SOLAR ENERGY ALTERNATIVES
FOR THE UNITED STATES EMBASSY
AND FOR RURAL DEVELOPMENT PROJECTS
WITHIN THE REPUBLIC OF UPPER VOLTA

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DISCLAIMER

ABSTRACT

At the request of the Department of Energy's Office of International Affairs and Photovoltaic Program Office, Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL) sent a representative to the Republic of Upper Volta in West Africa. The purpose was to advise U. S. Ambassador Pierre Graham on the possibilities of utilizing solar energy to cool a new office building in the Embassy compound and to be exposed to the energy needs of Upper Volta. Dr. Edward C. Kern, Jr., spent one week in the country and had ample time to inspect the new office building, make a preliminary assessment of the possibilities for solar cooling and recommend changes to the building design which would facilitate inclusion of a roof-mounted solar energy system. At the suggestion of the Ambassador, he visited the town of Fada N' Gourma and advised the Ambassador on the feasibility of electrifying the town using solar energy. En route to and from Fada and through discussions with the United States Agency for International Development (USAID) personnel, he gained some understanding of the subsistence agricultural life which is typical for over ninety percent of the Voltan population.

This report is organized in three sections: solar cooling options for the new Embassy office building, electrification of Fada N' Gourma using solar photovolatic versus conventional energy systems and an overview of the potential for village solar photovoltaic energy utilization in Upper Volta.

The analysis indicates that the least-cost alternative for cooling the new offices is to modify existing plans, which call for standard electric room air conditioning units, and to incorporate energy conservation measures in the building construction and operation. With already high and increasing electricity prices in Upper Volta, selection of a solar-powered central absorption chiller will result in lower monthly costs by the mid-1980's. An attractive variation of the absorption system option is to utilize a photovoltaic system to provide the approximately 25 kW-hrs of electric power required daily for pumps and fans. This will enhance the value of the installation by exhibiting a broader range of solar energy conversion alternatives to influential Upper Voltans.

Photovoltaic central power for Fada N' Gourma will become viable in the mid-1980's only if the number of electric power users there increases dramatically. Should the number of users not increase, distributed generation remains the best option with photovoltaic systems replacing diesel systems as they become economical in the mid-1980's.

Solar energy systems used in remote villages for water pumping, grain grinding, cooking and lighting could be the first application to have an impact on the economic growth of the Republic, which rests on boosting agricultural surpluses and increasing grain exports. Providing energy resources for pumping, grinding, cooking and lighting will enable farmers to devote more time to their crops to help attain this growth.

The present hardware cost for a photovoltaic system to provide electric power to a village of 100 residents is about $20,000, exclusive of development and shipping costs. At 1980 prices the system cost will drop to approximately $10,000, providing the Department of Energy's 1980 photovoltaic cost goal of $2,000 per peak kilowatt is met.

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1.0 INTRODUCTION

The considerable alternative energy research activity aroused in developed Western nations in response to escalating fuel costs could yield significant benefits in developing Third World nations. Whereas cost and reliability problems are currently impeding the acceptance of solar energy in the West, applications in developing countries can be technically and economically competitive in the more immediate future. This will happen as energy demands grow in developing countries lacking efficient fuel distribution or equipment service infrastructures. The Republic of Upper Volta is representative of such countries.

The promise for alternative energy systems in Upper Volta covers a spectrum from its cities to its smallest villages. Users range from Westerners accustomed to consuming great quantities of energy to those using electricity for the first time. The viability of solar energy will develop sooner here because conventional energy is more expensive and because these new electric power consumers will neither require nor pay the price for the small "loss of load probability"* (LOLP) demanded in developed countries. This greatly eases the burden on an intermittent source such as solar energy.

Energy usage in small isolated Upper Voltan villages is presently limited to human labor and wood fires for cooking. Using draft animals - donkeys and cattle - is a relatively new concept. There are virtually no conventional energy options because fossil fuels are not readily transported to remote villages and electric power grids are too expensive to build. Here solar energy has no competition, except the continuation of traditional patterns of life practiced for hundreds of years.

At Fada N' Gourma, a large town in eastern Upper Volta with a population of 16,000, there are a number of diesel-electric generator sets imported by Westerners seeking to maintain their own domestic way of life and to introduce Western technology and agricultural practice in the region. Approximately twenty diesel sets are distributed around the town. The principal ones are used to provide power at a Catholic mission, a Post, Telephone and Telegraph Office, a hospital, a Rural Development headquarters and several residences.

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*This is the probability that a utility will not have sufficient generating capacity to meet the demand of its customers.

Here the economics of a solar-energy system compete with those of an under-utilized diesel-generator set run several hours per day and during emergencies. Diesel fuel comes from overseas to Abidjan, Ivory Coast, a thousand-kilometers inland by rail and finally several hundred kilometers over single-lane paved and dirt roads. Because the dirt roads are easily washed out during the wet season, expensive inventories and storage facilities are maintained. Should the generator set need other than routine maintenance, it may take months for the problem to be diagnosed, a part ordered and installed. At the hospital, a complete redundant system is installed to cover this eventuality.

Ouagadougou, (pronounced "Wah-Gah-Doo-Goo"), Upper Volta's capital, is 225-km distant. Here foreign diplomats and technical advisors are a singular source for the diffusion of Western cultural values and technology. Their work is, for the most part, concerned with aiding the country. Air conditioners abound because the climate is hot year-round. The capital has a central electric power plant, one of five towns in the country to be electrified. This power is expensive, about $400 a month for the average American diplomatic family. Electric prices are as much as ten times greater than those in some parts of the United States.

Conceptual designs and economic analyses for U. S. Embassy cooling systems, central and distributed power systems for Fada N' Gourma and a small village power system are presented and compared in the following sections.

2.0 FEASIBILITY OF SOLAR COOLING FOR EMBASSY OFFICE BUILDING

The new office building nearing completion on the U. S. Embassy compound in Ouagadougou is a two-story structure, which will contain 13 offices and some storage space. Plans and elevations are shown in Figure 1. Figure 2 shows two photographs of the construction in early October 1977. The construction is on a poured-concrete slab and the upper floor is supported by both columns and bearing walls. The bearing walls, the exterior perimeter and two internal walls are concrete block 15-cm thick. Curtain walls are 10-cm block.

The external dimensions of the building are 24.15 meters long by 12 meters wide and 6.65 meters high. The upper floor consists of 11 offices and a wash room. The lower floor is used for larger offices, a meeting room and storage. Original plans for the roof were to lay an essentially level aluminum sheet roof on a rectangular grid of small I-beams. The relatively light roof loadings permit the use of approximately 10-cm deep I-beams wired atop one another to form the grid.

