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ANALYSIS OF BATTERIES FOR USE IN PHOTOVOLTAIC SYSTEMS

Volume 1. Final Report

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By
Amitava Podder
Mark Kapner

February 1981

Work Performed Under Contract No. AC01-79ET25202

Hittman Associates, Inc.
Columbia, Maryland

U.S. Department of Energy

Solar Energy

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ANALYSIS OF BATTERIES FOR USE IN PHOTOVOLTAIC SYSTEMS
VOLUME 1

Contract No. DE-AC01-79ET25202
Final Report

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and
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Submitted to:

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Division of Energy Storage Systems
Washington, DC

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February 1981

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

LIST OF TABLE (CONTINUED)

LIST OF TABLES (CONTINUED)

EXECUTIVE SUMMARY

A. Introduction

This volume describes Hittman Associates' evaluation of 11 types of secondary batteries for energy storage in photovoltaic electric power systems.* The evaluation was based on six specific application scenarios which were selected to represent the diverse requirements of various photovoltaic systems. Electrical load characteristics and solar insulation data were first obtained for each application scenario. A computer-based simulation program, SOLSIM, was then developed to determine optimal sizes for battery, solar array, and power conditioning systems. Projected service lives and battery costs were used to estimate life-cycle costs for each candidate battery type. The evaluation considered battery life-cycle cost, safety and health effects associated with battery operation, and reliability/maintainability.

This volume contains recommendations for a research and development program focused on battery energy storage for photovoltaic applications. It also contains a discussion of electrical interfacing problems for utility line-connected photovoltaic power systems.

B. Application Scenarios

The six application scenarios considered in the battery evaluation were:

(1) A single-family house in Denver, Colorado (photovoltaic system assumed to be connected to the utility line)

(2) A remote village in equatorial Africa (stand-alone power system)

(3) A dairy farm in Howard County, Maryland (onsite generator assumed to provide backup power)

(4) A 50,000 square foot office building in Washington, DC (onsite generator backup)

**The 11 battery types were:* *lead-acid, nickel-zinc, nickel-iron, nickel-hydrogen, lithium-iron sulfide, calcium-iron sulfide, sodium-sulfur, zinc-chlorine, zinc-bromine, Redox, and zinc-ferricyanide. The scope of work was restricted to these 11 types.*

(5) A community in central Arizona with a population of 10,000 (battery to be used for dedicated energy storage for a utility grid-connected photovoltaic power plant)

(6) A military field telephone office with a constant 300W load (trailer-mounted auxiliary generator backup).

The solar array size and battery voltage, capacity, and discharge rates for each application scenario are presented below:

Application	Array Size	Voltage	Battery Capacity	Maximum Discharge Rate
Residential	4 kWp	250V	15 kWh	C/5
Remote Village	3.3 kWp	120V	125 kWh	C/60
Dairy Farm	20 kWp	250V	50 kWh	C/3
Office Building	500 kWp	300V	700 kWh	C/7
Small Community	14.7 MWp	1000V	37.5 kWh	C/5
Military	2.5 kWp	60V	6 kWh	C/18

C. Cost Analysis of Battery Systems

A detailed analysis was performed to estimate the range of likely selling prices for the lead-acid, nickel-hydrogen, lithium-iron sulfide, calcium-iron sulfide, zinc-bromine, and Redox Batteries. Selling price projections were based on the EPRI Standard Costing Methodology for Utility Load-Leveling Batteries. Current materials prices were applied to the most recent battery designs, along with estimates of labor, equipment, and manufacturing plant requirements (supplied by battery developers). The selling price estimates allowed for a 30 percent (before tax) return on investment in the manufacturing facility. The ranges of likely selling prices for the other battery systems were obtained from manufacturers. The following selling prices were projected:

Lead-Acid	\$57 to 125/kWh
Nickel-Hydrogen	\$180 to 250/kWh
Lithium-Iron Sulfide	\$42 to 72/kWh
Calcium-Iron Sulfide	\$32 to 40/kWh
Zinc-Bromine	\$30 to 70/kWh
Redox	\$300/kW + \$14/kWh to \$615/kW + \$40/kWh

A life-cycle cost analysis was performed for all the batteries. The life-cycle cost of a battery is defined as the present value of the costs incurred by the user over the course of the project life (20 years for this study). It included the first cost, the present value of battery replacement costs over the project life, and the present value of operation and maintenance costs over the project life. Table 1 shows present battery life-cycle costs.

D. Evaluation Methodology

The evaluation considered three factors: cost, safety/health, and reliability/maintainability. Development risk was not included in decision making. Special requirements imposed by each application were also taken in account. For example, only batteries with a self-discharge rate of less than 10 percent per month were considered suitable for stand-alone applications. In estimating battery cost, estimated battery life-cycle cost, auxiliary system cost, and battery energy efficiency were considered. Relative costs were then normalized on a scale of 1 to 10. A set of weighting factors was applied to each application scenario to reflect the relative importance of each attribute for that scenario. Reliability/maintainability and health/safety of each battery were rated on a subjective basis, using a 1 to 10 interval scale. For each application, a figure of merit was then computed for each battery by multiplying the rating values for cost, reliability, and safety by their corresponding weighting factors and summing the products. Table 2 lists the batteries which were selected as the most promising candidates for the application scenarios.

TABLE 1. BATTERY LIFE-CYCLE COSTS, PRESENT VALUE (1980$)

(20-year project life, 10 percent discount rate)

Battery	Estimated Selling Price $/kWh	Cycle Life (Projected)	Present Value Cost ($/kWh)	Uncertainty in Present Value Cost ($/kWh)
Pb-Acid (Current)	$125	1,800*	$269	0
Pb-Acid (Advanced)	72	4,000	91	±37
Ni-Fe	82	2,000*	168	±66
Ni-Zn	55	1,000	202	±153
Ni-H_2	215	30,000	215	±33
LiAl-FeS	57	2,000	120	±61
LiSi-FeS	57	3,000	90	**
Na-S (Glass)	40	2,500	71	**
Na-S (β Alumina)	48	2,500	85	±23
CaSi-FeS	36	2,500	65	**
Zn-Br_2	50	5,000	60	**
Redox	$450/kW + $27/kWh	10,000	$450/kW + 27/kWh	**
$ZnCl_2$	$128/kW + $14/kWh	5,000	$152/kW + 17/kWh	**
Zn-$FeCN_6$	$230/kW + $32/kWh	5,000	$274/kW + 38/kWh	**

---

*Achieved

** Computed uncertainty exceeds estimated value.

TABLE 2. MOST PROMISING BATTERIES FOR THE APPLICATION SCENARIOS UNDER STUDY

	Residential	Remote Village	Dairy Farm	Utility	Office	Military
Lead-Acid	X	X	X	X	X	X
Redox		X				
Zinc-Bromine	X		X		X	
Zinc-Chlorine					X	
Calcium-Metal Sulfide					X	
Nickel-Hydrogen						X
Zinc-Ferricyanide			X			

There is a considerable degree of uncertainty in the ratings for all three attributes used in the ranking analysis. The reliability and health/safety attributes were rated subjectively, using available information on batteries. Most of this information is qualitative. A range of uncertainty of 25 percent is inherent in the process of assigning quantitative ratings on the basis of qualitative information. A quantitative uncertainty analysis was performed on the estimates for life-cycle costs. Uncertainty values for battery first costs, auxiliary cost, and cycle life were applied to the values for life-cycle costs, and the uncertainties were used in the evaluation and ranking of the batteries.

The batteries listed in Table 2 were selected as most promising on the basis of their figures of merit (FOMs). It must be noted, however, that the differences between their FOMs are smaller than the ranges of uncertainty in most of the FOMs. An important finding of this study is that the distinction between several battery types with regard to suitability for photovoltaic energy storage is somewhat obscured by the uncertainty in estimated battery cost and life expectancy.

E. Recommended Research and Development Program

A market assessment of photovoltaic power systems should develop realistic projections of the near-term and intermediate markets for batteries to meet the energy storage needs of the photovoltaic power market. The market assessment should project the number of batteries and their capacities and discharge rates. A decision should be made on whether or not development work should be directed toward utility batteries for co-located energy storage in utility grid-connected photovoltaic systems. Recent studies have suggested that such configurations are not always economical, and that utility system-wide general storage is preferable to photovoltaic dedicated storage. If this finding is confirmed, then further battery development for photovoltaics should be directed toward stand-alone systems and load-leveling applications.

Specific R&D needs for the most promising battery systems are as follows:

1. Lead-Acid

Develop a better method for protecting lead-acid cells from sulfation when the battery is at a low state of charge for long periods of time. Other development needs are already being addressed in the DOE/EPRI programs to develop load-leveling batteries for utilities.

2. Calcium-Iron Sulfide

Determine minimum practical cell size. Determine the effect of low charge/discharge rate operation. Other development needs are already being addressed in the load-leveling and electric vehicle battery programs.

3. Zinc-Bromine, Zinc-Chlorine, and Redox Flow

Determine minimum practical size (power and energy storage). Design low head pumps capable of very efficient operation at variable flow rate. Examine feasibility of automatic pump shutdown/startup.

Other development efforts (e.g., reducing membrane resistivity in Redox batteries, designing inexpensive reactant tanks, cycle life testing, reactant cost reduction study) are already underway.

4. Nickel-Hydrogen

This battery is not currently under development by DOE or EPRI. Research on Ni-H_2 cells has been supported by the U.S. Ar Force and by COMSAT. Becaus of their high reliability and long cycle life, Ni-H_2 batteries are beginning to replace nickel-cadmium batteries for energy storage in communication satellites. Cost is the key issue in assessing whether Ni-H_2 batteries can be competitive for terrestrial photovoltaic applications. Both electrodes, the sintered nickel cathode and the hydogen anode, are high-cost items in the state-of-the-art Ni-H_2 batteries. In deciding whether or not to initiate a full-scale development program for this battery, the following issues must be resolved:

(a) Can the quantity of platinum used to catalyze the hydrogen anode be substantially reduced or even replaced by a significantly cheaper material? What is the lowest-cost anode that still gives acceptable performance? (As determined by battery requirements listed above.)

(b) Can the sintered nickel cathode by replaced by a pocket-plate or pressed electrode?

(c) What would the self-discharge rate be if the maximum hydrogen pressure were reduced?

(d) What are the performance characteristics at reduced hydrogen pressures?

(e) What effect would the pressure vessel have on cost?

If there is a high probability that a redesigned Ni-H_2 battery that fulfills these requirements can be built for \$100 to \$150/kWh, a development program is recommended.

5. Zinc-Ferricyanide

(a) Evaluate alternative low-cost separator materials and determine specific resistance, iron and zinc permeation rates, and mechanical and chemical stabilities.

(b) Perform microscopic studies on the quality of zinc electrodeposition obtained using electrolyte additives and flow rate/flow distribution modification in half-cell cycling.

(c) Obtain additional information on the long-term stability of a sodium ferricyanide electrolyte.

(d) Investigate the use of a lower-cost electrode substrate than the porous nickel plaque now used.

I. INTRODUCTION

Hittman Associates performed an assessment of batteries that are suitable for use in various applications of photovoltaic systems. The objective of this study was to compile an up-to-date comprehensive data base for research, design, and development of photovoltaic systems, primarily in the areas of applications and battery technology, and secondarily in the area of power conditioning and photovoltaic array technology. The study involved the compilation and systematic organization of the available data on existing and potential terrestrial photovoltaic applications, with particular emphasis on six specific applications.

The documentation of this study consists of two volumes. This volume, Volume 1, contains the design and analysis of the photovoltaic systems with battery storage for each of the six end-use applications. For each end-use area, a scenario was developed in which the most promising storage battery systems have been identified. The R&D needed for the most promising battery systems have also been determined.

The six applications studied were:

- Remote - a remote village
- Residential - a single-family house
- Commercial/institutional - a commercial office building
- Industrial/utility - a dedicated utility for a small community
- Agricultural - a dairy farm
- Military - a field telephone office.

Sections II, III, IV, V, VI, and VII, shows the load profiles and discuss the preliminary design of the photovoltaic systems for the six end-use applications.

Section VIII contains the results of the cost analysis. The present value of the life-cycle cost of the batteries was calculated. The life-cycle cost included the first cost, replacement cost, and the projected life cycle of the batteries.

Section IX contains the evaluation and ranking of the battery systems for the six end-use applications. The most promising battery systems are identified in this section.

Section X describes the final design of the photovoltaic systems with the most promising battery systems.

Section XI discusses the interfacing considerations of the power conditioner, array, battery, and the utility.

Section XII contains the recommended R&D for the promising battery systems.

Section XIII contains the bibliography, and Section XIV contains a glossary of abbreviations used in this volume.

II. PHOTOVOLTAIC SYSTEM FOR AN AGRICULTURAL APPLICATION - A DAIRY FARM

A. Load Profiles and Characteristics

1. Background

As of 1974, there were 196,057 farms in the United States for which the sale of dairy products amounted to 50 percent or more of their revenue (1). During that same period, there were approximately 11.1 million milking head in the United States (2). Virtually all of these farms use electromechanical devices to milk their cows and electrochemical means to refrigerate the milk. The electrical energy requirements are substantial and represent a potential future application for photovoltaic electricity, provided the economics become more favorable.

Due to the lack of information in the literature on the electric energy use patterns of dairy farms, this scenario was based on an audit of a dairy farm located in Howard County, Maryland. At the time of the audit, the farm had 130 head, 110 of which were producing milk. The national average in the United States is around 55 head per dairy farm. However, 130 head is not atypical for a dairy farm.

The basic electrical needs of a dairy farm include:

(a) Electric power to run milking machines

(b) Electric power for refrigeration of milk

(c) Electric power for heating wash water (energy can be alternatively supplied by LPG or NG)

(d) Electric power for lighting.

On the dairy farm under study, the milking parlor is a New Zealand herringbone type. Under this system, there are 12 stalls set up in two rows of six. Six cows can be milked at one time. Six cows are brought in, their udders are washed and dried, and then they are milked. While the first six cows are being milked, the second set of cows are brought in and are washed.

When the first set of cows have been milked, the milking attachments are moved to the udders of the second set of cows. The first set of cows are moved out of the parlor and replaced by a new set of cows, which are then washed and milked. This process is repeated until the whole herd has been milked. The milking operation is performed morning and evening, seven days a week, 52 weeks a year. Typical hours of operation for 110 cows are 7:00 to 9:00 a.m. and 5:30 to 7:30 p.m.

The electrical elements of the milking system are:

(a) A vacuum pump to reduce pressure which draws milk out of the teat into the milker bottles.

(b) Pulsator motors to remove the vacuum on the teat and allow blood to circulate.

(c) A clean-up water pump to deliver hot water from storage to the cows.

(d) A milk pump to move milk out of the milkers to storage.

The next phase of the operation is refrigerated storage. At the farm under consideration, milk is stored in a 1,500-gallon stainless steel tank. A refrigeration system is provided to cool the milk and keep it cool while in storage. Milk is taken to market every other day. The electrical elements of the refrigeration system are:

(a) A compressor motor on the refrigerator

(b) A condenser fan motor on the refrigerator

(c) An agitator motor on the milk storage tank

(d) An automatic tank washer.

The hot water requirements of dairy farms are considerable, as proper sanitary controls are essential. Hot water is required for washing the cows, the milking system, and the milk storage system. Hot water is usually provided by liquid petroleum gas or natural gas, if available. Under the chosen scenario, however, water is provided by a well and heated by an electric resistance system. As an energy conservation measure, a heat recuperator has been added to the hot water system. This recuperator uses waste heat from the refrigeration equipment to preheat the water entering the hot water heaters. The electrical elements of the water system are:

(a) A water pump

(b) Electric resistance water heaters

(c) A heat recuperator system.

Other energy requirements of the dairy farm are space heating and lighting. The only heating requirements of cow barns is to keep the milking parlor warm enough for its human operators. In this scenario, the space heating requirements are met by liquid petroleum gas. The lighting for the milking parlor, milk storage room, and other work areas is incandescent.

2. Characteristics of the Load Elements

The following subsections discuss the power requirements, power factor, and transient characteristics of the major load elements.

a. Milking System. Table II-1 lists the electrical characteristics of the major load elements of the milking system.

Starting inrushes on motors will run five to six times the rated kVA shown in Table II-1. The most significant of these will be, of course, the inrush kVA for the five-horsepower vacuum pump motor, which will run at 30 to 36 kVA.

TABLE II-1. LOAD ELEMENTS OF THE DAIRY FARM MILKING SYSTEM

Device	Qty.	Volts	Hz	ph	FLA*	hp	kW	KVAR	kVA	pf
Vacuum pump	1	230	60	1	26	5	4.5	4.0	6.0	0.75
Clean-up water pump	1	230	60	1	4.9	3/4	0.8	0.8	1.1	0.70
Pulsator motors	2	230	60	1	2.8	1/3	0.4	0.5	0.6	0.60
Milk pump	1	230	60	1	3.4	1/2	0.57	0.6	0.8	0.65

*FLA = Full Load Amperes

b. Refrigeration System. Table III-2 lists the electrical characteristics of the major load elements of the refrigeration system.

TABLE II-2. LOAD ELEMENTS OF THE DAIRY FARM REFRIGERATION SYSTEM

Device	Qty.	Volts	Hz	ph	FLA*	hp	kW	KVAR	KVA	pf
Compressor motor	1	230	60	1	29.5	5	5.43	4.1	6.79	0.80
Condenser fan motor	1	230	60	1	3.6	1/2	0.53	0.70	0.83	0.70
Agitator motor	1	230	60	1	2.5	1/3	0.38	0.44	0.58	0.65
Automatic tank washer*	1	230	60	1	6.6	--	--	--	--	--
Automatic washer motor	1	230	60	1	4.9	3/4	0.8	0.81	1.13	0.70

**FLA of Automatic Tank Washer includes Automatic Tank Washer Motor.*

Starting inrush kVA on these motors will run five to six times the rated load kVA shown in Table II-2. The largest inrush will come from the compressor motor, which has a locked rotor current of 157 amps or 36.1 kVA at 230 volts.

c. Hot Water System. Table II-3 lists the electrical characteristics of the major load elements of the hot water system.

TABLE II-3. LOAD ELEMENTS OF THE DAIRY FARM HOT WATER SYSTEM

Device	Qty.	Volts	Hz	ph	FLA	Size	KW	pf
Water heater	2	240	60	1	10.4	82 gal.	2.5	1.0
Water pump	1	230	60	1	5.1	0.75 hp	0.79	0.80
Heat exchanger	1	230	60	1	0.26	---	0.03	0.50

d. Lighting Requirements. Table II-4 shows the lighting requirements of the dairy farm.

TABLE II-4. LIGHTING REQUIREMENTS OF THE DAIRY FARM

Device	Qty.	Volts	Watts	pf
Lighting (incandescent)	10	115	75	1.0
Lighting (fluorescent)	1	115	100	1.0

3. Energy Use Patterns and Load Profiles

Figure II-1 shows the load profile of the power at the chosen dairy farm on a summer day, using 15-minute average demand intervals. A study of the past energy usage shows that the maximum energy demand use is in the winter months. Thus, the load profile shown does not represent the maximum load. Assuming a direct correlation between energy usage for a month and peak power demand for that month, the maximum demand will be 15.2 kW during the winter months.

Since the load is largely created by motors, the power factor on the line will be quite poor, around 0.75 to 0.80 during the peak demand periods.

Figure II-2 shows the electric energy usage in kWh by month.

B. Sizing of the Array and the Battery

For this scenario, an onsite diesel-fuel electric generator was included in the parametric system design to provide auxiliary power. The generator was assumed to operate in the following manner:

- It is switched on when the electrical demand exceeds the combined output of the array and output capability (stored energy) of the battery. If the generator capacity exceeds the demand, then the generator itself supplies the demand. If the generator alone is inadequate, the battery and generator together supply the demand. If the demand is less than one-half the generator capacity, the generator runs at half its maximum capacity and charges the battery while at the same time delivering electricity to the load. A 15 kVA generator was included in the dairy farm PV system.

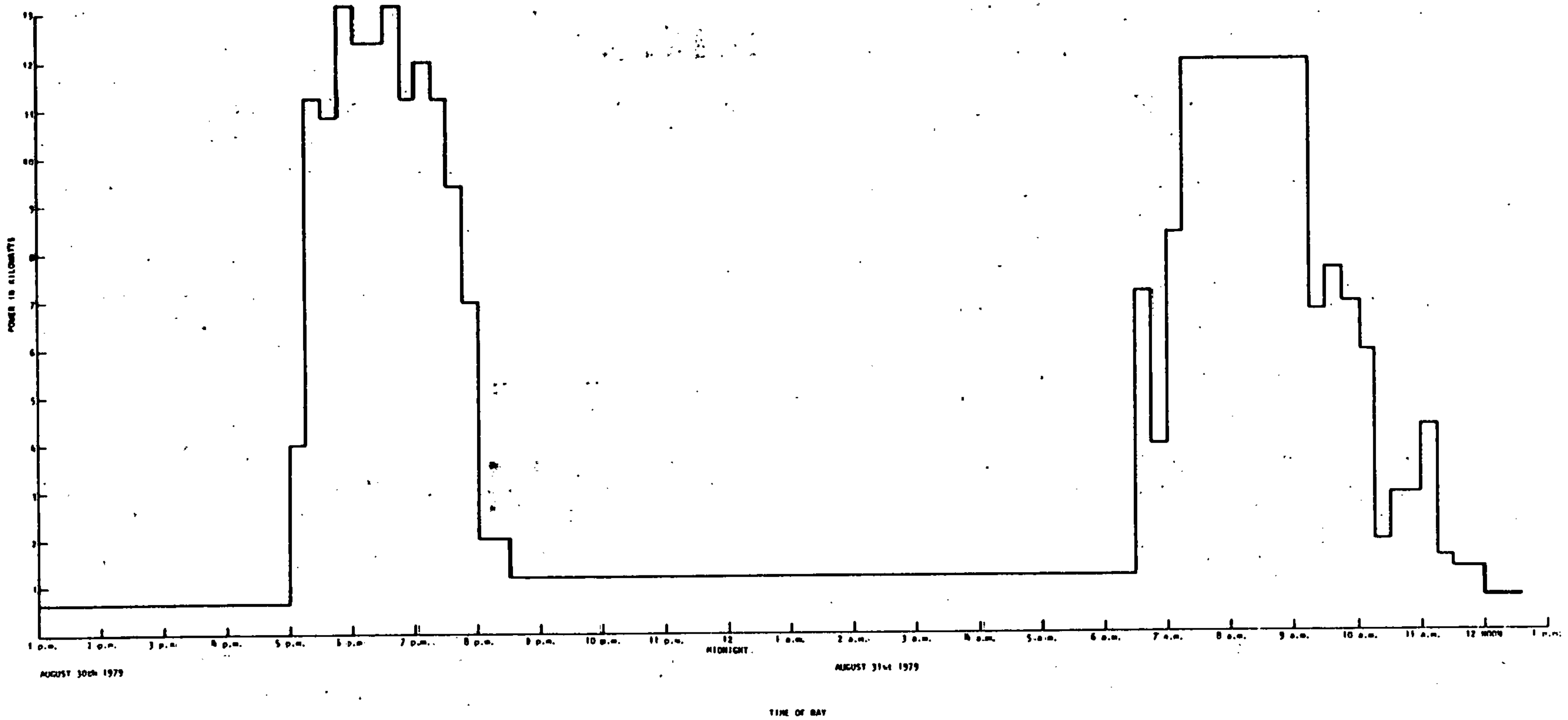

Figure II-1. Load Profile of Dairy Farm Electric Power Demand

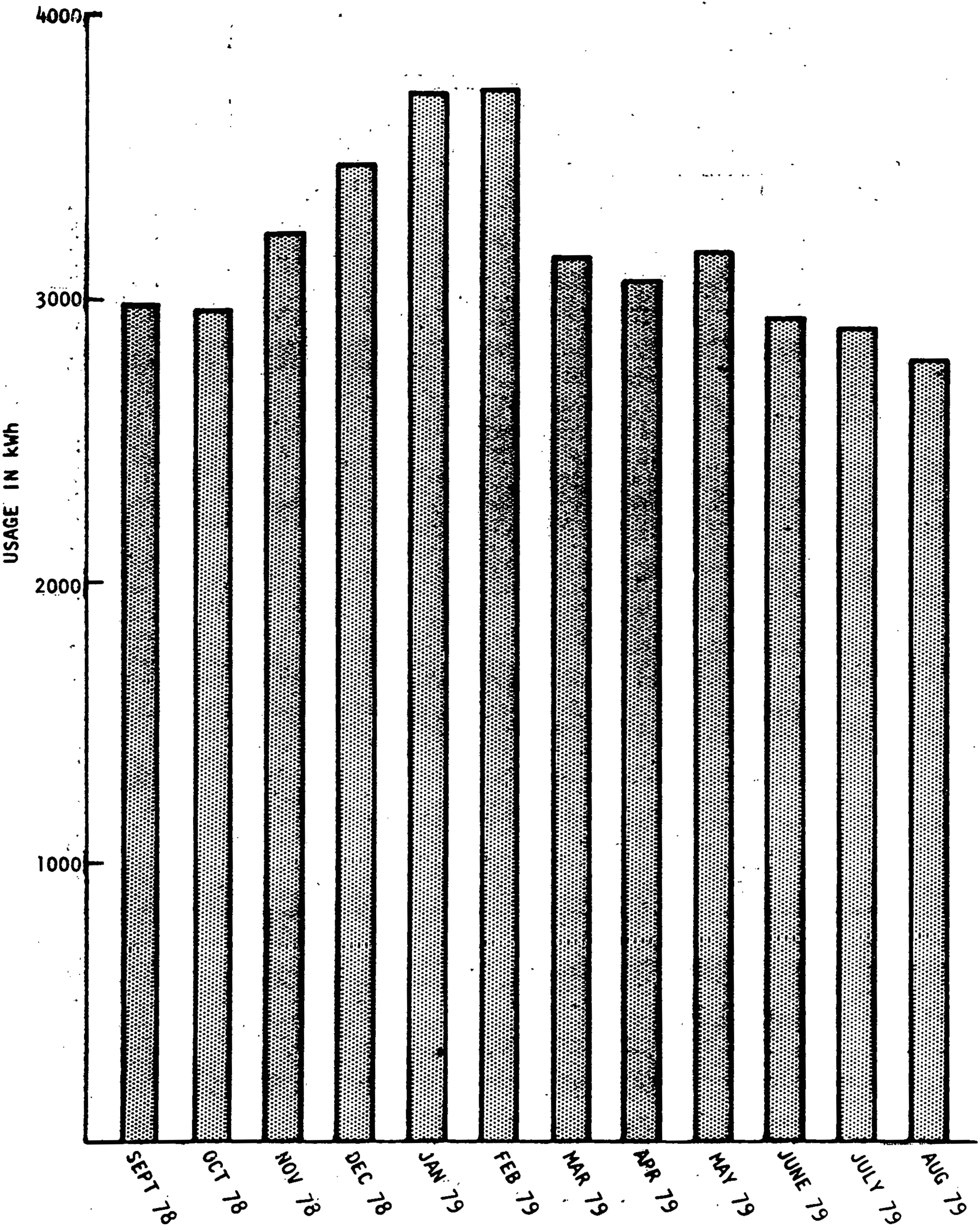

Figure II-2. Monthly Electric Energy Usage on Dairy Farm

A computerized simulation program called SOLSIM was developed for analyzing photovoltaic power systems with battery storage and onsite diesel generator backup. Figure II-3 shows how this simulation program operates.

