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Review of Stand-Alone Photovoltaic Application Projects Sponsored by U.S. DOE and U.S. Aid

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REVIEW OF STAND-ALONE PHOTOVOLTAIC APPLICATION PROJECTS
SPONSORED BY U.S. DOE AND U.S. AID

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ABSTRACT

The Lewis Research Center (LeRC) of the NASA has been a leader in photovoltaic (PV) research and development since 1960. In the early 1970s PV system technology developed for the space effort was applied to terrestrial applications with the subsequent installation of several small PV systems for use by other Federal Agencies. In 1976, the LeRC was asked to manage what has become the Department of Energy's (DOE) PV Stand-Alone Applications Project. Also in 1976, the U.S. Agency for International Development (US/AID) requested that the LeRC design and install a PV system for water pumping and grain milling for a village in Upper Volta, Africa, in support of its program "Studies of Energy Needs in the Food System." This beginning relationship with the US/AID has broadened into an extensive project to demonstrate the suitability of PV power systems for meeting basic electrical requirements in rural areas of developing countries. This paper references and briefly describes the systems LeRC has deployed, summarizes significant findings from the system's operations, and gives some insight into the type and range of planned DOE and AID projects.

1. INTRODUCTION

The NASA Lewis Research Center (LeRC) manages two projects involving the deployment of small-scale, decentralized photovoltaic (PV) power systems for rural or remote areas of the world. For the U.S. Department of Energy (DOE), LeRC manages the Stand-Alone Applications Project which is part of the National PV Program. The objective of this project is to accelerate the commercialization of PV through the stimulation of the latent worldwide market by means of cost-shared demonstration projects. For the U.S. Agency for International Development (AID), LeRC manages the PV Development and Support Project, the objective of which is to determine the suitability (i.e., reliability and cost-competitiveness) of PV power systems for development assistance activities in rural areas of developing countries.

The DOE and AID PV activities are both aimed at demonstrating the applicability of photovoltaics to a variety of users. While DOE is fulfilling its mandate to develop PV as an alternative energy source for the U.S. by the year 2000, AID is applying this technology as it exists to selected development assistance activities to evaluate its potential for meeting electrical energy needs in rural areas of developing countries. In the process, the user requirements from the AID applications are fed into the DOE technology development activities. In this regard, the DOE and AID projects are complementary. LeRC, as technical manager for both projects, coordinates and integrates the activities to assure appropriate interaction, facilitate technology transfer and prevent duplication of effort.

This paper reviews the results of PV application projects conducted to date by LeRC for both DOE and AID and describes similar projects slated for implementation in the near future. It also addresses the economic viability of PV systems relative to alternative systems for remote applications.

2. APPLICATION EXPERIENCE

The PV applications experience of LeRC dating back to 1976 is summarized in Table 1. Each of the applications employ stand-alone (i.e., no backup power) DC photovoltaic systems ranging in power output from 23 to 3500 peak watts. All-DC systems are used to enhance overall system efficiency and cost-effectiveness. The systems have been exposed to a range of environmental conditions including snow, ice, high and low humidity and temperature, wind, dust and blowing sand, and a wide range of insolation. Load profiles have varied from predominantly daytime to a mixture of night/day to a continuous 24 hour/day operation. This wide variety of requirements and conditions has provided an excellent opportunity for the evaluation of first generation PV systems.

The applications given in Table 1 are listed in two groupings. The first describes appliance-oriented systems in which the electricity from the PV system powers a single

device. The second group describes applications in which several devices consume power and the PV system is designed to be a general source of power.

2.1 System Descriptions

As indicated in Table 1, the PV systems deployed to date by LeRC for DOE and AID cover a variety of locations. The DOE sites range from Hawaii to Maine and from Alaska to the Florida Keys. The AID system is located in Upper Volta, Africa. With the exception of the pollution and seismic monitors, described briefly below, all systems are described in references 1 to 5. Because of their significance, the forest lookout and village applications are also described briefly below.

Air Pollution Monitor - A high volume air sampler system was installed at Liberty State Park, New Jersey directly opposite the Statue of Liberty, in May of 1980. This 60 volt DC system consists of a 360 watt peak array, a 561 ampere-hour battery and a control system. Although the air sampler is part of the New Jersey Department of Environmental Protection air pollution monitoring network, the system was designed primarily to demonstrate a photovoltaic system to people from the metropolitan New York area.

Seismic Sensor - A seismic sensor was installed at Heiheiuhula Puna, on the Island of Hawaii in January of 1980. The system, operated by Hawaiian Volcanoes Laboratory, consists of a 12 V, 40 watt peak array, a 75 ampere-hour battery and controls. The system powers a tiltmeter, a seismometer, a signal processor and VHF transmitter.

