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Operational Performance of the Photovoltaic-Powered Grain Mill and Water Pump at Tangaye, Burkina Faso (Formerly Upper Volta)

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SUMMARY

A photovoltaic (PV) system powering a grain mill and water pump was installed in the remote African village of Tangaye, Burkina Faso (formerly Upper Volta) under the sponsorship of the U.S. Agency for International Development (AID) and by the National Aeronautics and Space Administration (NASA) Lewis Research Center (LeRC) in early 1979.

The first two years of operation are covered in NASA TM-82767. The present report covers the second two years of operation from April 1981 through June 1983. During this time, the grain mill and water pump were operational 96 and 88 percent of the time respectively, and the PV system generated sufficient electricity to enable the grinding of about 111 metric tons of finely ground flour and the pumping of over 5000 cm^3 of water from the 10 m deep well The report includes a description of the current configuration of the system, a review of system performance, a discussion of the socioeconomic impact of the system on the villagers and a summary of results and conclusions covering the entire four-year period.

INTRODUCTION

A photovoltaic (PV) system powering a grain mill and water pump was installed in the remote African village of Tangaye, Burkina Faso (formerly Upper Volta) under the sponsorship of the U.S. Agency for International Development (AID) and by the National Aeronautics and Space Administration (NASA) Lewis Research Center (LeRC) in early 1979.

This report is a follow-on to reference 1 which documents the performance of the PV system during the first two years of operation (i e., from March 1979 through March 1981). During that time, the grain grinder and water pump were operational 90 and 97 percent of the time, respectively, and the PV system generated sufficient electricity to enable the grinding of about 55 metric tons of finely ground flour and the pumping of over 5500 m^3 of water from the 10 m deep well. This report summarizes system operation for the period April 1981 through June 1983. It includes a description of the current configuration of

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the system, a review of system performance, a brief discussion of the socioeconomic impact of the system on the villagers and a summary of results and conclusions covering the entire four-year period.

BACKGROUND

In 1976, the U.S. Agency for International Development (AID) initiated a program entitled "Studies of Energy Needs in the Food System." As one of four pilot studies conducted under that program, the Tangaye project had the two-fold objective of (1) determining the socioeconomic impact of relieving village women of the arduous and time-consuming task of grinding grain for human consumption and obtaining water for household use, and (2) determining the suitability of PV power systems for multiple use applications in remote areas where local technical expertise was limited. Through an interagency agreement between AID and NASA, signed in early 1978, LeRC provided a PV power system, water pump and grain mill for the village and assumed overall management responsibility for installation, training, monitoring and reporting.

Tangaye is a village of about 2900 people located 190 km east of Ouagadougou, the capital of Burkina Faso. The main occupations of its inhabitants are farming and cattle raising. The PV system was initially sized to provide 5000 L of water per day from the village well (enough to supply approximately 500 people) and 320 kg of ground grain per day (enough to serve approximately 640 people). These capacities were determined primarily by U.S. AID funding constraints. Accordingly, the complete system initially consisted of a 1.8 kW peak 120 V dc PV array, 540 A-hr of battery storage, a grain mill, and a water pump, all commercially available, a locally fabricated water storage tank, and control and instrumentation subsystems designed and assembled by LeRC.

From an overall standpoint, the project was intended by AID to determine the social and economic effects to be expected if a reliable energy supply were available to perform specific tasks.

The system was installed in January and February of 1979 and became operational on March 1, 1979. While the electrical performance of the system was satisfactory, problems were encountered almost immediately with the originally installed burr mill. Demand by the village women for flour much finer than originally anticipated caused destructive mechanical wear of the mill and severely reduced mill output. As a result, in September of 1979, the burr mill was replaced with a hammermill having considerably higher throughput (see ref. 1 for information on mill grinding characteristics). However, since the hammermill used a 3-hp motor rather than the 1-hp motor used on the burr mill, its run-time had to be limited to about one-third that of the burr mill to remain within the energy capabilities of the PV power system. Consequently, the hammermill was run for 4 to 5 hr/day, four days per week compared to the planned 8 hr/day for 6 days/week for the burr mill. As a result of the villagers' requirement for very fine flour and the limited operating time, the hammermill could only produce an average of 604 kg of flour per week.

Demand for flour milling by the village women was considerably higher than the system's capability. Generally, at the end of a milling day, there would be a considerable amount of unground grain still waiting to be processed. It would sometimes be several days before this grain was ground and many of the village women were understandably dissatisfied with this delay in service.

Water consumption, which was expected to be limited to about 5000 L/day based on the estimated well recovery rate, was often as high as 15 000 L/day in the dry season. The pump system, as installed, was easily able to handle this increased demand.

As a result of villagers' demand for greater milling capability, the Government of Burkina Faso requested that the size of the PV power system be increased. The LeRC subsequently presented a plan to AID to install a more efficient hammermill, double the size of the PV array and at the same time replace the original PV modules which were exhibiting an unusually high failure rate due to a module design defect. These changes were accomplished by NASA Lewis personnel with the assistance of the village residents in May of 1981. Surplus modules from the U.S. Department of Energy were used to replace all of the original modules and to increase the size of the PV array to 3.6 kW. This expansion, which is believed to be the first instance of a PV system being increased in size by a factor of two in a field operational setting, demonstrates the modularity characteristic of PV systems.

NASA LeRC engineers have visited Tangaye for technical purposes on the average of once a year since the system was installed in 1979. A listing of such visits is given in appendix A.

SYSTEM DESCRIPTION

The Tangaye PV power system consists of a PV array, batteries, controls and instrumentation. The PV system powers a hammermill, a water pump and lights in the mill building. In addition, lights and a refrigerator were installed in a nearby building during the system expansion in 1981. An outdoor light was later added at the building for evening adult education classes.

A detailed description of the original system and modifications made during the first two years of operation are given in reference 2. Details of modifications and expansion done during the second two years are presented in this report.

PV Array

The original array design used eight series-connected Solarex model 9200J modules in each of 12 panels to form a nominal 120 V, 1.8 kW array. The eight modules forming one string were mounted on a single panel and array structure. The replacement modules (Sensor Technology model 20-10-1452) installed in May of 1981 are approximately half the width and half the current output of the original Solarex modules. The physical design of the replacement modules was such that they could be mounted on the same support structure. Two Sensor Technology modules connected in parallel were mounted in place of one Solarex module and generated approximately the same current and voltage. Each of the original PV array panels contained eight series-connected PV modules to form one 120 V dc string. In the modified panel configuration, eight module pairs were connected in series to comprise one 120 V dc string. The power generating characteristics of the modified PV array panels are, therefore, approximately the same as that of the original panels.

Twelve additional panels were also installed in May of 1981 to increase the PV array output from 1.8 to 3.6 kW. The mechanical configuration of these panels is identical to that of the originals. The array field fence was extended to the east to accommodate the addition of four panels to each of the original three rows of panels. The resulting array consists of three rows of panels with eight panels in each row (fig. 1).