SOLSIM uses the following input data:

(1) Typical hourly electrical power demand values for 24-hour periods during each season (in kW) for the specified application

(2) Hourly total solar radiation on a horizontal surface (in kW/m^2) for the specified location and desired study period.

(3) Battery round-trip energy efficiency

(4) Power conditioner efficiency

(5) Array size (in kW peak) and collector tilt

(6) Battery effective capacity (defined as rated capacity x maximum depth of discharge) in kWh

(7) Generator rated capacity in kW.

The SOLSIM program performs calculations shown in Figure II-3 for each hour of the year (or representative months). It sequentially computes the values of energy stored in the battery and generator electrical output at the end of each hour. For each run of the program, the following statistics were reported:

(1) Total generator electrical output (for each season and for the year)

(2) Total electrical energy supplied by the photovoltaic array to the load (for each season and for the year)

(3) Maximum rate of charge and discharge of the battery

(4) Battery charge/discharge profile, displayed as a graphic plot of battery stored energy vs. time for any selected time interval.

SOLSIM was run for various combinations of array size and battery capacity, and photovoltaic energy supplied to the load was recorded for each combination. Figure II-4 is a graph of photovoltaic energy supplied to load vs. battery capacity, using a 20 kWp array. The computer run was made using a battery energy efficiency of 80 percent and power conditioner efficiency of 90 percent.

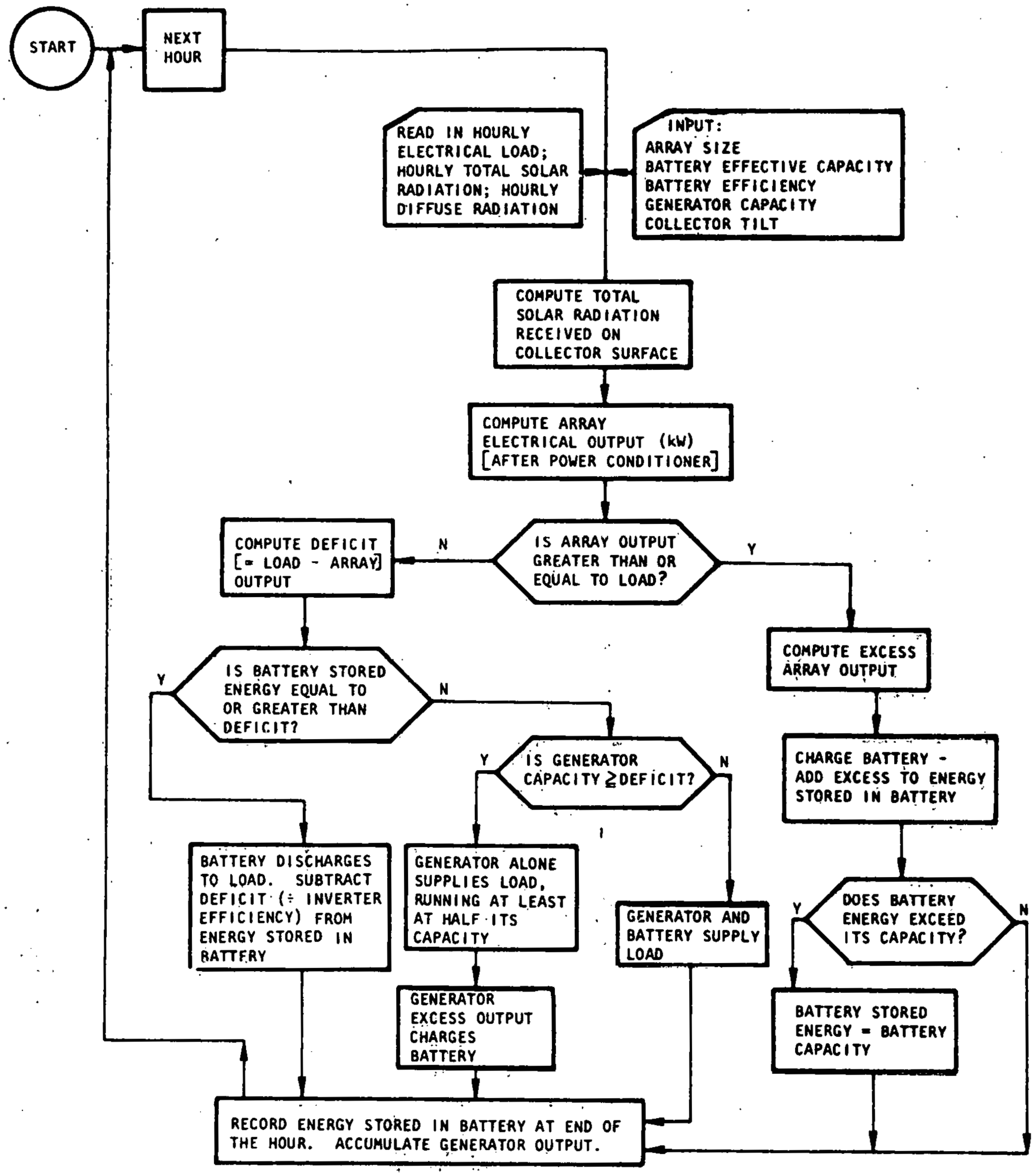

Figure II-3. Flow Chart of SOLSIM

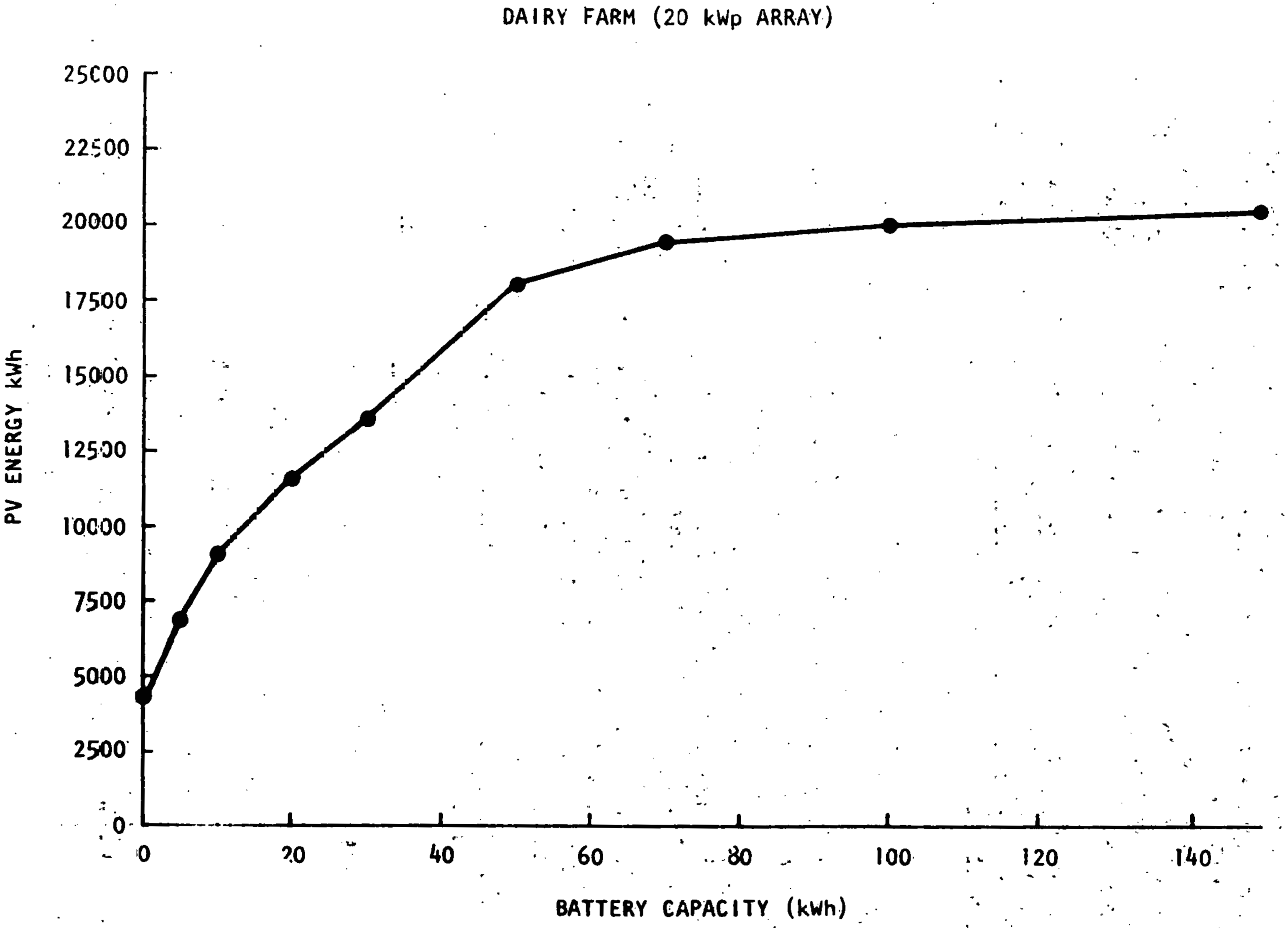

Figure II-4. Annual Energy Supplied to Dairy Farm from Photovoltaic Array vs. Battery Capacity (20 kWp Array)

The most economical battery size can be approximated by applying marginal analysis to these plots. For each increment of battery capacity added, the value of diesel fuel displaced is compared to the annual cost of the additional battery capacity.* For a battery with an annual cost of $10 per kWh of effective capacity, the most economical battery size for the dairy farm scenario is approximately 50 kWh.

The maximum battery discharge rate for the dairy farm scenario is 16 kW. Figure II-5 illustrates the battery duty cycle profile for a typical 120-hour period for the dairy farm photovoltaic system.

C. Sizing of the Power Conditioner

Figure II-6 is a simplified block diagram of the photovoltaic system for the dairy farm application.

The power conditioner chosen is a simple, self-commutated type. Figure II-7 shows the components of a single-phase bridge, self-commutated inverter. The AC interface consists of a filter to attenuate higher order harmonics and an autotransformer, center-tapped to provide the 220/110 volt output voltage needed for the residential system. Reduced voltage starters should be provided for the 5 hp vacuum pump and the 5 hp compressor motor to reduce inrushes.

The following are specifications of the self-commutated power conditioner:

Input	Specification
Operating range	150-260 volts DC
Output	
Voltage	220/110 V, 1 Ø 60 cycles
Power	15 kW
Short-term rating	22.5 kW for 10 seconds
Efficiency	90 percent from half to full load

**Specific fuel consumption of the diesel generator is taken as 0.09 gal/kWh (0.34 liter/kWh) or the dairy farm, which requires a 15 kVA generator. A diesel fuel price of $2.00/gal ($.53/liter) is assumed.*

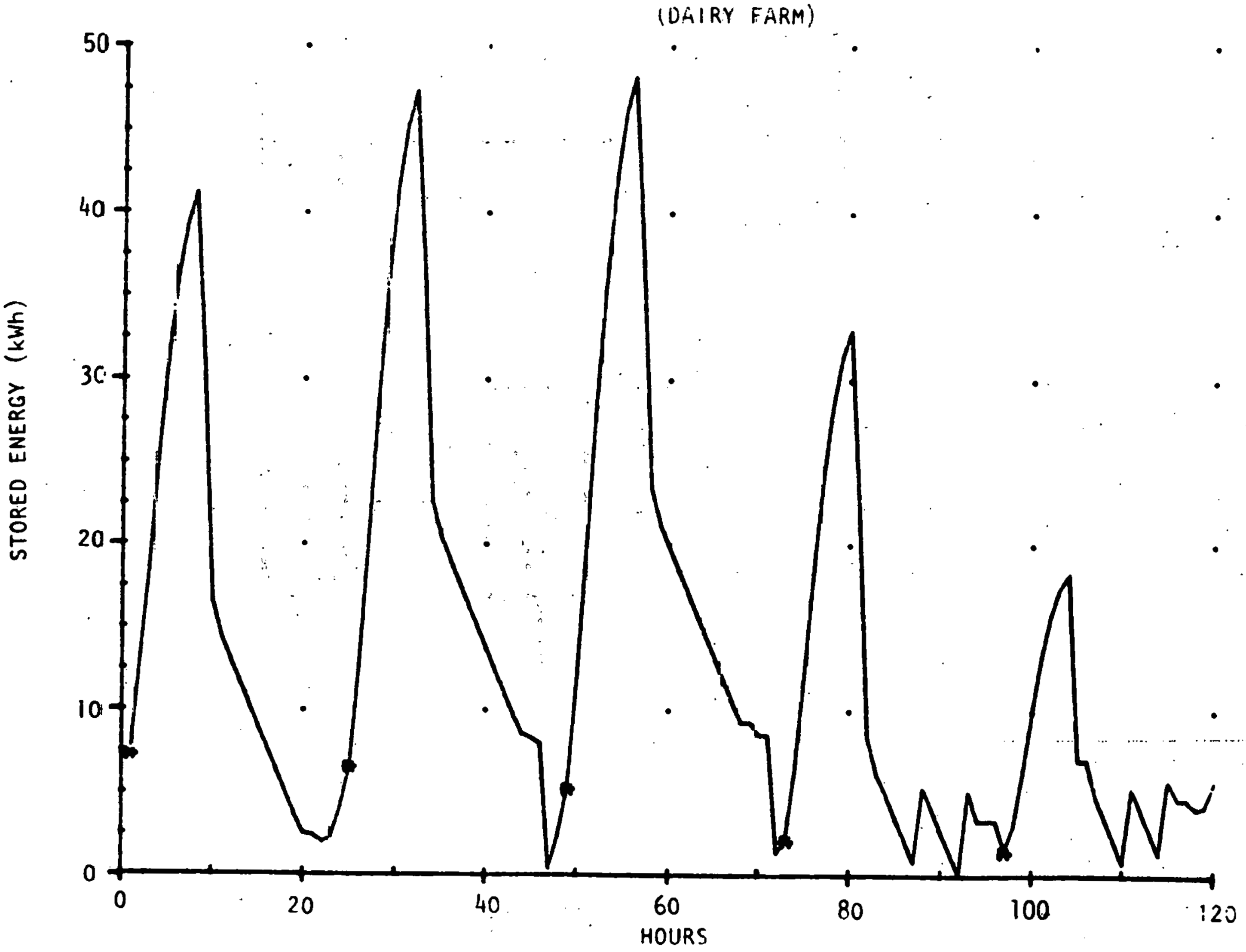

Figure II-5. Photovoltaic System Battery-Stored Energy (Dairy Farm)

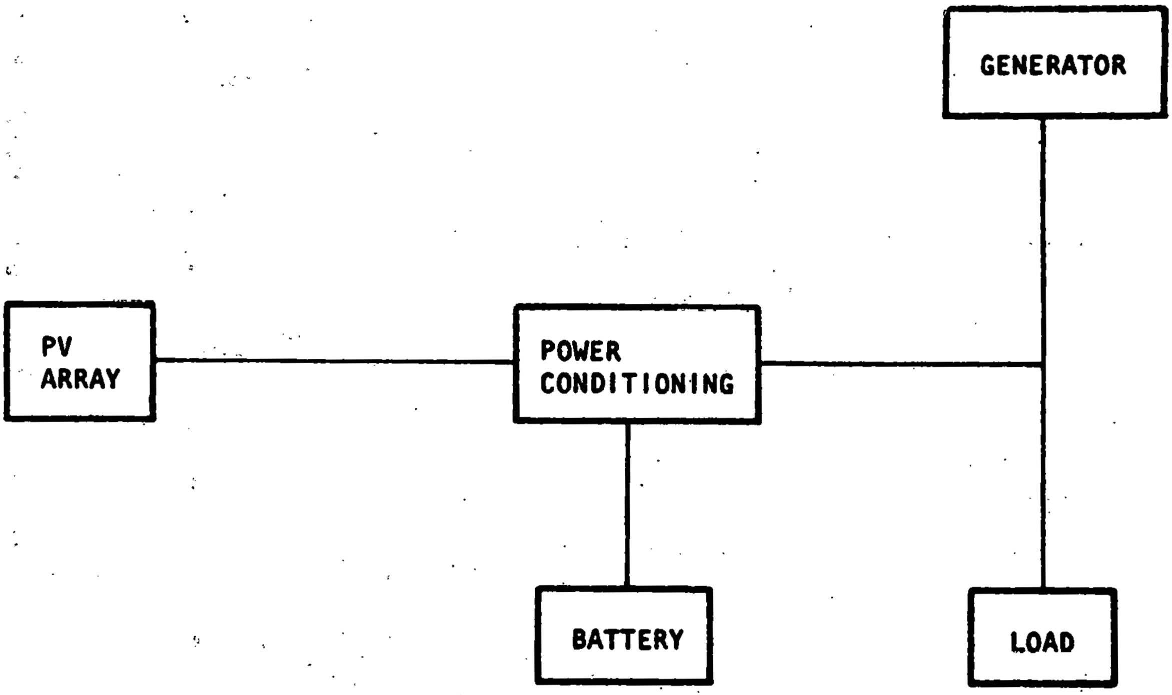

Figure II-6. Simplified Block Diagram of the Photovoltaic System for the Dairy Farm Application

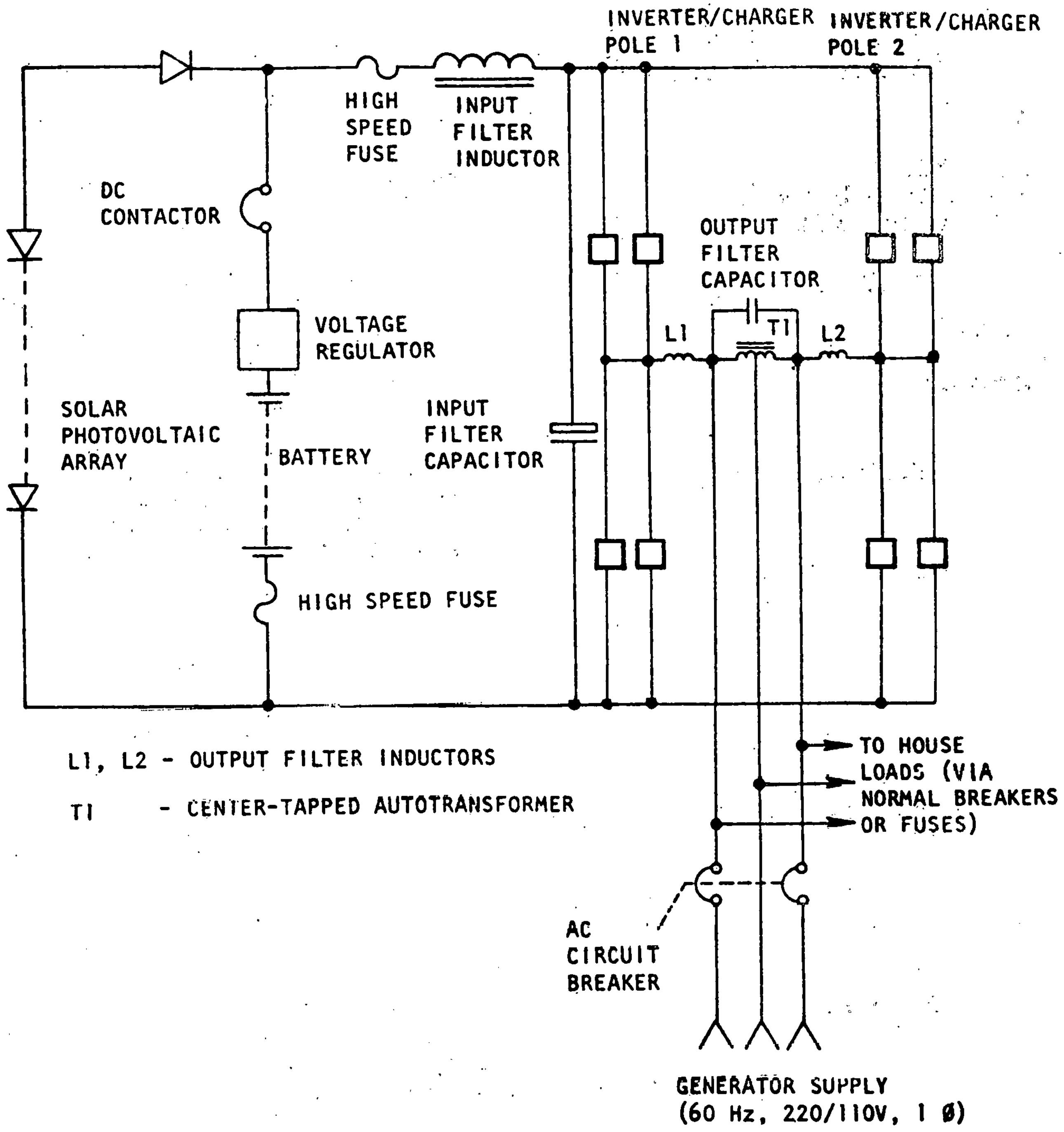

Figure II-7. Elementary Schematic of a Self-Commutated Power Conditioning Unit for the Dairy Farm Application (3)

Total harmonic distortion	5 percent maximum
Power factor	0.9 lead to 0.7 lag
Physical Characteristics	
Life	20 years
Reliability (Mean time between failures) MTBF	20,000 hours
Environment	Specification
Temperature	-10 to 50°C (14 to 122°F)
Humidity	0-95 percent
Protection	Automatic shutdown for input voltages greater than 260 and less than 150 volts, DC Input fuses Automatic starting and self-protection Output current limiter
Metering	Input voltage Output voltage Output frequency
Operation Mode	Stand-alone and generator

D. Summary of Battery Requirements

The following is a summary of battery requirements for the dairy farm application:

System voltage:	250 volts (to provide 220V AC)
Effective capacity:	50 kWh
Maximum discharge rate:	16 kW
Maximum charge rate:	15 kW
Self-discharge rate:	Not critical
Duty cycle:	Daily deep discharge cycle (See Figure II-5)
Maintenance:	Maintenance by service contract
Environmental, health, & safety:	Battery will probably be located in special shelter, separate from house or barn.