Forest Lookout Towers - PV power systems were installed at each of two U.S. Forest Service Lookout Towers in October of 1976. These towers, located in the Lassen and Plumas National Forests, respectively, in northern California, each employ a 294 watt(peak), 12 volt DC PV array and 3015 ampere-hours of battery storage. The systems each power a 3 cubic foot refrigerator; a bilge pump to pump water from a storage tank to a kitchen sink, shower and toilet; fluorescent and incandescent lights; a USFS radio; and, at times, an operator-provided 12 volt DC television set.

Schuchuli Village Power System - A 3.5 kW (peak), 120 volt DC PV system became operational in the Papago Indian Village of Schuchuli, Arizona on December 16, 1978. The system, which includes 2380 ampere-hours of battery storage, provides the villagers with electrical power for the village water pump (for domestic use and livestock), lights in the homes and community buildings, 15 family refrigerators, and a communal washing machine and sewing machine. Because of

unknowns regarding use of the loads and variations in insolation, a load management system was incorporated into the design to protect the batteries from excessive discharge and to maintain operation of the more critical loads at the expense of those that are less critical.

Power is distributed from the PV system to the homes and community buildings by means of an overhead pole line distribution system installed by the Papago Tribal Utility Authority. A major part of the PV system installation was performed by the Papago Construction Company.

Tangaye Village Grain Mill and Water Pump - Under U.S. AID sponsorship, a PV system powering a grain mill and a water pump was installed in the West African village of Tangaye, Upper Volta and became operational on March 1, 1979. The 1.8 kW, 120 volt system, including 540 ampere-hours of battery storage, supplies DC electrical power to a commercial 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.

Water is pumped from a well, located near the mill building, to a storage tank and dispensing facility. Water for both domestic and stock use is available to all villagers free of charge.

2.2 Significant Operational Results

In general, the first generation PV systems deployed to date have proven to be reliable and require minimum maintenance. As a prime example, the two forest lookout tower systems have exhibited a 100% on-line record since their installation in October 1976. One system has required no maintenance whatsoever, while the other has required only an annual washing and adding of water to the battery. The Schuchuli and Tangaye PV systems have also had good on-line records, 99% and 96%, respectively, although the particular PV module used has exhibited high failure rates (this will be discussed in more detail below). Load devices, in some cases, have also proved troublesome. For example, commercially available recreational vehicle type (DC) refrigerators proved inadequate in a desert environment. The special design refrigerators used at Schuchuli initially experienced motor failures which were eventually eliminated by replacing the 1/8 hp motors with 1/4 hp motors. The burr mill installed initially at Tangaye proved inadequate for commercial use and was replaced with a hammer mill. There have been

control system problems at both Schuchuli and Tangaye resulting from component failures (e.g., transistors, meter relay lights), but not from control system design. Results of the Schuchuli and Tangaye system operation are given in more detail below.

Schuchuli PV System - The PV array output and load consumption for the Schuchuli system are given in bar chart form in Figure 1. During the first year of operation, the system produced about 90% of its predicted annual output and load consumption tended to peak during the summer months when temperatures were high and the refrigerator and water pump requirements were the highest. It is difficult to generalize beyond that because of a number of factors. During much of the first year, problems were encountered with the custom-built refrigerators, primarily due to DC motor problems, which resulted in erratic use and energy consumption. In addition, late in November of the first year, the PV array circuit breaker tripped, because of a control instability, causing the system to operate solely off the battery. This condition went unnoticed for some eight days, causing battery discharge to the point where load shedding was initiated. By late December, battery state of charge had dropped to 40% (i.e., 60% depth of discharge). In January of 1980, the thermostatic control for the solar water heater freeze protection element failed in the closed position, causing further battery drain. As a result, the battery state of charge dropped to a low of 20% by January 11. With the load shedding system in operation through much of January, the battery state of charge was able to recover to 70% by the end of the month. An inspection of the system in April uncovered 7 failed (open-circuited) PV modules. This was later to be seen as the onset of PV module failures caused by fatigue cracking of the metal interconnects between cells (this is discussed further under Reliability).

Also of note is the consumption of water, which was very high during the hot and dry summer of 1980. For example, average water pumped for the month of June was 8250 gal/day, with a peak of 9800 gal/day, compared to the design value of 5000 gal/day. As a result of the high water pump and refrigerator operating times, coupled with the continued PV module failures, the system operated in the load shedding mode on a number of occasions during the summer. By the fall of 1980, the cumulative module failure rate had reached 28%. In October of 1980, a number of panels were retrofitted with a different type module, and other defective modules were replaced bringing the system back to its original design condition.

