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STATE-OF-THE-ART OF PHOTOVOLTAIC SYSTEM TECHNOLOGY

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There appears to be no single or simple answer to the energy dilemma of developing countries; it is likely, rather, that a mix of mutually supporting technical, institutional and developmental approaches will be needed. In regard to technical approaches, one most promising, particularly for rural development, appears to be photovoltaic energy conversion through the use of a semiconductor solar cell device which converts sunlight directly to electricity. Photovoltaic (PV) power systems appear to have the necessary flexibility, cost and reliability to meet a variety of small-scale, decentralized electrical energy needs of rural communities.

Contrary to popular belief, PV systems as a whole do not embody a significant amount of "high technology." The "high technology" portion of the system is to be found in the solar cell. The rest of the system--the array structure, the wiring, the controls, the battery, etc.--all consist of conventional, "off-the-shelf" materials and components. Similarly, the physical integration of the materials and components into a system involves moderate to low skilled labor and standard assembly and installation techniques. These observations when coupled with the fact that the solar cell module at present represents about 45% of the total system cost, and in the future may account for only about 20%, has important implications relative to the technical and economic feasibility of manufacturing PV systems in Third World countries.

The following presentation covers the current state-of-the-art of PV systems, designs, applications, costs and performance. Both flat plate and concentrator systems are addressed, although, for reasons based on experience and the state of development of the technology, flat plate systems receive the major emphasis. Likewise, with respect to solar cell types, single crystal silicon occupies the predominant part of the discussion. Where appropriate specific or special aspects of the utilization to PV systems to West Africa are touched upon.

FLAT PLATE ARRAY SYSTEMS

System and Components

The PV power system is the total assemblage of components necessary to provide electrical power to a designated load. The major system components are 1) modules, 2) array, 3) voltage regulator and controls, and 4) storage battery. Component costs and cost trends will be discussed in the cost section.

Modules - The module, the basic photovoltaic building block of the system, consists of a number of solar cells electrically interconnected covered and incased within a supporting structure. Many early commercial modules were made with the solar cells imbedded in a clear silicone rubber encapsulant and

an aluminum or fiber reinforced plastic substrate support. Lately many commercial modules are of a glass-plastic laminate construction. The glass is used as cover material and in some models also serves as a superstrate support; appropriate plastics are used to bond the solar cells to the glass and also to form a back and edge watertight seal for the module package. Single crystal silicon solar cell modules are available in a variety of operating voltages and currents and in a range of physical size from about 0.2 to 0.8 m^2. Module efficiency* runs from about 7% to 11.5% at 28° C and 1000 W/m^2 flux, the so-called Standard Condition (SC).

Given the daytime ambient temperatures found throughout West Africa, module operating temperature may range from 50° to 65° C. Since commercial solar module output power decreases about 0.3%/°C, a module, for example, with an output of 40 Wp at SC would have an output of only 37 Wp at 55° C operating temperature.

There are about two dozen manufacturers of silicon solar cell modules in industrial countries: U.S., Western Europe and Japan. Only two Third World countries at present have resolved to independently produce cells and fabricate modules in any quantity: India (Central Electronics), 15 kWp, in 1980; and Mexico (Centro de Investigacion y de Estudios Avanzados del Instituto Politicinco Nacional), 8 kWp, planned for 1981. In-country module manufacturing facilities have been, or are being, established in a few Third World countries by means of joint ventures with Western firms, for example, Morocco/Leroy Sommer-Solarex and Ivory Coast/Photowatt Afrique.

Array - The array is the free-standing support structure into which the modules are mechanically and electrically assembled. Modules within the array are interconnected in series and parallel arrangements to give the desired system voltage and current. Galvanized steel, aluminum, or chemically treated wood structural members have been used for array construction; the former two materials are likely to be the most durable in the West African environment. Concrete has commonly been used for array foundations; however, a special, low-cost foundation design employed for the Tangaye, Upper Volta array is worth noting. This design used local rock and earth-fill and required only pick and shovel for emplacement (Ref. 1). Arrays are designed to withstand the maximum wind loads expected in the region of deployment, typically this might be about 150 km/hr.

Voltage Regulation and System Controls - Because the voltage output of the PV array varies with solar insolation and temperature, systems with battery storage require voltage regulation to prevent excessive overcharging of the battery. Controls are used, as required, to accomplish a variety of system regulatory functions, e.g., maximum power point tracking, load management, emergency shutdown. The technology and design of voltage regulators and controls is well developed; the parts, e.g., diodes, transistors and switches, are commercially available as off-the-shelf items. System tests in a variety of environments have not revealed significant problems associated with these components.

$$*\text{Module Efficiency} = \frac{\text{Maximum Module Output Power, W}}{\text{Gross Module Area, m}^2 \times \text{Solar Irradiance, W/m}^2}$$

Temperature, °C

Storage Battery - Because of the large variations in solar insolation, diurnal and seasonal, a battery is used as an energy bank and a buffer between the solar array and the loads. The battery supplies energy to the loads during periods of low sun, or no sun, and stores energy from the array during periods of high sun; a battery enables the system to meet momentary peak power demand, e.g. during motor start-up, and to maintain stable voltage to the loads. Although systems of 2 kWp and larger generally use battery storage, certain smaller PV systems, e.g., for micro-pumping, have been designed without battery storage.

The two battery types that have been used for PV systems are lead-acid and nickel-cadmium. Due to the higher cost, lower energy efficiency and limited upper operating temperature (40° C), nickel-cadmium batteries have been employed in relatively few systems. Lead-acid cells and batteries are available in many capacity sizes as well as several service types, e.g., automotive (SLI), motive power, stationary, and "photovoltaic". For PV applications low self-discharge rate is a very important characteristic. Lead-acid batteries with calcium-alloyed grid, typically yield a self-discharge rate of 1%/month and are preferred; antimony-alloyed grid batteries typically have self-discharge rates 10-50 times greater.