E. References

1. Bureau of the Census. *Statistical Astract of the United States*, 1978, p. 694.

2. Ibid, p. 726.

III. PHOTOVOLTAIC SYSTEM FOR A COMMERCIAL APPLICATION - A COMMERCIAL OFFICE

A. Load Profiles and Characteristics

1. Background

The chosen scenario is a commercial office building with a peak demand in the range of 150 to 250 kW.

The office is a one-story building with block-type construction and a steel deck roof. The building provides office space for approximately 175 people, and is located in the Washington, DC, area. The building area is 50,000 square feet.

The building is heated by an oil-fired hot water system and is cooled by electrically powered air-conditioning units. Both hot and cold air are circulated through a venting system by electric fans on the air-conditioning units. Indoor lighting is provided by the typical rapid-start fluorescent fixtures, while the outdoor lighting (nighttime parking lot illumination) is provided by mercury vapor lamps. The energy demands of typical equipment installed to service such a building in the Washington, DC, area are shown in Table III-1.

TABLE III-1. INSTALLED CAPACITY OF BUILDING ELECTRIC EQUIPMENT

Equipment	Installed Demand (kW)
Five 25-Ton Air-Handling Units	232
Indoor and Outdoor Lighting	103
Miscellaneous	~25

2. Characteristics of Load Elements

a. Air-Handling Units. A typical air-handling unit will have the following elements which use electric energy: compressor motors, condenser fan motors, and evaporator fan motors. Table III-2 shows the electrical characteristics of a typical 25-ton unit which could be used for such an application.

TABLE III-2. TYPICAL ELECTRICAL CHARACTERISTICS OF 25-TON AIR-HANDLING UNIT (1)

Elements	Qty	Volts	Hz	ph	RLA Each	LRA Each
Compressor Motor	3	460	60	3	17.5	90
					FLA Each	hp
Condenser Fan Motor	3	460	60	3	2.6	1
Evaporator Fan Motor	1	460	60	3	11	7.5

RLA = Running Load Amps
LRA = Locked Rotor Amps
FLA = Full Load Amps

A three-phase compressor motor operating at 460 volts and drawing 17.5 amperes under steady-state conditions will require 13.9 kVA. A typical power factor for such steady-state operation is about 0.85 (1). For the representative 25-ton AC unit with three compressor motors, the total demand by the compressor will be 41.8 kVA at a power factor of 0.85 or 35.5 kW + 22 kVAR. Since air-conditioning units cycle on and off on a regular basis under normal operating conditions, the starting characteristics of the electrical components are important parameters for the design of the photovoltaic/battery power system. The locked rotor characteristics are a perfect analog of a motor's electrical characteristics during starting. A three-phase compressor motor operating at 460 volts with a locked rotor current of 90 amps will draw 71.7 kVA. A typical power factor for this starting impulse is about 0.65 (1). Under this assumed power factor for starting, the three-phase compressor motor under consideration will draw 46.6 kW + 54.5 kVAR.

The typical 25-ton AC unit also has three condenser fan motors. Each three-phase condenser fan motor will draw 2.6 amps at 460 volts, for a demand of 2.1 kVA. Power factor under steady-state conditions for this three-phase 1-hp unit will be about 0.55 with an assumed efficiency of 65 percent. Each motor will require 1.1 kW and 1.7 kVAR. Total demand with all three condenser fans operating will be 3.4 kW + 5.1 kVAR. Starting inrushes will run around 10.5 to 12.6 kVA. They are less significant than the much higher inrushes from the compressor motors.

The air-handling unit under consideration has one more electrical element requiring description: the 7.5-hp evaporator fan motor. This motor is a three-phase, 460-volt motor drawing 11 amperes under full load. The total demand is 8.8 kVA. With an efficiency of 75 percent, the power factor under full-load conditions will be 0.85. The motor will draw 7.5 kW + 4.6 kVAR under steady-state conditions. Starting inrushes will be around 44 to 53 kVA.

The total load for each 25-ton unit with all loads operating under steady-state conditions will be 46.5 kW + 31.7 kVAR, which is 56.8 kVA at a power factor of 0.82. Table III-3 summarizes the kW and kVAR demands for the various parts of the 25-ton unit (2).

TABLE III-3. ELECTRIC LOAD FOR THE TYPICAL 25-TON AIR-HANDLING UNIT

		Each			Total		
Load Element	Qty	kW	kVAR	kVA	kW	kVAR	kVA
Compressor Motor	3	11.9	7.3	13.9	35.6	22	41.8
Condenser Fan Motor	3	1.1	1.7	2.1	3.4	5.1	6.3
Evaporator Fan Motor	1	7.5	4.6	8.8	7.5	4.6	8.8
TOTAL UNIT					46.47 kW + 31.7 kVAR		

Note: See text for discussion of load elements.

b. Indoor Lighting. Lighting for the office space is provided by a set of 200-W fixtures dispersed about the building. The fixtures are mounted flush to a dropped ceiling eight feet above the floor area. A standard 200-W fixture consists of two sets of two 40-W fluorescent bulbs with a 12-watt ballast. Each set draws approximately 100 W. Alternate lamps are lead/lag, so the power factor presented to the line is, for all practical purposes, 1.0. The building contains 500 such 200-W fixtures, for a total connected-lighting load of 100 kW, or about 2 watts per square foot of building space.

c. Outdoor Lighting. Outdoor lighting for nighttime illumination of the parking area and building entrance is provided by ten 250-W mercury vapor lamps supplied by high-power-factor ballasts. These ballasts draw 37.5 VA per lamp. Total outdoor lighting demand will be 2.9 kVA at a power factor of 0.9.

d. Miscellaneous. Miscellaneous loads include various appliances such as refrigeration for lunchroom, microwave ovens, personal lighting fixtures, typewriters, and a small computer. This load is estimated to be 25 kW, using rule of thumb of 0.5 W per square foot of office space.

e. Power Factor. The power factor will, of course, vary according to which loads are drawing current at any particular time. Since the calculated power factor of the major load (the air-handling units) is 0.82 and the power factor of the secondary load (the indoor lighting) is close to 1.0, the power factor for the total load will fall between these two figures.

3. Energy Use Patterns and Load Profiles

Since the building is located in the Washington, DC, area and is heated by oil, it is a summer-peaking load. Table III-4 shows typical peak kW demand for various times of year.

TABLE III-4. SEASONAL VARIATION IN PEAK DEMAND

Season	Peak Demand for Time of Year (kW)
Summer	235
Fall	180
Winter	165
Spring	175

Load profiles have been developed using an assumed building use pattern. As is typical for commercial office buildings, the building is occupied five days a week between the hours of 8:00 a.m. and 5:00 p.m. The building is essentially unoccupied on the weekends. Figures III-1 through III-4 show typical load profiles for the 50,000-ft^2 office building.

The pattern of office occupancy determines the shape of the load profile to a large degree. The basic form of the load profile is determined by the two demand levels: unoccupied and occupied. As the building begins to be occupied around 7:30 a.m., the load quickly rises to the occupied demand level. As individuals leave the office at 5 p.m., the load quickly drops off. Since the miscellaneous and lighting loads will be the same regardless of the season, it is primarily the cooling demand that affects the magnitude of the demand during the occupied period in the summer season. A comparison of Figure III-2, Typical Daily Load Cycle During Summer Peak on a Business Day, with Figure III-3, Typical Daily Load Cycle During Springtime on a Business Day, reveals that the difference in the daytime demand is due to the difference in the cooling requirements of the building on the two days. As indicated in Figure III-4, the load profile for a weekend is essentially flat.

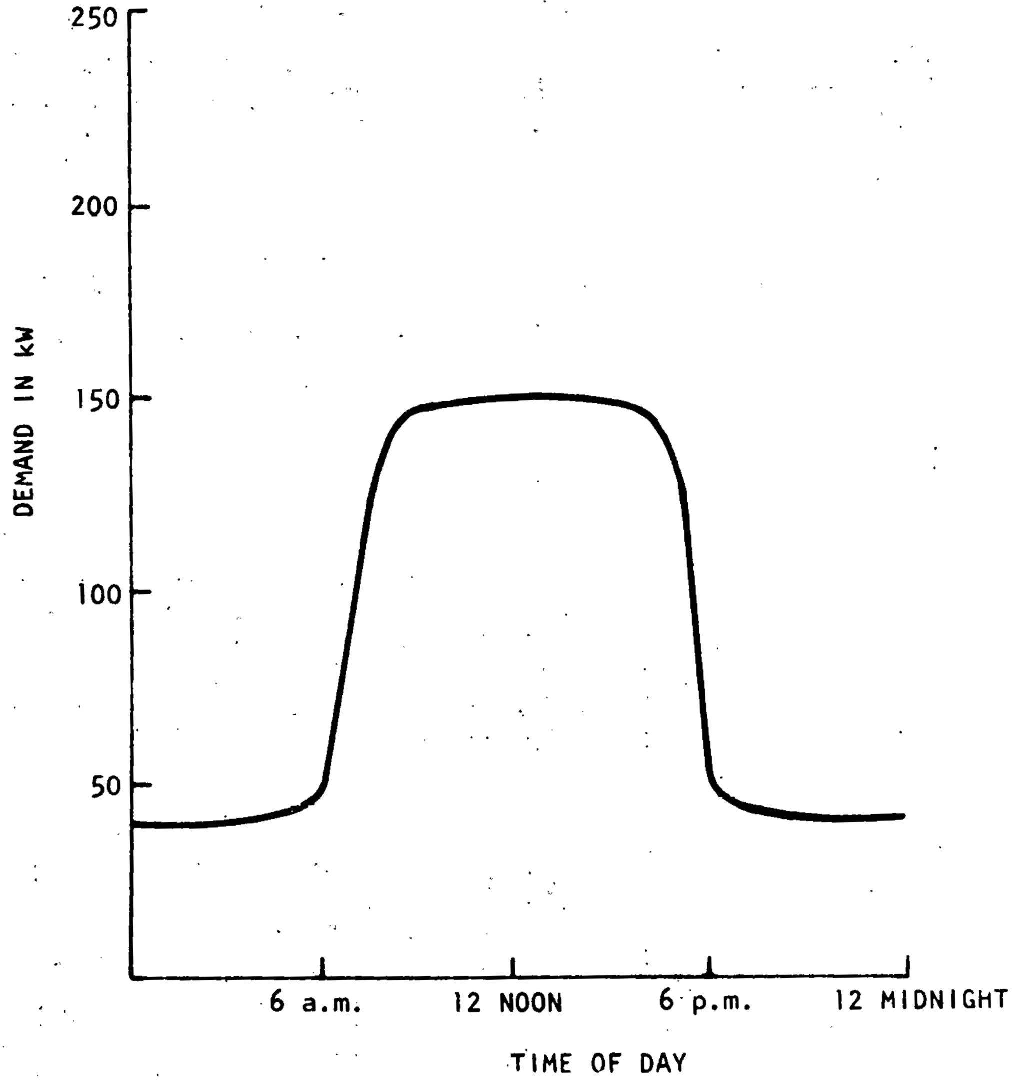

Figure III-1. Typical Daily Load Cycle During Winter on a Business Day

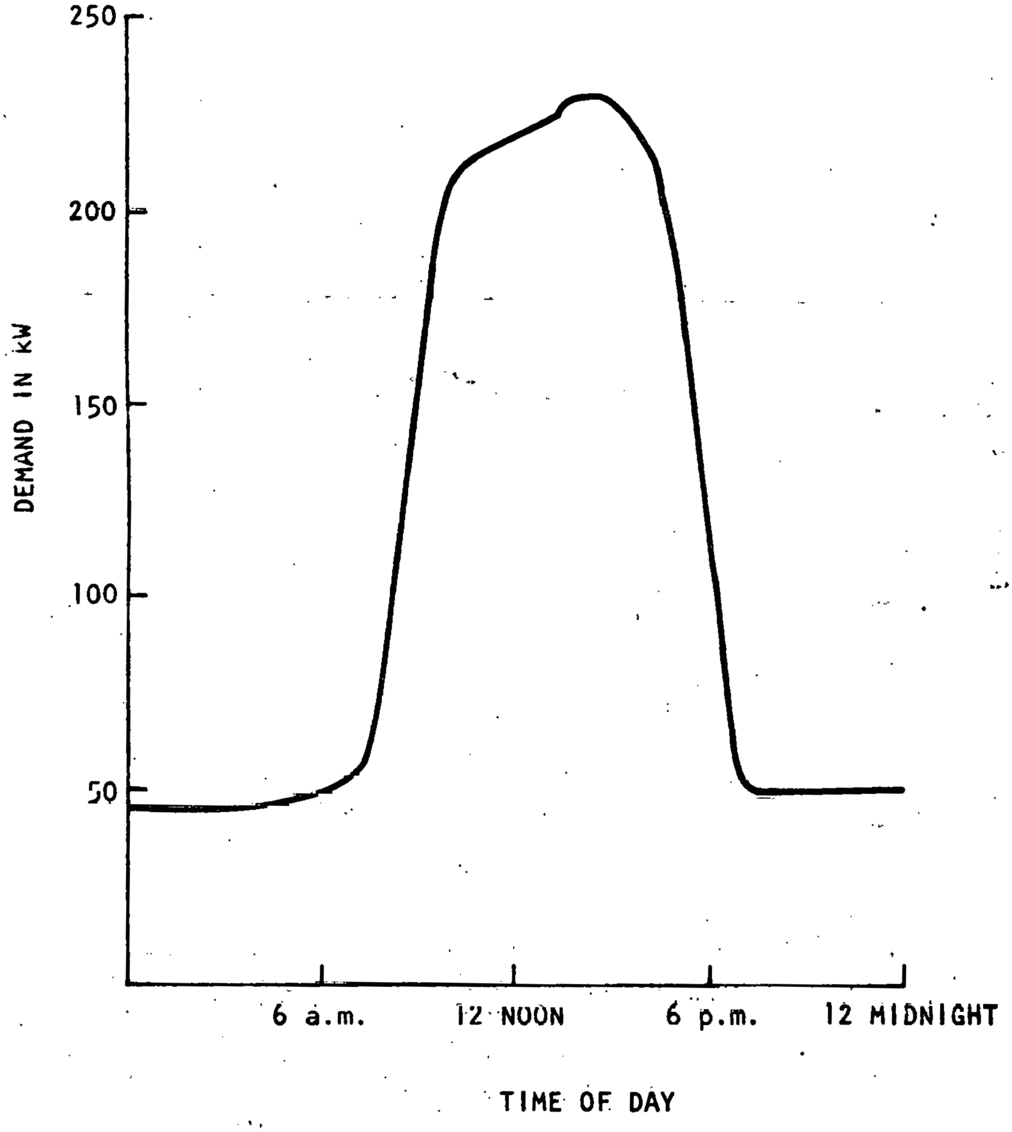

Figure III-2. Typical Daily Load Cycle During Summer Peak on a Business Day

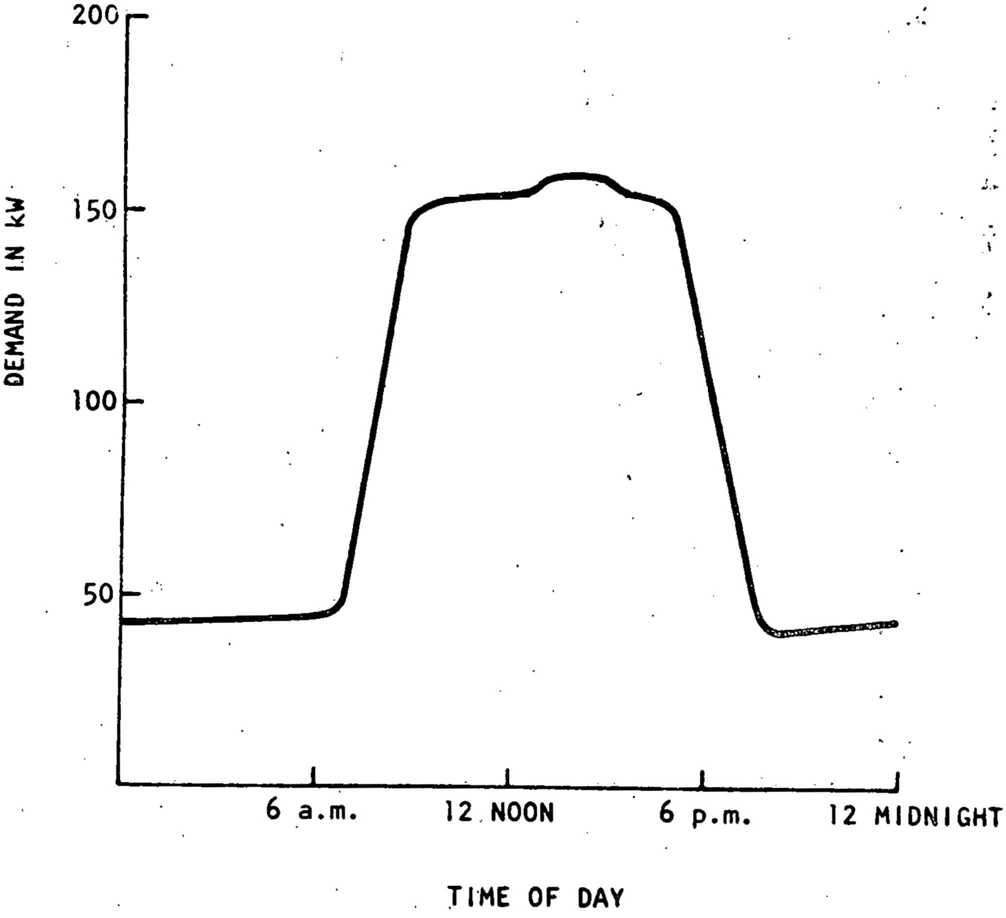

Figure III-3. Typical Daily Load Cycle During Springtime on a Business Day

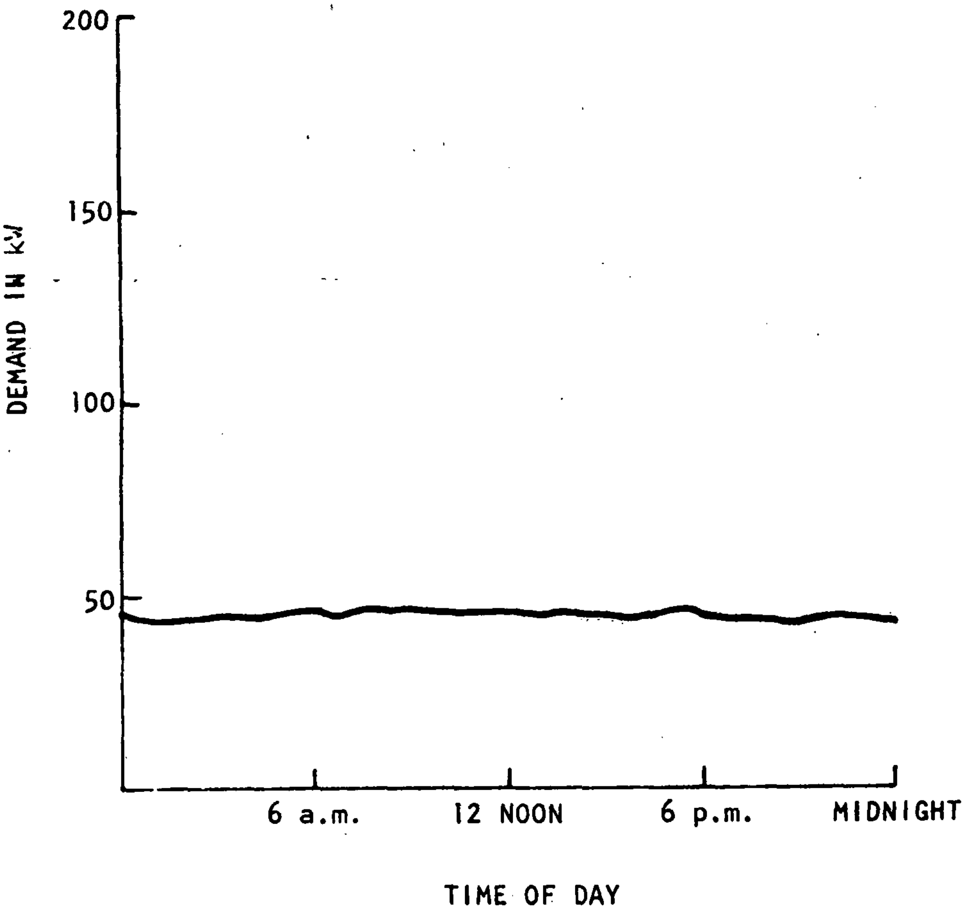

Figure III-4. Typical Daily Load Cycle During Non-Cooling Season on a Non-Business Day

Figure III-5 shows monthly variations in energy use for the chosen scenario.

B. Sizing of the Array and the Battery

For this scenario, an onsite diesel-fueled electric generator was included in the parametric system designs to provide auxiliary power. The generator was assumed to operate in the following manner:

> It is switched on when the electrical demand exceeds the combined output of the array and output capability (stored energy) in the battery. If the generator capacity exceeds the demand, the generator itself supplies the demand. If the generator alone is inadequate, the battery and generator together supply the demand. If the demand is less than one-half the generator capacity, then the generator runs at half its maximum capacity and charges the battery while at the same time delivering electricity to the load. A 200-kVA generator was considered for the commercial office building system.

The computerized simulation program used for this application was the same as that used for the dairy farm. Figure III-6 is a plot of photovoltaic energy vs. battery capacity for the commercial office building scenario, using a 500 kWp array. This array is the maximum size that will fit on the flat roof and parking area without one collector row shading the next row. (Combined roof and parking area is 10,000 m^2.) The computer run was made using a battery energy efficiency of 80 percent and power conditioner efficiency of 90 percent.

The most economical battery size can be approximated by applying marginal analysis to these plots. For each increment of battery capacity added, the value of diesel fuel displaced is compared to the annual cost of the additional battery capacity.* For a battery with an annual cost of $10 per kWh of effective capacity, the most economical battery size is approximately 700 kWh for the commercial office building scenario.

The maximum battery discharge rate for the commercial office building scenario is 100 kW. Figure III-7 illustrates the battery duty cycle profile for a typical 120-hour period (Monday through Friday) for the commercial office building.