Each of the new array panels was connected electrically in parallel with one of the original panels at the array junction box at the west end of each array row. The size of the wire installed initially between the array field and the control panel was large enough to carry the larger currents without significant losses.

Battery

The battery, as originally installed, consists of 55 series-connected C&D model KCPSD-7 cells rated at 540 A-hr each. As indicated above, the additional PV panels were installed to allow the mill to operate seven days a week and to increase the milling time each day. Since milling is mainly a daytime activity, no increase in battery capacity was required.

Controls and Instrumentation

The control subsystem has three controls: system voltage regulation and battery charge control, over- and under-voltage protection, and pump and mill controls. System voltage regulation and battery charge control are accomplished by array string switching. Two separate voltage controls provide additional system reliability. The primary control consists of a series of solid-state duty cycle regulators (DCR) designed and fabricated by NASA LeRC personnel. A commercially available drum-programmer (DP) electromechanical device is used as a backup control. No modification of the control system was needed during system expansion since all of the original panel current carrying elements for single panels (solid-state relays, fuses, wires, etc.) were of sufficient capacity to carry the additional current of a second panel. The array and battery circuit breakers were changed to 40 A breakers and the array ammeter and ampere-hour meters were changed to accommodate the increased array. No other controls or instrumentation modifications were required. Ampere-hour meters were used to record the amount of ampere-hours produced by the array, and used by the mill, pump, and mill building lights. The ampere-hours used by the lights and refrigerator in the auxiliary building were not recorded, hence, the effect of this unrecorded current consumption on system performance must be estimated.

Mill

In 1979, LeRC obtained and evaluated a Jacobson model 120-B hammermill for use in grinding grain for human consumption. This mill appeared to have a higher throughput and potentially lower maintenance than the Bell hammermill installed to replace the original burr mill. The Jacobson mill was installed at the time of the system expansion (fig. 2).

Pump

The water pump is a Jenson model 11W5A positive displacement pump which pumps water from a dug well into a 6000 L storage and distribution tank. Level switches in the well and tank control pump operation. The original submersible level switches, which failed due to water leakage, were replaced in May of 1981 with externally mounted float switches.

Lights

One fixture containing two 20-W fluorescent lights is located in the mill building to provide light for occasional evening milling operations. Three similar lights are located in the rooms of a nearby building which was used for living accommodations during site visits and is now being used for health care and adult educational purposes. A 12 V dc low-pressure sodium vapor lamp powered by a 120 to 12 V dc converter is located on a concrete patio of the auxiliary building to provide outdoor lighting for evening adult education classes.

Refrigerator

A prototype medical refrigerator which had been used for evaluation tests at NASA LeRC was installed in the auxiliary building during the system refurbishment visit in May of 1981. Initially, use of the refrigerator was limited to foodstuffs and beverages for personnel visiting the village. The 120 to 12 V dc converter was used to supply the required 12 V dc input. Having access to a refrigerator, the Tangaye stationkeeper eventually set up a cold drink concession which operated successfully until the summer of 1983 when the refrigerator malfunctioned. Since the refrigerator was not an essential part of the demonstration project and since replacement parts were not readily available, no attempt has been made to repair the unit.

OPERATIONS AND DATA SYSTEM OPERATION FROM MAY 1981 THROUGH JUNE 1983

PV Power System

For the two-year period following array refurbishment and expansion in May of 1981, the PV power system was operational 100 percent of the time, this in spite of a violent storm which hit the village in early 1982. That storm caused the roof of the mill building to blow off exposing the control box to drenching rains. The storm had no apparent effect on system performance. The array was inspected during a May 1983 visit and found to be in excellent condition. There was no noticeable deterioration of the modules or structure.

Battery

During the May 1983 system inspection, one failed battery cell was found. Several other cells showed some deterioration, but were operating properly. The failed cell was replaced with one of the spare cells provided initially.

Controls

One solid-state relay used to switch array strings on and off had failed and was replaced in May 1983. The system voltage meter-relay which sends control signals to the backup drum programmer control system had burned out. It was also repaired during the May 1983 visit.

Instrumentation

The DAT-3 automatic data logging system stopped operating in December of 1981. It was determined that sufficient data was being gathered manually and that it would not be practical to attempt to return the data logger to operation. The system was therefore disconnected and removed. Its removal had no effect on system operation.

Mill

The mill was 100 percent operational from the time of installation of the new mill in May of 1981 until approximately May 1 of 1983 when the mill motor brushes wore out after nearly two years of operation. Replacement brushes could not be found in the spares cabinet although several extra sets had been supplied when the larger mill motor was installed in September of 1979. A new supply of spare brushes was sent to AID/Ouagadougou in June of 1983.

Several sets of mill screens and hammers which were originally provided with the mill in May of 1981 were completely worn out by mid-1983. Anticipating this situation, replacements were ordered and shipped in October of 1982. However, since the shipment had not been received as of early 1983, a second set of screens and hammers were shipped in May of 1983. Both shipments arrived during the first week of July 1983.

With the arrival of the motor brushes and the mill hammers and screens, the mill again became fully operational. The mill was examined during the May 1983 visit and was found to be in excellent condition. No other parts showed signs of wear.

Pump

The pump was operational 88 percent of the time between April 1981 and June of 1983. On October 5, 1982, the pump push-rod broke just above the pump piston. On October 19, personnel from the Office of Hydraulique et Equipment Rural (HER) removed the pump, repaired the push-rod and placed the pump back in operation. On March 8, 1983, the push-rod again broke in another location. Because of this failure, the pump was out of service until the LeRC visit in May when the pump was removed and several sections of the rod were replaced. It was noted that most of the sections of the push-rod were showing bending near the rod coupling nuts. The rods were straightened and the pump reinstalled.

A pump push-rod modification was designed by LeRC personnel. This modification will consist of replacing the 7/16 in push-rod with standard 1/2 in galvanized pipe using specially fabricated stainless steel adaptors to mate the pipe to the piston and to the pump gear box polished rod. The adaptors were fabricated at LeRC and taken to Burkina Faso along with other spare parts in February 1984. The modification can be accomplished by local personnel using locally procured pipe. This change should eliminate the bending and breaking of the push-rod.

During the dry season of the spring of 1983, it was reported that the well water level had dropped below the pump intake and remained below this level for the rest of the dry season. This was an especially severe dry season and all of the other wells in the village had dried up. Most of the villagers were coming to the mill station well to draw water and this had lowered the water level to the point where the pump would not have been able to pump water even if it had been operational.

When the pump push-rod was being repaired, the pump piston and stuffing box cup-leathers, which had operated for four years and were nearly worn out, were replaced.