Automotive SLI batteries, although less expensive than other lead-acid battery types are most commonly manufactured with antimony-alloyed grids and are designed for shallow discharge (less than 5%) which severely limits their life in most photovoltaic applications to about 2 years. Stationary or "photovoltaic"-type batteries have a service life expectancy of 5-10 years, dependent on the battery model and nature of the duty cycle conditions imposed.

Design

The methodology for photovoltaic system design is relatively well developed. Once the load requirements are defined, the array and battery can be sized using known or estimated insolation and temperature conditions for a chosen site. Several handbooks are available to assist a competent engineer--with no previous photovoltaic experience--in the performance of the design computations and design and cost tradeoffs, Refs. 2, 3 and 4. Also of assistance are two reports containing detailed design information and engineering drawings for two village power systems, Schuchuli and Tangaye, which have been in operation since Dec. 1978 and Mar 1979, respectively, Refs. 1 and 5.

A detailed discussion of various considerations that enter into a system design is outside of the scope of this paper. One such consideration, d.c. vs. a.c. power output, however, is briefly treated here because of its potential influence on system cost.

Advocates of a.c. systems point out that there is a wide range of a.c.-powered equipment available worldwide and that a.c. power allows for a simple means of voltage and current transformation, comparative ease of switching and a nearly constant motor speed (characteristic of a.c. induction motors). On the other side of the argument it can be pointed out that the conversion of the d.c. array output to an a.c. system output requires an

inverter which increase complexity and cost and decreases reliability. Additionally, the tare (no-load) losses and the operating inefficiency of an inverter require an increase in array and battery size which further adds to system cost. This latter cost penalty is especially severe for small systems, for systems powering a high percentage of inductive load (e.g., motors) and for systems matched to load profiles having relatively small power requirements for extended periods.

The Schuchuli Village Power System, 3.5 kWp can be used by way of example of the magnitude of the potential cost penalty associated with a.c. output for a PV system. For the a.c. option, using state-of-the-art inverters, the additional array and battery required would have add 30% to the cost of the all d.c. system.

Applications

PV systems have been gainfully employed in a large number of different applications, for the most part, in remote and rural areas of the world. The state of development of certain applications is quite advanced, as can be judged by the worldwide sale of PV modules. Sales for 1980 were estimated to have been over 4 MWp and for 1981 to exceed 5 MWp. About 50% of the modules sold are used in communication applications, viz., rural telephone, emergency radio, VHF, UHF and microwave repeaters. A significant number of PV modules sold go into the following uses: anti-corrosion cathodic protection devices for bridges, pipelines and well casings; agricultural applications, e.g., electric fencers and water pumps; navigational aids; and remote sensing instrumentation.

In the near-term, PV applications will be directly linked with and paced by discrete product (service package) development; in the longer run, bulk electric generation applications will likely predominate. PV service packages most relevant to West African rural needs appear to be 1) water pumps (potable water 10-20 m^3/day and irrigation 50-100 m^3/day), 2) lights (20-40W fluorescent), 3) refrigerators (medical, 100 liter capacity), and 4) radio communication. Nevertheless, the commercial development of reliable, convenient, and minimum cost PV-powered electrical products such as water pumps and refrigerators is still in an early stage. And, because of the relatively high stresses imposed by the West African environment, e.g. ambient temperature up to 45° C and dust during the Harmattan season, certain load devices, such as refrigerator units, may require redesign to provide energy-efficient and dependable operation.

By way of illustration, an example of PV application experience in Upper Volta is provided in Appendix A.

Performance

For purposes of design and estimation of cost, the quality of service which a system is expected to deliver must be specified. Apropos electric power systems, three important indices of service performance are reliability, availability and voltage control.

Reliability - Is the probability that an item - a part, a component, an assembly, a unit or an entire system - will perform its intended function for the intended period of time under stated conditions (Ref. 8). Conversely, the probability that an item will fail on a specified period is simply 1 minus Reliability. Reliability, therefore, provides a measure of how often service may be interrupted because of an outage (failure).

Availability - Provides a measure of the duration of loss of service and is defined as the percentage of time that a system (or subsystem) is neither forced out of service or otherwise out of service because of scheduled or unscheduled maintenance (Ref. 8). The annual availability, A, can be expressed as, A=(1-MR)(1-FOR), where MR is the total maintenance days per year and FOR is the forced outage rate, outage hours per year.

For purposes of predicting availability of electric generation plants, two methods which are based on probability mathematics are employed by the electric power industry, namely, loss of energy probability (LOEP) and loss of load probability (LOLP), Ref. 11. Both represent the expected number of days within a stated time period during which the system generation will be less than the system requirement. Generation and load is expressed in terms of energy and power, respectively, for LOEP and LOLP.

The reader interested in learning more of the method for calculating loss probabilities will find illustrative examples for central station power plant systems in Ref. 11 and for PV systems in Ref 3. Please note that for the PV case the approach used assumes that LOEP is solely a function of the distribution probability of the solar insolation. As such it does not account for lost service time attributable to other effects. Let us designate this loss probability as $(LOEP)_I$. Later in the discussion this importance of the distinction will be elucidated.

Depending on the nature of the electric system, any or all of the following factors may affect availability:

1. probability distribution of supply of energy source;

2. number, capacity, and reliability of power generator(s), where reliability is a combined function of the reliability of each subsystem, component and part;

3. scheduled and unscheduled (for repairs due to outage) maintenance down-time;

4. probability distribution of loads;

5. probability distribution of "act of God" events, e.g., destructive lighting strike.