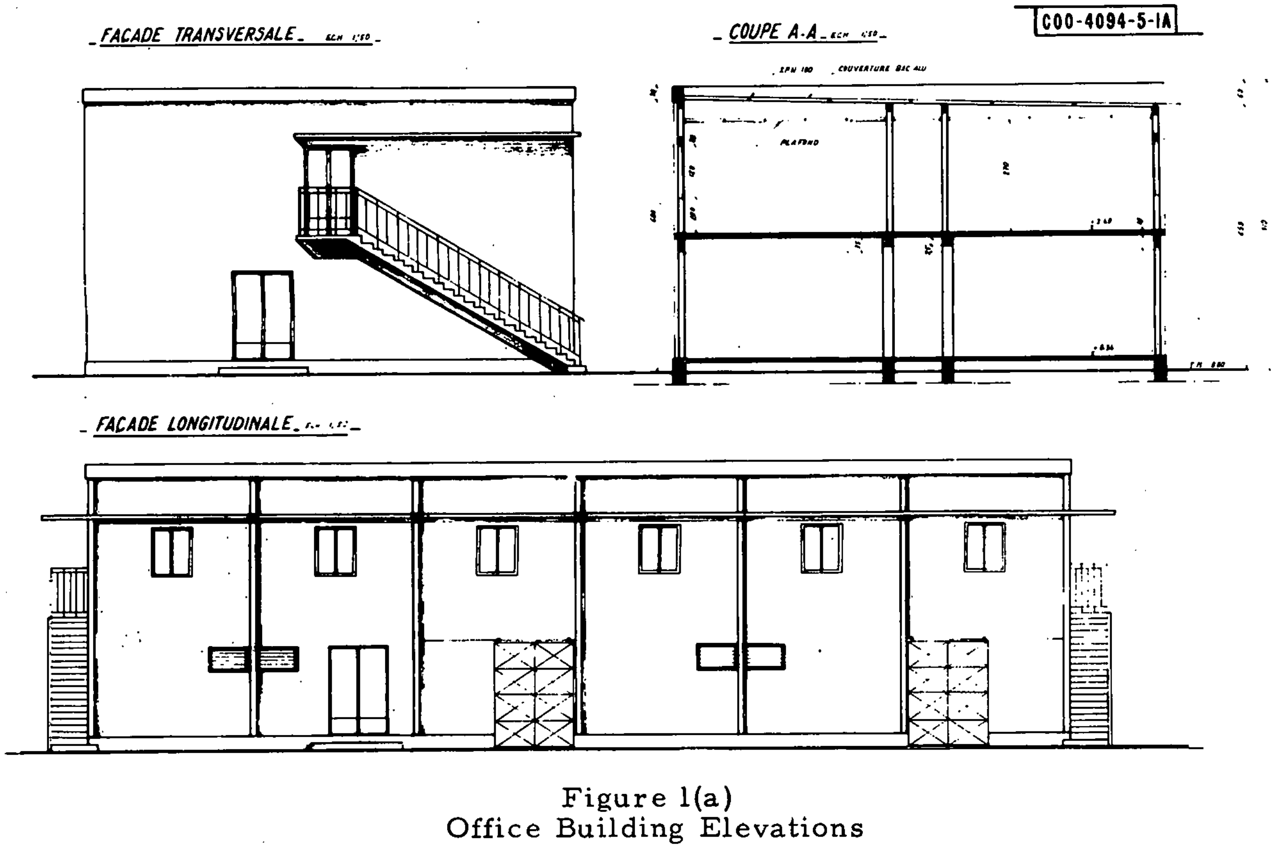

Figure 1(a)
Office Building Elevations

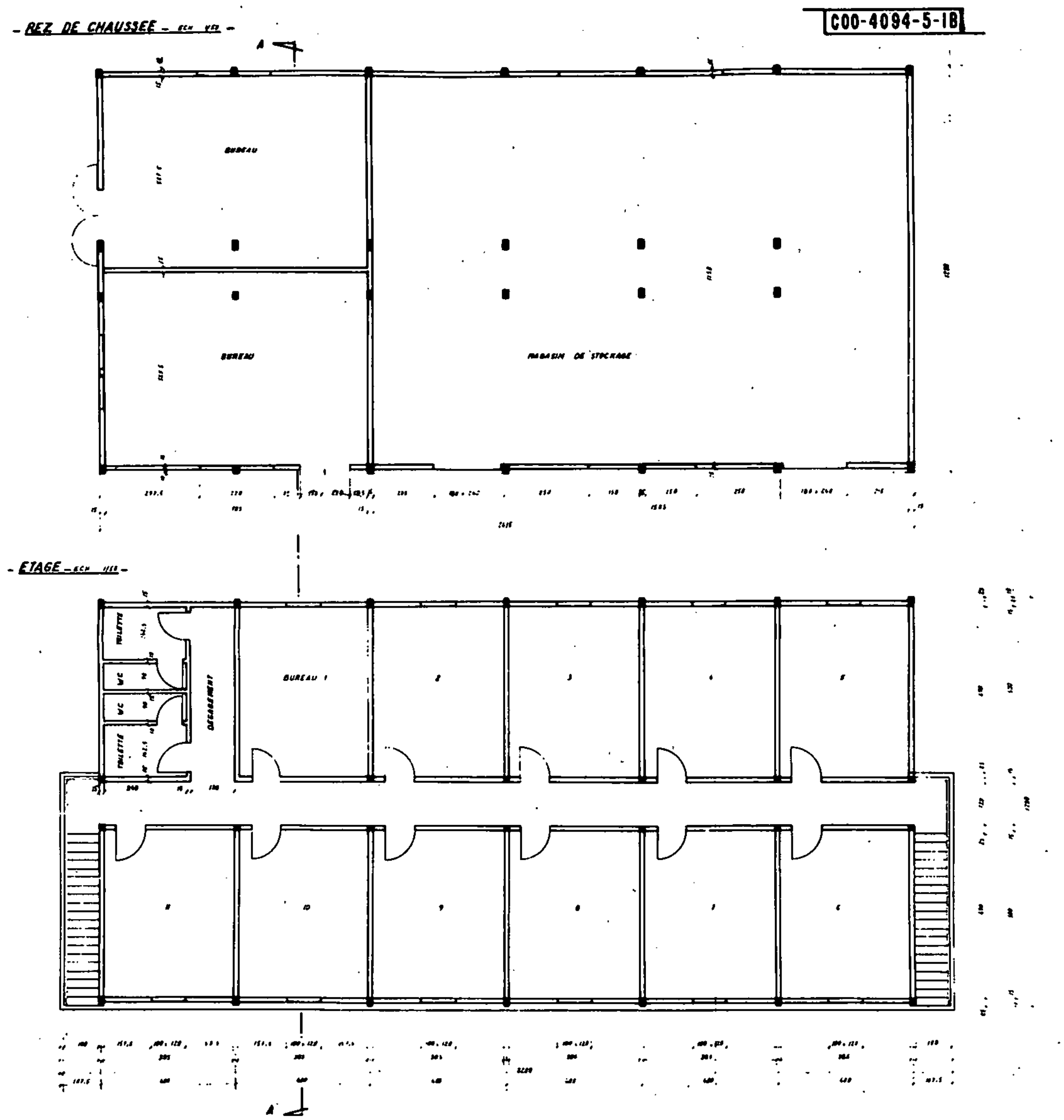

Figure 1(b)
Office Building Plans

To cool the building, the plans call for installing 18 one-ton window-type air conditioners. This represents a continuation of the standard practice in the Embassy compound of providing one air conditioning unit per average size office. There is no heating required in Ouagadougou and air conditioning is required almost year-round. Calculations of cooling loads for this building are given in Appendix 1. These calculations indicate a maximum heat gain rate of 145,000 BTU's per hour and a daily total heat gain of 1,200,000 BTU's (352 kWh).

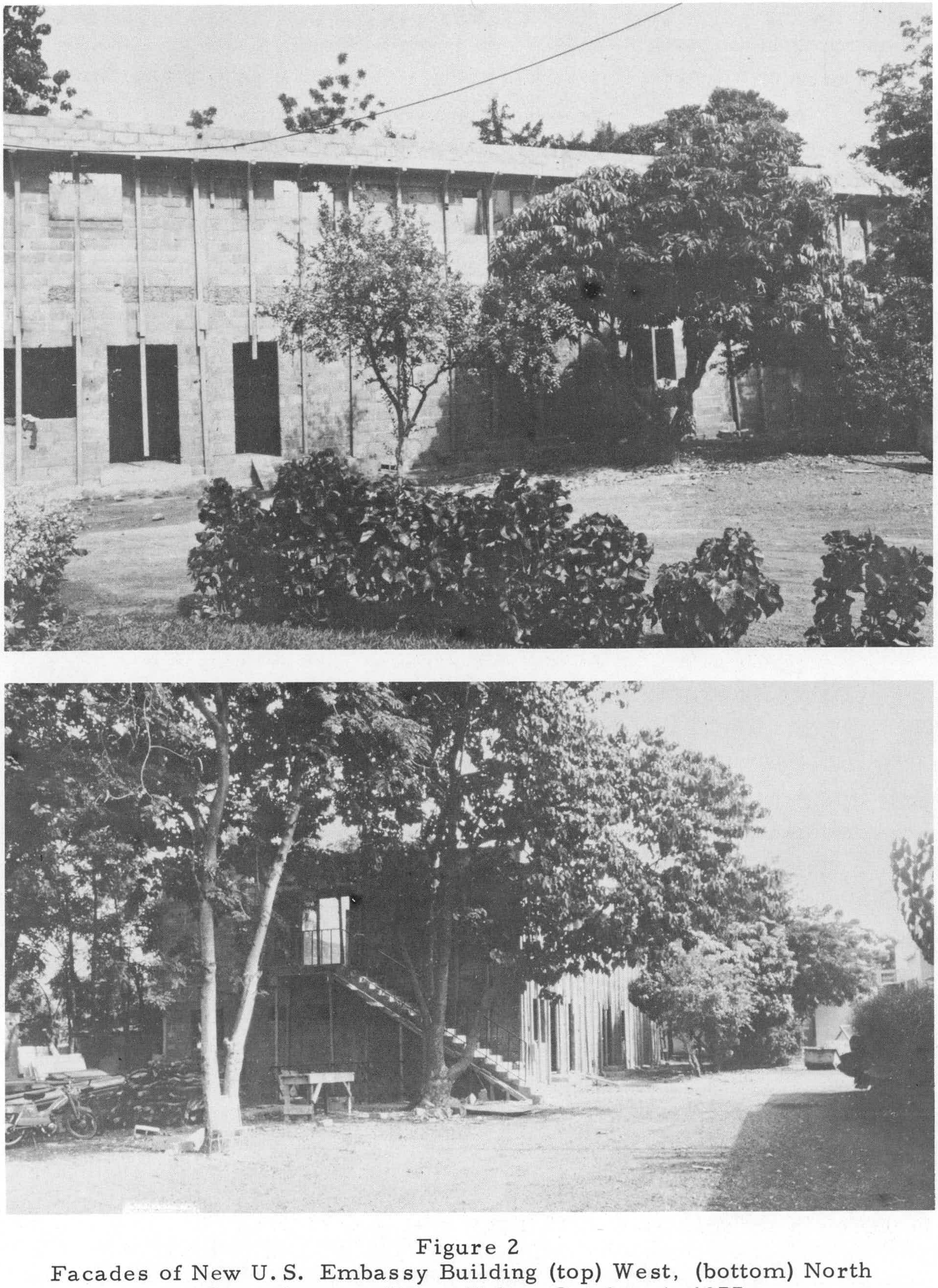

Figure 2
Facades of New U. S. Embassy Building (top) West, (bottom) North
Ouagadougou, Upper Volta, October 4, 1977

To counter this total daily heat gain using solar energy, two solar energy schemes are presented and their economics considered. In addition, the economics of air conditioning with conventional one-ton window-type units are presented for comparison. In the comparisons, monthly costs are calculated without including shipping costs or maintenance. An interest rate of 10% per year is used in establishing interest and principal payments.

2.1 Conventional Air Conditioning

The use of conventional window units will require the purchase of 18 one-ton air conditioners and the electric power to run them. Each unit is assumed to cost $300 and to have a 10-year life after which it has no salvage value. No maintenance is assumed and each unit is assumed to operate with a coefficient of performance of 2.5. (The air conditioning coefficient of performance is a measure of efficiency equal to the thermal energy removed from a building divided by the energy required to power the air conditioner.) Electricity costs are as taken as $0.21 per kilowatt-hour, the average of the present peak and ordinary rates for the Embassy. The initial cost for the units is $5400. At an interest rate of 10% per year (0.83% per month), this initial cost is equivalent to payments of $71 per month over the 10-year life. (In the solar-powered options, the collectors reduce the heat gain through the roof. Insulation to make the roof equally as heat retardant as the solar collector fitted roof (so equal cooling loads will apply) costs about $0.50 per square foot, or $1560 total, which adds $15 per month assuming a 20-year life.)

Operating cost calculations assume that each of these units will be run 10 hours per day rather than be controlled to maintain the office space at 75°F dry bulb. This is certainly more expensive than a controlled system, but is a practical reality of the standard use of such units. The electrical consumption is then 253 kW-hrs per day, or 5571 kW-hrs per month for which the cost is $1170.