Refrigerator

The refrigerator system was operational from its installation on June 3, 1981 until approximately the end of April of 1983. In our inspection in May of 1983, it was noted that the buffer battery installed between the 120 to 12 V dc converter and the refrigerator had failed completely, and that the refrigerator had stopped working about one month previously. Data on the operation of the refrigerator system was obtained from the time of installation until February 16, 1982. The data consisted of the energy consumed by the refrigerator itself and the energy consumed by the 120 to 12 V dc converter which supplied the electricity for the refrigerator and for the low-pressure sodium vapor lamp used for the evening education classes. This lamp was installed in October of 1981. The data indicates that the refrigerator consumed a relatively constant 0.95 kW-hr/day during the period for which there is data, whereas the consumption of the 120 to 12 V dc converter increased from approximately 1 to 1.5 kW-hr/day during the early part of the period to 3.5 to 4.5 kW-hr/day toward the end of the period. Part of the increase in consumption can be attributed to the low-pressure sodium vapor lamp, for which we have no consumption data The remainder is likely due to a progressive deterioration of the refrigerator battery. The converter may have provided considerable excess power in an attempt to charge the failing battery.

System Performance Summary - April 1981 Through April 1983

A summary of the system energy production and consumption during this reporting period is presented in table I The table also includes predicted values based on the assumptions and criteria used for the original design.

The potential energy production of the main array, the actual energy produced by the main array, and the energy consumed by the pump, mill and refrigerator can be seen in figure 3. The potential energy production was derived from the 12 V instrument array output which has been instrumented to record total potential array output.

The upper curve on the graph shows the potential output from the main array. Note from table I that this potential output as calculated from the measured instrument array output is only 75 percent of the predicted output (ref. 1). These predicted string outputs used insolation data obtained from reference 3. We do not have actual insolation data for this reporting period which might help explain the discrepancy. The curve shows a relatively small seasonal variation which is in agreement with the data used for system design.

The second curve presents the measured main array energy output. Data is missing for July and August of 1981 because of a problem with the main array ampere-hour meter. Except for the period between April and June of 1982, the actual energy output was less than the potential output. Insufficient data exists to explain the discrepancy between the measured output and the indicated potential output during that short period. Actual energy output will, in general, be less than potential output primarily because of the action of the control system (i.e., the control system disconnects array series strings as the battery becomes fully charged).

The third curve shows the combined energy consumed by the pump and mill (including the mill building light). It also includes the energy consumed by the refrigerator and low-pressure sodium vapor light during that period of time for which data is available. The difference between the energy consumed and array production can be accounted for by the energy consumed by the refrigerator and lights in the auxiliary building, by battery inefficiency, and by control subsystem energy requirements. The available refrigerator data accounts for a total of 665 kW-hr consumed during the time data was obtained. Using the average rate of consumption during this period, we estimate that approximately 2000 kW-hr were consumed by the refrigerator system and lights in the auxiliary building between June of 1981 and April of 1983.

The fourth curve presents the energy consumed by the mill and mill building light. This curve shows that the milling operation increased during the first several months following the installation of the new mill, then became relatively constant with no significant fluctuations that can be attributed to seasonal variations.

The fifth curve presents the energy consumed by the water pump. This curve shows the seasonal variation in pump use due to the rainy and dry seasons.

The sixth curve shows the energy consumed by the refrigerator and the low-pressure sodium vapor lamp from June of 1981 through February 16, 1983.

The flour production of the mill is shown in figure 4. After the beginning of October 1982, the station operators discontinued reporting mill output. Again, no significant seasonal variation is noted, with production being a relatively constant average of 984 kg/week. At various times during the reporting period, the grain ground during the week was not reported on the data sheets. Therefore, the amount of grain ground during these periods was estimated using mill operating hours and the average grinding rate for those periods when data was being reported. Combining actual and estimated production indicates that a total of 111 094 kg of grain were ground during this reporting period.

From table I, several significant differences between actual and predicted mill operation can be seen. The actual mill run-time is about 14 percent lower than that predicted. The data indicate that excess energy was available, hence, system use was governed by consumer demand rather than system energy capability as was the case before the expansion. Mill efficiency, as indicated by the mill grinding rates (kilograms per hour and kilograms per kilowatt-hour), is considerably less than predicted. There are three reasons for this loss of efficiency. First, the demand for finer flour than originally anticipated requires the use of finer screens in the mill, which reduces mill output considerably. Second, efficient mill operation requires that the mill speed be kept within a fairly narrow speed range. The mill is designed to operate at 3600 rpm and has an upper limit of 4000 rpm. Tests conducted at LeRC in 1980 indicate that mill efficiency drops with decreasing rpm, as shown in figure 5. The 4000 rpm upper limit means that mill and motor pulley sizes must be chosen such that an unloaded mill will not overspeed at the maximum system voltage. Since the mill could operate at system voltages close to 135 V, the pulleys were chosen to prevent overspeeding at this voltage. At normal system voltages of 110 to 115 V, the speed of a loaded mill will drop and the efficiency will be reduced below the optimum. The third reason for the loss of mill efficiency is that milling at the village is done in small batches, often 10 to 20 kg per batch This means that a considerable amount of mill operating time is spent waiting for the mill to clear itself from one batch before the next batch is started. This also results in reduced efficiency.

The volume of water pumped is shown in figure 6. A seasonal variation in water use from the station well is evident here. This is not attributed to actual variation in water use, but rather to the fact that during the rainy season, women would tend to use more convenient water sources nearer their homes. The slight dip in output for October of 1982 and the major drop in March of 1983 were due to the push-rod failures and reduction in well water level noted above.

A summary of energy use and product supplied for the entire four-year project period is given in table II.

SOCIOECONOMIC EFFECTS

The Tangaye demonstration was predicated on the assumption that provision of services such as grain grinding and water pumping would lighten a woman's workday. However, as it turned out, it proved difficult to measure with any precision the impact of the project on village women. Note: the PV-power facility will hereinafter be referred to as the "station."

Water Pump

Because of deficiencies in the methods and questionnaires used to obtain data for the baseline study and for the mid-project studies, it is not possible to draw neat comparisons of time spent drawing water before and after implementation of the station, and to quantify use of water in the compound. However, it is possible to outline some concluding impressions of the overall social impact of the solar-powered water facility.

We know there is more to "water-fetching" than fetching water. If time is saved in not having to go so far or to wait so long beside a hand-dug well for the slowly-dripping water to fill one's vessel (in itself a not-altogether-unpleasant task, for social reasons), it may be that more time is spent socializing, bathing, and doing the like, to use up that time saved, perhaps quite unconsciously. A water source is an important social focal point.

We know who uses station water and who does not and how this is a function of proximity. The station's primary water users are those living in closest proximity to the facility, while secondary ones live just beyond. Several hamlets are as close as, or closer than some of the secondary users, but have all-season wells much nearer which they use instead. Individuals from hamlets farthest from the station rarely, if ever, use its water.

We have some idea of how much water is used per person and how it is used. For example, a typical person from a nearby hamlet uses about 10 L of water per day from the well during the key dry season months and about 9 L/day overall. We know with what frequency and pleasure people come to bathe and wash clothes at the facility.