For example, factor 1 may be negligible in the case of a U.S. coal-steam generating plant. However, for PV systems located anywhere in the world the site specific, annual distribution probability of solar energy is always a major influence on availability. Factor 4 is consequential in the case of central station electric grid utility systems because of the typically large

daily and seasonal load variations; while for PV stand-alone applications this factor is of less importance since, the load is usually relatively constant. For any system, such as PV stand-alone or diesel generator, deployed in a remote location, factor 3, down-time for repairs, will have a major effect on availability. Included in repair down-time is the travel time needed for the repair person to reach the site, time to locate and identify the problem, time to replace parts of correct the fault, and time to obtain the necessary replacement parts, if spares are not on hand.

Voltage Control - Another basic index of service performance is voltage control. The electrical power entering a user's service area needs to be controlled such that voltage is within suitable limits for utilization by the loads. Most loads, i.e., appliances and equipment, will only operate satisfactorily, or at all, within a limited voltage range. Generally, voltage control to ± 5% from nominal voltage is considered favorable, Ref. 12.

Service Performance of Electric Systems - To be competitive a PV system should deliver a level of service performance equal or better than competitor systems of the same location. Competitors to PV stand-alone systems are central station electric grid and diesel-generators, and in principal it would be useful to adopt their historical service performance as benchmarks and guides to setting of PV system performance requirements.

Information on the operational history of electrical system service performance, unfortunately, is exiguous. (In view of the sensitivity of electric utilities concerning quality of service provided to customers, not an unexpected result.) Displayed in Table 1 is the small amount of performance information gleaned by this author.

Table 1 - Service Performance of Electric Systems

System Type	Service Area	Average Availability	Voltage Control	Refs.
Central Station - Electric Grid	U.S. Urban/Rural	0.9998	±5%	13
	Lahore/Pakistan-Urban	0.99	±25%	14,15
	Tunisia-Urban/Rural	0.99		16
	Basaisa, Egypt/Rural	0.74		17
Diesel Generator Stand-Alone 5-15 kW	U.S. - Various	<0.95	±3%	18
PV Stand-Alone 15 Wp-3500 Wp	U.S. - Remote	0.97	±5%	19

The average service availability for grid systems may be of limited value as a measure of quality of service from the perspective of the individual customer, particularly if the customer's level of service is among the set of lower values in the total statistics that yield the average. In any country those in rural or remote areas, usually receive the poorest service from the grid. Rural service is generally inferior to urban service because of several

factors, among which are longer and more difficult to service distribution lines, lower assigned priority in event of system overload, paucity of trained maintenance and service personnel, and, in some instances, poorer management.

It may be that grid electric power availability is about 0.99 in urban areas of certain developing countries; nevertheless, the presence in many cities of back-up diesel generators in hotels and public buildings would argue that availability is in reality much less than 0.99. For rural areas, the Basaisa data may be representative. Corroborating evidence is found in Ref. 20, which summarizes two studies of electric grid service in rural India. (N.B.: in India there is a strong financial motivation to use electricity, as it is heavily subsidized.) A study in Karnataka State reports, "many farmers with electric pumpsets also have stand-by diesel pumpsets because of power cuts and unreliability of power supply." A second study of the Ludhiana District of the Punjab, a district with all villages electrified, reports, "the number of electric motors for water lifting increased from 11051 in 1969-70 to 15322 in 1974-5, while the number of diesel engines (for stationary and mobile use) increased from 24206 to 42070 to 43769 over the same period. Many farmers have both because of the unreliability of electric supply.[11]

The diesel stand-alone system data given in Table 1 are based on U.S. military specifications for 5-15 kW diesels; the specs being derived from operation experience. For this situation, the availability value represents that which is achieved with diesel units that enjoy a high level of maintenance and the proximity of trained personnel and spare parts. Stand-alone diesels in a less structured setting, which is the more common situation, can be expected to exhibit higher forced outage rates and consequently lower availability. Additionally, from the aspect of service provided to a user, even if diesel equipment is in an operational state, it may be put into operation only a few hours each day. Such scheduling is common for rural and small city electric service and results in extremely low availability values.

The PV stand-alone systems data referenced in Table 1, represents 14 first-of-a-kind systems, which were placed in operation in remote locations at various times between 1976-80 and have accumulated a total of 484 months of service time. Down-time experienced was the result of 7 outages among 5 of the 14 systems.

The design $(LOEP)_I$ for each of the systems is 0.999 or greater. Therefore, it would be expected that observed availaibility values less than 0.999 would be due to the effect of factors other than insolation. This, in fact, is in line with the results. The outage causes (and numbers) are as follows: regulator failures (2); controller failures (2); user negligence (2); and defective load appliance (1). Module failures, although they occurred, did not result in system outage. The consequences of solar cell module failure are discussed in the next section.

It is credible to assume that PV systems can be designed to yield operational availability of 0.99 or better. (The causes of failure observed above, for example, are correctible or mitigable.) However, in the near term, when most of the PV applications will be in rural and remote areas, there is

little justification for PV systems to meet such a high level of availability when competitor systems performance is much lower. Also, as will be seen in the Cost Section, there is a strong financial incentive to design systems to values of $(LOEP)_I$ as low as circumstances will allow.

Reliability of Modules - The information discussed below is derived from U.S. Department of Energy-sponsored programs of PV system tests and application demonstrations managed by MIT-Lincoln Laboratory (since 1976) and the NASA Lewis Research Center (since 1975). The solar cell modules which form the base of the reliability test data use single crystal silicon cells; cadmium sulfide modules, to this date, have not been produced in commercial quantities and polycrystalline silicon modules have only recently been offered for sale. All of the modules are of U.S. manufacture, representing 6 companies, 11 different models and production runs from 1976 through 1979. They were purchased through JPL Block Procurements I, II, and III and as such were required to meet rather stringent qualification/acceptance test specifications.

