2. Energy and Agriculture in the Third World. A. Makhijani and A. Poole. Bollinger Publishing Co., Cambridge, Mass., 1975.

3. Robert S. McNamara, Address to the Board of Governors of the World Bank, 1976.

4. Japan's Solar Cell Technology is Moving Ahead Rapidly. T. Tsuji. JEE, June 1976.

5. Personal communication with Wright Associates, Inc., Longmont, Co.

6. Impact of Balance of System (BOS) Costs on Photovoltaic Power Systems. G. Hein, et al., DOE/NASA/1022-78/40, June 1978.

7. Cost of Photovoltaic Energy Systems as Determined by Balance-of-System Costs. L. Rosenblum. NASA TM-78957, June 1978.

8. Personal communication with Dr. Charles Weiss, World Bank.

9. Rural Electrification, A World Bank Paper, page 5, October 1975.