People from nearby hamlets enjoy bathing at the station. Water carried long distances for bathing is a labor luxury few can permit themselves frequently. People depending upon other wells do not use as large a proportion of water drawn there for bathing at the site; those using station water tend to bathe more frequently, and many of those not using the water for household tasks still come to the station to bathe.

Washing clothes is another important at-station task in which it is easier to bring the activity to the water source than it is to carry the water to the activity. For cleanliness and as a social activity, people using station water wash their clothes more often than do those depending upon other wells; and people not using station water for household purposes may come there nonetheless to do their laundry.

Even households too far from the station to use its water in everyday chores still profit by bathing, washing their clothes or watering their small animals there.

House construction is facilitated directly for individuals using station water to make bricks and mortar, and indirectly, for those using wells no longer exploited by women for household needs. Quantities of water used for house construction show a seasonal curve. Given the considerable quantities required and the necessity to make bricks as close as possible to the construction site, men will opt for whatever water is nearest. People living in more distant hamlets complain that those around the station are spoiled by the ease with which they can procure water for building. It is likely that the hamlets around the station will receive more house construction then those where obtaining water during the dry-season building months never ceases to present problems.

Whereas house construction shows a seasonal curve, beermaking does not. The beverage is always popular! The process requires large quantities of water, sometimes several hundred liters over the course of eight or nine days' brewing. This has been a significant use of station water.

The only complaint voiced about the station water facility is from those living too far away to profit from it. Those using it constantly are very pleased to have it at hand.

Mill

While the "productive" tasks a woman might undertake during time freed by use of station facilities proved difficult to measure, by the time of the last social impact field study (ref. 4) it was evident that some women were using the mill with significant frequency. The 82 women of two studied hamlets used the mill an average of about three times a month. For most, the PV-powered mill does not provide for all flour preparation, but for many, it is a handy aid when guests arrive, a feast is to be offered, or a woman is too ill to stone-grind flour. Most women interviewed said they do or would use time freed to engage in increased "penny capitalism" in local markets.

Women questioned generally feel that they are not using the mill as much this year as last year. This feeling may be due to the recent world-wide economic conditions which have affected Tangaye as well as the rest of the world, and to the poor crops of the last growing season; however, the records indicate that there has been some significant increase in mill use over the last two years. The millers report that people are now coming from 30 or 40 km away to use the mill at Tangaye. This is especially true for grinding maize and white sorghum, which cannot be ground by other area mills without an intermediate step of soaking and decorticating, tedious work which people would rather avoid.

The great majority of Tangaye women use the mill infrequently; however, those unable to avail themselves of the service bemoan the poverty that prevents them from doing so. For most women, the presence of the mill has done little to free time for increased attention to other all-important chores.

Using the mill eliminates most of the labor of flour preparation, although the grain still must be winnowed and sorted. Flour ground at the mill is most often of sufficient quantity to last two days or slightly longer. Women do not use their stock of it all at once, but intersperse meals prepared with mill-ground flour with rice or bean dishes, or with those made with stone-ground flour.

Proximity to the mill is certainly a large factor in its frequency of use although several other factors have been observed. There seems to be a correlation between large extended families and relatively greater mill use, and one between polygamy and higher mill use as well. There is also a relationship between the size of a woman's fields and her use of the mill.

A sketch of the hypothetical woman who uses the mill frequently shows that she is of a polygamous marriage, lives in one of the hamlets closest to station, and has relatively large fields of her own -- the greater their area, the greater her participation.

Women who use the mill more than one would expect, given their relatively small fields are the great beer brewers of the hamlet. Mill-ground flour is not used in the brewing itself, since sprouted sorghum is damp, and must be stone-ground before setting the mash to ferment; but use of the mill does permit women to direct their attention more whole-heartedly to the time consuming task of beermaking; and brewers have the wherewithal to consider the ensuing cost as a part of their overhead.

The reasons given for using the mill include being too ill to prepare flour, and the requirement for large amounts of flour for funeral feasts or for work parties in a man's or woman's fields.

Judging the amount of time saved is a matter complicated by many different social factors. Best indications that women do perceive the mill as useful was the long lines awaiting service on milling days (in 1980 when milling service was restricted by limited array output). Also, mills (and solar-powered pumps) have been repeatedly requested for other hamlets of Tangaye.

General

Residents draw pleasure and esteem from the notoriety of the station. The chief of Tangaye lists this as one of the accomplishments of his reign for which he will be remembered through association.

Most time freed is done so in the dry season, when freed time can be used mostly for crafts, celebrations, visits to and from kinsmen and friends, trips to the big city, and "just sitting around."

Villagers need to know what new uses they may make of the time that has been freed as a result of the pump and mill to enable them to maximize their productivity and stimulate further use of the mill. This highlights the lack of integration of rural development with regard to the Tangaye project.

Station Management

A cooperative was formed to oversee station organization and activity, working in close conjunction with the village chief, AID project managers and, one would presume, with HER and other GOUV staff upon their assumption of direct responsibility for the demonstration. Most cooperatives in the area have never gotten started, have had disappointing results or have failed altogether. This cooperative, however, was formed from male and female representatives (the only one in this region to include both men and women) from the other 14 village cooperatives and has proven to be very successful. The cooperative's responsibilities include setting operating hours and prices, hiring and overseeing the millers, and resolution of problems which occur during day-to-day activities.

The cooperative has set the prices for milling, first below, now at parity with area mills. Mill profits were first kept in Tangaye despite frequent requests from the AID project manager that cooperative members establish a bank account; people were afraid of going to a bank in an urban center where they might be humiliated as lacking proper knowledge of banking rules and practice and scrutinized by possibly hostile government authorities. They were equally wary of entrusting such important tasks and sums to any particular villager. When the treasurer's house burned, funds were rescued and a bank account established without further difficulty.

There are four individuals or groups who are party to most decisions: the cooperative president and his advisors; the village chief; the station manager (originally intended primarily to be a data collector for U.S. AID and to assist in mill operation); and the millers. The first station manager was chosen by the AID project manager. A young man from a village 20 km from Tangaye, the first manager established excellent rapport with the village chief and took a predominant role in station management. He helped organize a number of grassroots development projects, including a subscription fund from villagers to finance sports and other activities and a community reforestation project. When AID offered the manager other employment, a replacement was selected by the outgoing manager with ratification by the chief and cooperative members. The new manager is a local young entrepreneur with kinship ties to many people in Tangaye including the chief, and feels "a son of the village cannot speak any which way" in asserting his will when senior kin may wish otherwise. Others now take a larger share of decision-making regarding station affairs. A new "mill president" (a resident retired sergeant major) and the millers now have a greater influence in station activities.

Spin-Off Activities

The PV-powered lighting introduced in 1981 to the auxiliary building (formerly the project anthropologist's residence) has permitted a number of other activities to be organized there. Local missionaries run an infant-care clinic at this house; the station manager and several others offer adult literacy classes; agricultural support products (e.g., fertilizer) are stored there; and distinguished visitors have used the building as a rest stop or guest house. In part because of the station and its locus of activities, Catholic and Protestant missionaries have increased their attention to the village, using the station as a center. A new store was built by an entrepreneur, facing the station. An attempt was made in 1982 by several villagers to secure a Partners for Progress small-business loan for further commercial development; the outcome is not known.