The data set consists of a total of 11,553 modules which were used in about two dozen field tests and demonstrations throughout the United States, except for one demonstration in Upper Volta (Refs. 19 and 21). Test time has been 1 1/2 to 5 years duration to date, with most of the tests still in operation. The index of reliability used is the average monthly failure rate, $\overline{MFR}$ = no. modules failed/total vs. modules/no. months in operation. The following summary provides the percentage of the 11,553 modules which fall into one of four $\overline{MFR}$ groups: 81%, $\overline{MFR}$ 0-0.0001; 14% $\overline{MFR}$ 0.0001-0.0026; 0% $\overline{MFR}$ 0.0026-0.0134; 5% $\overline{MFR}$ 0.0134 and greater. By and large the reliability performance is good: 95% of the modules show excellent to fair performance and 5% (representing 1977-8 vintage modules from two manufacturers) exhibit unacceptable performance.

It must be emphasized, though, that the modules tested were purchased to certain qualification/acceptance test standards. There is no reason to believe that the ordinary commercial offering of modules came up to these standards. Some perspective of the situation may be gained if consideration is given to the fact that PV modules are the products of a fledgling industry and which have undergone almost annual design and production changes. Until module design and production methods are stabilized and more experience acquired, it is likely that the quality of modules will be somewhat variable. In such a situation the prudent buyer will protect himself by negotiating an appropriate warranty agreement. For very large purchases, or where the application places a premium on reliability, the purchaser may wish to require certification from the manufacturer that the modules meet appropriate qualification and acceptance test specifications. In this regard the latest JPL specifications will be of assistance (Ref. 22).

Because of the electrical circuit redundancy that can be designed into PV arrays, module failures when they do occur seldom result in a system outage. This is the dominant fact concerning module reliability. Even in extreme cases where cumulative module failures reached 25 and 30%, (Schuchuli and Tangaye, respectively), the systems experienced no lost time; rather, there was a cumulative reduction in total energy delivered by the array. This gradual (over several months) reduction in energy output required either temporary partial load shedding (Schuchuli) or partial reduction in hours per day mill operation (Tangaye).

Cost

The capital cost of a PV system includes all costs for labor, materials and parts. Elements of system cost include the following: solar cell modules, array structure and foundations, electrical grounding, site preparation and security, electrical connectors and conductors, controls, regulators, instrumentation, storage battery and enclosure. All items of labor, materials and parts other than solar cell modules are referred to as the balance-of-system, BOS (Ref. 23).

System costs fall into one of three categories, viz., cost directly related to the area of the array, C_a; costs directly related to the size of the battery, C_b; and fix costs, C_o. A cost algorithm can be set up in the form,

$$\text{System Cost, } C = C_o + AC_a + BC_b,$$

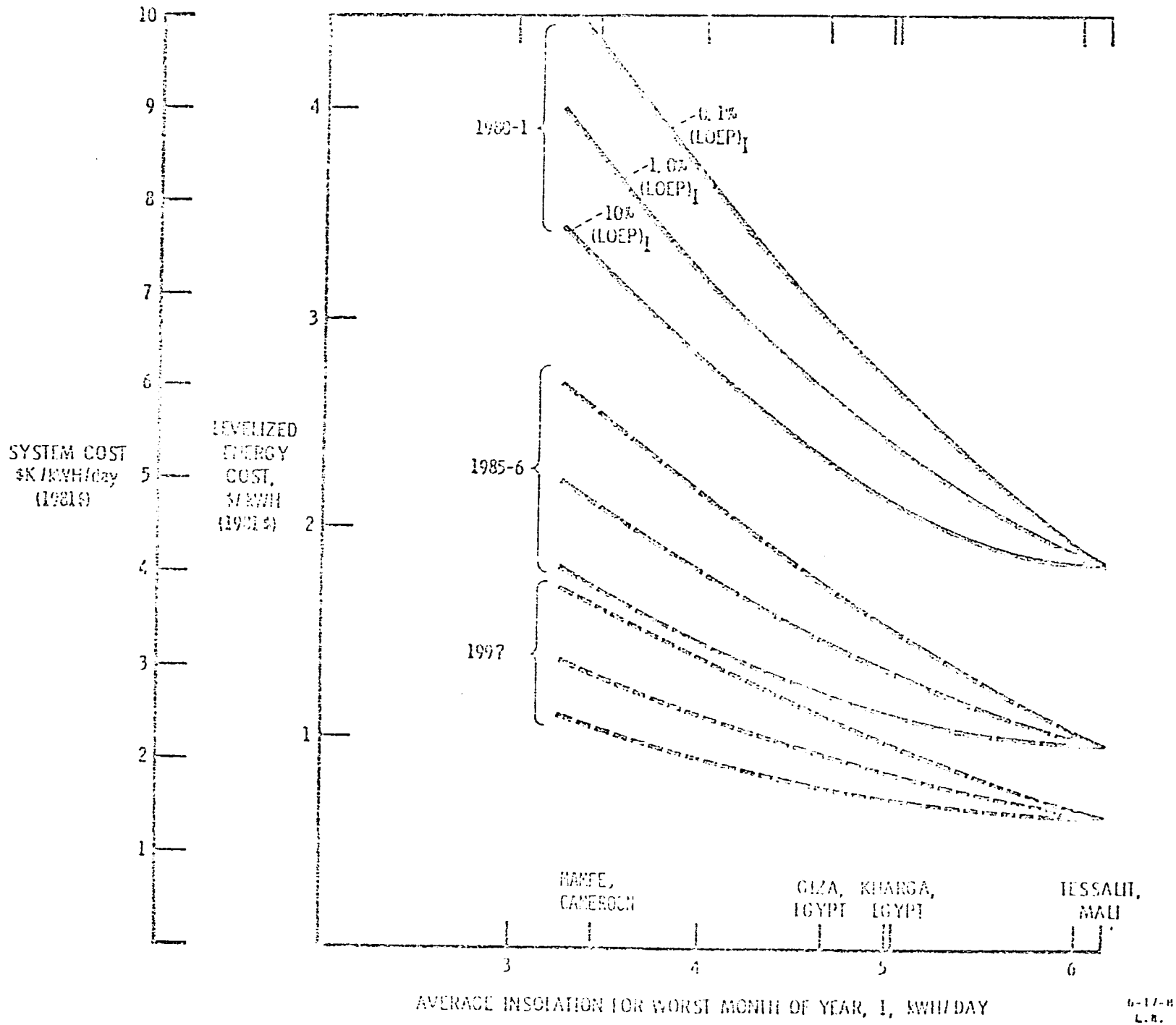
where A is array area and B is battery capacity. Thus the essential starting information needed to estimate system cost is the size of the array and battery required to deliver the desired amount of energy within a given period of time. This information, as a first order approximation, is a function of local insolation and the specific system design LOEP.