The above mentioned problems have all been dealt with in such a way that the system is now functioning properly. However, they

must be taken into account in examining the performance chart in Figure 1. Of note is the fact that only two system outages occurred during the first 20 months of operation. In both instances, the cause was a burned out lamp in an optical meter relay. This device has been modified to prevent recurrence of this problem.

Tangaye PV System - As of October 12, 1980, the PV system in Tangaye, Upper Volta, had been operational 96% of the time (i.e., 567 out of 591 days). Because the burr mill, installed initially exhibited excessive wear, it was replaced with a commercial hammer mill in August of 1979. As a result of the down-time attributed to the burr mill mechanical problems, the mill has been operational only 89% of the time.

A summary of the data for water pumping is given in Figure 2. 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. During a recent visit to Tangaye in December 1980, LeRC personnel were told by an elder that the villagers no longer get sick from drinking the water from the well (since the well was covered following installation of the pump).

The average weekly output and hours of operation of the grain mill are shown in Figures 3 and 4, respectively. Because of the previously mentioned problems with the burr mill, data from March to August of 1979 were erratic and not included in the figures. A cyclic trend can be seen, however, in that usage tends to increase in October-November, during and after harvest, and drops off in July-August, as the stored grain from the previous season is depleted. The PV modules, which are of the same type installed at Schuchuli, also exhibited the premature failures noted earlier, in this case beginning in mid to late 1980. Approximately 30% of the modules had failed by the end of 1980, requiring an occasional curtailment of grain grinding. Replacement modules, sent to Upper Volta to replace the defective modules, were installed by local personnel with the assistance of AID personnel, bringing the system back to its original design condition. In spite of these problems, as of October 12, 1980, a total of 36,138 kilograms of grain had been ground in about 1000 grinding hours. Demand for ground grain is high and the mill is even patronized by people from other villages since the hammer mill used at Tangaye does not require dehulling of the grain prior to grinding.

Because of the success of the project and the high demand for ground grain, the villagers have requested through AID/Upper Volta that the capacity of the mill be increased. With the approval of AID/Washington, plans were initiated to refurbish and upgrade the system,

using PV modules of a different design, provided from the DOE program, to replace the existing modules. The refurbishment will be implemented in the Spring of 1981, increasing the system peak power from 1.8 to 3.6 kW(peak) and replacing the existing hammer mill with a more efficient model. The system will be monitored and maintained locally by the L'Hydrauliaire et de L'Equipment Rural, an agency of the Government of Upper Volta.

A socio-economic impact study relative to the Tangaye Project was conducted in the summer of 1980 by Dr. Allen F. Roberts of the University of Michigan.

2.3 Reliability

Twenty experimental PV systems have been installed by LeRC in the U.S. and overseas since 1976. Operational experience to date, representing an average of three years operating time, indicates the following concerning reliability.

Of a total of 630 modules installed, approximately 330 modules (consisting of units from three different U.S. manufacturers) evidenced less than 1% failures. The remaining 300 modules (consisting of one manufacturer's units of a single model type) exhibited from 20 to 30% failures within the first 18 months of operation. Failure of these latter modules at Schuchuli and Tangaye, as noted earlier, resulted from thermal stress induced fatigue cracking of the cell electrical interconnects, apparently due to an inappropriate choice of module substrate material. It may be noted that for the two PV systems in question, there was no abrupt inferruption of power. The systems continued to operate as module failures accumulated over an 18-month period, although with a progressively diminished overall energy output. As noted earlier, full system operational output was restored by replacement of failed modules.

For some systems, minor, readily remedied component malfunctions or design problems (e.g., voltage regulator, refrigerator compressor motor) were experienced, while other systems, such as the fire lookout towers, have operated for over four years with no problems whatsoever.

Power system reliability is strongly dependent on system design and proper selection and assembly of the components, i.e., modules, batteries, controls, regulators, structure and wiring. In general, operating experience from the variety of geographically dispersed applications indicated excellent system reliability. Outage rates for PV systems are generally lower than for U.S. central station electric utility power and considerably lower than for electric utility power in many developing countries.