In-Country U.S. Support

Although great enthusiasm has been shown by members of a variety of GOUV institutions (e.g., University, L'Hydraulique et de L'Equipement Rural (HER), Institute for New Energy Research (IREN)) for photovoltaic technology generally, and the Tangaye demonstration more specifically, the personal interest in the project shown by the original AID manager, Larry Dominessy, made success possible. Were there many PV or other renewable-energy projects operational in Burkina Faso with an attendant infrastructure of support and service personnel and equipment, then Dominessy's attention would not have been of such critical importance. HER and other GOUV staff were offered this demonstration as a learning experience, although personnel changes within such agencies and the difficulty of getting definite personnel commitments to the project meant that this aspect of the project was not maximized.

The PV array, battery and loads are designed to operate with no or minimal intervention; as a first demonstration of the stand-alone capacity of a PV-powered system, AID and NASA LeRC staff were uncertain as to how to best facilitate local management of this system. Tangaye residents in turn live in rural isolation and are not familiar with modes and means of ordering parts for faucets and the like (although much initiative and innovation by station managers and millers has been shown). If, as opposed to the one-of-a-kind nature of Tangaye, a series of projects is programmed at once (as in Mali through the AID-funded Solar Energy Lab), then local cadres can institute programs of instruction and oversight to maximize efficiency of use while developing local participation.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations relative to the four-year AID/Burkina Faso PV demonstration project are provided below.

System Design

PV array. - The failures of the originally installed PV modules (i.e., thermal stress induced fatigue cracking of the cell electrical interconnects), during the second year of the project indicated a deficiency in the module qualification testing procedures used initially (viz, the thermal cycle test). As a result, the qualification testing program, implemented by the Jet Propulsion Laboratory as part of the DOE National PV Program, was subsequently modified to facilitate detection of similar module design defects. The replacement modules have exhibited no failures and were still operating satisfactorily as of February 1984. The array structure has proved to be sound and appears to be especially suitable for remote locations where the ground mounting conditions are difficult to assess.

Battery. - Energy storage remains one of the major problems with PV systems which must operate at night or during periods of low insolation. At present, lead-acid batteries are commonly used; however, the batteries are fairly expensive and shipping can be difficult and costly as well. Accordingly, each system should be examined carefully to minimize, if not completely eliminate, expensive battery storage. One method of doing this is through the use of product storage rather than energy storage. Such an approach is appropriate for water pumping because such a system can operate unattended; however, it would be much more difficult to completely eliminate battery storage with a grain grinding system because a mill requires human intervention, and to schedule personnel operating hours around the vagaries of the solar insolation would cause major operating problems. Furthermore, the use of a hammermill requires relatively constant operating power to maintain mill speed (rpm). A batteryless system would cause several problems; first, mill speed and resulting efficiency would be severely reduced during periods of low insolation; secondly, in order to limit mill speed to safe limits, considerable energy would go unused during periods of high insolation; thirdly, a batteryless system would require a much more complicated and difficult to maintain control system.

Accordingly, with regard to a mill system, it is recommended that sufficient battery storage be provided to maintain mill speed, provide for load surges and permit operation of up to four or five hours under conditions of low insolation.

During the rainy season of 1980, the Tangaye battery racks began to sink into the dirt floor of the battery room and started to tip over. Planks were used to temporarily support the battery cells. During the system expansion, the floor of the room was concreted to provide a stable battery base. Hence, for future battery system installations at remote sites, it is recommended that a concrete floor or pad be provided.

It can be expected that, in due time, the Tangaye battery will deteriorate and need replacement. Since the type of large stationary-type battery cells used are not readily available in Burkina Faso, it is recommended that when the Tangaye battery has to be replaced, that it be replaced with a string of good quality automotive-type batteries. Such batteries, however, would not last as long as the stationary-type battery and would not have comparable deep-cycle capability.

System Controls and Instrumentation. - At the time the system was designed, few if any battery charge control subsystems were commercially available for multi-kilowatt PV systems. Based on a design decision to use electromechanical controls instead of electronic controls, a control system based on an electromechanical drum programmer was selected for the Tangaye system. Coincident with the system design, an electronic duty cycle regulator (DCR) control subsystem was being developed at LeRC. Subsequently, it was decided to install both control subsystems in the Tangaye system to obtain comparative operating data and to field test the DCR subsystem. Following a DCR failure during system checkout due to a faulty printed circuit-board layout, the DCR's were redesigned and reinstalled in September 1979. They have been used as the primary system controller since then and have operated without any additional failures. The drum programmer control system, on the other hand, has failed several times, generally due to a failure in the meter relay voltmeter providing operating signals to the programmer. In addition, being a mechanical device, the drum programmer is susceptible to mechanical wear. During checkout of the system following the expansion, it was discovered that the drum programmer did not respond rapidly enough to control the system voltage following mill shutdown resulting in tripping of the system high-voltage limit devices. This response time problem was largely the result of doubling array size but not changing battery capacity. Nevertheless, it is recommended that future systems use the DCR-type control subsystem.

Several failures have occurred in the solid state relays used to switch the main array strings for battery charging control. These failures generally do not adversely affect system operation and the relays are easily replaced. Therefore, it is recommended that such relays be used in future systems.

The electronic clock circuits originally used to limit mill operating time did not prove satisfactory due to electrical interference (ref. 2). In subsequent operations without the mill clocks, it was determined that the mill operators were able to properly control the operating time by observing the system voltage and stopping operation when the voltage began to fall. This showed that, at least in the Tangaye operating situation, the clocks were not needed. The need for such clocks in any future system should be evaluated on a case-by-case basis.

It is recommended that future systems include, as a minimum, instrumentation to enable monitoring of system voltage and array and load currents. In some instances, system utilization would be enhanced by the use of battery ampere-hour instrumentation.

Mill. - Soon after the initial installation, it became clear that the original burr mill was not properly designed for the type of use it was receiving at Tangaye. Both subsequent hammermills have operated satisfactorily, although the Jacobson mill has experienced fewer problems than the Bell mill. The main problem encountered in using a hammermill with a PV system relates to mill speed control as discussed above. It is recommended that improved mechanical or electronic speed control devices be developed to enable operation of the mill within its optimum speed/efficiency range. Independent of the use of such controls, a hammermill like the Jacobson mill would be a good choice for future mill systems. Locally available mills could also be used in some instances. This would facilitate repairs since spare parts would be more readily obtained. At the time of the initial site visits to Burkina Faso, hammermills were not commercially available in Ouagadougou; however, during the system expansion visit, several types of hammermills were being offered for sale in local stores.