**Specific fuel consumption of the diesel generator is taken as 0.075 gal/kWh (0.28 liter/kWh) for the office building which requires a 200 kVA generator. A diesel fuel price of $2.00/gal ($.53/liter) is assumed.*

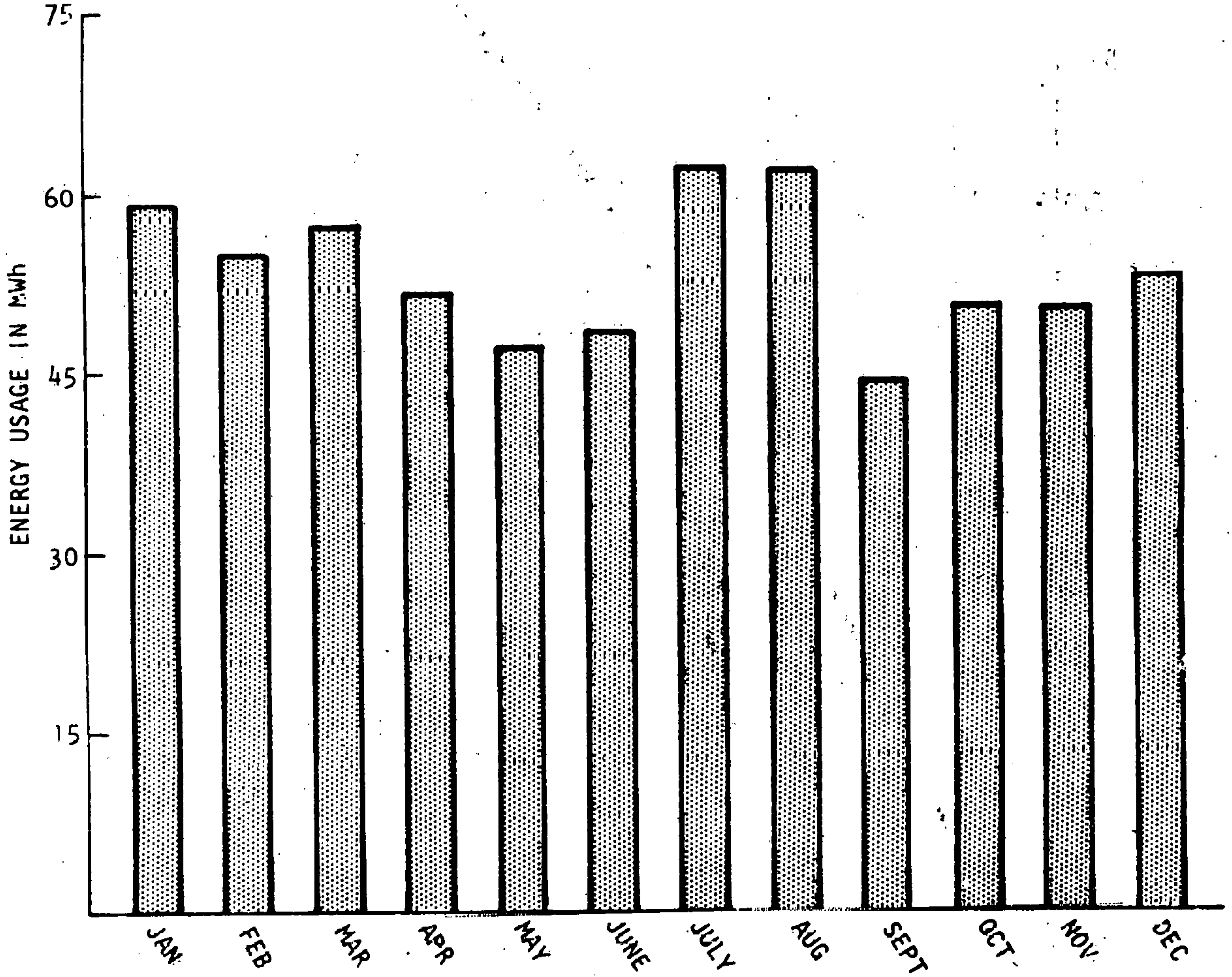

Figure III-5. Graph of Monthly Electric Energy Usage for the Office Scenario

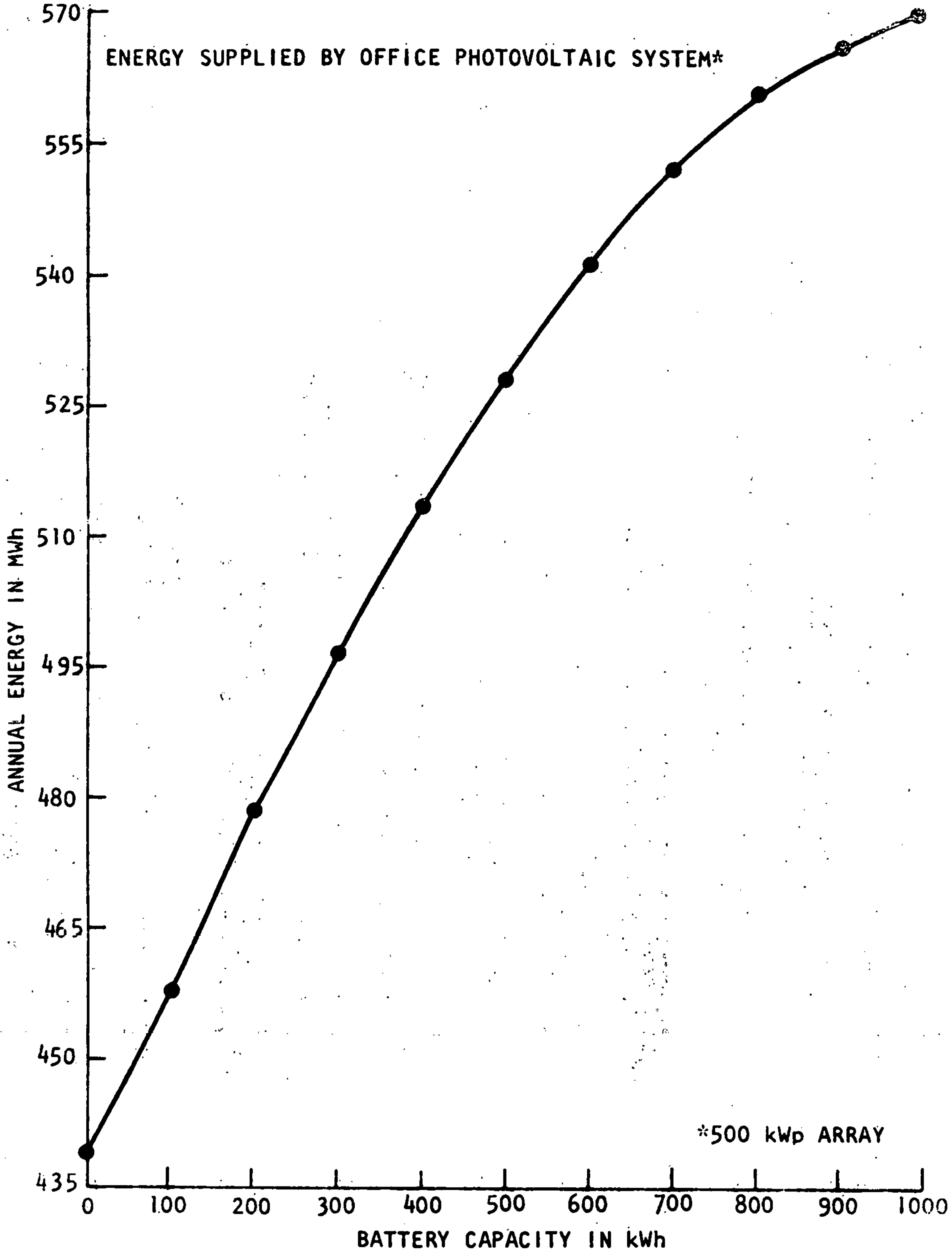

Figure III-6. Annual PV Energy Supplied vs. Battery Capacity, Commercial Office Building Scenario (500 kWp Array)

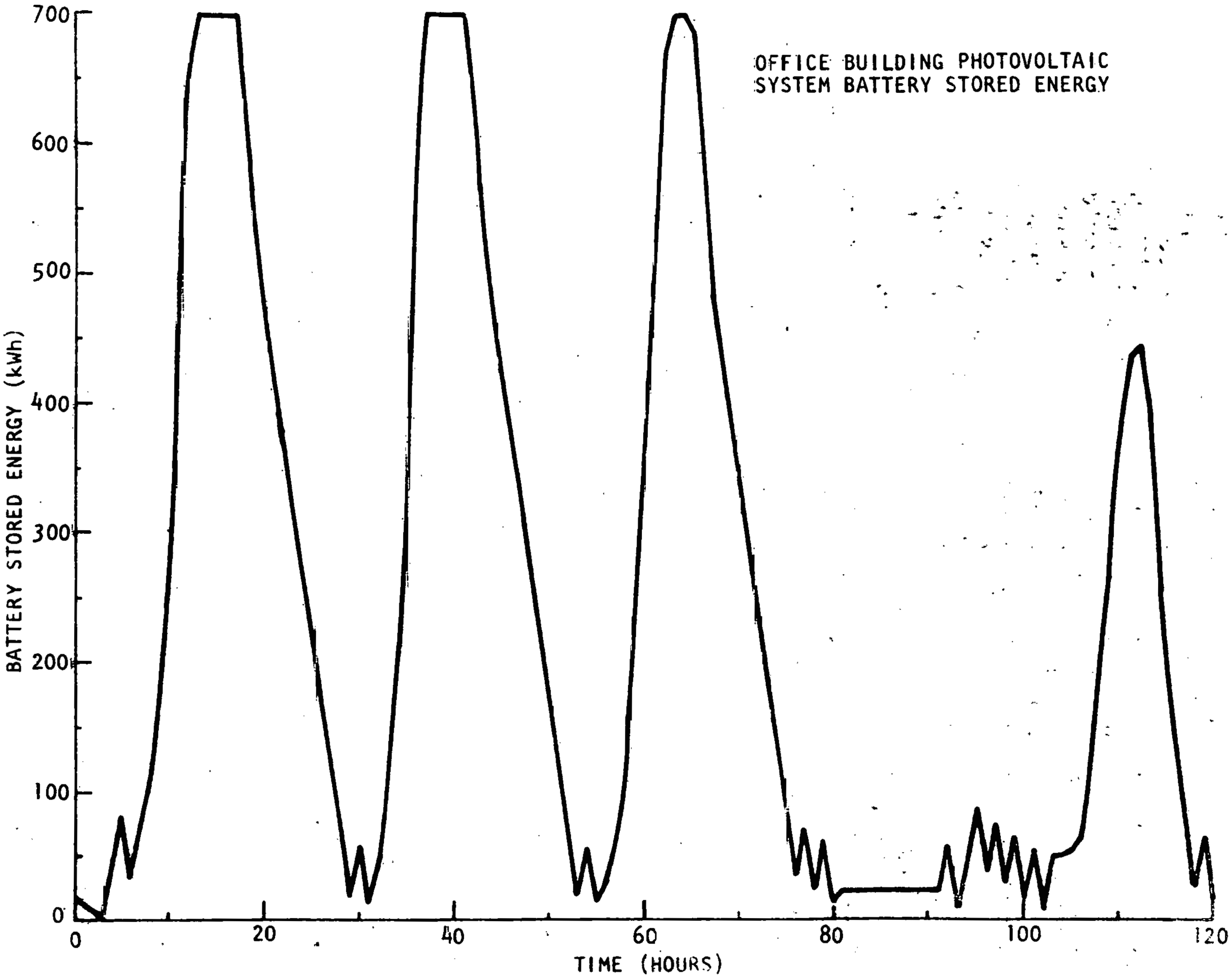

Figure III-7. Battery Duty Cycle Profile, Five-Day Period, Commercial Office Building PV System

Figure III-8 is a simplified block diagram of the photovoltaic system for the commercial office building application. The power conditioner chosen is a current-fed DC/AC type (Figure III-9). A current-fed inverter is a two quadrant device with unidirectional current and bidirectional voltage capabilities. DC reversing switches are provided to allow both charge and discharge of the battery. A simple thyristor bridge arrangement is used as shown. A high-speed DC interrupter is needed to clear inverter commutation faults. Thyristors have a speed advantage and are marginally lower in cost if the simple thyristor bridge configuration is used. The autotransformer produces a three-phase voltage. Capacitors and inductors are installed at the secondary side of the transformer to filter the harmonics. Power factor correction capacitors are also installed to improve the power factor. A protective diode, which may be internal to the array, is used to prevent the backflow of power to the array.

The following are specifications of the power conditioner:

Input	Specification
Maximum voltage	400V DC
Minimum voltage	200V DC
Normal operating range	200-350V DC
Output	
Voltage	480/277V, 3 Ø, 4 Wire
Power	225 kW
Short-term rating	338 kW for 30 seconds
Efficiency	92% at full load 90% at 50% load 87% at 25% load
Total harmonic distortion	Less than 5%
Power factor	0.9 lead to 0.7 lag
Operation Mode	Stand-alone and generator

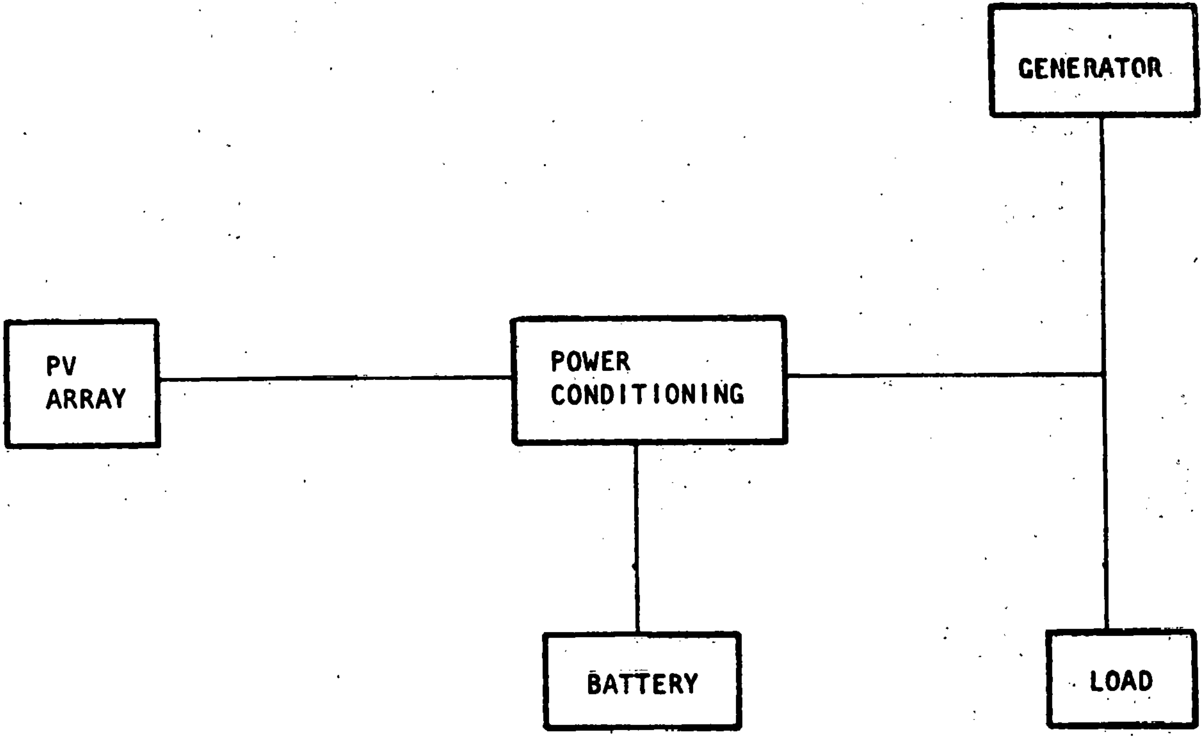

Figure III-8. Simplified Block Diagram of the Photovoltaic System for the Commercial Office Building Application

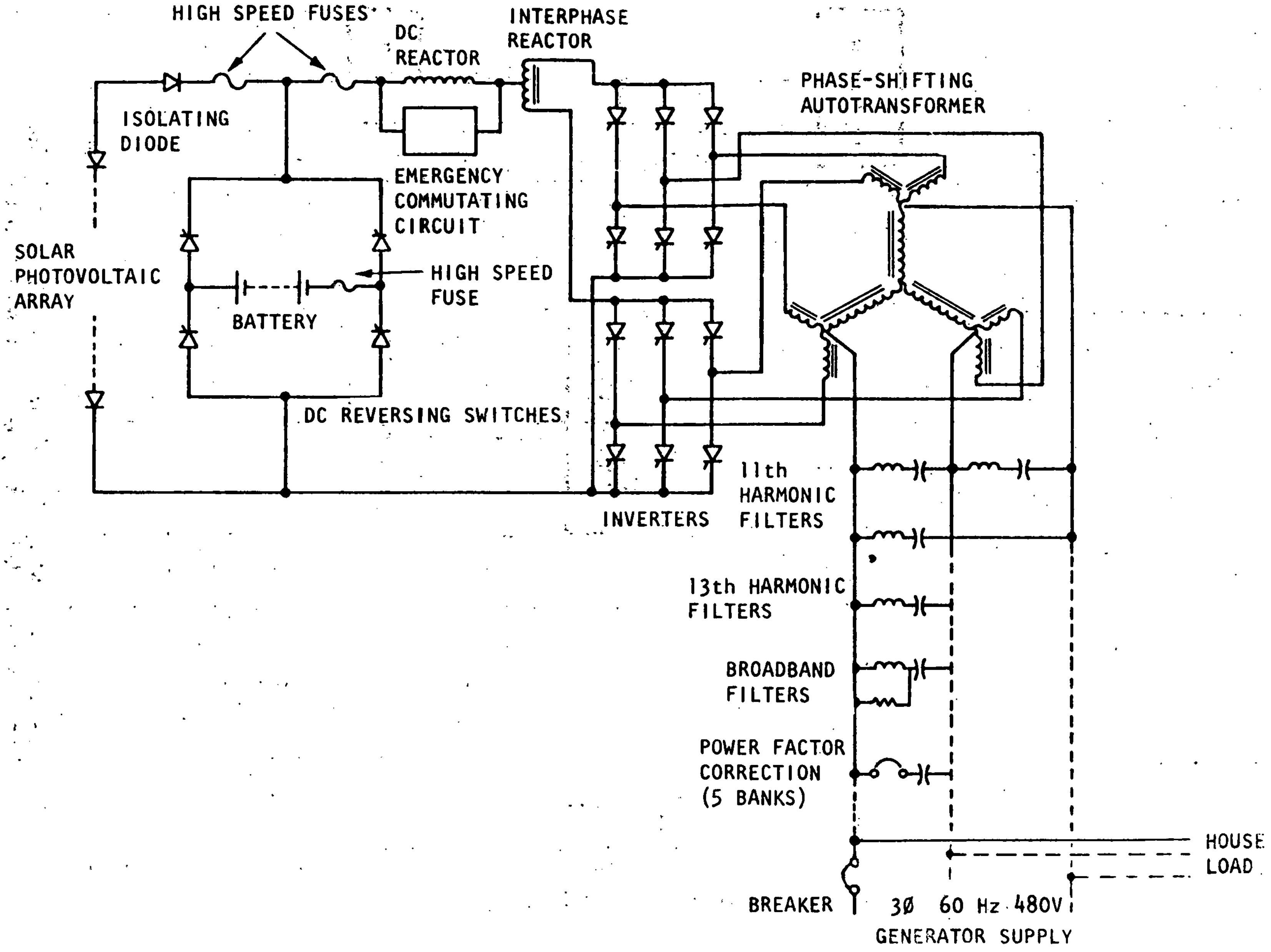

Figure III-9. Power Conditioning Unit Used for a Commercial Application (3)

Physical Characteristics	Specificaton
Life	20 years
Reliability (MTBF)	20,000 hours
Environmental	
Ambient temperature	-10 to 45°C (14 to 113°F)
Relative humidity	96% (non condensing)
Barometric pressure	790 to 520 mm Hg (31.1 to 20.5 in. Hg)
Protection	Input fuses
	Output current limiter
	Over/undervoltage protection
	Abnormal frequency protection
Meters	DC & AC Ammeters
	DC & AC Voltmeters
Additional	Output frequency meter
	Load shed signal on overload
	Battery charger control signal
	Automatic startup and generator grid paralleling

C. Summary of Battery Requirements

The following is a summary of the battery requirements for the commercial office:

Battery system voltage:	~300 volts (to provide 480/227V AC)
Battery effective energy capacity:*	~700 kWh
Maximum discharge rate:	~100 kW
Maximum charge rate:	70 kW
Duty cycle:	Daily deep-discharge cycle (see Figure III-7) with frequent smaller cycles, sometimes hourly
Self-discharge rate:	Not critical
Environmental, health, & safety:	Battery would be enclosed in weatherproof shelter, with access by maintenance personnel only. Temperature inside battery shelter should be within 10-32°C (50-90°F). Must meet local code requirements (if any are applicable).
Maintenance:	Auxiliary systems would be designed to automate routine maintenance operations, such as adding water. Maintenance provided by service contract.

D. References

1. General Electric Co. "Electrical Distribution Handbook." 1944.

2. Based on Nameplate of a Trane 25-ton Air Conditioner.

3. Pittman, P.F. *Conceptual Design and Systems Analysis of Photovoltaic Power Systems*. Prepared for U.S. Energy Research and Development Administration, by Westinghouse Electric Corporation, May 1977.

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*Rated capacity = $\frac{\text{Effective Capacity}}{\text{Max. Depth of Discharge}}$

IV. PHOTOVOLTAIC SYSTEM FOR A RESIDENTIAL APPLICATION - A SINGLE-FAMILY RESIDENCE

A. Load Profiles and Characteristics

1. Background

The chosen scenario is a three-bedroom, split-level single-family home in Denver, Colorado. The building area is 1,800 square feet.

The building is heated by a gas-fired forced air system. No central air cooling is provided. The appliances that use electric energy are:

(a) Electric range/oven

(b) Clothes washer

(c) Refrigerator/freezer

(d) Dishwasher

(e) Electric clothes dryer

(f) Hair dryer

(g) Incandescent lights

(h) Color television

(i) Furnace fan

(j) Electric iron

(k) Humidifier

(l) Electric clocks

(m) Window fans

(n) Radio

(o) Sewing machine

(p) Vacuum cleaner

(q) Coffeemaker

(r) Blender

(s) Toaster.

2. Characteristics of Load Elements

This section describes the power demand and energy usage characteristics of the electric appliances in the chosen scenario Table IV-1 shows the electrical characteristics of the small appliances. Table IV-2 shows the electrical characteristics of the large appliances.

TABLE IV-1. SMALL APPLIANCE ELECTRICAL CHARACTERISTICS (1,2)

Device	Voltage	Quantity	Rated Wattage	Annual kWh Usage
Color television	115V	1	200	440
Furnace fan	230V	1	500	650
Iron	115V	1	1100	60
Coffeemaker	115V	1	1200	140
Blender	115V	1	300	1
Toaster	115V	1	1146	39
Humidifier	115V	1	177	163
Clocks	115V	2	2.5	44
Window fans	115V	3	500	510
Radio	115V	1	71	86
Vacuum cleaner	115V	1	630	46
Sewing machine	115V	1	75	11
Hair dryer	115V	1	381	14
Lighting	115V	-	1600	2200
TOTAL SMALL APPLIANCE ENERGY USAGE				4404 kWh

TABLE IV-2. LARGE APPLIANCE ELECTRICAL CHARACTERISTICS (1,2)

Device	Voltage	Quantity	Rated Wattage	Annual kWh
Range/oven	230V	1	12,200	700
Refrigerator/ freezer	115V	1	500	1,500
Clothes washer	115V	1	512	103
Dishwasher	115V	1	1,201	363
Clothes dryer	115V	1	4,856	993
TOTAL ANNUAL LARGE APPLIANCE ENERGY USAGE				3,659 kWh

As indicated in Table IV-1, the total annual electric energy use of the small appliances is 4,404 kWh. The total annual energy usage of the large appliances, as calculated in Table IV-2, is 3,659 kWh. The total annual electric energy usage for the residence will be 8,063 kWh.

With regard to the power factor of the load, the appliances can be classified into two categories:

(a) Resistance appliances with essentially unity power factor such as: incandescent lighting, electric range/oven, and toaster

(b) Fractional horsepower motors in appliances such as fans, refrigerators, clothes washers, and blenders, which have poor power factors around 0.6 (3).

The actual power factor of the load as seen by the photovoltaic/battery/power conditioning system will vary, of course, depending on the type of appliances used at any particular moment. The power factor could therefore vary from as low as 0.6 to as high as 1.0. The average power factor for the chosen scenario will be around 0.87, where the average power factor is the ratio of the average real power to the average kVA.

Transients were also considered in this characterization of the electrical loads. The largest of the motors and, hence, the one reflecting the worst-case design situation, would be a one-third hp washing machine. Typical inrush on a one-third hp washing machine motor will be 5.3 kVA at a power factor of approximately 0.84 (3).

3. Energy Use Patterns and Load Profiles

Figure IV-1 is a typical load profile for a single-family residence with essentially the same appliances as those assumed in this scenario (4). This profile indicates that that the heaviest electric load for this typical day occurs in the evening when the high-wattage loads (i.e., lighting and cooking) are more likely to be in use. The shape of the load profile is very sensitive to the appliance use patterns of residents.