3. FUTURE PROJECTS

As part of LeRC's management responsibility for DOE for all international PV applications, exclusive of the so-called "bilateral agreement" projects, additional PV systems will be installed overseas. For example, "community service" PV packages will be installed in remote villages in Gabon as part of a cooperative, cost-shared demonstration project between the Government of Gabon and the U.S. DOE. The goal of this project is to demonstrate the value of PV power systems in assisting development and improving the quality of life in rural areas of Gabon. Selected as the test sites are four central villages of 1000-1500 population located in the Bougandji, Nyoli, Donguila, and Bolossoville provinces. Energy for four public service applications will be supplied to each village as follows: 1) health - lighting, and ventilation, and medical refrigerator for the dispensary; 2) education - lighting and audio-visual teaching equipment for the school; 3) water supply - water pump, storage and distribution system; and 4) area lighting - outdoor pole light. Standard power packages and loads will be provided to all the villages for each public service application. Operation is projected for late 1982.

Under another cooperative, cost-shared project, in this case between the Government of Tunisia and the U.S. AID, PV, wind and solar heating units will be installed in the village of Hammam Biadha. The goal of this project is to demonstrate the value of alternative energy resources and technologies in assisting the development and improving the quality of life in Tunisia. The village of Hammam Biadha (population 120) and the surrounding farm area (600 hectares) are situated 130 km southwest of Tunis. The PV portion of the project will consist of the following: 1) a 10 to 20 kW, 220 volt, 50 Hz system to serve the domestic, public and commercial sectors of the village; 2) a 1 kWp system for a remote farm; and 3) two 600 Wp systems to power drip irrigation for a greenhouse and an orchard. Operation is scheduled for August of 1982.

As part of an activity involving both DOE and AID, PV-powered refrigerators for cold-chain preservation of vaccines will be field tested at 18 sites around the world, eight for DOE in conjunction with the Center for Disease Control, and 10 for AID. This project is of particular interest because of the pressing need for a reliable refrigerator/freezer for storage and transportation of vaccines (i.e., the cold chain) for rural areas of developing countries. In many such areas, conventional electricity is either unavailable or unreliable. Power outages and varying voltage occur often, leading to shortened life and/or damage to compressors (with the resultant deterioration and loss of the vaccine activity). For areas without electricity,

kerosene-fueled, absorption-type refrigerators are typically used. However, such units cannot meet World Health Organization (WHO) requirements for vaccine preservation and exhibit a number of operational problems as well (e.g., high maintenance, fuel cost, availability and quality). In response, NASA-LeRC, on behalf of the DOE, has entered into a joint cost-shared project with the Center for Disease Control (CDC) to develop PV-powered medical refrigerators which meet the WHO requirements. Once these units have passed the appropriate qualification and acceptance tests, additional units will be purchased and deployed for both CDC and AID field tests. Deployment of the first prototype test units is scheduled for late 1981.

Under the AID PV Development and Support Project, PV power systems will be installed at rural health facilities in Ecuador, Guyana, Kenya (two systems), and Zimbabwe in 1982. These sites, considered typical of other similar facilities in developing countries, stress preventative health care and are staffed by paramedical health officers, interns and/or nurses. The provision of relatively modest amounts of electricity to such facilities is expected to result in a significant improvement in health delivery effectiveness. Characteristic uses of electricity include lighting, refrigeration, sterilizers and 2-way radios.

4. ECONOMIC CONSIDERATIONS

Total PV system capital cost generally includes the following component, material and labor costs: solar cell modules, array structure, site preparation, electrical wiring and interconnects, controls, storage battery, enclosures, design engineering, and assembly labor. For purposes of comparison with an alternative power source, such as diesel/electric or extension of utility lines, levelized annual costs and energy costs are calculated for each system. The resultant PV and diesel/electric energy cost comparisons are given in Figure 5. The following assumptions were employed for all systems: 20-year life and 15% discount rate; for diesel/electric - 4 kVA unit, \$3.00/gal. fuel cost (delivered) in 1980\$; 7% per year fuel escalation rate, O&M costs as specified by diesel manufacturer; for PV - annual solar insolation typical of areas between 30° N and 30° S latitude (resulting in 1 Wp producing 1.6 kWh (electric) per year), and levelized annual O&M costs = 15% of levelized annual capital costs.

The results indicate that for applications having an annual electrical demand of 6,000 kWh or less, the energy cost for a PV system is less than for a small diesel/electric system. Points of reference for annual electric demand are the Schuchuli Village System (6255 kWh/yr) and the Tangaye Village System (about 3,000 kWh/yr).

A similar comparative analysis involving the extension of utility lines indicates that PV systems are competitive at today's prices with utility line extensions of 16 km (10 miles) or more, again for electrical energy consumption of about 6000 kWh/yr or less. This "break-even" level of energy consumption is projected to extend to 20,000 kWh/yr or more by 1986.