The principal objective of this section is to provide a general review of the sensitivity of present system costs to insolation and $(LOEP)_I$. Additionally, future cost trends are conjectured. Patently the ability to obtain accurate cost estimates will hinge on the accuracy of the BOS and module cost elements and validity of the related assumptions which enter into C_o, C_a and C_b.

For 1980-1, to arrive at a system selling price, F.O.B. factory, the cost elements that entering into C_o, C_a and C_b were derived from historical data for stand-alone systems deployed by LeRC. The following conditions and assumptions are imposed: system size range; 4 to 20 kWp; module efficiency (28°C), 11.5%; module cost, 8 \$/Wp (28°C); Operation and Maintenance costs not included; mark-up to account for overhead, warranty, profit, etc. - 60% on labor, 25% on materials; and very small volume production. A special design condition was also imposed, namely, the minimum size battery must provide at least two days reserve capacity. For 1985-6, the same conditions and assumptions as for 1980-1 were used, with the following changes: module efficiency (28°C), 13%; module cost, 4 \$/Wp (28°C); improved array design, approximately one-half 1980-1 cost; large volume (greater than 10,000 units/year) production. For 199?, the same conditions and assumptions as for 1985-6 were used, with the following changes: module efficiency (28°C), 18%; module cost, 1 \$/Wp (28°C); Redox energy storage system in place of lead-acid battery at 60% the cost. All costs are given in 1981 dollars. Levelized energy costs were calculated directly from system costs assuming a 20 year life and 15% discount rate.

In Figure 1 system cost in thousands of dollars per kWH per day and levelized energy cost in dollars per kWH are plotted versus insolation for 0.1, 1 and 10% $(LOEP)_I$. The LOEP calculation was based on the method

FIGURE 1 - EFFECT OF $(LOEP)_I$ DESIGN SPEC. ON SYSTEM AND LEVELIZED ENERGY COSTS



described in Ref. 3. In any location there will be one month for which the average insolation is lower than any other month of the year; this represents the month with the maximum potential for loss of energy. The abscissa in Figure 1 is in units of worst month average insolation. Noted on the abscissa are specific locations as points of reference, from the lowest worst month insolation in the costal regions, e.g., Mamfe, Cameroon (or Port Harcourt, Nigeria) to the highest in the arid regions, e.g., Tessalit, in northeastern Mali.