The total monthly cost for this approach is $1256, 93% of which buys electric power. If electricity prices increase at 3% per year, this figure will increase to $2200 by 1997.

2.2 Solar-Photovoltaic System

A photovoltaic array could be installed on the office building roof to provide a portion of the electricity needed to run the air conditioners. As a practical limit, an area of about 270 square meters is available on the roof.

- Nominal array power in full sunlight (1 kW m^{-2}), 6% efficient array*

  $.06 \times 270\ m^2 \times 1\ kW\ m^{-2} = 16.2$ kWpk

- Total incident solar energy per day

  $7\ kWh\ m^{-2}\ d^{-1} \times 270\ m^2 \times 1\ day = 1890$ kWh

- Conversion to electricity with a 6% efficient array operating at 28°C

  $1890 \times .06 = 113.4$ kWh or $7\ kWh\ m^{-2} \times 16.2$ kWpk = 113.4 kWh

- Losses due to an array operating temperature of 66°C

  $113.4 \times 0.005 \times (66°C - 28°C) = 21.6$ kWh

- Net electric power available

  $113.4 - 21.6 = 91.9$ kWh

The energy produced will be 92 kilowatt-hours per day. Conversion to alternating current with a 90%-efficient inverter will leave 83 kilowatt-hours of useful energy. This equals approximately one-third that required by the air conditioning system. Since this energy is less than the demand of the system, no batteries are needed for its useful consumption. The costs, assuming 10% interest per year, a 20-year life with no salvage value at the end and no maintenance are as follows:

• Photovoltaic Array (16.2 kW pk @ $12,000/kW pk)	$194,400
• DC to AC Inverters (16 kW @ $1,500/kW)	$ 24,000
• Building Structure Modifications	$ 10,000
• Photovoltaic System Wiring	$ 10,000

The total first cost is $238,000, equivalent to a monthly cost of $2297; this covers only the solar-energy collection system. Additional costs of $5400 are required to purchase air conditioners, ($71 per month) and 170 kWh of electricity per day ($785 per month), to supplement the array output. Altogether the total monthly cost is $3153 for this option.

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*Appendix 3 describes the procedures used in rating photovoltaic arrays.

If the 1980 DOE photovoltaic cost goals of $2000 per kW for photovoltaic modules and $500 per kW for DC to AC inverters are met, the monthly cost drops to $1512, which includes supplementary utility power at 1980 costs. By 1997, utility prices will have increased so as to make this option cost $2072. Photovoltaic modules have been assumed to last 20 years. Replacements around the year 2000 will be at a cost below that in 1980 and will reduce the monthly cost.

2.3 Solar-Powered Absorption System

Another solar option is an absorption system which uses heat to run a cooling machine. The cycle is similar to that used in gas- or kerosene-powered refrigerators. This system would entail covering the new office building roof with solar-thermal collectors.

The system proposed has 2900 square feet of double-glazed water collectors of thermal efficiency, η, given by the following expression:

$$\eta(\Delta T, I) = 0.8 - \frac{\Delta T}{I}$$

where ΔT is the collector fluid temperature less the ambient temperature (°F) and I is the insolation (Btu h^{-1} ft^{-2}). A 4,000-gallon water tank is used for thermal storage and is capable of storing 33,600 Btu's per degree F. Thermal energy is utilized by a 25-ton absorption chiller derated to 15-ton capacity. Each room in the office building will be thermostatically controlled, and thus the load profile on the machine will vary during the day according to the overall required heat rejection from the building. Heat is ultimately rejected from the system with a 50-ton capacity cooling tower.

To assess the system performance a model was used to predict its performance on a day with a maximum cooling load and above average insolation. The results are shown in Figure 3. Only between the morning hours of 7:00 and 10:00 a.m. does the building cooling demand approach the capacity of the chiller, which is low because of the low source (tank) temperature available during these hours. If the storage tank is increased to 6000 gallons, the average operating temperature increases as shown and the chiller operates with greater margins during early morning hours. The smaller tank size would appear to be adequate for the job.

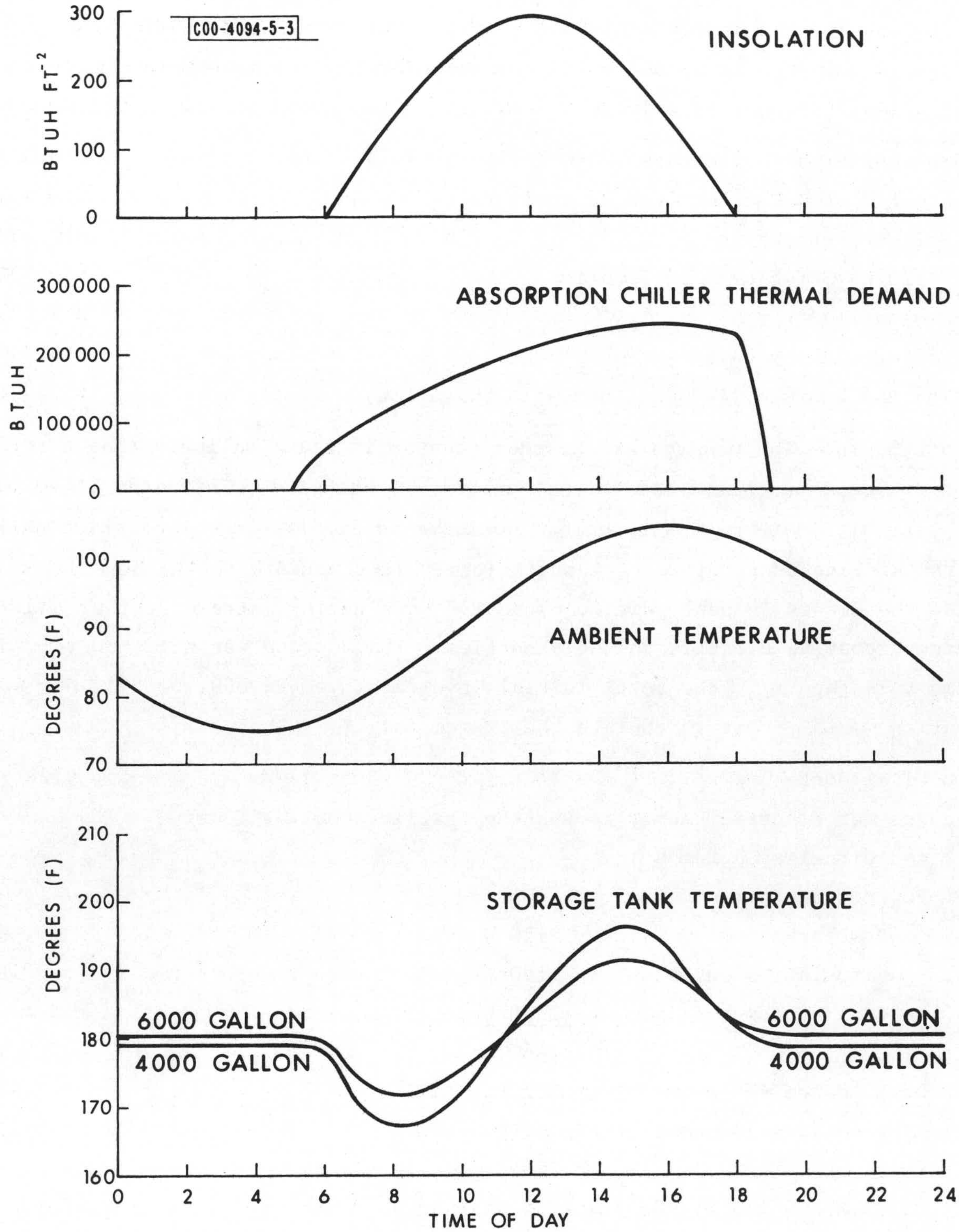

Figure 3
Simulated Cooling System Performance

The cost of the absorption chiller system was calculated, again based on 10% interest (0.83% per month) and a 20-year life for the system components at the end of which they have no salvage value. The first costs are given below.

• Solar-Thermal Collectors (2900 ft^2 @ \$15/ft^2)	\$43,000
• Arkla 25-ton Chiller Derated to 15 tons	\$16,500
• Collector Plumbing	\$10,000
• Building Structure Modification	\$10,000
• Cooling Tower	\$ 2,100
• Office Cooling Units	\$ 5,000
• Thermal Storage (4000 gallons at \$.50/gallon)	\$ 2,000

For backup, the window units are assumed because it seems unlikely that a solar system could be installed before the building is occupied. This adds \$5400 to the cost. (An alternate backup technique would be to oil fire the absorption chiller when the storage temperature is insufficient. This would have the benefit of keeping the Embassy's peak power consumption down during extreme weather and avoiding excessive electric demand penalties. This option was not, however, developed in this report.) The total initial investment is \$94,500, or \$912 per month. The entire monthly cost to operate the system is:

- Capital Cost — \$ 912
- Costs for Electric Energy to Run the Chiller, Cooling Tower and Circulation Pumps

  Power Consumption

Chiller	150 W
Circulation Pumps	1190 W
Cooling Tower	1120 W
	2460 W

  Daily Usage (10 hours)

  2.46 kW x 10 h = 24.6 kWh

  Cost

  24.6 kWh x \$.21 kWh^{-1} x 22 working days/month = \$ 114
- Total Monthly Cost — \$1026

2.4 Introduction of Energy-Conservative Practices

The amount of energy needed to cool the new Embassy office building could be reduced by adding insulation and by regulating the output of the cooling system. In the previous analyses, only the absorption system was assumed to be thermostatically controlled. This assumption is based on the general practice of letting individual room air conditioners run continuously and of regulating the output of central cooling systems with thermostats in each cooling zone of a building.

Thermostatic controls are generally not used with individual room air conditioners. The unconventional use of controls at the Embassy office building could result in considerable savings in electric-energy usage. These air conditioners are sized to handle peak air conditioning loads, and therefore, have a maximum capacity twice that which is required for average conditions. Frequently they may be used at full capacity during periods when much capacity is not required. As a result, office space is either colder than necessary or windows and doors are carelessly left ajar allowing much of the cooled air to escape.