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. Furthermore, over the next several years it may be anticipated that PV system costs will continue to drop steadily. Thus, within a decade, it is likely that PV could become the least expensive and most reliable source for many decentralized electric power applications in the developing world.

5. CONCLUDING REMARKS

Operating experience to date with PV systems and products has confirmed their value in serving a variety of basic needs in rural areas of both the U.S. and developing countries. In the near future, PV holds the promise of significantly contributing to the development process which seeks to improve the quality of life and increase economic opportunity in rural areas of the Third World. If all goes as planned, by the turn of the century, PV power systems will provide a renewable energy resource which will markedly lessen dependence on imported fuels.

6. REFERENCES

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TABLE 1

NASA LEWIS RESEARCH CENTER PHOTOVOLTAIC APPLICATION SUMMARY

<u>APPLIANCE ORIENTED POWER SYSTEMS</u>				
<u>Application Category Sponsor and Use</u>	<u>User and Date Operational</u>	<u>Location</u>	<u>Power Level, W_p</u>	<u>No. PV Modules</u>
Refrigeration (DOE) Food Preservation	USNPS June 1976	Royale Isle, MI	220	24
Refrigeration (DOE) Medical	Village Residents July 1976	Sil Nakya, AZ Papago Tribe	330	30
Instrument (DOE) Weather Data	NOAA Apr.-Sept. 1977	1) New Mexico; 2) New York; 3) Hawaii; 4) Alaska; 5) Maine; 6) Florida	75-150	64
Highway (DOE) Dust Storm Warning Sign	DOT-AZ April 1977	Casa Grande, AZ	116	20
Instrument (DOE) Insect Survey Trap	USDA May 1977	College Station, TX	23 & 163	64
Refrigeration (DOE) Water Cooler	Interagency Visitor Center October 1977	Lone Pine, CA	446	48
Instrument (DOE) Air Pollution Monitor	NJ-DEP November 1979	Liberty State Park, NJ	360	20
Instrument (DOE) Seismic Monitors	USGS January 1980	Kilauea Volcano, HI	36	4
<u>GENERAL POWER SYSTEMS</u>				
Fire Lookout (DOE) 2-way radio, refrig., lighting, potable water	USFS October 1976	1) Pilot Peak, CA 2) Antelope Peak, CA	294	64
Village Power (DOE) Water, lights, refrig., washing and sewing machines	Village Residents December 1978	Schuchuli, AZ Papago Tribe	3500	192
Village Power (AID) Potable water, grain milling	Village Residents February 1979	Tangaye, Upper Volta	1800	100