Pump. - The PV-powered pump at Tangaye has operated satisfactorily throughout the entire evaluation period. It has consistently pumped more water than originally anticipated due largely to a greater than anticipated well yield. For future systems it is recommended that externally mounted float switches be provided in the well and storage tank to control the pump (as was provided for the Tangaye system during the expansion), and a stiffer push-rod be used as proposed for the current system. A pump system using the same type pump operating alone would be a good candidate for a batteryless system. Such a system could include a maximum-power controller subsystem between the array and pump motor. Submersible dc turbine pumps are now also available for this type of application.

On the merits of dug versus drilled wells, it is interesting to note that of the numerous PV-powered water pumps currently operating in Burkina Faso, Mali and other countries of the Sahel, most are installed in small-bore wells. These wells are effectively closed for further use by the villagers should the pump itself not function. There are a number of "horror stories" of such PV-powered pumps being installed without proper study of seasonal water table fluctuations. These pumps have often failed during the dry season when water tables have dropped below the level of the submerged pumps. This causes the motors to burn out rendering the wells completely useless. The 2-m diameter Tangaye well, however, which was dug and cemented prior to project implementation, allows water to be drawn by hand even if the pump stops working. The disadvantage of this arrangement is that the water might not be of the same purity as it would were it taken from a relatively deep drilled well.

Refrigerator and lights. - As noted earlier, the refrigerator was provided only as a convenience for field engineers during their extended stays at Tangaye. The refrigerator served its primary purpose and, upon its failure, was removed from service. PV-powered medical refrigerator systems are being investigated separately as part of other AID and DOE projects. Reports documenting these activities will be available in the future.

The lights installed in the mill building and auxiliary building have worked well, providing light for evening milling operations, adult education classes and nighttime lighting for visitors. Similar lights are recommended for future projects.

Modular designs. - One of the most important characteristics of PV systems is system modularity, i.e., PV array size, battery capacity, and controls can easily be incremented (augmented) to meet increasing load demand. Thus, a PV system can be designed and installed in consonance with immediate energy needs and available funds. As energy demand and funds increase, additional modules, and batteries and controls can easily be added to the system. This modular concept was dramatically illustrated at Tangaye when in May of 1981 the PV array size was increased to 3.6 kWp from 1.8 kWp to meet growing demand for additional milling time.

Mill Management

The success of the Tangaye project has, in large part, been due to the effectiveness of the cooperative (or groupment) formed to manage the PV system. The villagers of Tangaye have used this form of management for many of their communal projects, hence, it was a natural way to organize the operation of the system, particularly the mill operation. As a result, the villagers took an active part in the project and viewed the system as "theirs" rather than that of the village chief, an individual entrepreneur or some foreign entity. They developed a concern for the project and were very cooperative in trying to make it successful. Accordingly, for future projects, it is recommended that the local forms of management be examined and utilized, where possible.

Problem Solving at Tangaye

As part of the Tangaye PV project, LeRC developed operating and maintenance (O&M) manuals and troubleshooting and repair (T&R) manuals for the system. Because of the modifications to the system, the latter manuals were never finalized. A copy of the T&R manual draft was placed at Tangaye, but was little used. The manual was written only in English (because of funding limitations, it was never translated into French) and, therefore, could not be used by the local operators and station manager. When problems of any consequence arose, the station manager would contact AID personnel in Ouagadougou. Often, the AID personnel either would advise the manager as to how to fix the system, or would make a trip to Tangaye to fix it themselves. In some cases, AID/OUAGA would cable LeRC with a description of the problem. In most cases, the problems could be resolved without requiring a visit by LeRC personnel. LeRC visits were required, however, to completely resolve the problems of the first burr mill failures and the deterioration of the Solarex modules. (A complete list of technical visits by LeRC personnel is given in appendix A.) It should be noted that the broken push-rod in the water pump was fixed initially by HER technicians without requiring any contact with LeRC. Tangaye villagers have shown a great deal of initiative and innovation during the project. For example, screens for their hammermill were altered by the millers to allow the grinding of fermented millet for beer brewing.

There have been some difficulties at Tangaye with regard to ordering new parts for the hammermill, water faucets and other loads. Communication between

Tangaye and Ouagadougou, and then to the United States, is difficult. An attempt has been made to use locally available parts. Even so, this may mean that villagers will be required to somehow contact a party in the capital or provincial city where parts such as faucets, springs, and washers might be stocked. People do have mechanical ability and with proper instruction can take care of minimal repairs on the village level and should be taught to call in the help of a regional repairman such as from HER or a local entrepreneur who is trained in system repairs and will maintain a local stock of needed parts.

This points out a problem to be addressed whenever any new technology (not necessarily "high" technology, but any technology which is unfamiliar to the local population) is being introduced. In such instances, there is the need to develop appropriate infrastructure to handle the new technology, including provision of expertise to maintain and repair systems, and provision of spare parts and supplies. In our travels throughout Third World countries, we have seen numerous instances of projects which have failed soon after the installing technicians have left because the local people did not have the spare parts and knowledge to maintain the systems. This appears to be a common failing, not only of U.S. assistance projects, but of other countries as well. Where technology has been successfully introduced, it has generally been accomplished by foreign nationals coming to the country (generally natives of the country of which the local country was a colony), bringing with them knowledge and access to equipment and supplies. Over a period of time, usually measured in years, local entrepreneurs have picked up on the knowledge and have branched out on their own. It is recommended that U.S. AID address this problem in their planning of other projects.

CONCLUDING REMARKS

The technical objective of the Tangaye PV project has been met. Following the replacement of the defective PV modules installed initially, the "high technology" PV-power system has operated reliably. Essentially all the problems encountered since the system expansion have involved the loads themselves (viz, grain grinder and water pump). Since the load devices were purchased in the United States, the ordering of spare parts has presented somewhat of a problem to the local users. Furthermore, personnel with the requisite skills to perform major repairs on the pump and/or mill are generally not available in villages such as Tangaye.

Regarding the PV power system itself, it is important to note that the Tangaye system was designed and built in 1978 to 1979. Since that time, simple packaged control modules have been developed and are now commercially available. The use of such improved technology in the Tangaye system should certainly facilitate maintenance, repair and troubleshooting by local personnel.

EPILOGUE

Although responsibility for operation of the PV system was transferred to the Government of Burkina Faso in 1983, two site visits were made to Tangaye in 1984 in conjunction with installations of PV-medical refrigerators elsewhere in Burkina Faso and Liberia. The purpose of the first visit was to inspect the system and to make minor repairs. The main purpose of the second visit was to upgrade the control subsystem.

The first visit was made in February of 1984. Upon arrival, the LeRC engineer found the mill inoperative. A switch in the mill motor control system was found to be defective and was replaced. This restored the mill to operation. The water pump push-rods also had failed again; however, the pump motor was operable. Replacement hardware (couplings) were left with local personnel who were to effect repair at a later date.