By introducing thermostatic controls, over cooling could be reduced. An effort to make personnel aware of the waste associated with cracks in doors and windows would have to be made.

The cost of the required controls is estimated to be $1800. A potential savings of $500 per month for electric power certainly warrants installing these controls. The monthly costs for the conventional and photovoltaic systems with controls are:

- Conventional System - reduced from $1256 to $755 per month.
- Photovoltaic System - reduced from $3153 to $2670 per month.

The above calculations were made for 1977 photovoltaic and fuel prices. At the assumed 1980 fuel and photovoltaic prices, the photovoltaic option appears particularly attractive with a monthly cost of $964.

Changes in the building's insulation would be desirable, but probably impractical since the construction is complete. Of particular value could have been a layer of insulation on the west wall. A significant reduction in the heat gain through the roof will result from insulating the ceilings. These considerations were previously discussed in the section describing conventional cooling systems.

The estimated monthly costs for energy conservative (regulated) system usage are summarized in Table 1 together with costs for the other proposed systems.

Table 1

Embassy Cooling Costs ($/month)*

	- Year -		
System	1977	1980	1997
Conventional (Free Running)	1256	1365	2200
Conventional (Regulated)	755	815	1280
Solar-Thermal Absorption (Regulated)	1026	1037	1118
Photovoltaic (Free Running)			
- 1977 Photovoltaic Costs	3153	3226	3786
- 1980 Photovoltaic Cost Goals	--	1512	2072
Photovoltaic (Regulated)			
- 1977 Photovoltaic Costs	2670	2682	2873
- 1980 Photovoltaic Cost Goals	--	964	1155
Combined Solar-Thermal-Absorption With Photovoltaics			
- 1977 Photovoltaic Costs	1500	1500	1500
- 1980 Photovoltaic Cost Goals	--	1032	1032

*Assumes Utility Electric Prices Rising at 3% per Year.

2.5 System Comparison

In conclusion, the least-cost solution at present Upper Voltan electric prices is to concentrate on the effective utilization of conventional equipment through better building insulation and system controls. Such an effort would require a thorough review of existing (planned) equipment and the installation of thermostats in individual offices. The caveat, however, is "present" electric prices. For roughly $300 per month extra, a solar-thermal system could be installed that would be almost free from future electric utility price increases and provide essentially all of the cooling required. A positive aspect of the particular absorption chiller envisioned for the job is that it is not used at full capacity. More collectors could be added at a later date at the Embassy and additional offices could be cooled. A negative aspect is that the cooling tower may require up to 500 gallons of water per day. A photovoltaic system is more costly by a factor of two or three at present prices. Most of the cost is in the modules, however, and the overall cost of such a system may become competitive within a few years.

This discussion has focused on the technical and economic issues of solar cooling for the U. S. Embassy in Ouagadougou. Much of the transfusion of Western technology to developing countries is by the example of Western individuals and countries. Solar-energy utilization by Upper Voltans - as described in the

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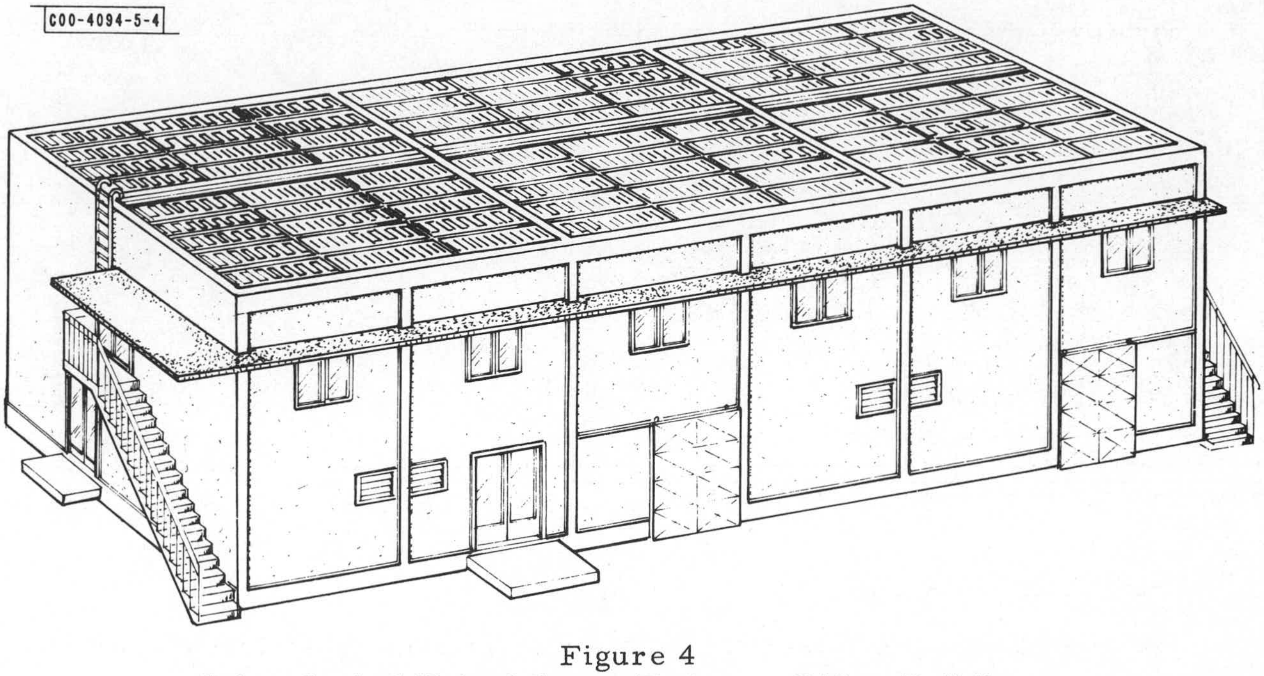

Figure 4
Solar-Cooled United States Embassy Office Building
Ouagadougou, Upper Volta

following sections - may become economically viable in the near future. Solar energy utilization by the U. S. Embassy can help demonstrate this viability to Upper Voltan policymakers in the capital.

The demonstration/example of solar cooling will undoubtedly shape the perception of what solar energy "is" among influential Upper Voltans, thus it would be a mistake to overplay solar-thermal energy collection at the expense of photovoltaic-energy conversion. This is particularly true in Upper Volta where the most promising solar applications use photovoltaic modules and have no thermal-energy requirements.

An auxiliary array of photovoltaic modules could be mounted atop the adjoining USAID building to provide sufficient electric power to drive the absorption air conditioner. Although not the most cost effective from a near-term cost perspective, such a combined thermal and photovoltaic system would enable the United States to demonstrate a larger range of solar options to Upper Voltans. The economics of such a combined system are summarized in Table 1.

3.0 ELECTRIFICATION OF FADA N' GOURMA

Fada N' Gourma is 225-km east of Ouagadougou on the principal east-west road in Upper Volta which goes on to Niamey, the capital of Niger. It is a narrow two-lane road and is paved about halfway, as far as Koupela. The unpaved sections often become impassable during the wet season from June through September. Fada is the largest town in the eastern third of the country. Figure 5, a road map of southern West Africa, shows these towns. The overall area shown on the map is about equal in size to the United States east of the Rocky Mountains.

Fada has no central electric generating facility, instead there are numerous diesel-generator sets in the town which provide power to a hospital, a Catholic mission, a small plow-making shop, the Post, Telephone and Telegraph Offices and homes of several Western agricultural advisors.

The person most knowledgeable about electric power usage in Fada is a German who teaches at the Catholic mission. He is aware of the diesel-generator sets in town and provided data on how each is used. These data are the number of hours per day each of the sets is run and in some instances the exact hours each was run. Figure 6 has been drawn using the exact running hours data when available and by making educated guesses concerning the running hours of the other sets. It shows the weekly distribution of total generating capacity. The daily figures are given in Table 2.

Four options for Fada will be discussed: the present system, a central diesel system, on-site photovoltaic systems, and a central photovoltaic system. To determine the load which must be met by these options, the existing diesel-generator sets are assumed to generate each day 50% of the energy of which they are capable. The capacity requirement for them is taken to be equal to the maximum capacity of the present system as it is currently run, as illustrated in Figure 6. The assumed energy demand per day is given in column three of Table 2.

3.1 The Present System

Presently the village has 316-kW installed capacity. (The hospital has a redundant 50-kW system for backup; the Post, Telephone and Telegraph is assumed to have 10-kW redundant capacity.) These systems produce a total