Table IV-3 shows the monthly kWh usage by appliances for the chosen Denver residence. In order to generate these monthly usage figures, it was assumed that all the appliances (except the lighting, furnace fan, window fans, and humidifier) would use electric energy equally for each month during the year. The furnace fan, window fans, and humidifier were

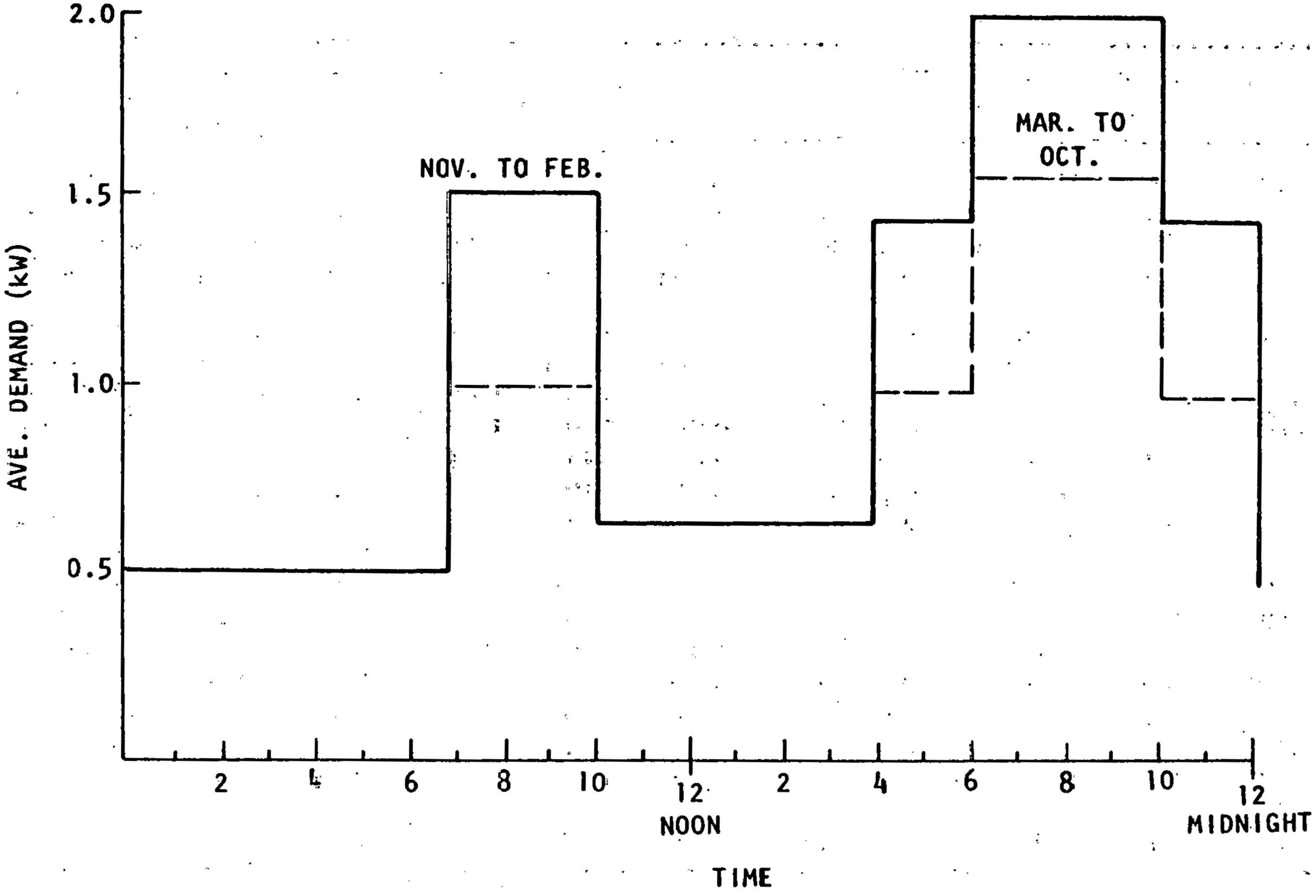

Figure IV-1. Load Profile of a Single-Family Residence

TABLE IV-3. MONTHLY kWh USAGE BY APPLIANCE FOR DENVER RESIDENCE

Appliance	JAN	FEB	MAR	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Color TV	36 2/3	36 2/3	36 2/3	36 2/3	36 2/3	36 2/3	36 2/3	36 2/3	36 2/3	36 2/3	36 2/3	36 2/3
Furnace Fan	110.5	85.75	78	52.65	26.65	0	0	0	27.95	46.15	95.55	124.6
Iron	5	5	5	5	5	5	5	5	5	5	5	5
Coffeemaker	11 2/3	11 2/3	11 2/3	11 2/3	11 2/3	11 2/3	11 2/3	11 2/3	11 2/3	11 2/3	11 2/3	11 2/3
Blender	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12
Toaster	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25	3.25
Humidifier	27.7	22	19.6	13.2	6.7	0	0	0	7	11.6	24	31.[illegible]
Clock	3 2/3	3 2/3	3 2/3	3 2/3	3 2/3	3 2/3	3 2/3	3 2/3	3 2/3	3 2/3	3 2/3	3 2/3
Window Fan	0	0	0	0	45.9	114.75	158.15	150.45	40.8	0	0	0
Radio	7.17	7.17	7.17	7.17	7.17	7.17	7.17	7.17	7.17	7.17	7.17	7.17
Vacuum Cleaner	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83
Sewing Machine	11/12	11/12	11/12	11/12	11/12	11/12	11/12	11/12	11/12	11/12	11/12	11/12
Hair Dryer	1 1/6	1 1/6	1 1/6	1 1/6	1 1/6	1 1/6	1 1/6	1 1/6	1 1/6	1 1/6	1 1/6	1 1/6
Lighting	264	220	220	176	132	88	88	132	176	220	220	264
Range/Oven	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3	58.3
Refrigerator/ Freezer	125	125	125	125	125	125	125	125	125	125	125	125
Clothes Washer	8.58	8.58	8.58	8.58	8.58	8.58	8.58	8.58	8.58	8.58	8.58	8.58
Dishwasher	30.25	30.25	30.25	30.25	30.25	30.25	30.25	30.25	30.25	30.25	30.25	30.25
Clothes Dryer	82.75	82.75	82.75	82.75	82.75	82.75	82.75	82.75	82.75	82.75	82.75	82.75
Total Energy Usage for the Residence	780.5	708	695.9	620.2	589.55	581.1	624.45	660.75	630	656	717.9	798.3

assumed to have a seasonal energy use pattern which varies with the seasonal heating or cooling requirements. The seasonal variation in lighting was assumed to follow a pattern developed in a recent study (5).

The seasonal variation of the furnace fan and humidifier was assumed to vary precisely with the monthly heating requirement of a 1,000 ft^2, three-bedroom, split-level type single-family home located in Denver and described in a study performed by Hittman Associates, Inc. (6). The window fans were assumed to follow the cooling requirements of this same house.

Figure IV-2 is a graph of the monthly energy use for the chosen scenario. Table IV-3 is the total monthly electric energy usage for the residence.

B. Sizing of the Array and the Battery

The residential photovoltaic power system is assumed to be connected to the utility grid. Whenever the load exceeds the power available from the array and battery, the deficit is puchased from the utility at $0.10 per kWh. The short-term peak power demand will also be supplied by the utility. Neither time-of-day rates nor sell-back provisions were considered.

The SOLSTOR computer code (developed by Sandia Laboratory) was used to determine the optimal battery and array sizes for each of the candidate storage batteries being investigated. SOLSTOR sizes these components so as to minimize the levelized annual cost over the lifetime of the system (assumed to be 20 years). The following economic data were supplied as inputs to the SOLSTOR program:

Income tax rate	30 percent
Interest rate	10 percent
Discount rate	10 percent
Down payment	20 percent
Federal tax credit	0 percent
Annual operation and maintenance	1.5 percent of initial capital cost

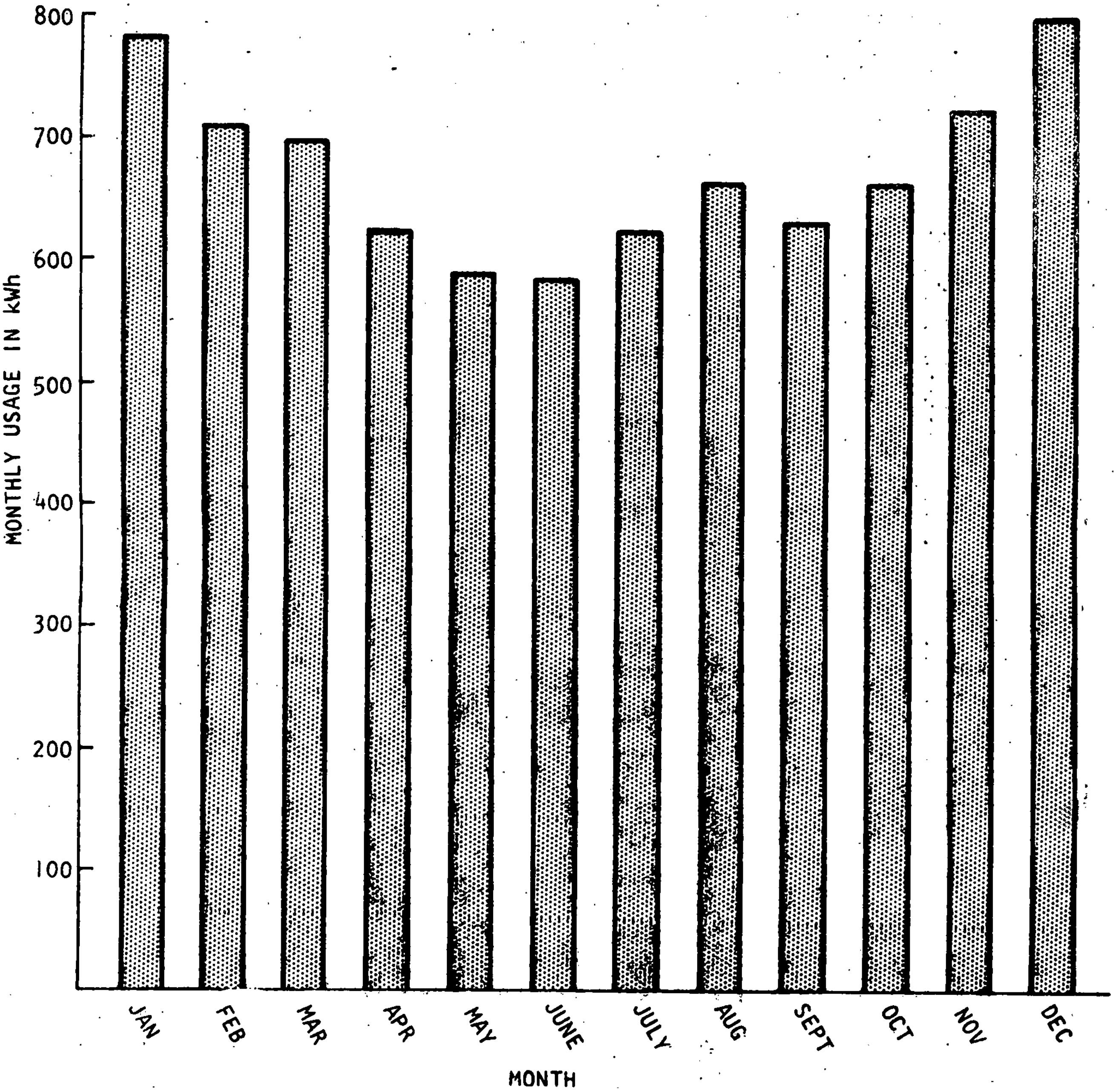

Figure IV-2. Monthly Electric Energy Usage for Residential Scenario

PV array installed cost:	$1,000 fixed + $1,063/kWp
Battery present value cost, including battery auxiliary system:	Input for each battery

The optimum array size for most of the battery types was found to be approximately 4 kWp. Optimal battery capacity was found to be approximately 15 kWh. There was relatively little variation between these results for different battery types.

Maximum discharge rate for the battery would be approximately 3 kW; maximum rate of charging would also be about 3 kW. Since the battery would normally be fully discharged by early morning, and would be recharged only by the photovoltaic array output, the battery must be capable of remaining in a discharged state for several days. This would occur during a period of overcast skies lasting several days.

C. Sizing of the Power Conditioner

Figure IV-3 is a simplified block diagram of the photovoltaic system for the residential application.

The power conditioner chosen is a simple, self-commutated type. Figure IV-4 is the schematic of a single-phase bridge, self-commutated inverter. The AC interface consists of a filter to attenuate higher order harmonics and an autotransformer, center-tappd, to provide the 220/110 volt output voltage needed for the residential system. Circuit controls should be provided to prevent flow of power to the utility line. Also, motor-starting transients will be supplied by the utility line.

The following are specifications of the self-commutated power conditioner:

Input	Specification
Operating range	150-260 volts DC
Output	
Voltage	220/110V, 1 Ø, 60 cycles
Power	10 kW

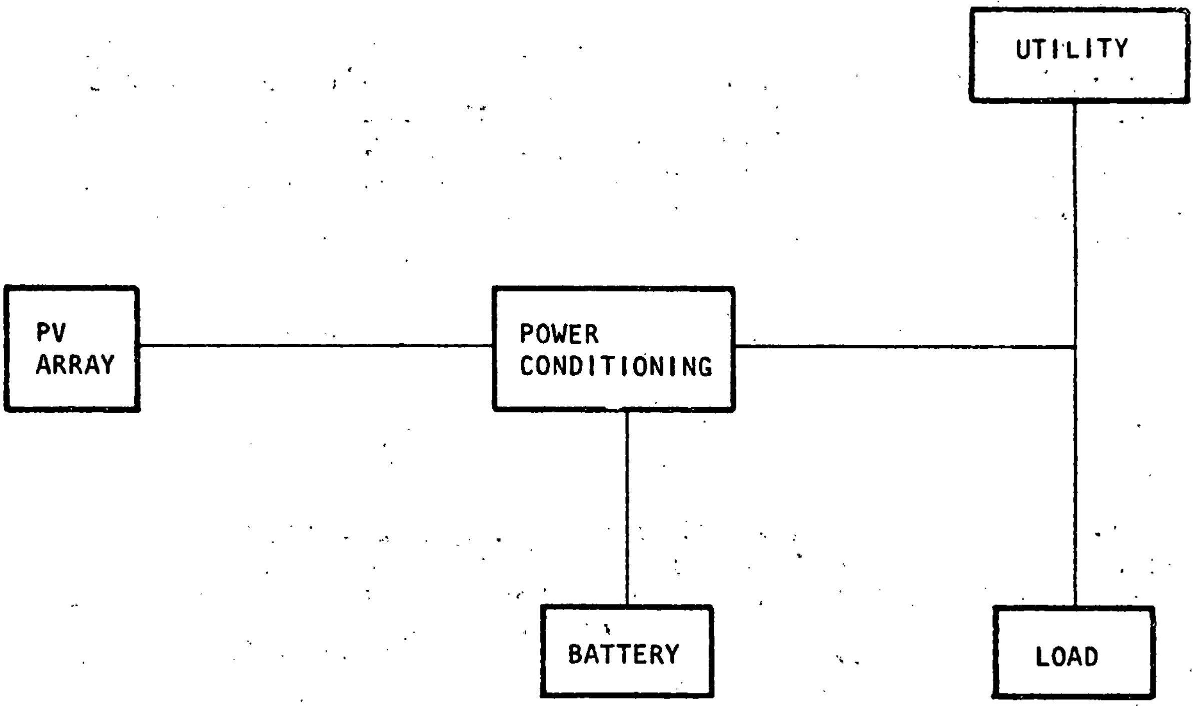

Figure IV-3. Photovoltaic System for the Residential Application

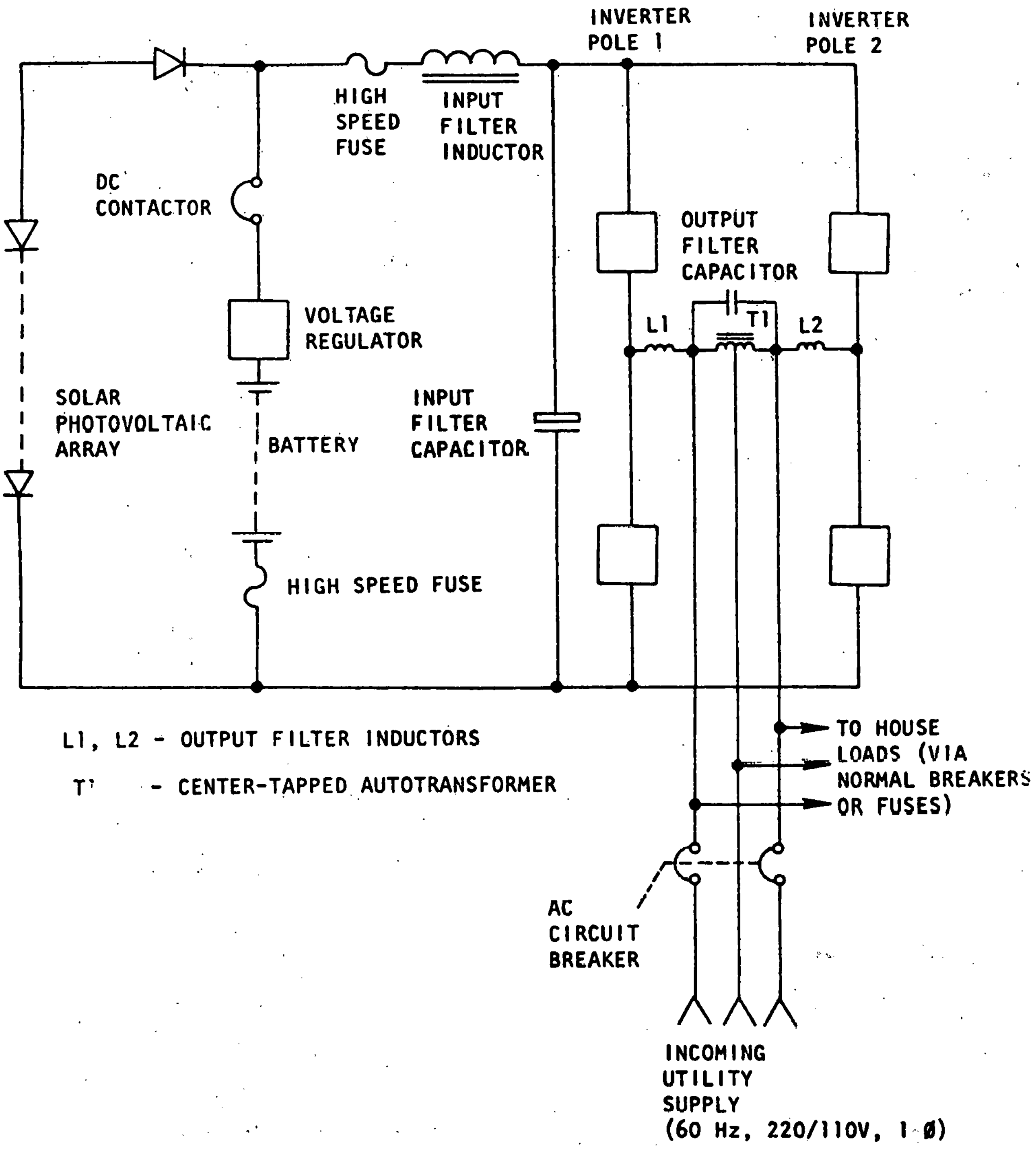

Figure IV-4. Self-Commutated Power Conditioner for a Residential Application (3)

Efficiency	90% from half to full load
Total harmonic distortion	5% maximum
Power factor	0.9 lead to 0.7 lag
<u>Physical Characteristics</u>	
Life	20 years
Reliability (MTBF)	20,000 hours
<u>Environment</u>	
Temperature	-10 to 50°C (14 to 122°F)
Humidity	0-95%
	<u>Specification</u>
<u>Protection</u>	Automatic shutdown for input voltages greater than 250 and less than 150 volts DC Input fuses Automatic starting and self-protection Output current limiter
<u>Metering</u>	Input voltage Output voltage Output frequency
<u>Operation Mode</u>	Stand-alone and utility

D. Summary of Battery Requirements

The following is a summary of battery requirements for the single-family residence:

System voltage:	~250 V (to provide 110/220V AC)
Effective capacity:	~15 kWh
Maximum discharge rate:	3 kW
Maximum charge rate:	3 kW
Duty cycle:	Daily deep discharge cycle, rapid changes in discharge rate
Self-discharge rate:	Not critical
Environmental, health, & safety:	Very important. Battery would probably be located in basement. Battery gaseous emissions would have to be very carefully controlled (either recombined with electrolyte or vented to outside). Must satisfy local code requirements for residential buildings.
Maintenance:	By service contract. Simple routine maintenance could be performed by occupant.

E. References

1. Electric Energy Association, EEA201-73.
2. Edison Electric Institute EEI-PB. No. 75-61 Rev.
3. General Electric Co. Electric Distribution Handbook. 1944.
4. Bechtel Corporation. Battery Storage Performance Requirements for Terrestrial Solar Photovoltaic Power Systems, ANL/OEPM-77-3. August 1977.
5. Hammond, B. Solar Photovoltaic Power for Residential Use. ASME Publication 79-SOL-11.
6. Alereza, Taghi. Hittman Associates, Inc. Denver Residential Energy Consumption. HUD Contract No. H-2280R. September 1976.

V. PHOTOVOLTAIC SYSTEM FOR A REMOTE APPLICATION - A REMOTE VILLAGE

A. Load Profiles and Characteristics

1. Background

The load characteristics of this scenario are based on the assumed energy needs of a 500-person village located in Western Africa at 10°N latitude. For the purposes of this study, the energy needs of this village to be supplied by the photovoltaic/battery system are:

(a) Potable water supply

(b) Grain grinding

(c) Lighting for schoolhouse

(d) Television set for schoolhouse

(e) Ventilation for schoolhouse.

In order to size the electrical equipment that would be required to provide these services, it was necessary to make certain assumptions. For the purpose of this study, the water supply requirement of this village was assumed to be 50 liters per day per person (13 gallons per day per person). This is equivalent to a total village requirement of 2,500 liters per day (6,604 gallons per day).

The milled flour requirement of the village was assumed to be .12 kilogram per person per day (approximately 1/4 pound per person per day). This amounts to 60 kilograms (132.25 lb) of flour milled per day for the whole village. The remaining electrical requirements are a television set, lighting, and fans for the schoolhouse. The area of the schoolhouse is 92.9 m^2 (1,000 ft^2).

2. Characteristics of the Load Elements

a. Potable Water System. The total village potable water requirement was defined as 25,000 liters per day (6604 gallons per day). Assuming a total dynamic head of 30 meters (98 ft), a water pump efficiency of 70 percent, and an eight-hour daily pumping schedule, a water pump supplying 25,000 liters per day would have a mechanical drive requirement of 365 watts (0.5 horsepower). A DC permanent-magnet motor rated at 0.5 hp was therefore chosen as the drive for the potable water pumping system. Since the output of the chosen motor is slightly higher than the calculated power, pumping time to supply the required 25,000 liters per day will be reduced to 7.8 hours. For an assumed motor efficiency of 90 percent, the power demanded by the motor during the pumping operation will be 414 watts. Total energy consumed per day in the pumping operation will be 3,233 watt-hours.

b. Grain Grinding. The total village flour requirements were defined as 60 kilograms per day (132.25 pounds per day). For the purposes of this study, the grain is assumed to be ground to flour by a commercially available pulverator-type hammermill. A 1.5-horsepower model has a rated capacity of 13.6 kilograms per hour. The daily flour needs of the village could be supplied, therefore, in 4.4 hours of mill operation. Assuming a DC permanent magnet motor rated at 1.5 horsepower as the drive for the mill, the electrical demand for the motor, for an assumed efficiency of 90 percent, will be 1,243 watts. The daily energy usage for the grain-grinding operation will be 5,469 watt-hours.

c. Schoolhouse. The chosen scenario includes a 1,000 square foot school house for which lighting, fans, and a television will be provided. The illumination level provided will be 1.5 watts per square foot, or 1,500 watts of fluorescent lighting. Solid-state inverter ballasts for DC power supply operation of fluorescent lamps are commercially available. The air movement will be provided by five 1/8-horsepower DC fans. For an assumed motor efficiency of 80 percent, DC power demand with all fans running will be 583 watts. The television is rated at 200 watts. Assuming that the school operates six hours a day, with TV instruction provided two hours a day, the daily energy usage of the schoolhouse will be 12,898 watt-hours.

3. Energy Use Patterns and Load Profiles

In this scenario, the water and flour needs of the village are supplied daily. If it is assumed that the school operates only four days a week, it is possible to calculate the daily and weekly energy use of the village. Table V-1 shows daily energy use on a school day. Table V-2 shows daily energy use on a non-school day. Table V-3 presents the weekly energy use, based on the school schedule described above.

TABLE V-1. DAILY ENERGY USAGE ON A SCHOOL DAY

Load	Energy Usage (Wh)
Water system	3,233
Grain grinding	5,469
School	12,898
Total	21,600

TABLE V-2. DAILY ENERGY USAGE ON A NON-SCHOOL DAY

Load	Energy Usage (Wh)
Water system	3,233
Grain grinding	5,469
Total	8,702

TABLE V-3. WEEKLY ENERGY USAGE

Load	Energy Usage (kWh)
4 school days	86.4
3 non-school days	21.1
Total	107.5

The load profile was generated using certain assumptions about the hours of pump operation, hours of hammermill operation, and the hours of school operation. Figure V-1 shows the load profile for a school day for the following assumed operating schedule:

(a) The pump starts operating at 8 a.m.

(b) School operates in two sessions: 9 a.m. to 12 noon and 2 p.m. to 5 p.m.

(c) Television operation is 10 a.m. to 11 a.m. and 3 p.m. to 4 p.m.