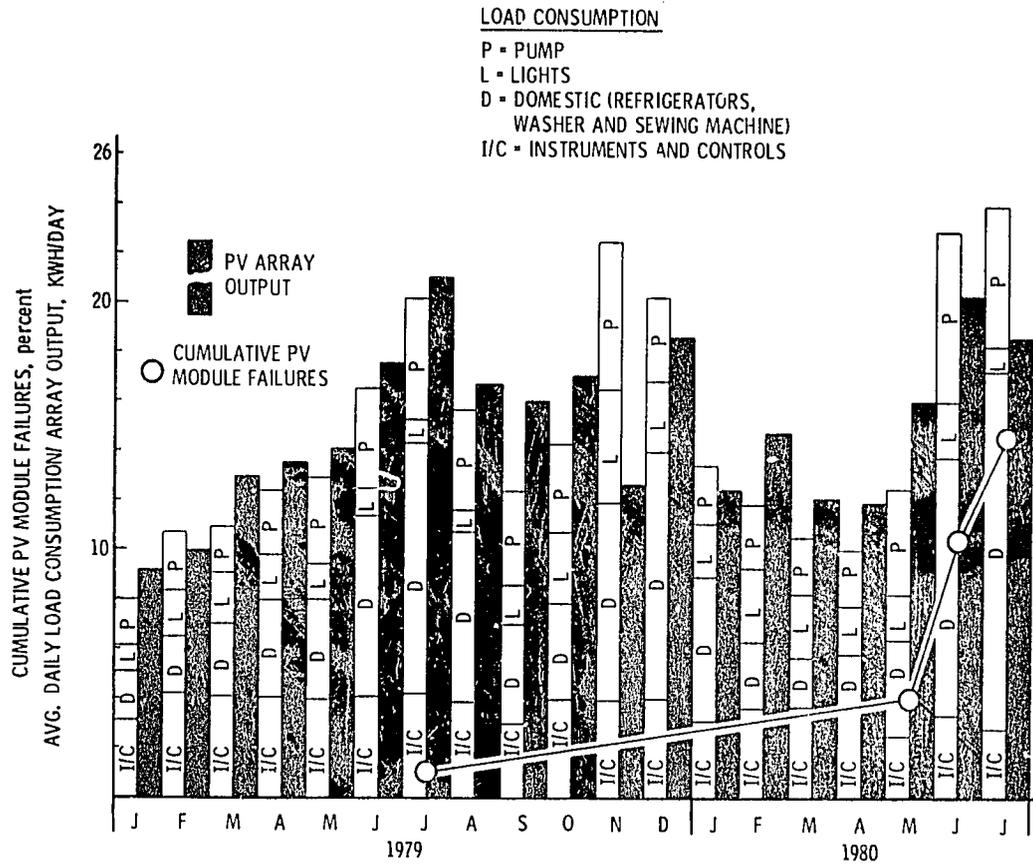


Figure 1. - Schuchuli Village PV Power System Performance Summary.

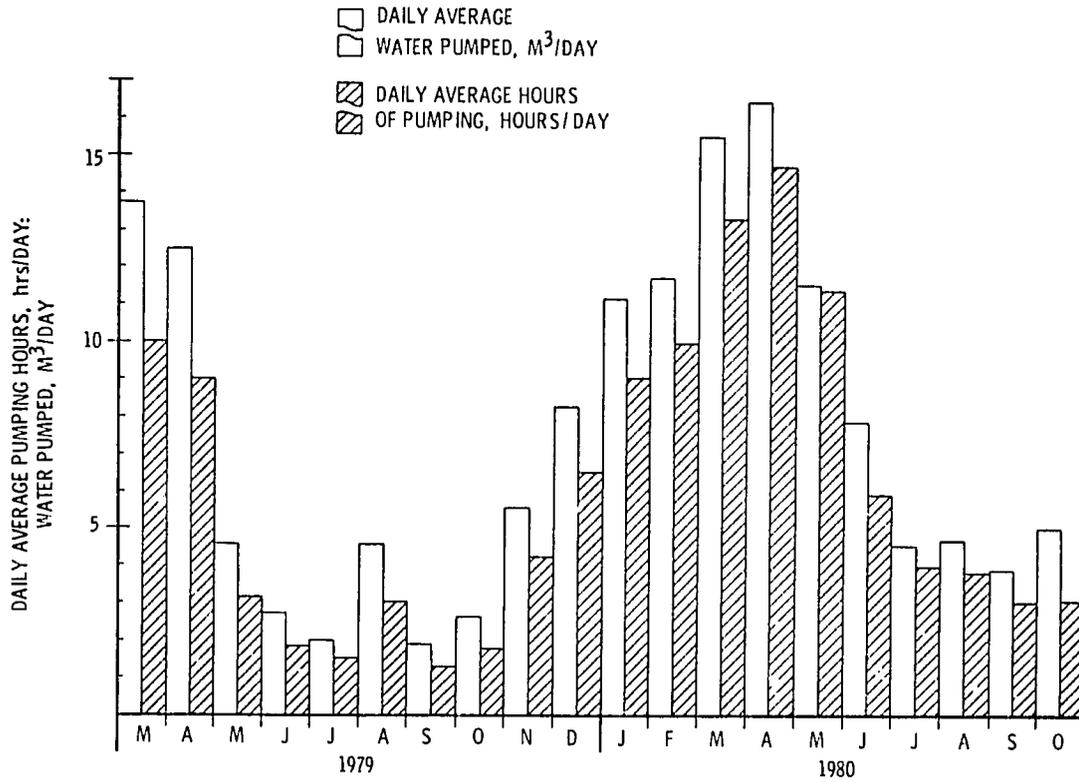


Figure 2. - Tangaye, Upper Volta Water Pump Operational Data.