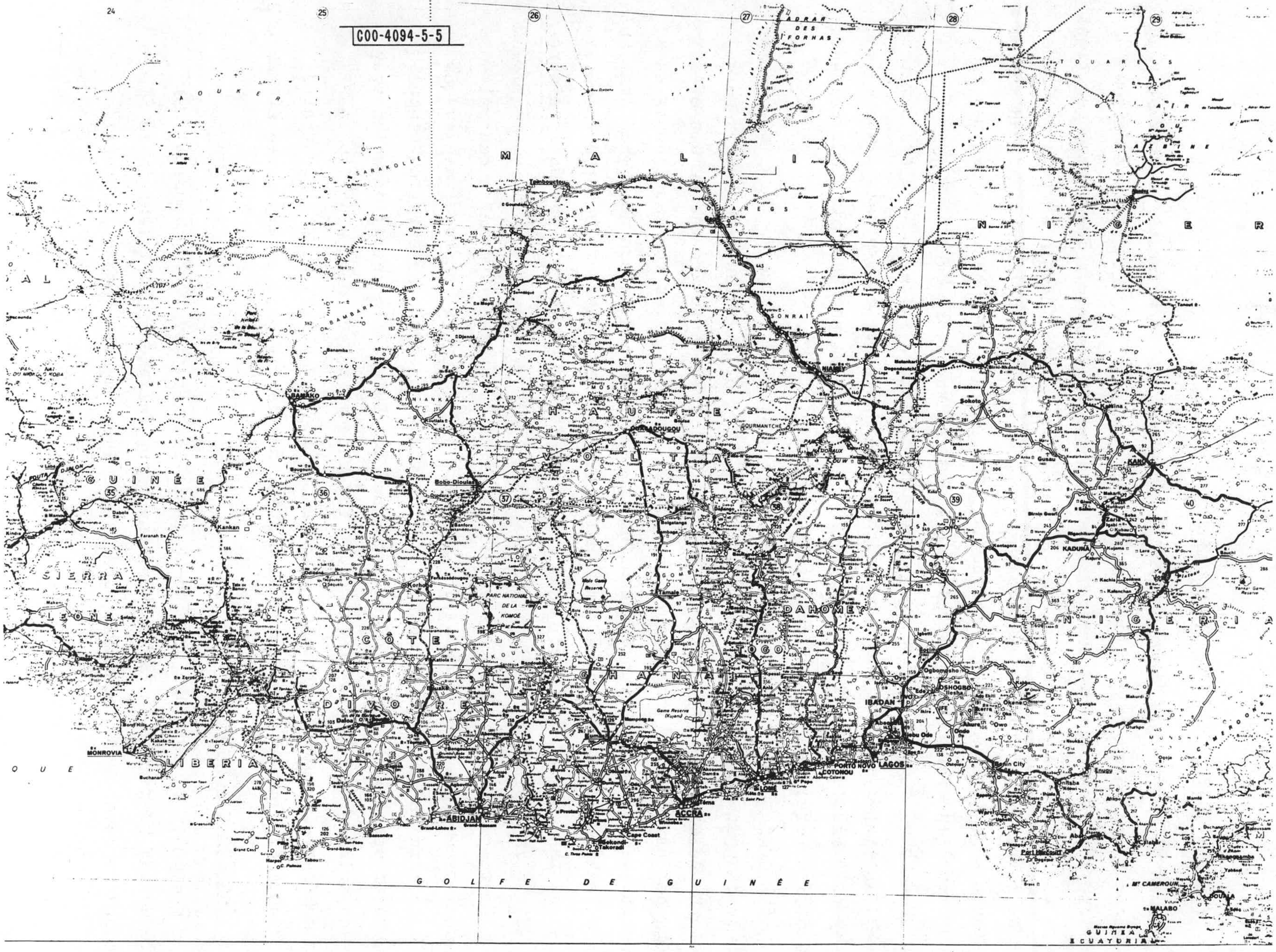

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Figure 5
Road Map of Upper Volta

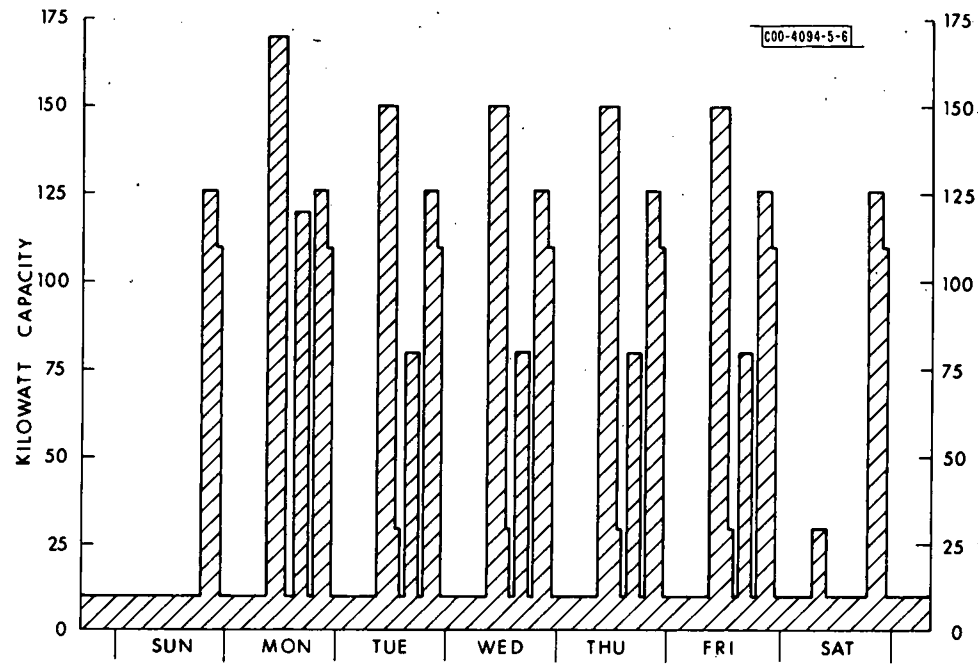

Figure 6
Weekly Generating Capacity for Fada N'Gourma

Table 2

Present Electric Power Usage in Fada N' Gourma

	Maximum Available Supply kWh d^{-1}	Peak Capacity kW	Assumed Demand kWh d^{-1}
Sunday	688	126	344
Monday	1658	170	829
Tuesday	1478	150	739
Wednesday	1478	150	739
Thursday	1478	150	739
Friday	1478	150	739
Saturday	748	80	374

Weekly Total Capacity 9006 kWh

Weekly Total Demand ~4500 kWh

Weekly Maximum 170 kW

of 4500 kW h d^{-1}. Diesel costs (FOB Ouagadougou) are given approximately by:

$$C = 1180\ P^{0.56}$$

where C is the plant cost in U. S. Dollars and P is the rated capacity in kilowatts. This function describes a curve fit to price data for sets currently available in the 5 to 1000-kW range. Diesels are assumed to consume 0.21 liters of fuel per hp-h and generators are assumed 80% efficient in converting mechanical to electrical power at all load levels. A liter of diesel fuel presently costs 100 CFA (West African Francs) or $1.56 per gallon in Fada.

The cost of the existing inventory of sets in Fada is given in Table 3.

Table 3

Present Installed Diesel Capacity in Fada N' Gourma

Location	Size (kW)	Cost ($)
Hospital	50	10,551
	50	10,551
Mission	40	9,312
	20	6,316
	16	5,574
Post, Telephone & Telegraph	10	4,284
	10	4,284
House 1	15	5,376
House 2	15	5,376
House 3	10	4,284
House 4	10	4,284
Rural Development Organization	20	6,316
	50	10,551
	316 kW	$87,059

Assuming the collective systems produce 4500 kWh week^{-1}, the mechanical work from the diesels is 5630 kWh week^{-1} (7550 hp-h week^{-1}). This in turn requires 1594 liters of fuel with a weekly cost of 159,380 CFA ($656). Neglecting maintenance, the annual cost of the present operation assuming a 20-year life and 10% interest is:

Operating Cost	$34,107	
Capital Cost	10,226	
Total Annual Cost	$44,333	(18.9¢/kWh)

Anticipated diesel-fuel price increases will drive this cost to 20.3¢/kWh in 1980 and 30.7¢/kWh in 1997.

3.2 Central Diesel Plant

In a central diesel plant it is desirable to have more than one engine since peak loads are experienced for only a small fraction of the time and diesels are not fuel-efficient under partial load. Furthermore, such operation may cause significant maintenance problems. Based on the weekly capacity requirement profile given in Figure 6 a base-load diesel of 25-kW capacity and a peaking diesel of 175-kW capacity were selected. The capital costs are $21,226 and $7139 for the large and small units, respectively. A rough layout of the town with a central generating plant and distribution system is shown in Figure 7. Such a distribution

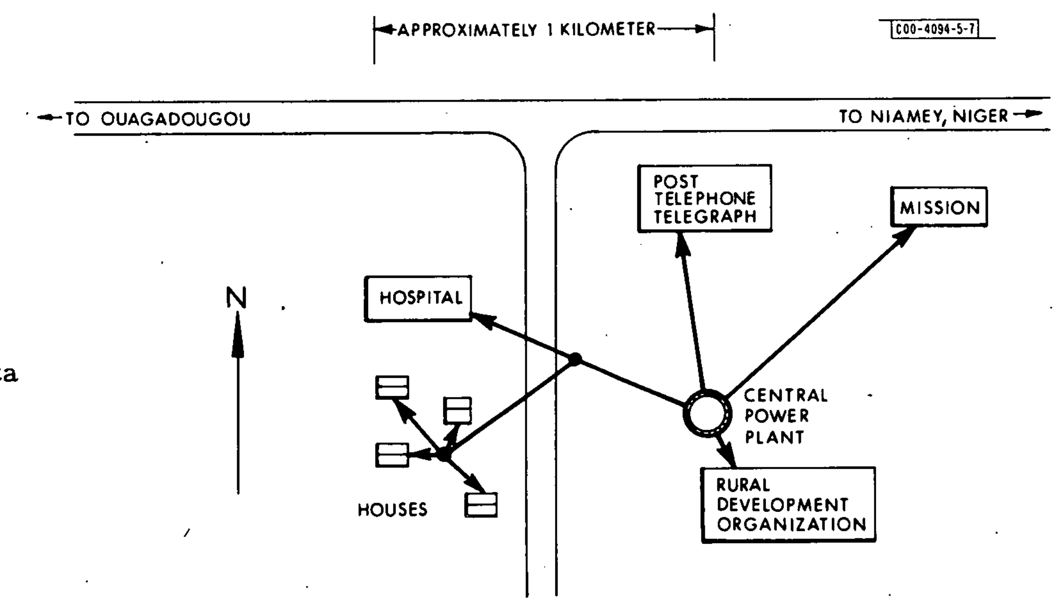

Figure 7
Central Power System
Fada N'Gourma
Upper Volta

system has been estimated to cost $150,000 by the German electrician. Assuming three kilometers of distribution wiring, the unit cost is $50 m^{-1}, which seems excessive. A cost more in line with estimates for rural electrification sub-transmission is $20 m^{-1} and thus a rough total cost estimate of $60,000 was made. The total capital investment is then $88,365. Operating costs are assumed to be 10% higher than the on-site systems to account for distribution line losses. Neglecting maintenance, the annual cost of a central diesel system is then (again assuming 20-year life and 10% interest):

Operating cost	$37,518	
Capital cost	10,380	
Total Annual Cost	$47,898	(20.5¢/kWh)

At assumed 1980 diesel fuel prices this will become 22.4¢/kWh and at 1997 prices it will reach 30.7¢/kWh.