(d) The mill is operated in two shifts, starting at 9 a.m. and 2 p.m., respectively.

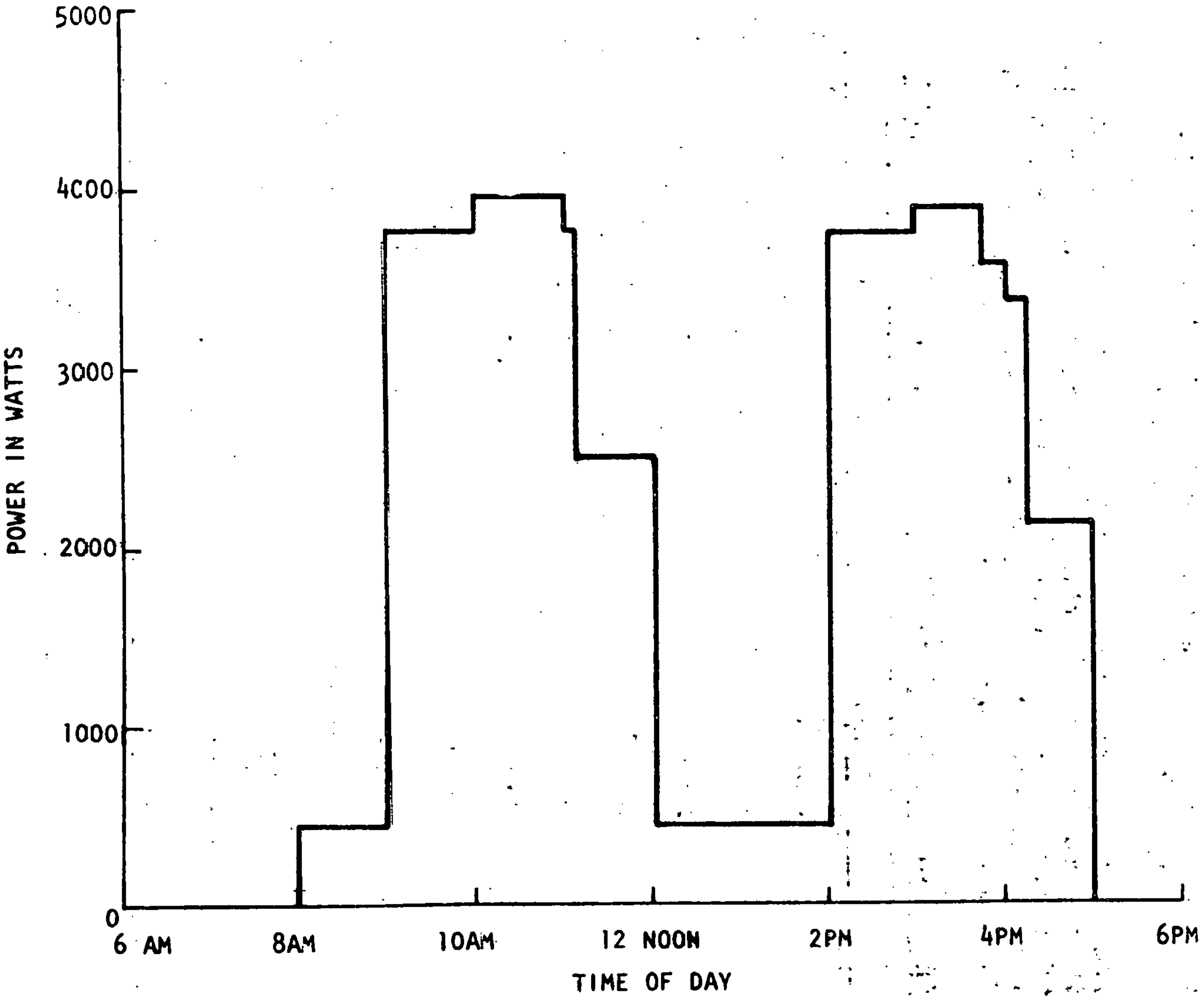

Figure V-1. Load Profile on a School Day

Figure V-2 shows the load profile for a non-school day for the following assumed operating schedule:

(a) The pump starts operating at 8 a.m.

(b) The mill is operated in two shifts, starting at 9 a.m. and 2 p.m., respectively.

The monthly energy usage pattern was generated using certain assumptions about the annual school schedule. Figure V-3 and Table V-4 show the monthly energy use, assuming school is in session in the months of February, March, April, May, September, October, November, and December.

TABLE V-4. MONTHLY ENERGY USAGE IN THE REMOTE VILLAGE

Month	Energy Usage (kWh)
January	269.8
February	428.4
March	488.8
April	480.1
May	514.8
June	261.1
July	269.8
August	269.8
September	467.4
October	428.4
November	480.1
December	488.8

B. Sizing of the Array and the Battery

Two alternative system configurations were considered for this scenario: one was a stand-alone design consisting of a photovoltaic array, a storage battery, and a DC/DC power conditioner; the other included an auxiliary DC electric generator (diesel-powered) as well as a PV array, battery, and DC/DC power conditioner.

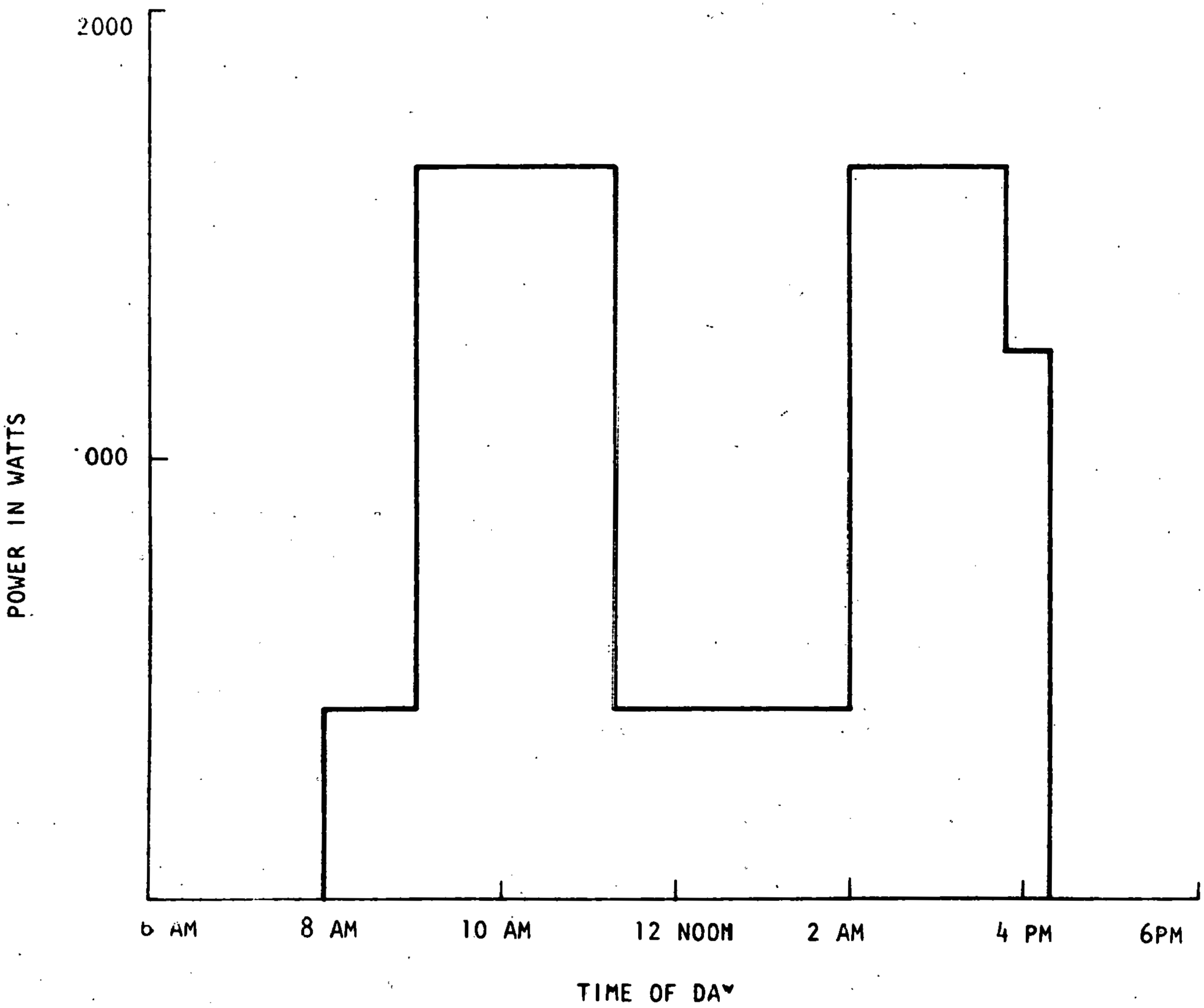

Figure V-2. Load Profile on a Non-School Day

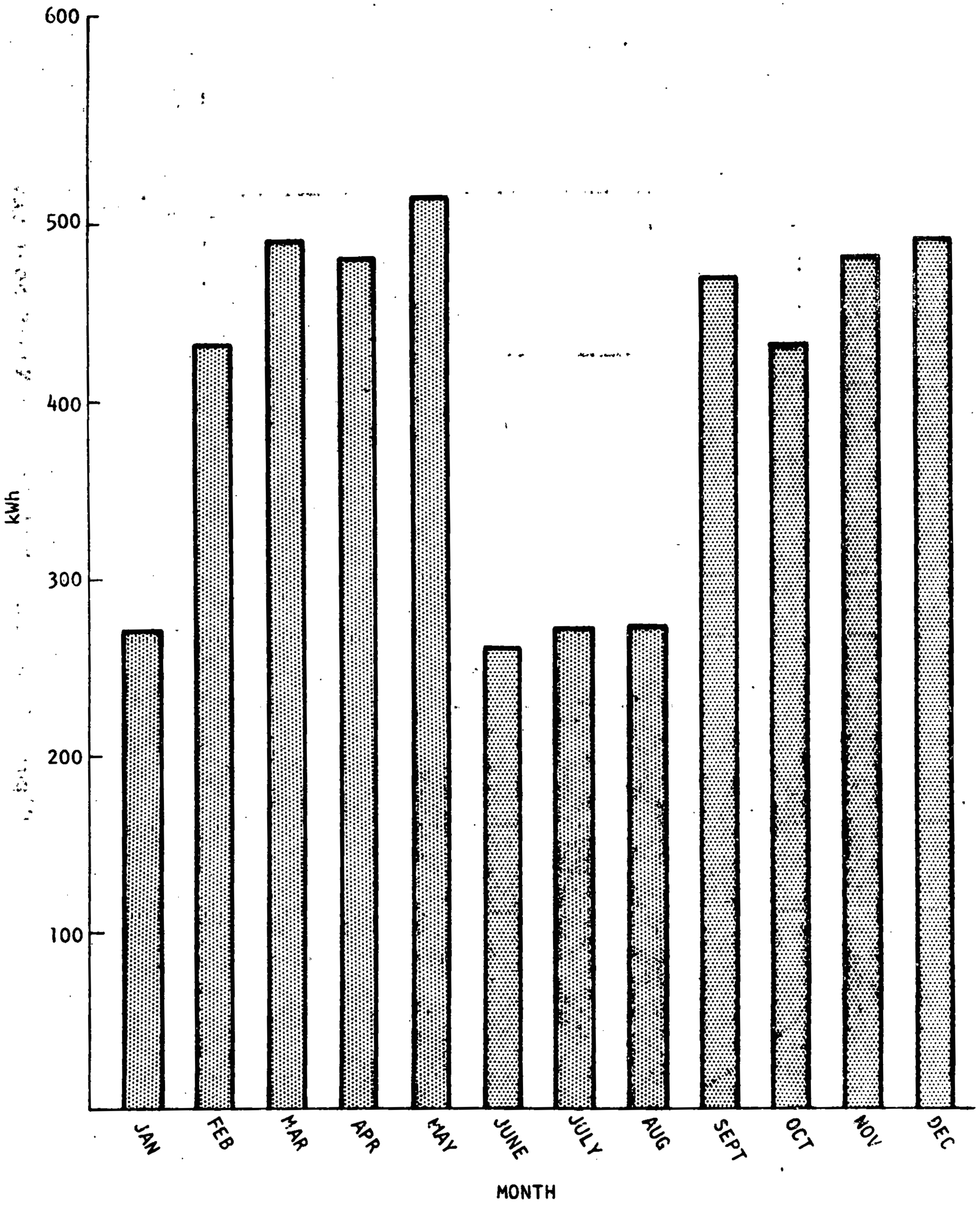

Figure V-3. Monthly Energy Usage in a Remote Village

1. Stand-alone System

It was assumed that the water pumping and grain grinding portions of the load do not require electrical energy storage since their outputs do not have to be consumed immediately. Therefore, one part of the array was sized for the school portion of the load, which requires storage, and another part was sized for the grain grinding/water pumping portion of the load. These two parts were then summed to determine the total array size required. For the grain grinding/water pumping load, array size was computed by the formula:

$$A = (\bar{L} \cdot 1.0 \frac{kWp}{m^2})/(\eta_p \cdot \bar{I})$$

Where: A = array size in kWp

$\bar{I}$ = average daily solar radiation (kWh/m^2-day) averaged over the year

$\bar{L}$ = average daily load (kWh/day)

η_p = power conditioner efficiency.

For the values of $\bar{I} = 5.80$ kWh/m^2-day, $\bar{L} = 8.7$ kWh/day, and $\eta_p = 0.9$, then $A = 1.7$ kWp.

The school operates eight months per year (school is not in session during January, June, July, and August), four days per week, between the hours of 9 a.m. to 12 noon and 2 p.m. to 5 p.m. The daily energy requirement when the school is open is 12.9 kWh.

It can be seen from Figure V-4 that during school days, a portion of the array output is delivered through the power conditioner directly to the load, and the remainder of the array output is stored in the battery and delivered to the load, either the same day or the next day. The expression for energy delivered to the school building from array output that day is:

$$E = A \cdot \bar{I}_m \times [\eta_p X + \eta_p \eta_B \ (1-X)]$$

Where: A = array size, kWp

$\bar{I}_m$ = daily solar radiation for the month m, kWh/m^2-day

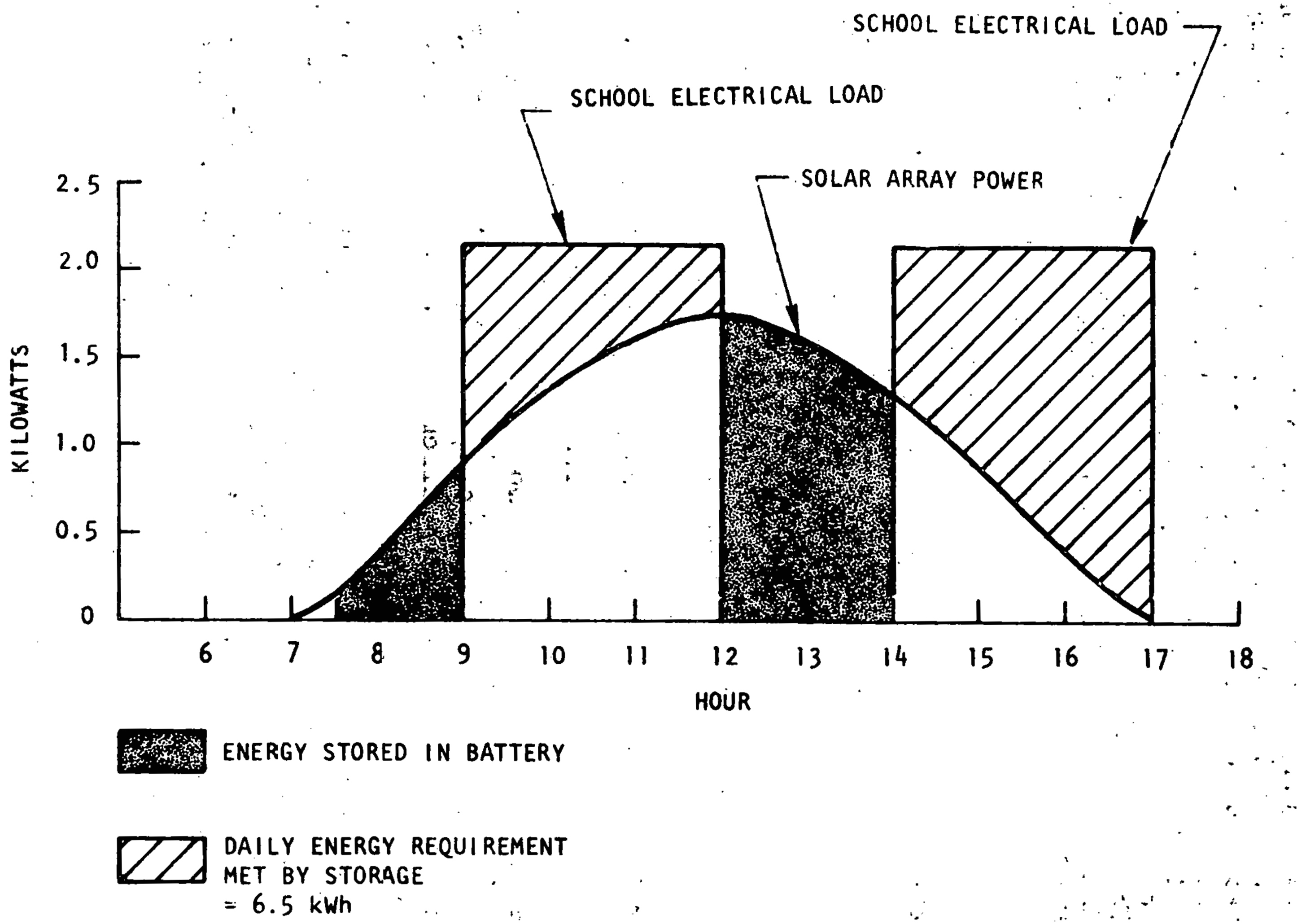

Figure V-4. Daily Load and PV Array Output Profiles

η_p = power conditioner efficiency

η_B = battery "round trip" energy efficiency

X = portion of array output delivered directly to the load, expressed as a decimal

E = Energy output of the array, kWh/day.

For non-school days, the array output can be stored if there is battery capacity available. The expression for energy added to the battery during a non-school day is:

$$A \cdot \bar{I}_m \times \eta_p \times \eta_B$$

The minimum array size is determined by setting the value of energy delivered to the load (either directly, or through storage), accumulated over the year, equal to the annual cumulative school energy requirement (1806 kWh).

$$1806 = \sum_m [A \cdot \bar{I}m \cdot \eta_p \eta_B]\,[1\text{-SDR}] \cdot NSD_m + [A \cdot \bar{I}m \cdot (\eta_p \cdot X + \eta_p \eta_B (1-X))] \cdot SD_m$$

m = month indicator

Where: NSD_m = non-school days in month m

SD_m = school days in month m

SDR = Self-discharge rate per month, expressed as a decimal

The value 1806 kWh/yr is the product of 12.9 kWh/day and 140 school days per year.

Once the array size is specified, the battery capacity required for that array size can be determined. To find required battery capacity, the cumulative deficit or surplus for each month is first computed. Deficit/surplus is the cumulative array output available to the load minus cumulative load for the month. Since the school operates for two terms, separated by the month of January, the battery can be partially recharged during January. Thus, the required battery capacity is determined by summing the monthly deficits for the eight school months and subtracting the energy charged to the battery in January. Figure V-5 shows the relationship

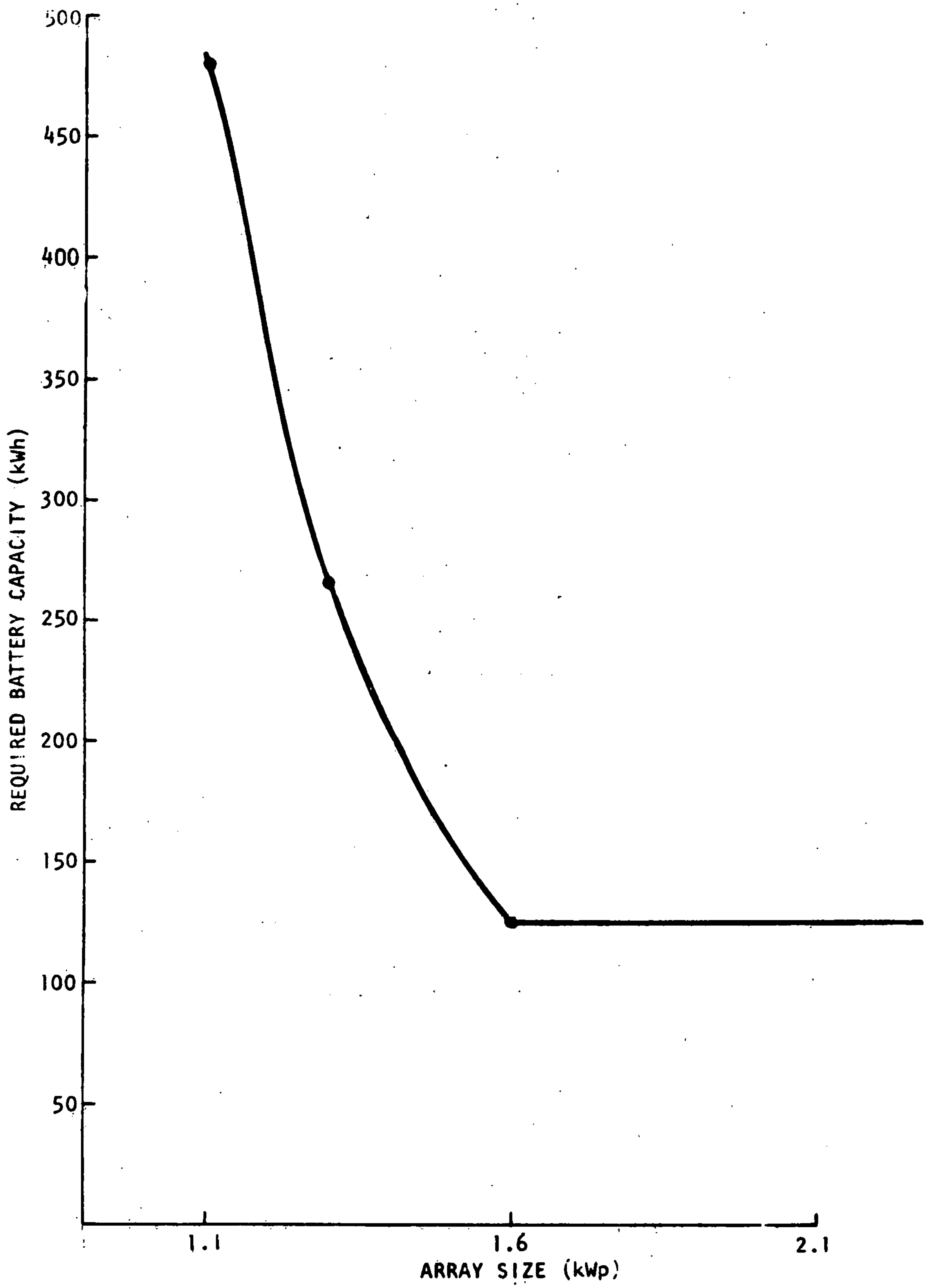

Figure V-5. Battery Capacity/Array Size Relationship for Remote Village School Photovoltaic Power System between array size in kWp and battery effective capacity required. For an array size of 2.1 kWp, the array output over a 3-day weekend (when school is not in session) is adequate to recharge the battery sufficiently to supply the load during the school week. Thus, for this array size, a battery capacity of only 21 kWh is required.

The minimum battery capacity should be adequate to supply the load in the event of two consecutive weeks of overcast weather. This is 103 kWh (2 weeks x 4 schooldays/week x 12.9 kWh/day). Therefore, an array size of 1.6 kWp and a battery with effective capacity of 125 kWh was selected for the school building portion of the load. Maximum discharge rate of the battery is 2.2 kW.

The complete system would contain a 3.3 kWp array, a 125 kWh (effective capacity) battery, and a power conditioner with at least 3.3 kW capacity.

Figure V-6 shows the annual state-of-charge profile for the battery. The battery experiences a single annual complete discharge cycle, as well as smaller weekly cycles, and even smaller daily cycles during school weeks. Since it is undesirable to discharge some batteries below a specified maximum depth of discharge, the rated capacity is found by dividing effective capacity by this maximum depth of discharge.