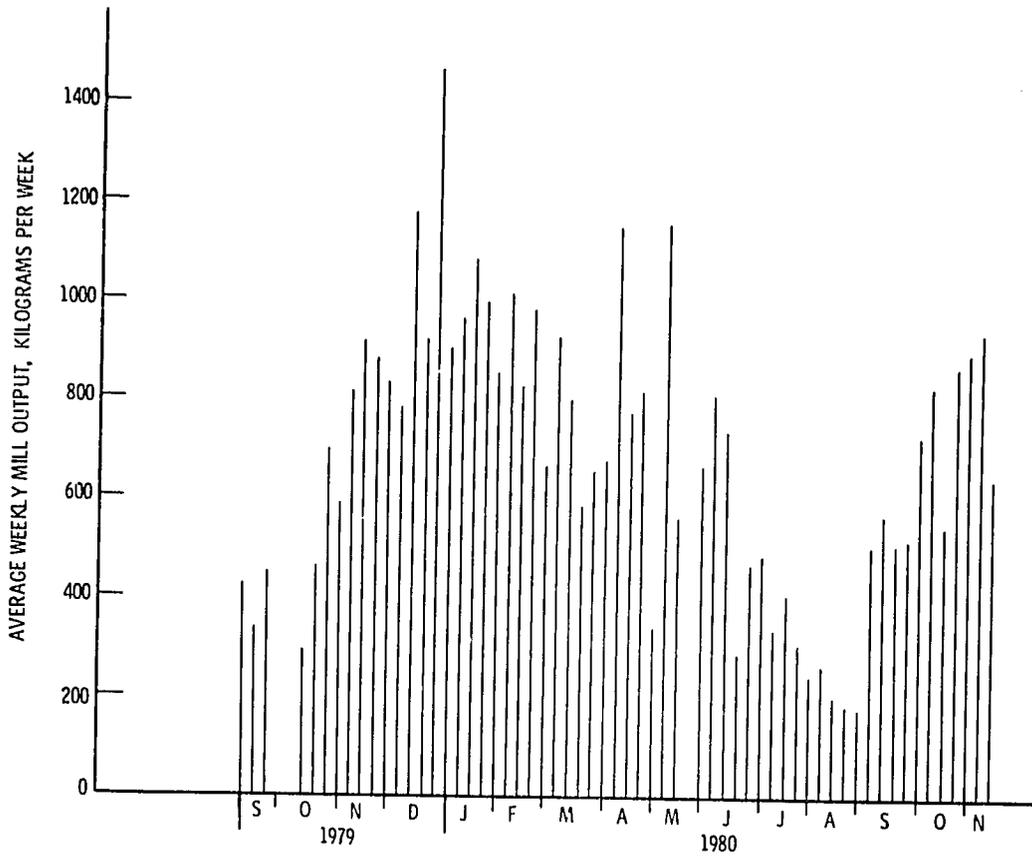


Figure 3. - Tangaye, Upper Volta Grain Mill: Average Weekly Output.