3.3 Central Solar-Photovoltaic System

A low concentration photovoltaic system is assumed for this application. To generate 4500 kWh $week^{-1}$, after accounting for a 10% distribution loss, a 10% inverter loss and a 15% battery loss, the photovoltaic system must produce 6540 kWh $week^{-1}$. The yearly average insolation on a single-axis tracking surface is about 6.5 kWh d^{-1}. The photovoltaic array size, Ppk, is determined by:*

$$(Ppk)\ (6.5\ kWh\ d^{-1})\ (7\ d\ w^{-1}) = 6540\ kWh\ week^{-1}$$

$$Ppk = 144\ kW$$

With a concentration factor of 2.0, the photovoltaic array size is reduced to 72 kW, and the required concentrator area is 2400 m^2. At current photovoltaic costs ($12,000 per kW) and mirror costs (taken as $60 per m^2) the cost of the array is $1,000,000. Because the load cycle has minimums over the weekends, some energy stored over a weekend could be used during the following weekdays. Accordingly, battery storage for two day's consumption (at the weekday rate) was allowed for. This amounts to 1478 kWh storage. This amount of battery storage would cost $111,000 ($75 per kWh) and would have an average life of seven years. Inverters would also be required at a current cost of $1500

*Appendix 3 describes the procedures used in rating photovoltaic arrays.

per kW capacity. A peak capacity of 200 kW would be required, costing $300,000. Finally, the distribution system would cost the same as in the diesel central plant, namely $60,000. The total initial investment is then about $1,480,000. Yearly costs assuming 20-year life (except for batteries, which have a seven-year life) and 10% interest rates are:

Batteries	$ 22,770	
Remainder	160,685	
Total Annual Cost	$183,455	(79.5¢/kWh)*

At the 1980 DOE cost goals of $2000 per kW for photovoltaics, $500 per kW for inverters and batteries at $50 per kWh, the initial system cost drops to $575,000 assuming a 170-kW-pk array. In this calculation no concentration is assumed because at these prices it will be less expensive. The yearly cost is:

Batteries	$ 15,179	
Remainder	58,730	
Total Annual Cost	$ 73,909	(32.7¢/kWh)*

At 2000 cost goals the central photovoltaic system will drop in price to 10.3¢/kWh.*

3.4 Distributed Photovoltaic Systems

Distributed photovoltaic systems require no power transmission, which eliminates the associated line losses and capital costs. Such systems do, however, require larger on-site inverters to handle peak on-site loads. If the system for Fada N' Gourma were comprised of on-site photovoltaic systems, the total inverter capacity required would be 250 kW; the total battery storage would be 1478 kWh and the total photovoltaic arrays would be 156 kW pk. At 1977 costs, this option would cost 76.2¢/kWh; at 1980 goals it would cost 29.9¢/kWh and at 2000 cost goals it would be 10.3¢/kWh.**

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* This figure includes 1.1¢/kWh for backup diesels which must be maintained for extended periods of low insolation, but whose operating costs are not included.

**All of these calculations assume 1.6¢/kWh for diesel backup capacity but no fuel costs.

3.5 Comparison of Systems for Fada N' Gourma

Costs for the various options are summarized in Table 4. Because of the present high cost of inverters, photovoltaic modules and distribution systems, on-site generation using diesels is currently the least-cost alternative. The costs for a central diesel plant are almost as low as for the on-site diesels

Table 4

Fada N' Gourma Electricity Costs (¢/kWh)

System	- Year - 1977	1980	2000
Existing Distributed Diesels*	18.9	20.3	33.1
Central Diesel Plant*	20.5	22.4	36.1
Central Photovoltaic Plant**			
- 1977 Costs	79.5		
- 1980 Cost Goals		32.7	
- 2000 Cost Goals			11.7
On-Site Photovoltaics ***			
- 1977 Costs	76.2		
- 1980 Cost Goals		29.9	
- 2000 Cost Goals			10.3

* Assumes diesel fuel costs rising at 3% per year

** System sized for 100% of load, includes 1.1¢ per kWh for capital cost of back-up diesel but no diesel operating costs

*** As above, with 1.6¢ per kWh capital cost

and, if installed, could lead to a rapid increase in electric power usage in Fada because the marginal costs of added capacity would decrease with system size. At current prices neither the central nor the distributed solar plants are competitive with the diesel alternatives. However, they will become superior to the diesel in the early or mid-1980's if the Department of Energy can meet its cost goals for photovoltaics. The distributed solar approach will cost slightly less than the central solar plant option.

Fada's current and anticipated future energy needs will dictate the choice of the most appropriate system. A distribution system will make sense only if a greatly expanded number of users is expected. For the present few users, on-site generation makes most sense. A solar option which may soon become viable is to augment the present on-site diesels with distributed photovoltaics.

4.0 UPPER VOLTAN VILLAGE ENERGY USAGE

The preceding discussions concerning Ouagadougou and Fada N' Gourma are not applicable to the overwhelming majority of Upper Voltans who live in small villages and practice subsistence farming for their livelihood. Ouagadougou is not representative of most of the country because Western influences are present in the form of electricity, paved roads, cars and motor bikes, multi-story buildings, city water and sewers (which are open except in Western residential areas). Fada N' Gourma is a step further down in scale, where occasional motor bikes, a small Western community (Peace Corps, Catholic and Protestant missions, USAID agricultural advisors), a Post and Telegraph Office and a small hospital are found. Electric power is generated on-site by small diesel-generator sets at each of these Western introduced facilities as was described previously. Fada is a big town, however, and most people live in small villages. To assist in considering solar energy usage in such villages it is helpful to have some understanding of village life. Appendix 2 provides a brief description.

Could appropriate solar energy technologies make a significant impact in rural Upper Volta where most of the motive energy is derived from human labor and the thermal energy utilized is already solar, namely, wood burning for cooking? Village-scale water pumping and grain-grinding devices have been identified as applications for photovoltaic systems by USAID. Such devices could fit into the daily life of the people, allowing the utilization of the freed time for other purposes such as cultivating additional crops. Water supply is the more significant. If the water table can sustain the demand, greater utilization of water can be expected to yield multiple benefits. First, a reduction in waterborne disease and a resulting decrease in infant mortality can be expected. (Infants are most vulnerable when they are weaned and directly exposed to contaminated water.) Second, more easily acquired water will make it easier to keep cattle in the central region of the country during the dry season. This will not only improve diets with meat and milk, but also make animals available for plowing fields. Current USAID efforts are directed toward establishing a plow-fabricating shop in Fada and introducing animal traction and plows to replace the traditional hoes used for field preparation. Finally, more easily acquired water may make additional vegetable crops possible during the dry season.

Another end use of photovoltaic power could be cooking. Photovoltaics are not generally considered for thermal end-use applications, and current development programs to introduce direct solar cooking using circular parabolic mirror concentrators seem more straightforward and appropriate. These programs, however, are apparently having difficulties overcoming both practical and cultural hurdles. The practical one is finding a way to stir thick toah,* the national food, in a pot suspended at the focal point of a parabolic mirror. This problem may eventually be overcome with time and cooperative inputs from the villagers using these solar cookers. A cultural acceptance problem is that Upper Voltans are accustomed to eating in the evening, not shortly after solar noon. Furthermore, wood fires contribute to the taste they've acquired for toah. Acceptance of these cultural changes is by no means certain.

Solar cooking is practiced by the Upper Voltans because they use wood, a renewable resource. The total stock of trees, however, is declining thus making the long-term future for wood burning uncertain. One possibility worthy of investigation is whether lumber growth for firewood can be accelerated economically through the use of solar-powered water pumping systems for subsurface trickle irrigation. Such an endeavor, if economically viable, could maintain the utilization of wood as a primary fuel. It hinges on whether small amounts of irrigation could produce truly singular effects on lumber growth rates.

Photovoltaic devices used with battery storage could be applied directly to cooking and overcome the cultural problem associated with cooking at noon. The wood-fire-derived taste would, however, be hard to replace. An insulated "crock pot" like device would require less than 1 kWh per meal preparation and stirring the toah in such a device would be no problem. With sufficient battery storage such a system would function on cloudy days. Finally, such cooking pots are uncomplicated electrical devices and could be manufactured in Upper Volta. This is an important consideration for a country with few resources for foreign trade.

A village or large family which utilized a small photovoltaic array to provide a significantly improved water supply, grind grain and replace fire-

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*Uncertain spelling; pronounced "toe."

wood as the cooling energy source, would undoubtedly develop other uses for electric power. A photovoltaic system which would provide the energy needs for a village of 100 inhabitants is described in the following sections.

4.1 Water Pumping

A water pump to provide 25 liters per day per person from a 10-m-deep well using a 50%-efficient pump, a 50%-efficient electric motor and an 85%-efficient battery would require the following daily electric energy input, E_w:

$$E_w = \frac{(25\ l\ d^{-1})(1\ kg\ l^{-1})(9.8\ m\ s^{-2})(10\ m)(100\ people)}{(.5)(.7)(.85)} = 824\ kJ\ d^{-1},$$

which is equivalent to $E_w = 0.23\ kW\ h\ d^{-1}$

4.2 Grain Grinding

The largest dealer in diesel-powered mills in Ouagadougou has sold 45 diesel/mill sets in the last two months. They come in two sizes, an 8-hp diesel with a 40-cm diameter grinding stone which will grind millet at a rate of 200-300 kg h^{-1} and costs 527,000 CFA ($2170); and a 16-hp diesel with a 50-cm diameter stone which will grind millet at a rate of 300-400 kg-hr^{-1} and costs 727,000 CFA ($2990). An average figure for these rates is 25 kg hp^{-1} h^{-1}. According to this diesel dealer a family of 8 consumes about 3 kg of grain per day, thus for 100 people 37.5 kg d^{-1} must be ground. With a 70%-efficient electric motor and an 85%-efficient battery the grinding will require the following daily energy usage, E_g:

$$E_g = \frac{37.5\ kg\ d^{-1}}{(25\ kg\ hp^{-1}\ h^{-1})(.7)(.85)} = 2.52\ hp\ h\ d^{-1}$$

which is equivalent to $E_g = 1.88\ kW\ h\ d^{-1}$

4.3 Cooking

Some rough assumptions concerning the current practice of cooking over open wood fires are that a family of eight, in cooking their evening meal, will burn five pieces of wood each 30-cm long and 4 cm in diameter. Wood tends to have a specific gravity of 0.7 and a heat value of 16.3 MJ kg^{-1} (7000 Btu lb^{-1}).