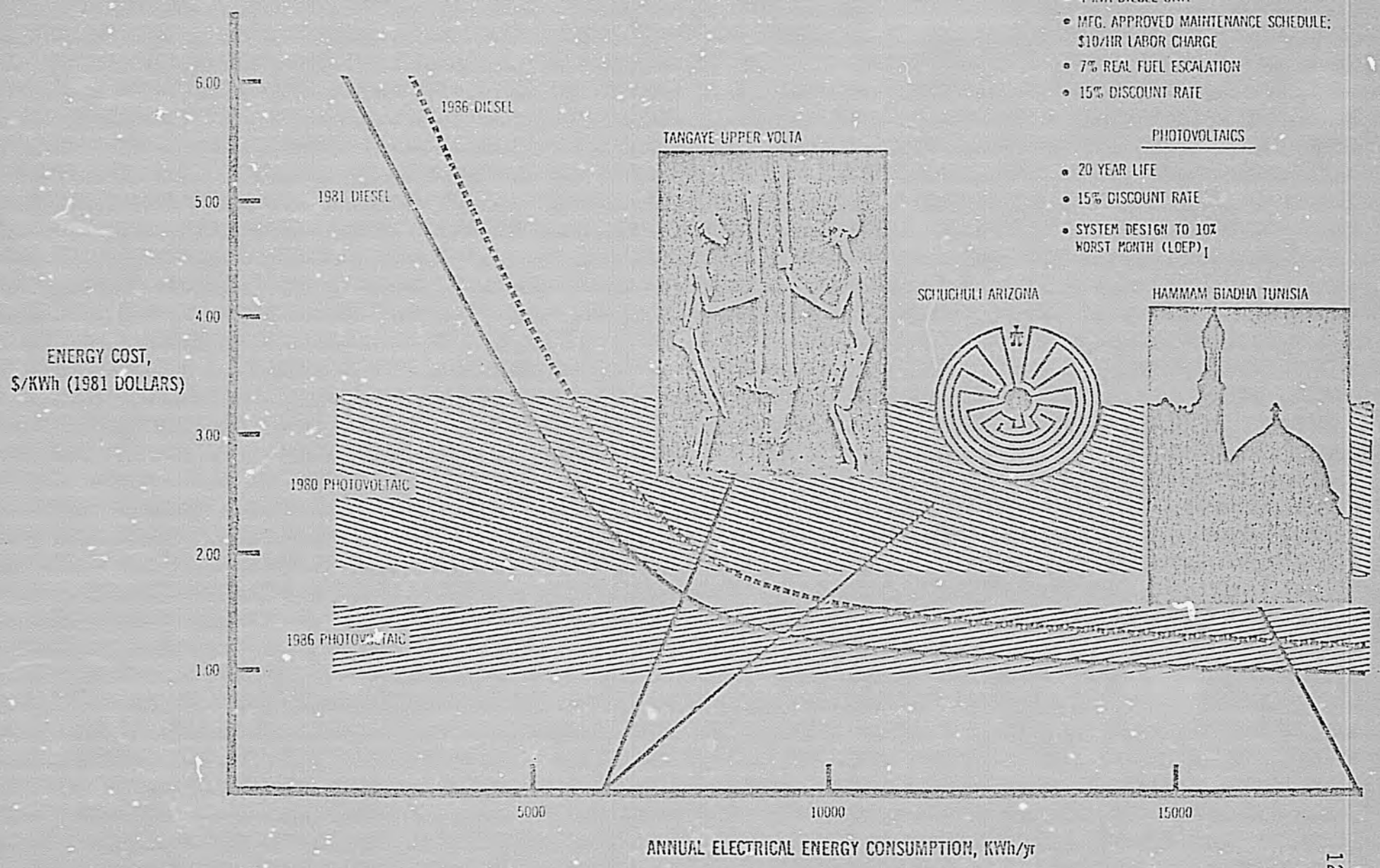
A system design with an array and battery sized to a worst month $(LOEP)_I$ of 10%, for example, would be expected, on the average, to experience 3 days in that month when the energy generated plus the remaining battery capacity would be insufficient to meet the load demand. Since the annual $(LOEP)_I$ is the average for the 12 months of the year, a 10% worst month $(LOEP)_I$ might typically correspond to about a 1% annual $(LOEP)_I$, or 3.7 days per year. The fact that the cost - $(LOEP)_I$ curves converge at higher insolations results from the requirement to augment the very small battery, (consequent to favorable sun regions) in order to meet the special design condition, noted earlier, for a minimum size battery which will provide two days capacity in the event of a non-insolation related outage; e.g. regular failure or user negligence.

It is evident that the effect of the choice of system design $(LOEP)_I$ on cost is quite significant. Based on the discussion in the Performance Section, a worst month $(LOEP)_I$ of 10% (i.e., annual $(LOEP)_I \approx 1\%$), for example, should provide a service availability superior to competitor systems in all rural and remote areas, and even many urban areas, of developing countries. Lower values yet of worst month $(LOEP)_I$ could be used for system design, balancing system cost saving against the needs of the application, the expection of the user, and competitor systems performance.

Figure 2 presents a comparison of levelized energy cost, $/kWH, for 4 kVA diesel and PV systems, over a range of annual energy consumption, kWH/year, for the 1980 and 1986 periods. The following assumptions are employed: for all systems - 20-year life and 15% discount rate; for diesel/electric - 4 kVA unit, $3.00/gal. fuel cost (delivered), 7%/yr. fuel escalation rate, O&M costs as specified by diesel manufacturer; photovoltaic - annual solar insolation typical of areas between 30° N and 30° S latitude and 10% worst month $(LOEP)_I$.

The results indicate that for applications having an annual electrical demand of 6,000 kWH or less, the energy cost for a photovoltaic system is less than for a small diesel/electric system. Points of reference for annual electric demand are the Schuchuli Village and Tangaye Village Projects, 6,000 kWH/yr. Within the range of annual energy use up to 6,000 kWH lie many important applications of immediate relevance to development in rural areas of Third World countries, such as water pumping for domestic and agricultural uses, refrigeration and lighting. Furthermore, over the next several years it may be anticipated that photovoltaic system costs will continue to drop steadily; note projected 1986 energy costs. Thus within a decade it is likely that photovoltaics will become the least expensive and most reliable source for all decentralized electric power applications in the developing world.

PHOTOVOLTAIC AND DIESEL ENERGY COST COMPARISONS



ASSUMPTIONS

DIESEL

- 20 YEAR LIFE
- $3/GALLON FIRST YEAR FUEL COST
- 4 kVA DIESEL UNIT
- MFG. APPROVED MAINTENANCE SCHEDULE; $10/HR LABOR CHARGE
- 7% REAL FUEL ESCALATION
- 15% DISCOUNT RATE

PHOTOVOLTAICS

- 20 YEAR LIFE
- 15% DISCOUNT RATE
- SYSTEM DESIGN TO 10% WORST MONTH (LOEP)[1]

Appendix A

The Tangaye Village PV Project

As an illustration of recent PV application experience in West Africa, the Tangaye Village PV Project is selected for presentation, in as much as it is the most completely documented activity of its kind that is available, Refs. 1, 6 and 7.