3. Diesel Generator Backup System

This system contains a small (approx. 3 kVA) diesel generator. Specific fuel consumption of such generators is typically 0.38 liters per kWh (0.10 gallons per kWh). If there were no PV array for the school portion of the load, the generator alone could supply the school's electrical energy requirements (1,806 kWh/yr). Approximately 180 gallons (681 liters) of diesel fuel would be used annually. Adding a 1 kWp array and a 15 kWh battery would reduce the generator annual energy requirement by 840 kWh, to 960 kWh. This is determined by the formula:

$$\sum_{m} A \cdot I_m \cdot \eta_p \cdot SD_m \approx 840 \text{ kWh, where } A = 1 \text{ kWp.}$$

The battery would be charged by the array output before 9:00 a.m. and between noon and 2:00 p.m. on school days. The battery would also be completely recharged during the three weekend days. The generator would run after school hours each day to bring the battery to nearly full charge. Thus, the battery would experience a complete discharge cycle every school day (140 per year).

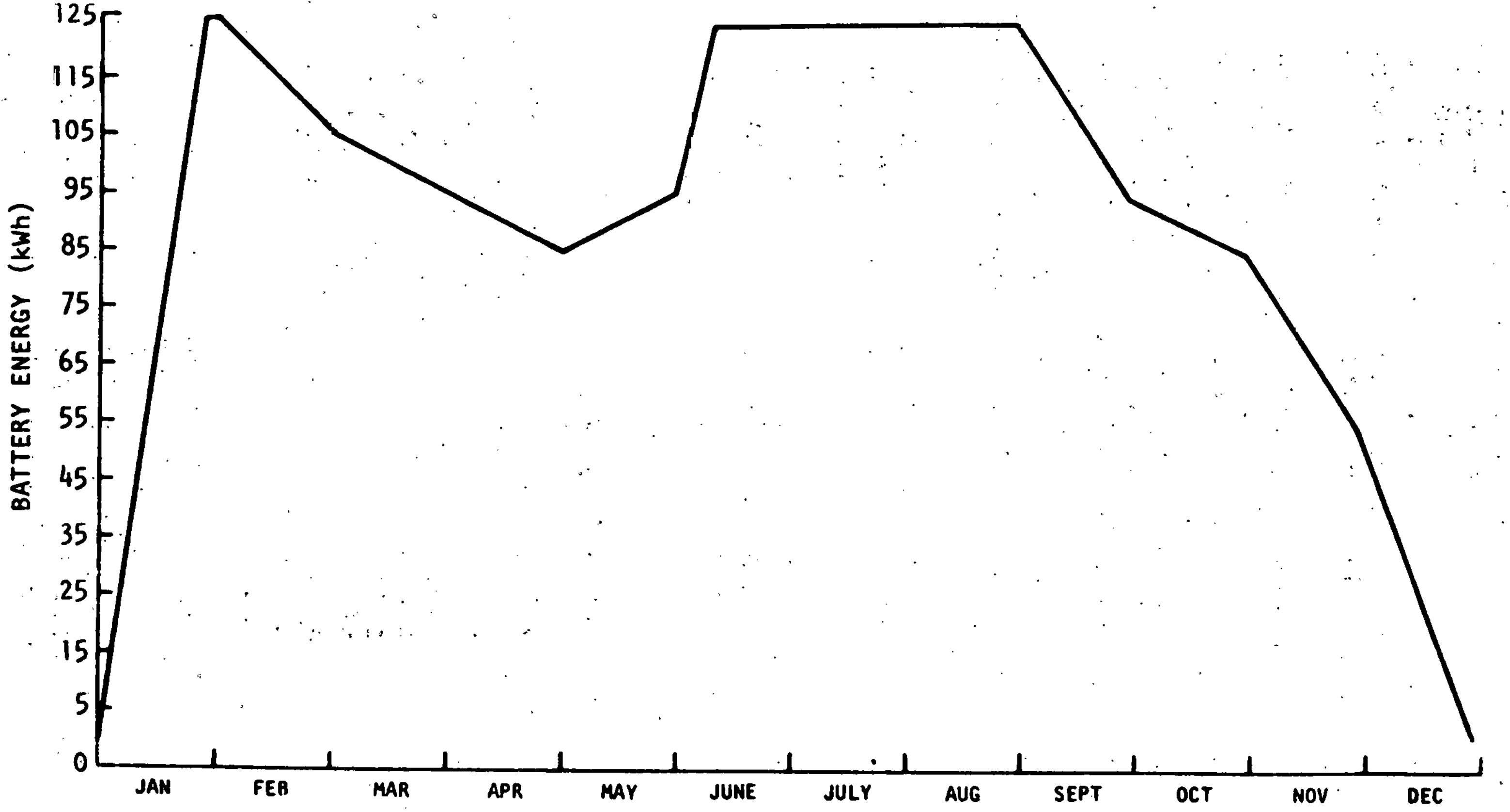

Figure V-6. Annual Cycle for PV - Remote Village
(Battery Effective Capacity = 125 kWh)

This design would use fewer than 100 gallons (378 liters) of diesel fuel annually, and the generator would operate approximately 400 hours per year.

C. Sizing of the Power Conditioner

1. Stand-Alone System

Figure V-7 is a simplified block diagram of the photovoltaic system for the remote village application.

The power conditioner chosen is a DC/DC type. Figure V-8 is a simplified block diagram of the unit. The converter operates like an automatically controlled "DC Variac." The control circuitry selects the ratio of the input voltage to the output voltage. The control circuitry includes controls for peak power tracking. When the power from the array exceeds the load demand and the battery is charged to its full capacity, the controls automatically increase the array voltage and reduce array power output, thus preventing overvoltage of the battery. The filters function to reduce the ripple on the array and the battery.

Detailed specifications of the DC/DC power conditioner follow:

Input	Specification
Operating range	100-150V DC
Output	
Voltage	120V DC
Power	4 kW
Short term rating	8 kW for 10 seconds
Efficiency	90% from half to full load

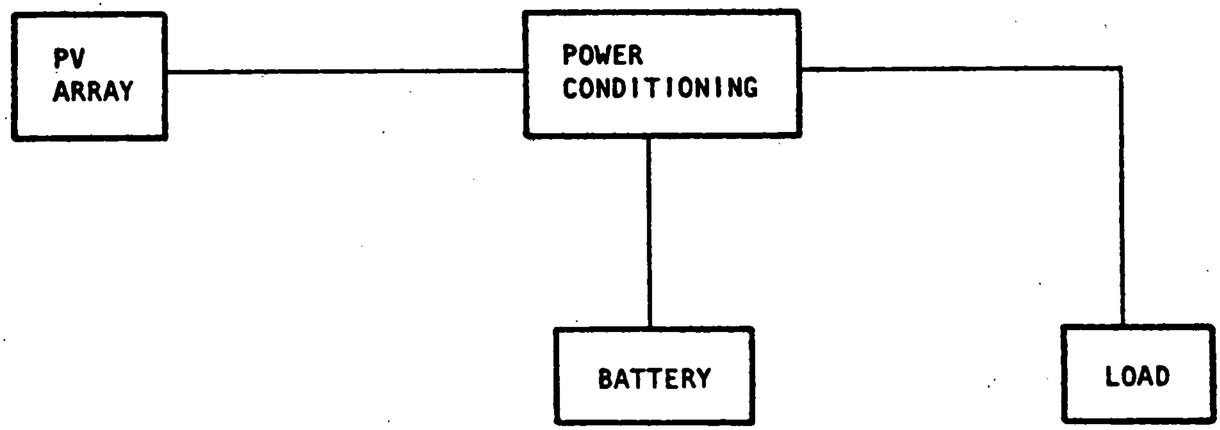

Figure V-7. Photovoltaic System for the Remote Village Application (Stand-Alone)

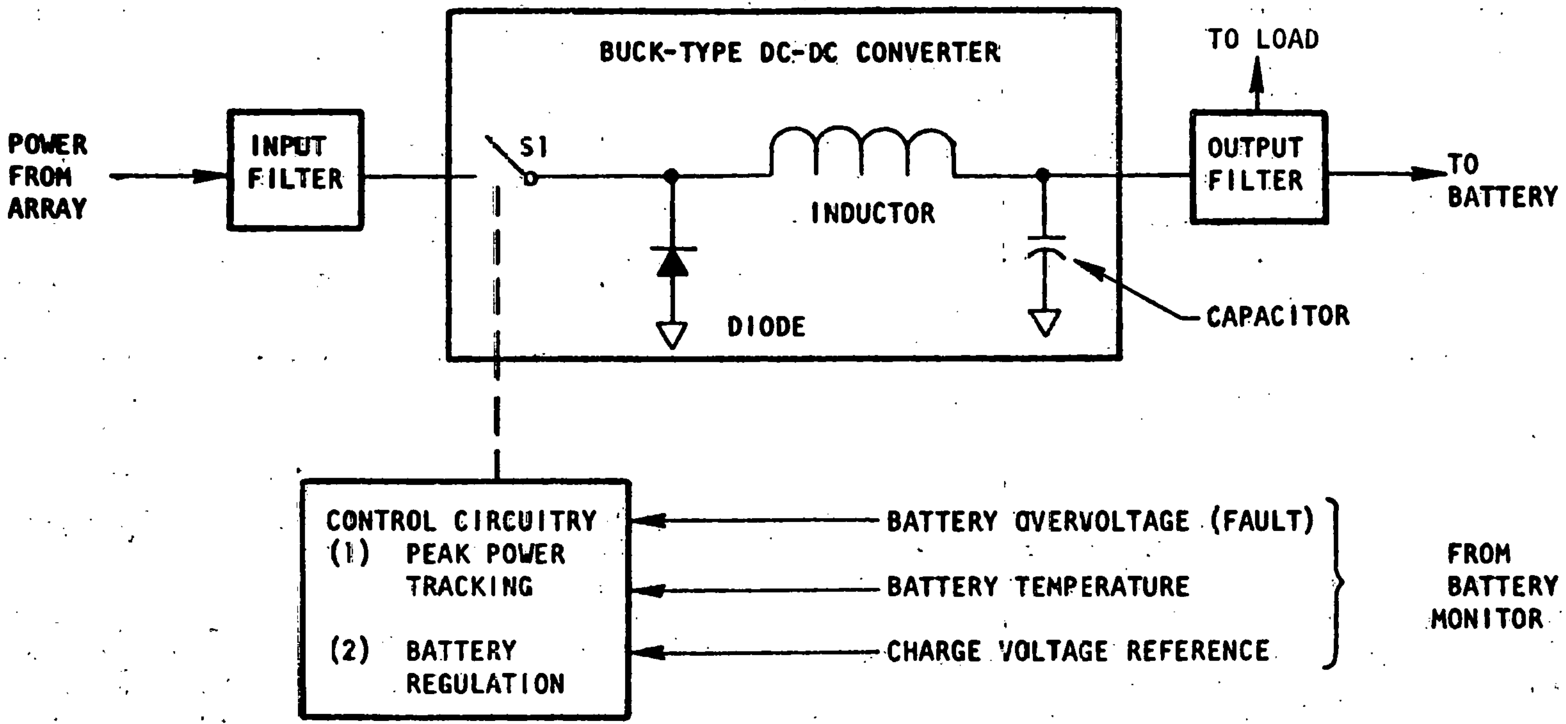

Figure V-8. DC/DC Power Conditioning Unit Used for a Remote Stand-Alone Application (1)

Physical Characteristics	Specification
Life	20 years
Reliability (MTBF)	20,000 hours
Environment	
Temperature	10 to 65.6°C (50 to 150°F)
Humidity	0-95%
Protection	Input fuses Output current limiter Automatic starting and self protection Automatic shutdown for input voltages greater than 300 and less than 200 volts DC Over temperature Over/undervoltage
	Specification
Metering	Input voltage Output voltage Output frequency
Operation Mode	Stand-alone only

2. Diesel Generator Backup System

Figure V-9 is a simplified block diagram of the photovoltaic system for the remote village application with generator backup.

The power conditioner chosen is a DC/DC type. Figure V-10 is a block diagram of the unit. The converter operates

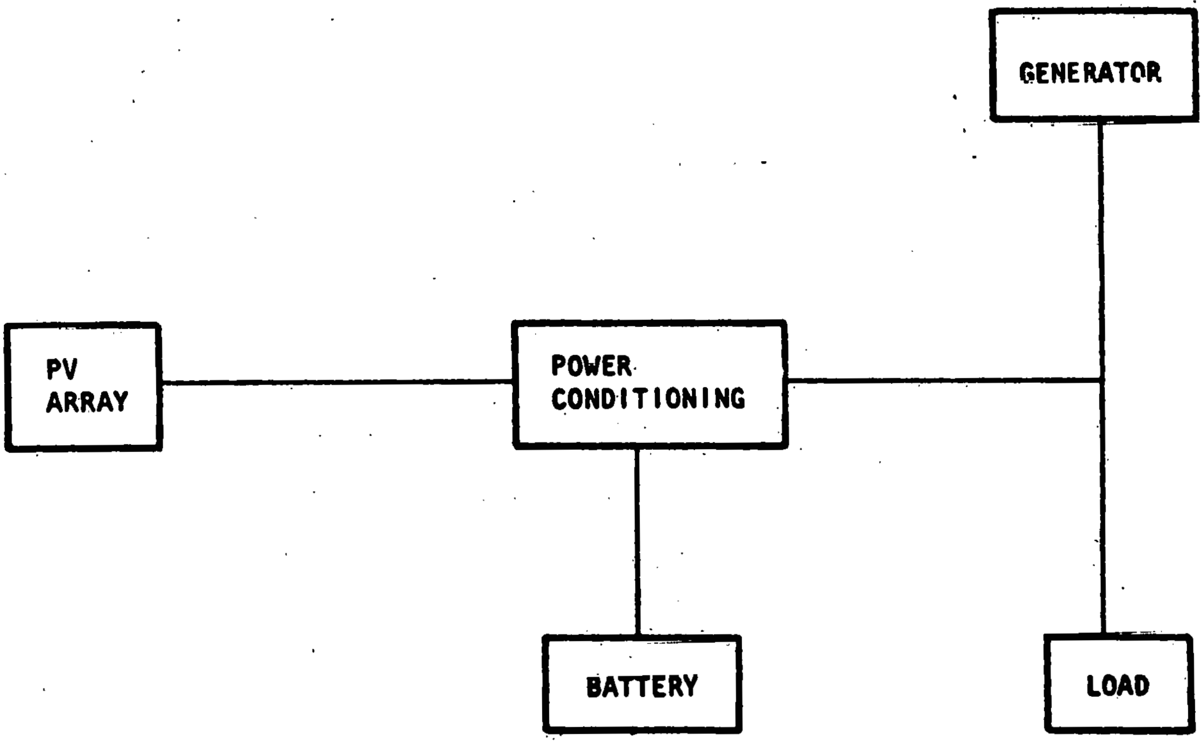

Figure V-9. Photovoltaic System for the Remote Village Application (Generator Backup)

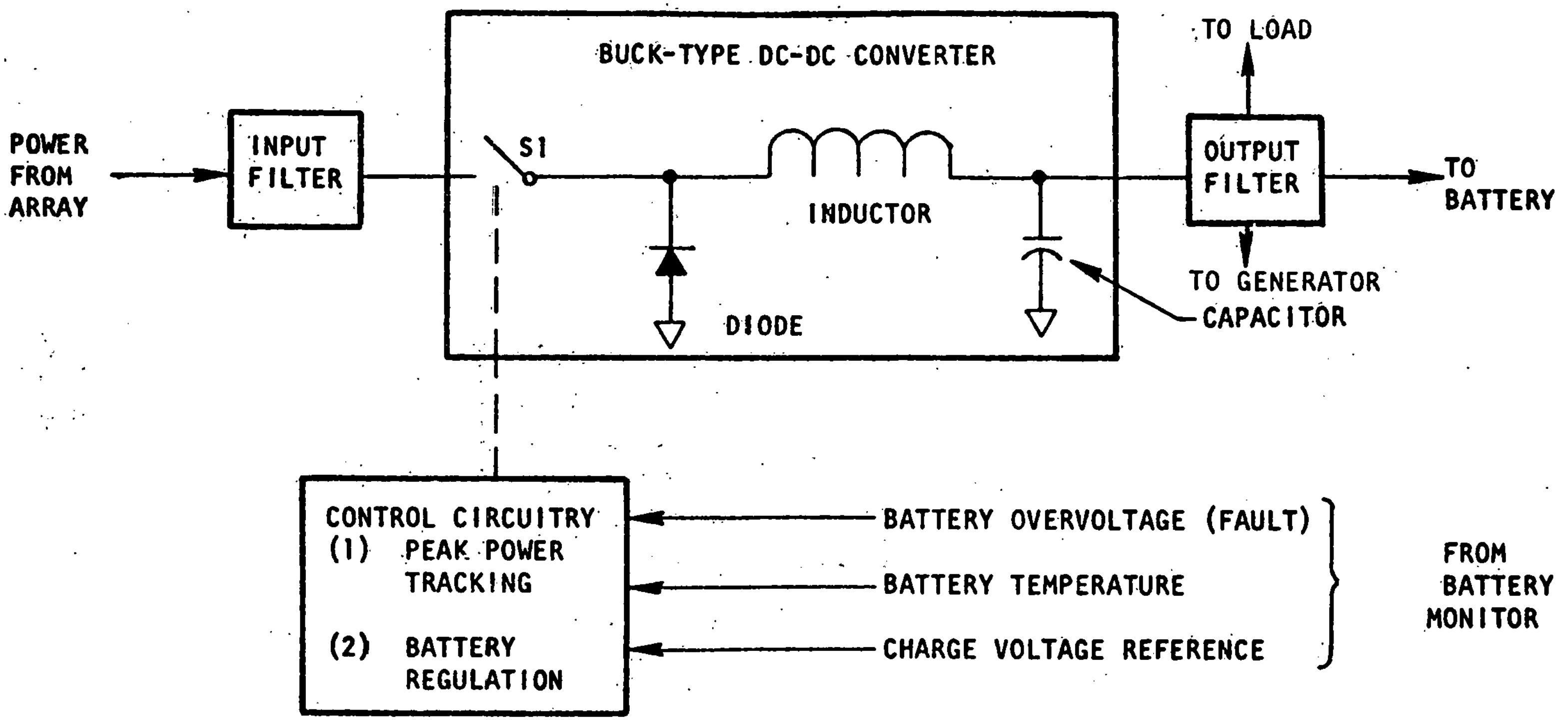

Figure V-10. Power Conditioning Unit Used for a Remote Application (1) like an automatically controlled "DC Variac." The control circuitry selects the ratio of the input voltage to the output voltage. The control circuitry includes controls for peak power tracking. When the power from the array exceeds the load demand and the battery is charged to its full capacity, the controls automatically increase the array voltage and reduce the array power output, thus preventing overvoltage of the battery. The filters function to reduce the ripple on the array and the battery.

Detailed specifications of the DC/DC power conditioner are shown below:

Input	Specification
Operating range	100-150V DC
Output	
Voltage	120 volts DC
Power	4 kW
Short-term rating	8 kW for 10 seconds
Efficiency	90% from half to full load
Physical Characteristics	Specification
Life	20 years
Reliability (MTBF)	20,000 hours
Environment	
Temperature	10 to 65.6°C (50 to 150°F)
Humidity	0-95%
Protection	Input fuses Output current limiter Automatic starting and self protection

	Automatic shutdown for input voltages greater than 300 and less than 200 volts DC
	Over temperature
	Over/undervoltage
Metering	Input voltage
	Output voltage
	Output frequency
Operation Mode	Stand-alone and generator

D. Summary of Battery Requirements

1. Stand-Alone

The following is a summary of battery requirements for the remote village (stand-alone):

System voltage:	120 volts DC
Battery effective capacity:	125 kWh
Maximum discharge rate:	2.2 kW
Maximum charge rate:	1.6 kW
Self-discharge rate:	As low as possible. Must be less than 5 percent per month
Duty cycle:	One annual complete discharge, partial weekly discharges during weeks when school is in session, recharge during weekends
Reliability:	Very important
Maintenance:	Must be capable of operation for several months with only minimal maintenance by unskilled personnel

Environmental:	Must be capable of operating in very high ambient temperature (120°F, 50°C) and relative humidity (95%)
Special requirements:	Must be able to tolerate standing at low state of charge for several months. Also must be able to operate for years without forced full charge or full discharge (i.e., other means for cell equalization must be provided because period of full charge is seasonal).

2. Diesel Generator Backup System

The following is a summary of battery requirements for the remote village (diesel generator backup):

System voltage:	120 volts DC
Battery effective capacity:	15 kWh
Maximum discharge rate:	2.2 kW
Maximum charge rate:	2.0 kW
Self discharge rate:	Not critical
Duty cycle:	Approximately 140 deep cycles per year
Reliability, Maintenance, and Environmental:	Same as remote, stand-alone application.

E. References

1. Manufacturer's published literature. Delta Electronic Control Corporation, Irvine, California.

VI. PHOTOVOLTAIC SYSTEM FOR AN INDUSTRIAL/UTILITY APPLICATION - A DEDICATED UTILITY FOR A SMALL COMMUNITY

A. Load Profiles and Characteristics

1. Background

The chosen industrial/utility end-use application is a small community which will be partially supplied by a dedicated photovoltaic/battery utility. Interties to other utilities supply baseload and backup energy.

The chosen scenario is a hypothetical small town in southern Arizona (33°N latitude) with a population of 8,000 people. Its connected load consists of a mix of commercial, industrial, residential, and street-lighting loads.

2. Characteristics of the Load Elements

Since the connected load consists of a mix of commercial, industrial, residential, and street lighting loads, the total system power factor (uncorrected) will never exceed 0.8 lagging during heavy load periods. During light load periods, when the percentage of motor load connected to the system is also low, the power factor will be much higher. The size of any individual motor, compared to the total system load and supply capacity, will be such as to make motor inrushes an insignificant factor in sizing the power conditioners.

3. Energy Use Patterns and Load Profiles

The chosen load is assumed to contain, because of the climate in which it is located, a high degree of air-conditioning load. The system will therefore peak in the summer months. The system peak demand is 21 MW. Figure VI-1 shows the load profile of the total system on the peak summer day. The cooling season in this part of the country is quite long and system peaks close to this level will occur in the months of June, July, August, and September.

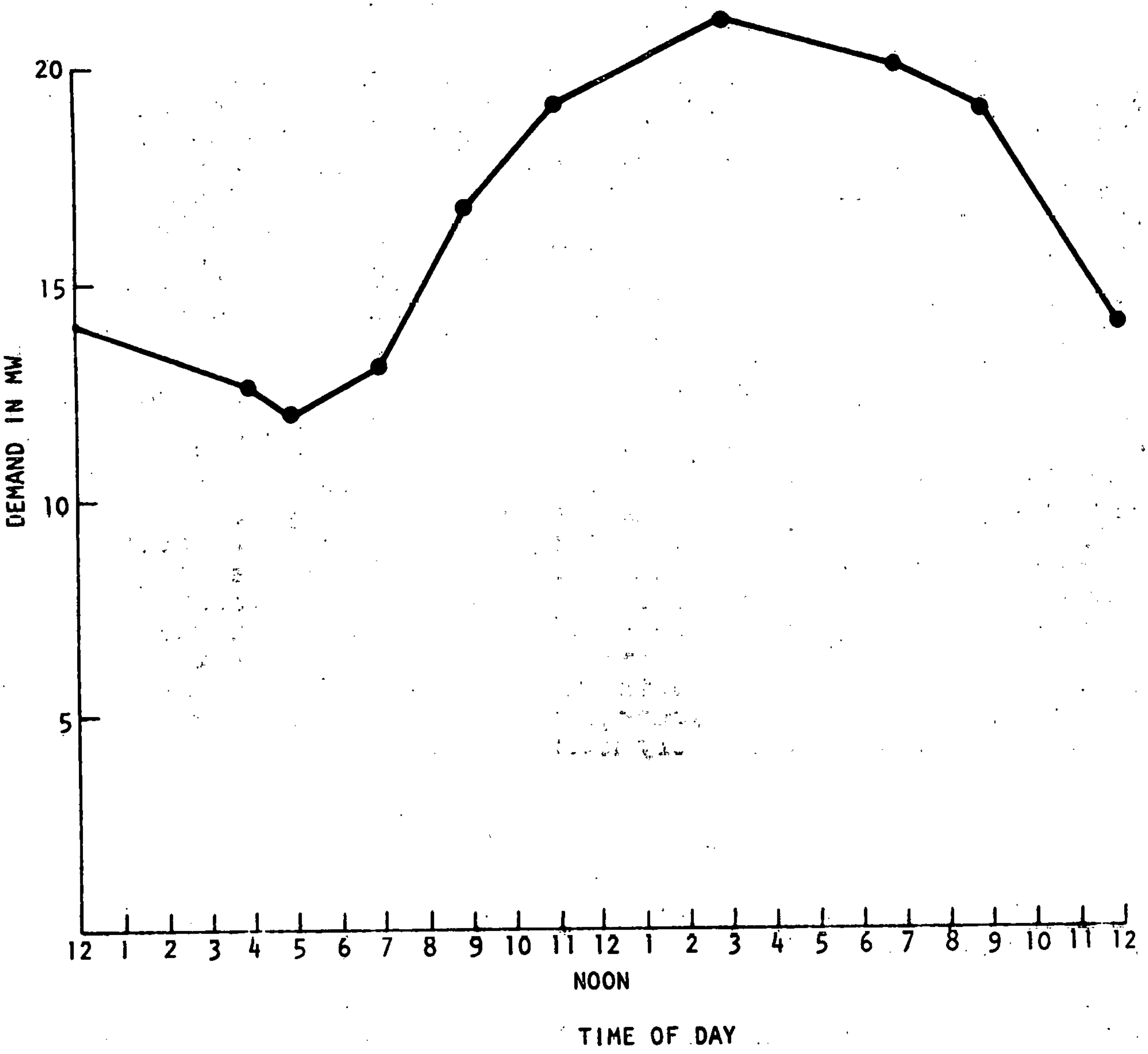

Figure VI-1. Load Profile of a Small Community on Peak Summer Day

For the purposes of this scenario, the annual load factor of this system was defined as 55 percent. This results in annual electric energy use of 101,178 MWh. Figure VI-2 gives a breakdown of the kWh usage on a monthly basis.