The energy released in wood fires is then about 22 MJ or 6 kWh per family per day. Assuming one hour for cooking, the power is 6 kW. An alternative using more efficient electrically heated units will require approximately 1 kWh per meal preparation. Assuming an efficiency of 85% for storage batteries, the entire village (12 families) would require the following daily energy, E_c:

$$E_c = \frac{12 \times 1}{(.85)} = 14.7 \text{ kWh d}^{-1}$$

4.4 Lighting

Providing each family with a 50-W light for several hours each evening could make a significant social impact for a moderate increase in overall system size. It may also be needed to replace light given by the wood fire. For three hours per evening this load with 85%-battery efficiency is:

$$E_1 = 2.1 \text{ kWh d}^{-1}$$

4.5 Village Photovoltaic Power

In all a total of 18.9 kWh d^{-1} would be used by this village of one-hundred residents. Neglecting cooking, the requirement is only 4.2 kWh d^{-1}. Water pumping, with the smallest demand by an order of magnitude, could have the most significant near-term impact. Considering the Upper Voltan and Sahel firewood problem, however, all four uses are considered in the following design calculations for a small village.

The array size to produce approximately 20 kWh d^{-1} is determined assuming a low concentration ratio of 2 which will result in approximately a 40% reduction in the array cost at current prices. The average direct solar radiation is about 7 kWh m^{-2} d^{-1}. The required photovoltaic array area (excluding concentrators) is determined using the following equation:*

$$(\text{Array Ppk})(2 \times \text{concentration})(7 \text{ kWh d}^{-1}) = 20 \text{ kWh d}^{-1}$$

$$\text{Array Ppk} = 1.43 \text{ kW}$$

*Appendix 3 describes the procedures used in rating photovoltaic arrays.

The photovoltaic area in such an array is approximately 20 m^2. Also, 40 m^2 of mirror concentrators are needed and battery storage for one day's consumption is required. The present (1977) cost of the system is based on unit costs of $12,000 per kW for photovoltaics, $60 per m^2 for mirrors and $75 per kWh for batteries, and amounts to about $21,000 for the photovoltaic system. The cost of the pump, mill and DC electric motor will add about $2000 to the first cost. The monthly cost of such a system (using 10% annual interest) is about $240. At 1980 DOE cost goals for photovoltaic modules and batteries, the investment becomes about $8300 and the monthly cost is $94. The technical and economic aspects of a small village system are summarized in Table 5.

Table 5

Technical and Economical Aspects of Village Photovoltaic Power*

Component	First Costs ($)		Monthly Costs**	
	1977	1980	1977	1980
Photovoltaic modules 1.45 peak kilowatt capacity (20 m^2)	17160	2860	166	28
Mirrors used for low concentration (40 m^2)	2400	2400	23	23
Lead-acid batteries for energy storage (20 kWh)	1500	1000	25	17
Direct-current motor, grain mill, water pump, cookers and lights	2000	2000	26	26
Total Costs	$23060	$8260	$240	$94

*Designed to provide for the grain grinding, potable water supply, cooking and lighting needs of a small village of one-hundred residents

**Based on 10% interest rates

This analysis has been based on many rough assumptions which should be researched and specified more precisely. The costs - especially at photovoltaic prices appoaching DOE cost goals - and the potential rural development benefits to be derived from on-site photovoltaic generation warrant further study and the initiation of development activities.

In concluding that power systems using photovoltaic modules have many promising applications in Upper Volta, a critical issue is raised concerning the degree to which such devices can be manufactured within the country. Upper Voltans are industrious, but they have little to export, and hence can not be expected to purchase large quantities of assembled modules from foreign suppliers. Minimization of foreign imports and maximization of the use of Voltaic human resources greatly enhances the prospects for introducing any new technology. Future application studies should also address the feasibility of module assembly within the Republic of Upper Volta.

APPENDIX 1: Embassy Cooling Load Calculations

The following analysis is based on the steady-state heat gain of the building under extreme conditions. Because thermal-mass effects tend to level heat gain maximums and permit night radiation of heat gained during the day, the peak calculations which follow overestimate the required heat rejection capacity of the cooling system. The daily cooling load is inferred in this analysis from the daily maximum rate. To determine this total daily load a load profile over an entire day, not just a peak rate, is needed. As a safe assumption (over designed capacity), the design-capacity profile is assumed to attain the peak day rate. The assumed profile is given in Figure 8. The sharp drop at 18 hours (6 p.m.) occurs when the system is turned off for the night.

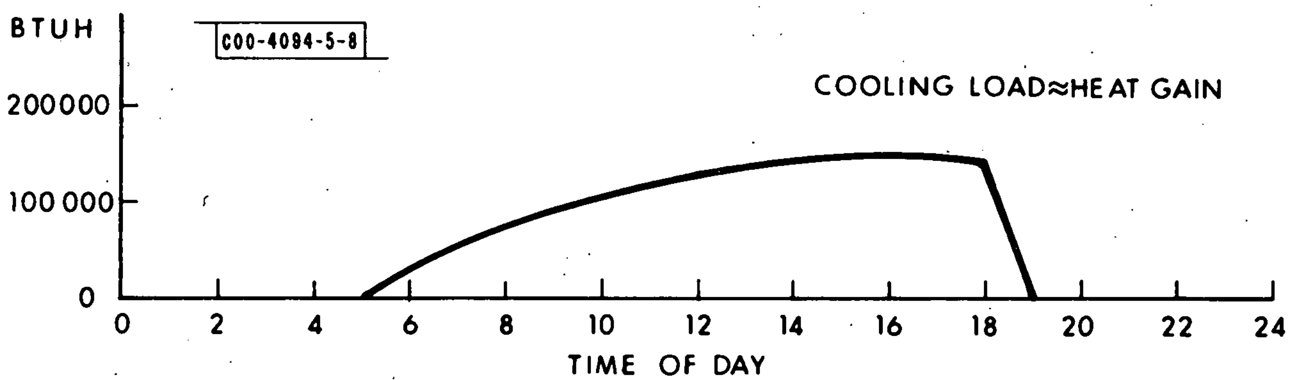

Figure 8
Heat Gain Daily Profile

Maximum heat-gain-rate calculations are determined using the equation $Q = A \cdot U \cdot \Delta T$ where Q is the heat gain in BTU's per hour (Btuh), A is the area of a surface (ft^2), U is the thermal conductivity through the surface (Btuh $ft^{-2}\ °F^{-1}$) and ΔT is the temperature difference through the wall. Assumed temperatures–are:

Outdoor design temperature 110°F dry bulb
85°F wet bulb

Indoor design temperature 75°F dry bulb
62.5°F wet bulb

1. The roof is assumed to be steel with 2" of insulation (U=0.125 Btuh/ft^2°F) completely shaded from direct sun by solar collectors and therefore at the ambient outside air temperature. The roof area is 3119 square

feet. Q_r = (3119) x (0.125) x (110^o - 75^o) = 13,647 Btuh

2. The north, south and east wall gains are calculated assuming 1" stucco and 8" concrete block (U = 0.349 Btuh/$ft^{2o}F$) construction. The walls are partially shaded so that the average surface temperature will be only approximately 5^oF above ambient. The wall area is 3447 square feet. Q_{nse} = (3447) x (0.349) x (115^o - 75^o) = 48,120 Btuh

3. The west wall is exposed to the afternoon sun and experiences larger heat gains. The construction is the same as other walls, although some insulation would be helpful (U = 0.349). The area of the west

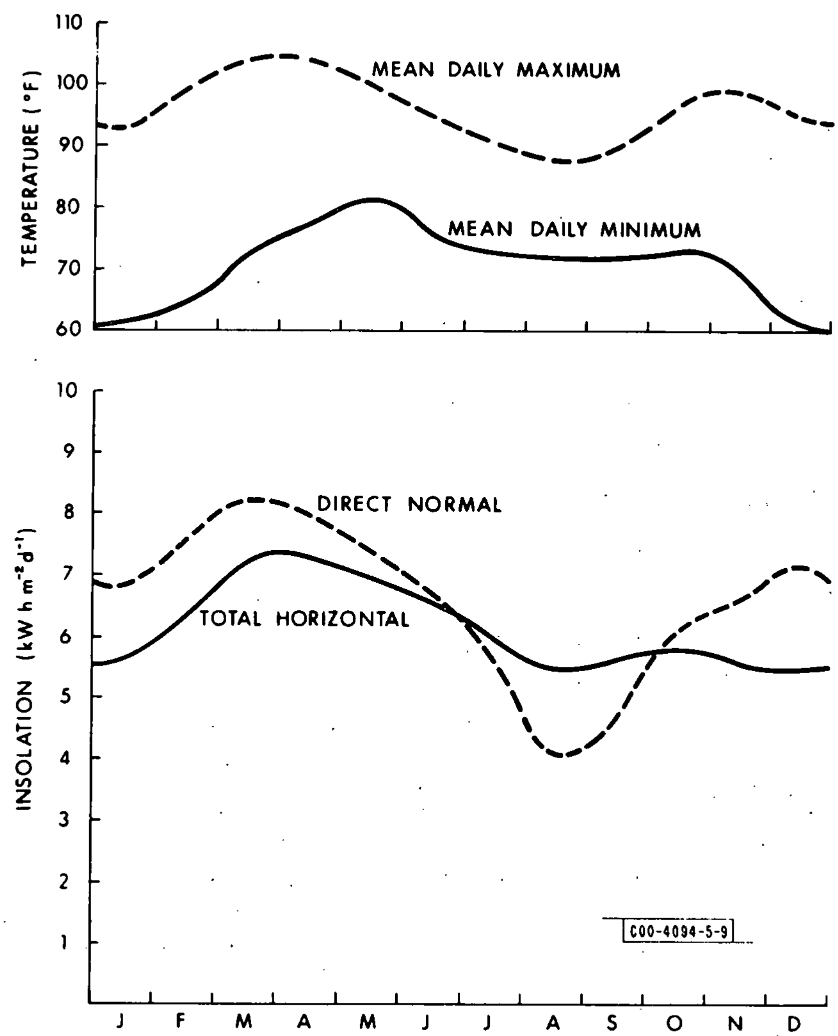

Figure 9
Annual Ouagadougou Temperature and Insolation Profiles

wall is 1729 square feet and the surface temperature is taken to be $20^{o}F$ above ambient. It is only partially shaded.