Relative to the PV system itself, the array and battery were in good condition, however, the following system components were damaged, apparently due to a lightning strike:

Damage	Remedy
1 blocking diode (short across insulating mica washer)	A replacement washer was made and installed by LeRC engineer using available plastic material.
6 solid-state relays were shorted	Replaced 3 with available spares.
2 burned out shunt trip coils (in array and load circuit breakers)	Replaced with spare circuit breakers.
2 light ballasts in guest house lamps	Replaced during the September, 1984 visit by the LeRC engineers.

During this visit, the LeRC engineer became aware of the fact that the Burkina Faso Government representatives responsible for the maintenance of the system were reluctant to accept the maintenance responsibility. This appeared to be due mainly to the complexity of the control subsystem and their unfamiliarity with it. A contractor engineer visiting the site with the LeRC engineer suggested that the control subsystem could be replaced with commercially available packaged control modules which use current technology. Although these modules do not use the DCR technology recommended for use in future systems, they are off-the-shelf items and would be much easier for local personnel to maintain and repair.

During the summer of 1984, a new control subsystem was procured and designs were completed for incorporating it into the Tangaye system. In September, 1984, a second visit was made to Tangaye as part of another African trip. During this trip, the control subsystem was replaced with the new design. We believe that now the Burkina Faso people should be able to maintain the system without NASA intervention. During this same trip, a faulty wire leading to the array field was replaced with a spare wire and the pump push-rod was replaced, returning the pump to operation. It was noted that, due to the drought in Africa, the water level in the well was unusually low for that time of year.

APPENDIX A

TECHNICAL VISITS TO TANGAYE, BURKINA FASO by NASA LeRC ENGINEERS

Date	Purpose of Visit
January-February 1979	Installation of system; training of users
August 15-September 6, 1979	1. Replace burr mill with hammermill 2. Install redesigned system voltage regulator
May 18-June 3, 1981	1. Refurbish and double size of array 2. Install a more efficient type of hammermill 3. Install lights and a refrigerator at the guest house
July 4, 1982	Inspection of system following a violent storm which caused local damage. PV system unaffected by storm.
May 1983	Final inspection and training of users. System turned over to Government of Burkina Faso.
February 1984	Inspection of system in conjunction with installation of medical refrigerator at another site in Burkina Faso. LeRC engineer found failed switch in mill control system; replaced with spare provided earlier. Mill operational. Water pump motor operational; however, pump push-rod broken again. LeRC engineer left new hardware for local repair.
September 1984	In conjunction with the installation of a medical refrigerator in Liberia, the control subsystem was replaced with a commercially available design which should simplify system maintenance and repair. Repaired array wiring and replaced water pump push-rod.

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TABLE I. - TANGAYE DATA SUMMARY MAY 1981 TO JUNE 1983

Array	Actual	Predicted
Total amp-hrs produced	85 271 A-hr	139 584 A-hr
Total energy produced	10 232 kWh	16 750 kWh[a]
Potential energy production	12 595 kWh	
Hammermill		
Total running hours	5021 hr	5840 hr
Motor current	13.1 A	21 A
Total amp-hrs used	65 707 A-hr	122 640 A-hr
Total energy used	7885 kWh	14 717 kWh
Total grain ground (reported)	74 820 kg	
Total grain ground (estimated)	111 094 kg	298 009 kg
Grain grinding rate	22.13 kg/hr	51 kg/hr
	13.03 kg/kWh	20.2 kg/kWh
Pump		
Total running hours	4573 hr	2504 hr
Motor current	1.16 A	2.5 A
Total amp-hrs used	5318 A-hr	6260 A-hr
Total energy used	638 kWh	751 kWh
Total water pumped	5367 m^3	3650 m^3
Water pumping rate	1.08 m^3/hr	1.46 m^3/hr
	8.47 m^3/kWh	4.9 m^3/kWh
Refrigerator		
Verified energy used (6/81-4/82)	664.8 kWh	
Estimated energy used (6/81-5/83)	2084 kWh	
12 V instrument system		
Total amp-hrs produced	26 240 A-hr	
Total energy produced	315 kWh	
Summary (120 V system)		
Total potential energy production	12 595 kWh	
Total energy produced	10 232 kWh	
Total energy used (verified)	9188 kWh	
Total energy used (estimated)	10 607 kWh	

[a]Prediction assuming insolation from reference 1.

TABLE II. - TANGAYE DATA SUMMARY

MARCH 1979 TO JUNE 1983

Mills	
Total run time	7182 hr
Total energy used	11 163 kWh
Total estimated grain ground	159 955 kg
Pump	
Total run time	9103 hr
Total energy used	1209 kWh
Total water pumped	10 906 m^3
Refrigerator	
Total estimated energy used	2084 kWh
Totals	
Total energy used	14 456 kWh

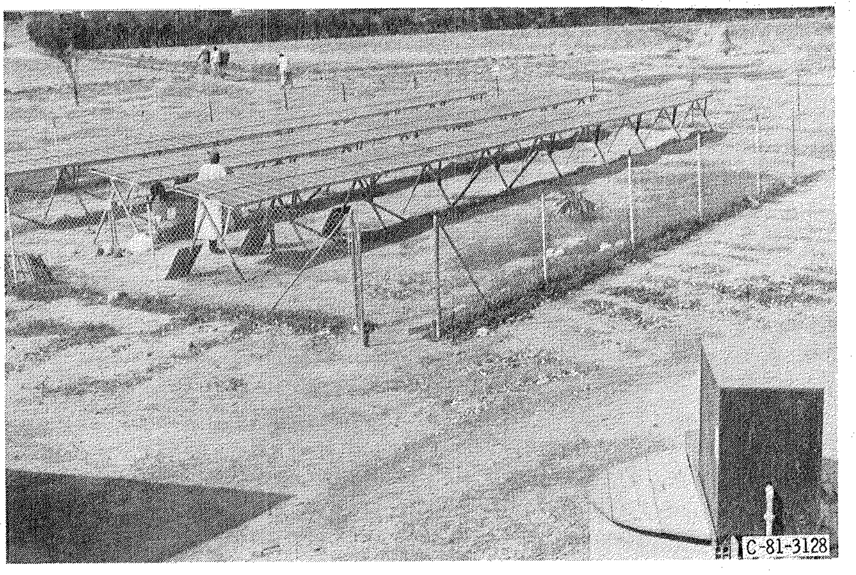

Figure 1. - PV array.