Under U.S. AID sponsorship, a PV system powering a grain mill and a water pump was installed by NASA-LeRC in the village of Tangaye, Upper Volta and became operational on March 1, 1979. The 1.8 kWp, 120 volt system, including 540 ampere-hours of battery storage, supplies DC electrical power to a commercial-type hammer mill and a positive displacement water pump. A cooperative was formed by the villagers of Tangaye to manage the mill. About 60 village families invested in the enterprise. Charges for milling are set by the cooperative and are competitive with commercial mills in the region. Proceeds from membership and milling are used to pay two full-time millers and to accumulate funds for spare parts and repairs. Additional profits are distributed to cooperative members.

The burr mill, installed initially, exhibited excessive wear and was replaced by a hammer mill in September 1979. As a result of down time attributed to the burr mill problems, grain milling was operational only 89% of the time, March-August 1979. Since October 1979 the mill was operational 96% of the time, i.e., 567 out of 591 days. The average weekly output of the mill from October 1979 through April 1981 is shown in Figure 3. A total of 36,138 kilograms of grain were ground in about 1000 hours of elapsed operating time. A general cyclic trend in customer patronage of the mill is apparent. Usage tended to increase beginning during the harvest season, peaked in the months following harvest, then dropped off in the summer months perhaps due to depletion of grain stocks.

Water is pumped from a well located near the mill building to a storage tank with a dispensing facility. Water for both domestic and livestock use is freely available to everyone. A summary of the water pumping data is given in Figure 4. It can be seen that water consumption has followed a seasonal pattern to some degree, the maximum use occurring at the height of the dry season in March-April. The total amount of water pumped as of October 12, 1980, was 4,623,000 liters covering over 3700 hours of pumping.

About 7 months after installation failures began to show up in the model 9200J solar cell modules; from that time on failure of the modules continued at about 2% per month on the average. The failures were analyzed and identified to have resulted from thermal stress induced fatigue cracking of the cell electrical interconnects. Replacement modules were provided by NASA and installed in the array periodically beginning September 1980 by personnel either from Direction de l'Hydraulique et de l'Equipement Rural (HER) or NASA, with the assistance of resident AID personnel.

System operation continued uninterrupted in spite of cumulative module failures. The most significant effect on system performance was a progressive diminution of overall system energy output as failures accummulated; full

system output was restored by replacement of the failed modules. As can be seen in Figure 4, water pumping was unaffected. In fact, water use increased somewhat during this period; nevertheless, the pump was supplied with the requisite energy to meet the demand. On the other hand, the grain mill operation, Figure 3, had to be curtailed somewhat; the overall cutback was about 25%, roughly corresponding to the cumulative percentage of module failures. Based on the meter readings of daily energy generation and consumption, the millers made the decision as to when to shut down mill operation each day. This load management procedure was highly successful in two respects: 1) until repairs could be made, it enabled the system to operate near its maximum potential without driving the battery to an unacceptable level of discharge; and 2) it provided a demonstration of the ability of technically untrained personnel to manage the power flow of a relatively large PV system under constantly varying conditions over long periods of time.

Because of the success of the Tangaye Project in its essentials and the growing demand for grain milling, the official representatives of the village have requested through AID that the capacity of the mill be increased. With joint cooperation by the U.S. Department of Energy and NASA this request was approved by AID. During May and June 1981 the Tangaye PV system was refurbished and enlarged to 3.6 kWp using a model of PV modules which has shown in other field tests a much higher reliability than the original ones. Also, the existing hammer mill was replaced with a more efficient model. The system, now is in the process of being turned over to the Government of Upper Volta, will, in the future, be monitored and repaired, as needed, by HER; maintenance of the system will continue to be carried out by local village personnel as before.