$Q_w = (1729) \times (0.349) \times (130^{o}F - 75^{o}F) = 33,188$ Btuh

4. Ventilation loads are based on supplying 15 cubic feet per minute of outside air for each of the assumed twenty occupants of the building. As a practical matter this will most likely result from air infiltration rather than using an air-handling system. Double entrance doors might be needed to keep the infiltration from exceeding this amount. The air-change load is composed of both latent and sensible gains.
   a. Sensible*
      11,531 Btuh
   b. Latent*
      17,431 Btuh

   The total ventilation load is 28,962 Btuh.
5. Lighting loads result from the use of electric lights in offices. A load of 250 watts (per person) is assumed or 5 kW for the building. This equals a thermal load of 17,061 Btuh.
6. People radiate heat at a rate of approximately 200 Btuh resulting in a combined load of 4,000 Btuh.

The sum total of all these peak heat gains is 144,978 Btuh or just in excess of 12 tons of peak cooling capacity (1-ton cooling equals 12,000 Btuh). To predict the integrated capacity required over a day the assumption is made that the demand varies as sketched in Figure 8. The daily total heat gain is 1,200,000 BTU's.

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*These calculations are based on equations 53 and 55 given on page 422 of the ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1974.

APPENDIX 2: Upper Voltan Village Life

A composite small village, as drawn up from observations and discussions with USAID personnel, is 10 kilometers down a path from the main road and located in an absolutely level savanna landscape. A dozen families live there. These are extended families - headed by the eldest male. With him lives his wives, children and grandchildren. When he dies, his wives will become the wives of his next younger brother. The family structure is the smallest unit in an organized rural social structure. The village chief forms the link between the families and the government. He collects an annual head tax for the government and keeps a small part for himself and village projects.

Each family has a compound of small (~3m diameter) round huts with thatch roofs and mud brick walls. A wall enclosing the compound - partly mud brick and partly woven elephant grass - confines poultry and goats. Prosperous families may have purchased, listed in increasing levels of opulence, a transistor radio, a bicycle, a metal roof for one hut or a motorbike.

The family activities vary with the seasons. Most of the rain in the area falls between May and October. During this time crops of millet, red and white sorghum, groundnuts (peanuts) and rice (in scattered swampy areas) are grown. Fields are small, perhaps a quarter hectare. Planting is not in rows, different grains may be planted together and the overall field shape probably is not rectangular. Nevertheless the particular piece of land is known to belong to a specific family even though it may be a kilometer or two from their compound. The men in a family work the land; it is generally the only work they do during a year. They begin by "plowing" the field. Traditionally this is done with a small wooden hoe fitted with a heavy-gauge metal blade. At the end of the growing season, the grains are left to dry on the stalk and are harvested only after the beginning of the dry season in mid-October. When the crop has dried it is cut, the chaff beaten off and the grain stored. Fodder crops and vegetables are occasionally planted during the end of the rainy season and grown in the fall. During the remainder of the year, the women in the family do most of the work.

Their daily activities include gathering firewood, fetching water, going to "market," grinding millet and sorghum for cooking "toah,"* the mainstay of

*Uncertain spelling; pronounced "toe."

their diet, and cooking. In addition there are children. A man must plan to have six children to "guarantee" a surviving male son. Because the society is polygamous, however, each woman need not have six children.

Firewood gathering occupies a woman on the average several hours per day. This wood, generally of branch size (ten centimeters in diameter maximum) is essential for cooking toah. A woman may have to walk up to 5 kilometers from her village collecting wood which she will carry on her head in a basket. (The resulting poise and posture of African women is immediately apparent to a Westerner.) Wood for the people of Ouagadougou, however, is currently carried from as far as 50 kilometers by a seemingly endless conveyor line of small donkey carts on the main roads. Supplying wood is a major problem - it occupies a lot of time and the pressure on the sparse stock of trees is apparently a cause of the gradual desertification in the northern Sahel portion of the country.

Fetching water is also time consuming. Women carry it on their heads in earthenware jugs. During the wet season a shallow well near the family compound may be used. During the winter, however, women must walk several kilometers to the one deep hand-dug well in the area. Here she will throw a bucket on a rope down perhaps 10 meters to bring up the water. If fortunate, a crude winch will be fixed over the well so the water need not be pulled up hand over hand.

Every three days women from the village go to market at a larger central village. They leave early for they must first walk 10 km to the main road and then 5 km to the town. At the "marché" people from surrounding villages gather to trade. They may be trading their surplus grain for clothing, some vegetables, perhaps a new battery for a radio. They may also have some millet ground at a diesel-powered mill, paying the mill owner with a fraction of the grain.

Most grain, however, will be ground in the family compound using a large earthenware mortar and a wooden pestle formed from a straight branch about 10 centimeters in diameter and 1.5 meters long. This ground millet is then used to make toah, a millet "hot cereal" which has a consistency between that of thick oatmeal and dumplings. Toah is cooked over a wood fire in the evening and must be stirred during preparation. A separate fire is often used for a sauce which is eaten with the toah. This sauce consists of a chile or tomato base and may contain other vegetables and some fresh meat when available. The meal is eaten with one's fingers - no utensils. In the morning - after sleeping inside or outside depending on the weather - breakfast will consist of the cold leftovers from the previous night.

There are few frills or surpluses in Upper Voltan village life and by any Western standard these villages are extremely poor. They hover on the edge of subsistence, suffering disease, malnutrition and even starvation during extended droughts such as occurred in the early 1970's. In spite of their lot, however, these people seem genuinely content. They are extremely outgoing and friendly and harbor no apparent resentment of most Westerners' relative affluence.

APPENDIX 3: Nominal Rating of Photovoltaic Arrays

The size of a solar photovoltaic power system is generally given in terms of the photovoltaic array's (the energy collectors exposed to the sun) "peak power" defined by the symbol Ppk. The peak power of an array is the amount of power produced when the sun's radiation (insolation) in the plane of the array measures one kilowatt per square meter (1 kW m^{-2}) with the individual solar cells at a temperature of 28°C (82.4°F). A relatively simple mathematical expression can be used to predict solar array output for other insolation levels and cell temperatures. The dependence of power on insolation is linear, dropping to zero power at zero insolation and passing through the "peak power" when the cells are at 28°C. In the approximate operating temperature range for silicon solar cells from 0°C to 100°C, the effect of the temperature difference from 28°C is to reduce the value at 28°C by about 0.5% for each degree Centigrade rise in cell temperature.

The combined insolation and temperature effects are expressed mathematically by the following expression:

$$P(I,T) = Ppk\ I\ [\ 1.0 - 0.005\ (T-28)\ ]$$

where I is the instantaneous insolation in kW m^{-2} received at the outer surface of the collector and T is the cell temperature.

The insolation received on an array varies over the day as does the ambient temperature and, therefore, cell temperature. The total daily energy, Ed, produced by an array is exactly computed with:

$$Ed = Ppk \int_0^{24} I(t)\ [\ 1.0 - 0.005\ (T(t) - 28)\ ]\ dt$$

where I and T are shown to be functions of time, t, which is the time of day in hours. (The range of integration could obviously exclude the periods before dawn and after dusk, but definition of these events is imprecise. Note that sunrise and sunset cannot be used because of the light in the sky when the sun is below the horizon.)

Solar radiation data are frequently recorded in terms of the total solar energy falling on a horizontal square meter during a day. Proven algorithms can be used to estimate the daily amount of solar energy falling on various tilted surfaces from their measurement on a level surface. Thus the quantity

$$Id = \int_0^{24} I(t)\, dt$$

is generally obtainable for making estimates of photovoltaic system performance.

To proceed farther, it is necessary to specify an average cell operating temperature, To, for substitution in the equation for the total (daily) energy, Ed. Then one has:

$$Ed = Ppk \ [\ 1 - 0.005\ (To-28)\ ] \int_0^{24} I(t)\, dt$$

$$= Ppk \ [\ 1 - 0.005\ (To-28)\ ]\ Id$$

which relates the energy produced daily to the peak power, the average cell temperature and the daily insolation.

The units of the variables and constants in the above expression are often misinterpreted and can result in some confusion. Ed is measured in kilowatt-hours of electric energy per day ($kWhe/d^{-1}$) and Id in kilowatt-hours of solar radiation incident upon a square meter of array surface per day ($kWhs\ m^{-2}/d^{-1}$). To is given in degrees Centigrade and the constant, 0.005, has units of inverse degrees Centigrade. The true units of Ppk are then kilowatt hours electric per kilowatt hours solar per square meter ($kWhe/kWhs^{-1}/m^2$), or just square meters (m^2). Common usage, however, is to give Ppk in kWe by cancelling the hours units and assuming unit insolation, 1 kWs m^{-2}.

In making rough analyses of photovoltaic array output, temperature effects are often ignored and the energy generated in a day is calculated with the product of the array peak power and the daily insolation,

$$Ed\ (kWhe) \approx Ppk\ (kW)\ \ Id\ (kWhs\ m^{-2}\ d^{-1})$$