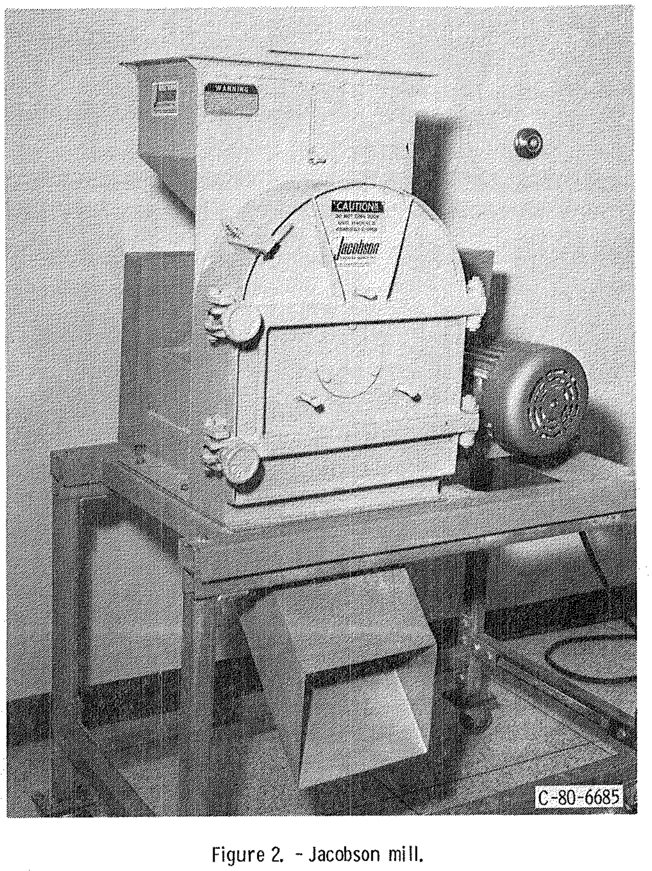

Figure 2. - Jacobson mill.

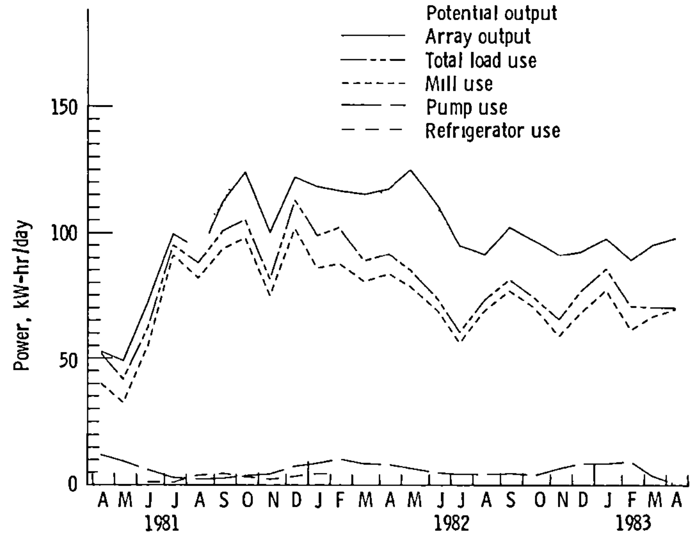

Figure 3. - Tangaye photovoltaic system performance.

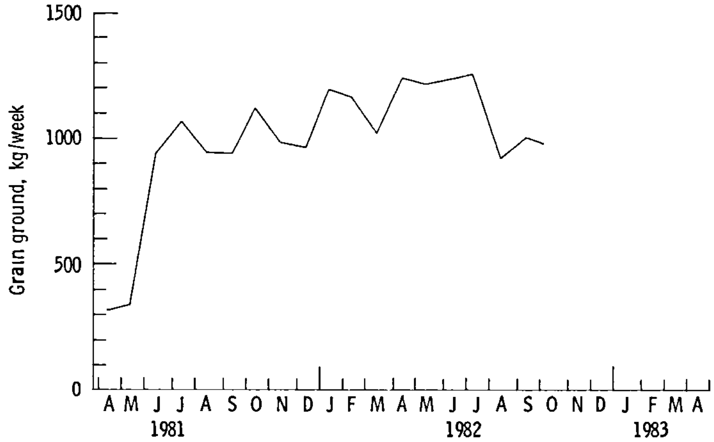

Figure 4 - Flour production with Tangaye photovoltaic system

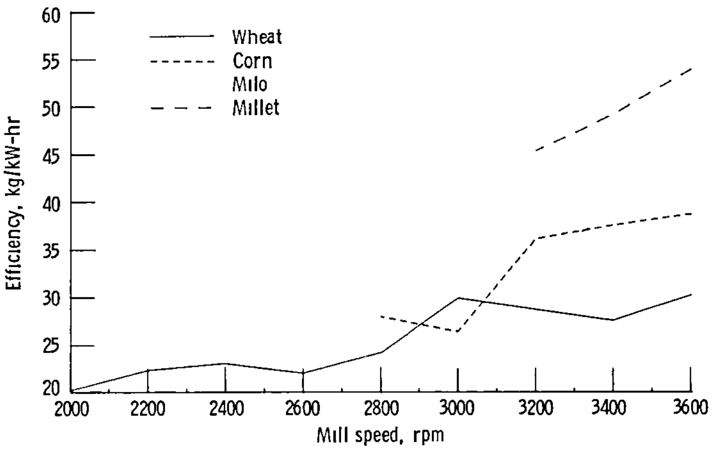

Figure 5. - Effect of mill speed on efficiency for the Jacobson model 120-B hammermill.

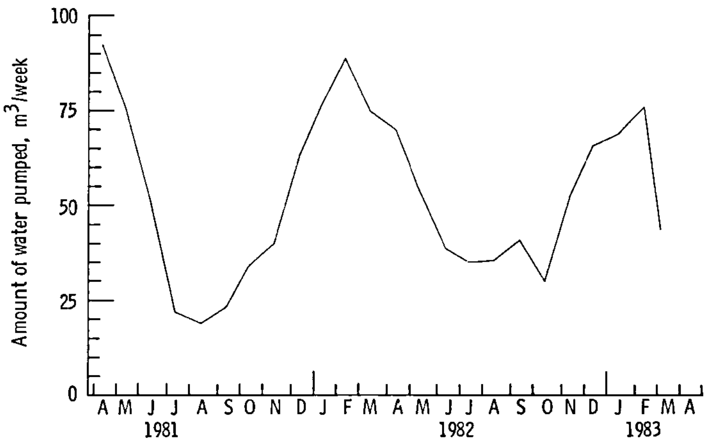

Figure 6 - Amount of water pumped with Tangaye photovoltaic system.

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15 Supplementary Notes

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16 Abstract

A photovoltaic (PV) system powering a grain mill and water pump was installed in the remote African village of Tangaye, Burkina Faso (formerly Upper Volta) under the sponsorship of the U.S. Agency for International Development (AID) and by the National Aeronautics and Space Administration (NASA) Lewis Research Center (LeRC) in early 1979. The first two years of operation are covered in NASA TM-82767. The present report covers the second two years of operation from April 1981 through June 1983. During this time, the grain mill and water pump were operational 96 and 88 percent of the time respectively, and the PV system generated sufficient electricity to enable the grinding of about 111 metric tons of finely ground flour and the pumping of over 5000 cm^3 of water from the 10 m deep well. The report includes a description of the current configuration of the system, a review of system performance, a discussion of the socioeconomic impact of the system on the villagers and a summary of results and conclusions covering the entire four-year period.

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