Figure .3 - Tangaye Village Photovoltaic Project

Grain Milling Operational Data

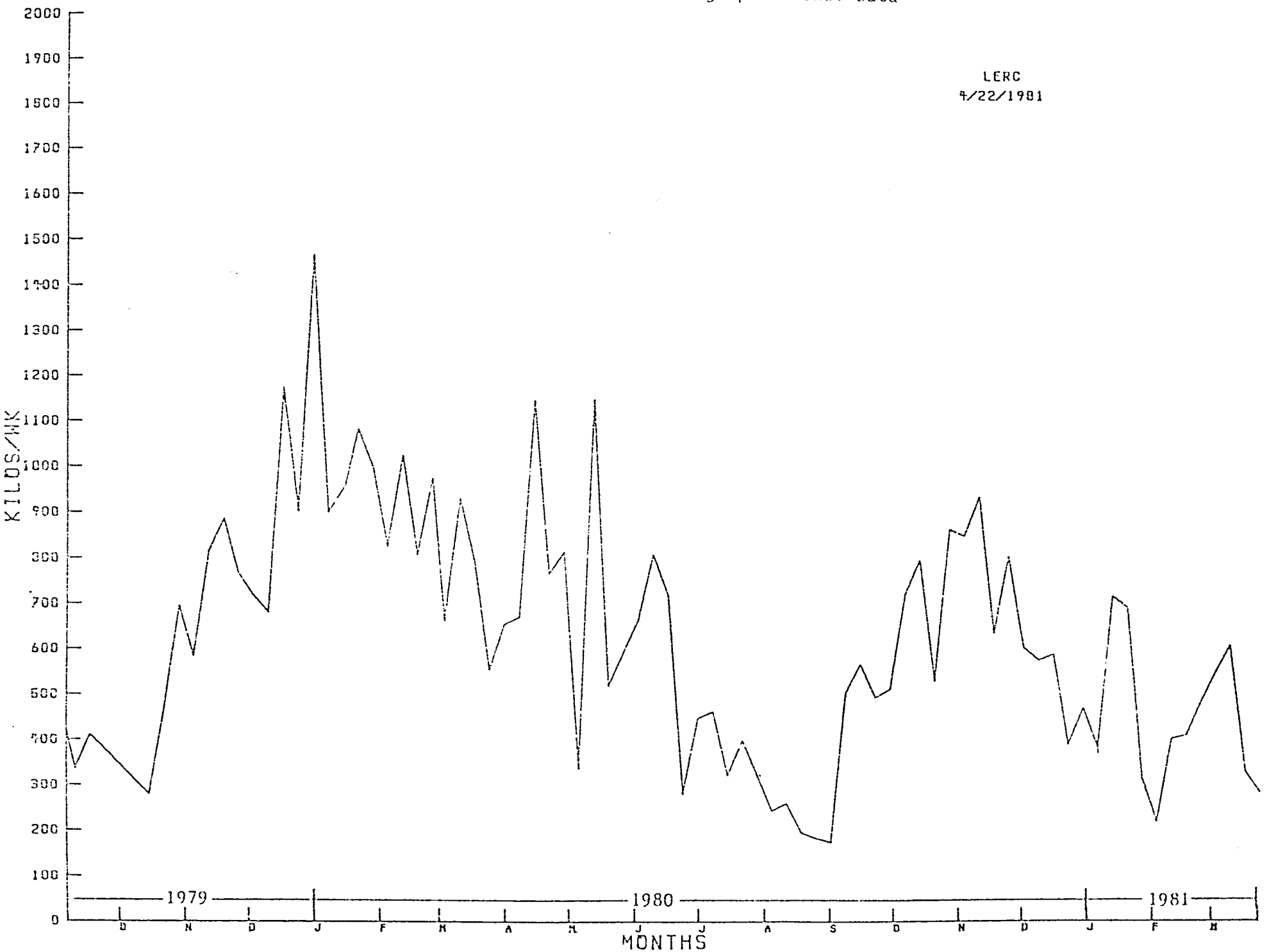
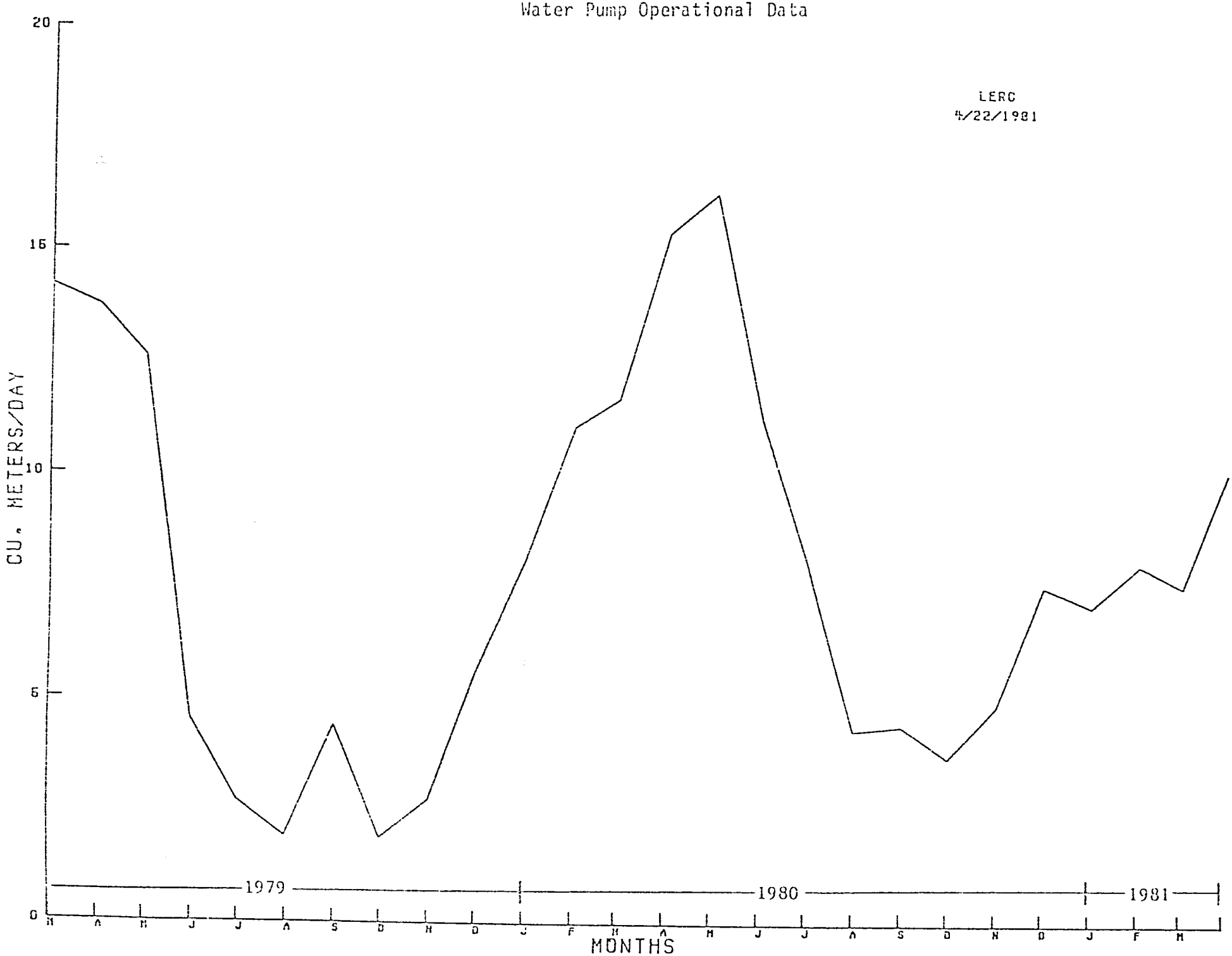


Figure 4 - Tangaye Village Photovoltaic Project

Water Pump Operational Data



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