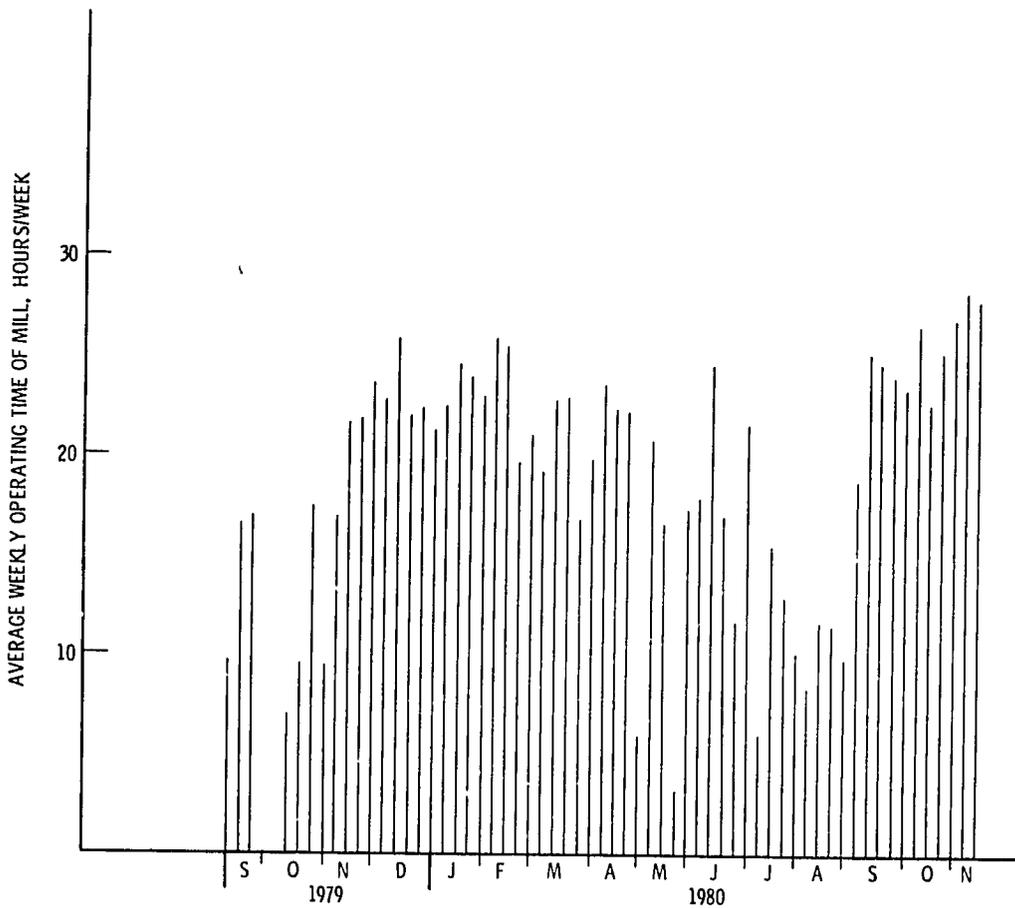
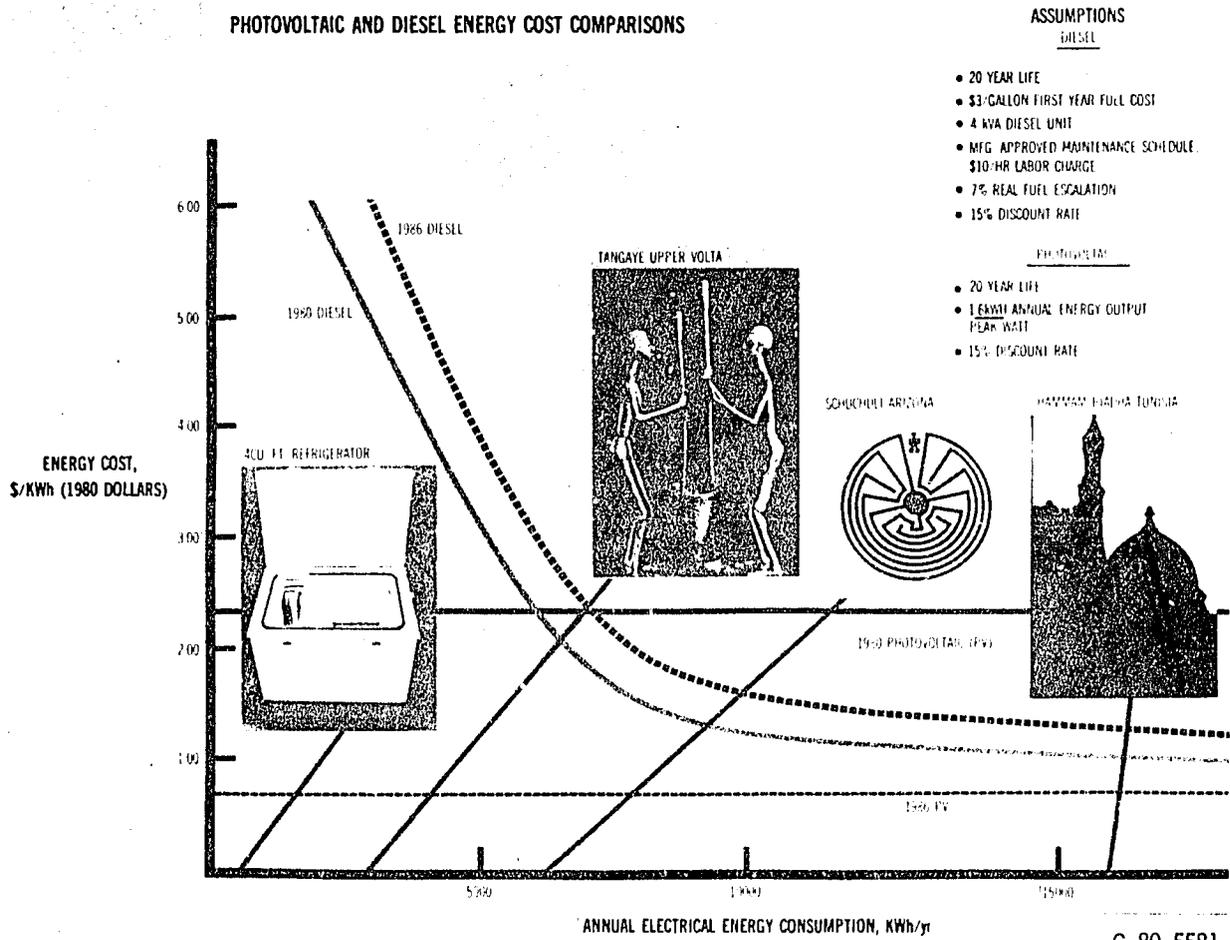


Figure 4. - Tangaye, Upper Volta Grain Mill: Average Weekly Hours of Operation.

PHOTOVOLTAIC AND DIESEL ENERGY COST COMPARISONS



C-80-5581

Figure 5. - Photovoltaic and Diesel Energy cost comparison.

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