B. Sizing of the Array and the Battery

In this scenario, a power plant serving the intermediate and peak load demand of a small community in Arizona is connected to a larger utility grid. Baseload generators throughout the grid supply the baseload electrical power requirements of the community. A photovoltaic power system with battery energy storage is to be parametrically designed to displace as much of the fuel requirement of this power plant as economically practical. It is assumed that this photovoltaic-battery system is backed up by the conventional generators throughout the utility grid.

The photovoltaic array and battery system are sized to supply the electrical energy demand above 13 MW during a clear day during August (see Figure VI-3). The first 13 MW is considered base load, and is supplied by conventional generators. A 2-axis continuous sun-tracking array is specified for this application. A computer simulation model (a simplified version of SOLSIM) was used to determine the minimum array size and required battery effective capacity. For an 80 percent efficient battery and 90 percent efficient power conditioner, the array size is 14.7 MWp, and the required battery effective capacity is 37.5 MWh. Figure VI-4 shows the battery charge/discharge profile. The maximum power capability of the battery must be 7 MW.

C. Sizing of the Power Conditioner

Figure VI-5 is a simplified block diagram of the photovoltaic system for the utility application.

A simple current-fed, line-commutated power conditioner was chosen for the system. Figure VI-6 is a schematic of the power conditioner. The system consists of two inverter substation modules with dedicated arrays feeding each inverter substation unit.

The basic interface between the arrays and the inverter is composed of a reactor, batteries, and a regulator. The reactor supports the ripple voltage at the inverter DC terminals and maintains the peak ripple current at a reasonable level.

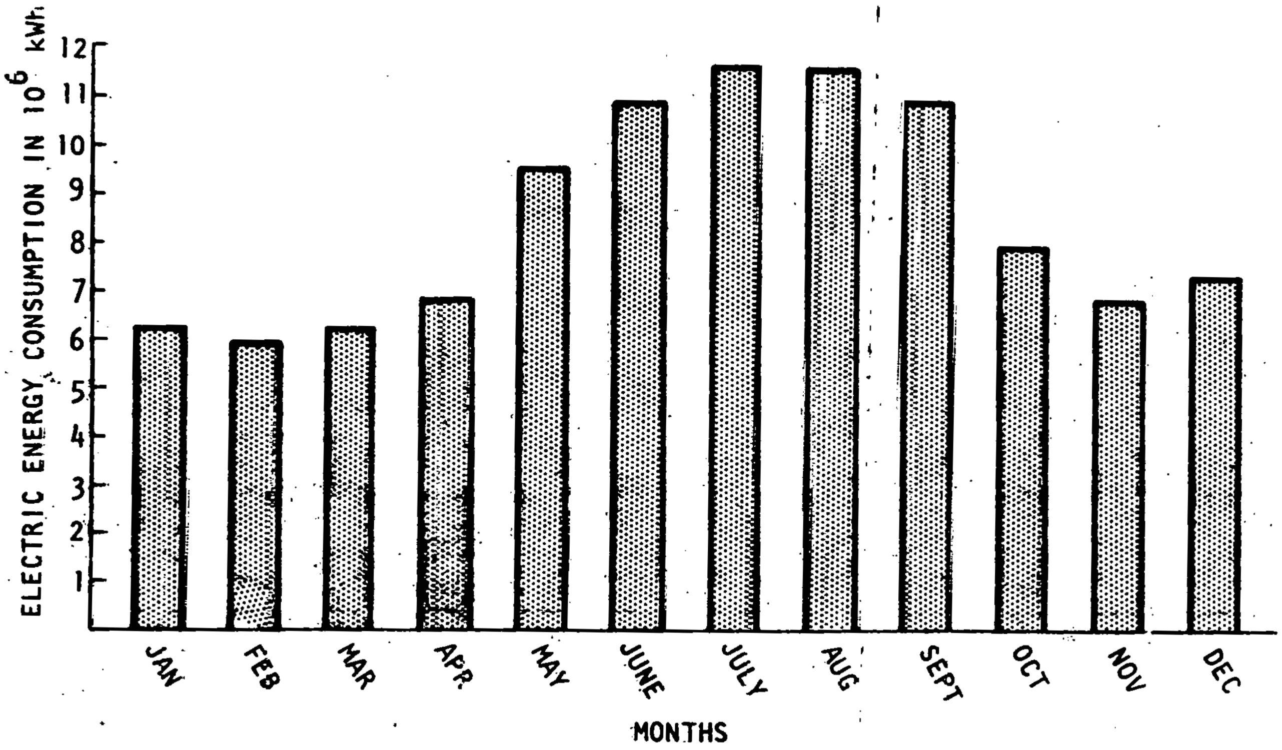

Figure VI-2. Monthly Electric Energy Usage in a Small Community

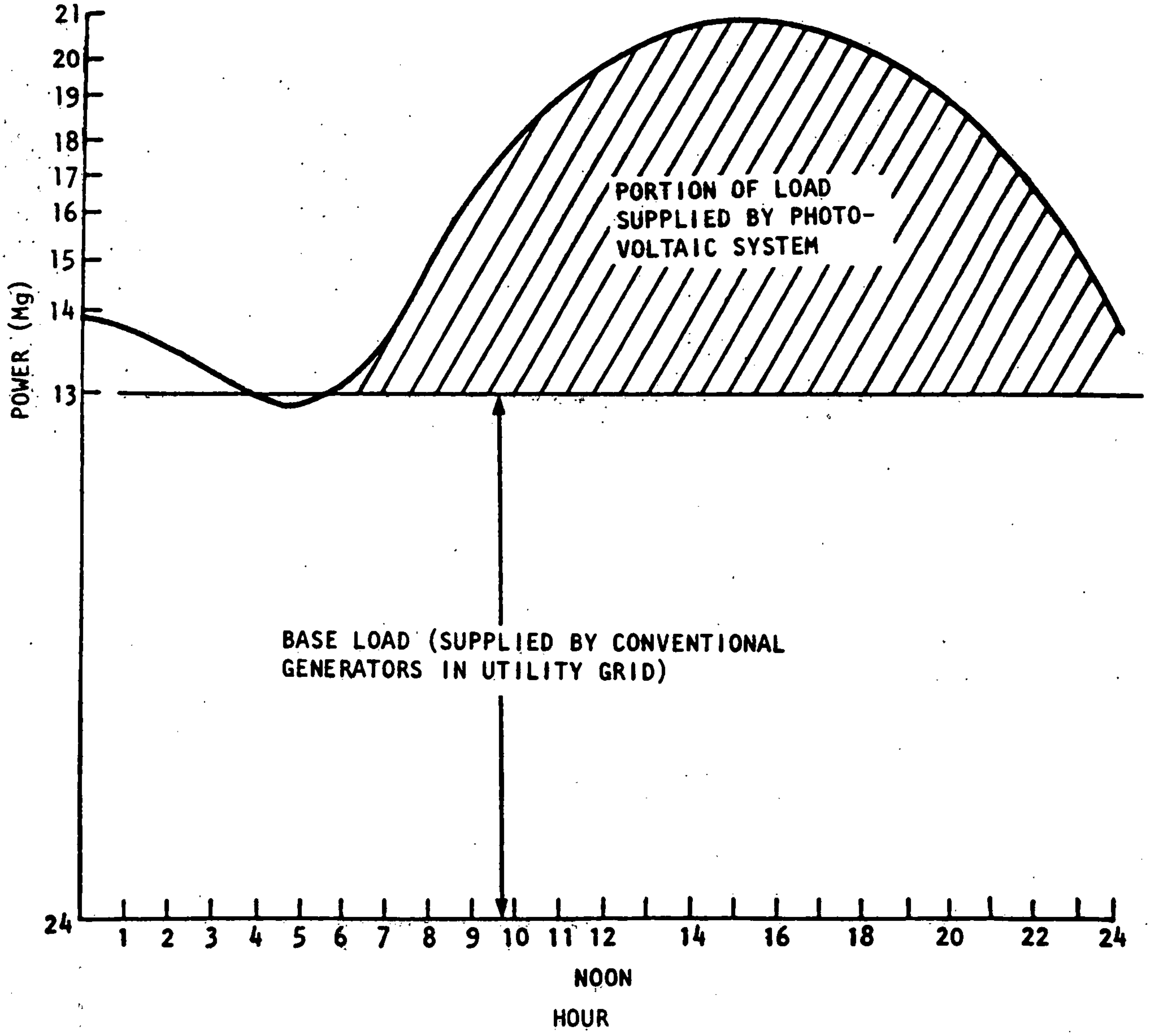

Figure VI-3. Dedicated Utility Load Curve for August

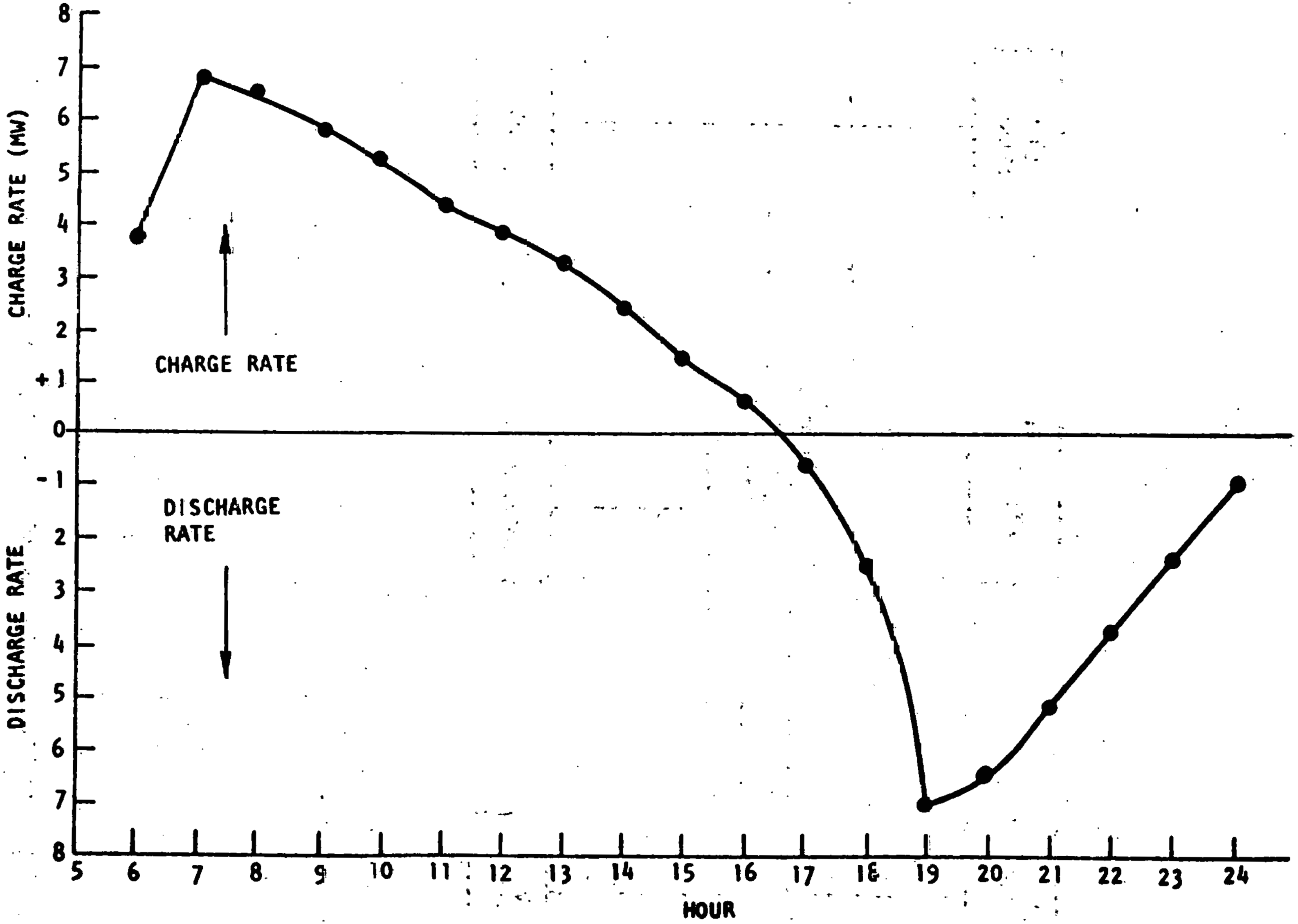

Figure VI-4. Battery Charge/Discharge Rate vs. Hour

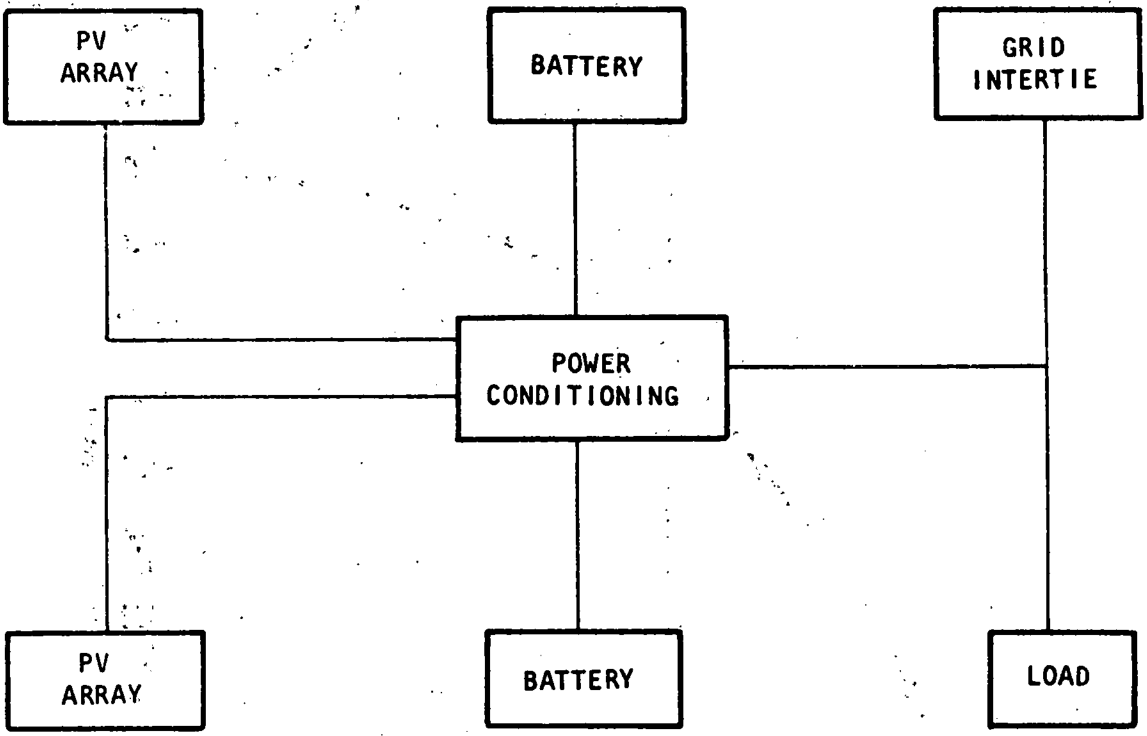

Figure VI-5. Photovoltaic System for the Utility Application

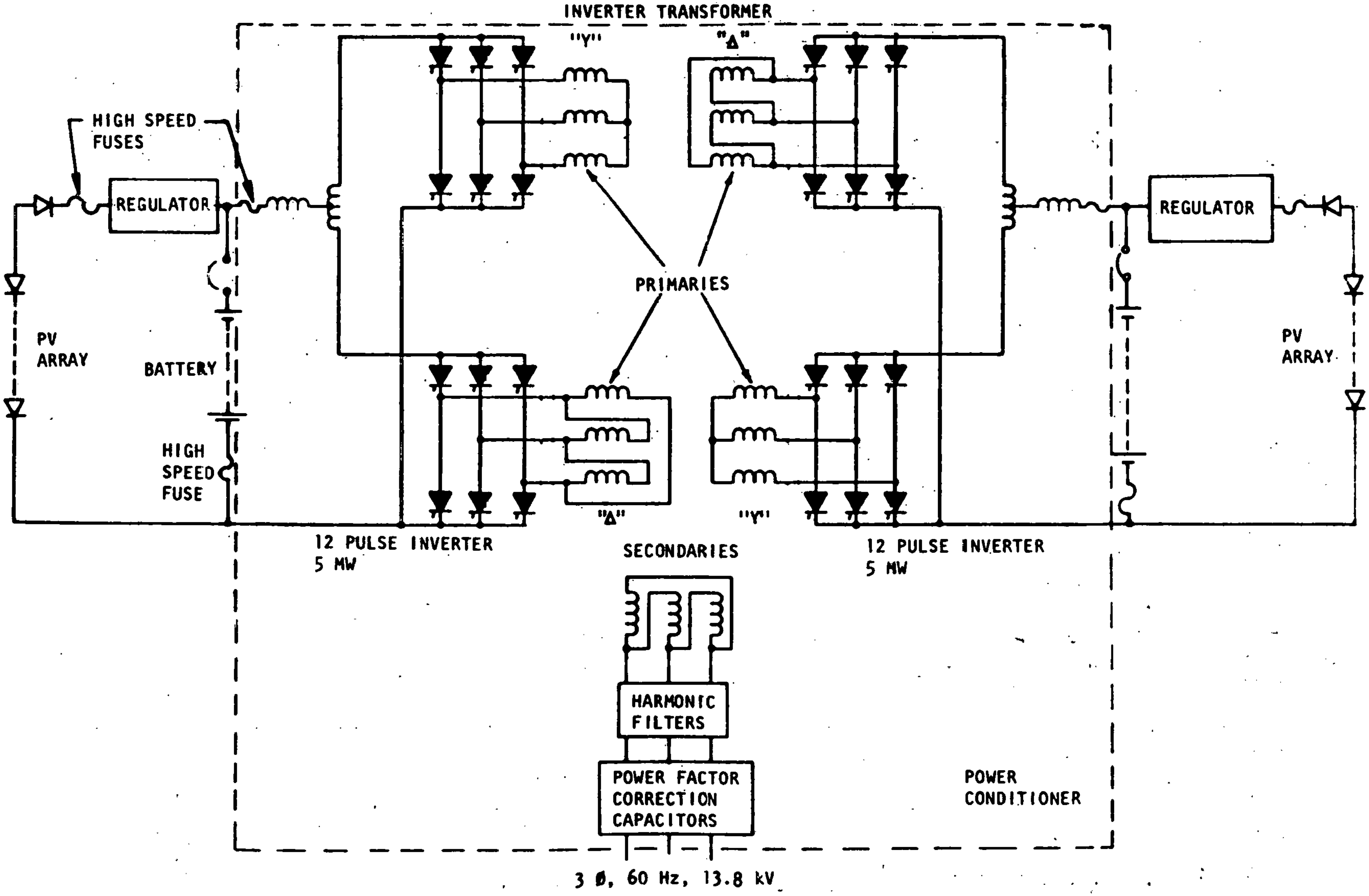

Figure VI-6. Current-Fed Line-Commutated Power Conditioner Used for a Utility System (1)

The interphase transformer is connected between the DC terminals of the two 6-pulse bridges, forming a 12-pulse system. This element supports the difference in ripple voltage between the two inverters.

Motor-operated disconnects should be used between the inverter and inverter transformer. This will facilitate isolation of faulted units.

The transformer secondary voltage chosen is 13.8 kV. Harmonic filters and power factor correction capacitors are provided at the transformer secondary to minimize harmonic distortion and to improve the power factor of the system. Lightning arresters should also be provided at the transformer secondary.

The following are detailed specifications of the power conditioner:

Input	Specification
Operating range	1-1.5 kV DC
Output	
Voltage	13.8 kV, 3 Ø, AC
Power	10 MW
Efficiency	90% from half to full load
Total harmonic distortion	<5%
Power factor	0.9 lead to 0.9 lag

Physical Characteristics	Specification
Life	20 years
Reliability (MTBF)	20,000 hours
Environment	
Temperature	-10 to 50°C (14 to 122°F)
Humidity	0-95%

	Specification
Protection	Automatic shutdown for input voltages higher than 1.5 kV and less than 1 kV
	Input fuses
	Over/undervoltage
	Over temperature
	Output current limiter
	Overload
	Out of phase with the generator system
Metering	Input voltage
	Input current
	Input power
	Input watt-hours
	Output voltage
	Output current
	Output power
	Output watt-hours
	Output VARS
	Output frequency
Alarms	Input overvoltage
	Input undervoltage
	Input overcurrent
	Output overvoltage

Specification
Output undervoltage
Overload
Over temperature
Blown fuse
Out of phase with the generator system

D. Summary of Battery Requirements

The following is a summary of battery requirements for the utility:

System voltage:	1,000 volts
Effective capacity:	37.5 MWh
Maximum discharge rate:	7.0 MW
Maximum charge rate:	7.0 MW
Duty cycle:	Daily deep discharge cycle
Self-discharge rate:	Not critical
Health & safety:	Battery will not be located in populated area.
Maintenance:	Skilled personnel will be available to perform maintenance.
Reliability:	Very important

E. References

1. Pittman, P.F., Westinghouse Electric Corporation. Conceptual Design and Systems Analysis of Photovoltaic Power Systems. Volume III (1) - Technology. Prepared for U.S. Energy Research and Development Administration, under Contract No. E(11-1) 2744, May 1977.

VII. PHOTOVOLTAIC SYSTEM FOR A MILITARY APPLICATION -- A MILITARY FIELD TELEPHONE OFFICE

A. Load Profiles and Characteristics

1. Background

The chosen scenario is an AN/MTC-1 Telephone Central Office (1). The AN/MTC-1 is a truck-mounted communications system used in military field operations as a telephone operator switchboard, and control center for telephone communication within and between battalions, brigades, division, and Corps. The unit is capable of handling 200 local lines and 20 trunk lines, and under normal operating conditions is manned by three switchboard operators and one repair person (2).

The unit consists of the telephone switchboard, switching relay equipment, and ancillary equipment. This equipment is divided into two subunits: an AN/MTA-3 and an AN/MTA-4. Each subunit is housed in an 8 by 12 ft communications shelter mounted on its own 2-1/2 ton truck. The system is designed to run on 48 volt DC power.

The subunit AN/MTA-3 has the following electrical loads:

(a) Lighting

(b) Fans (for equipment cooling)

(c) Resistance heater

(d) Intercom.

The subunit AN/MTA-4 has the following electrical loads:

(a) Lighting

(b) Fans (for equipment cooling)

(c) Resistance heater

(d) Intercom

(e) Battery exhaust fan

(f) Power distribution panel.

2. Characteristics of Load Elements

The power demand and energy consumption characteristics of the load elements in the chosen military communication station are shown in Table VII-1.

TABLE VII-1. MAXIMUM POWER DEMAND OF THE AN/MTC-1 TELEPHONE CONTROL OFFICE'S ELECTRICAL LOADS (2)

Device	AN/MTA-3 Maximum Demand (W)	AN/MTA-4 Maximum Demand (W)
Lighting	190	260
Fans	300	300
Heater	3,000	3,000
Intercom	32	64
Battery fan	---	10
Power distribution panel	---	600
TOTAL MAXIMUM DEMAND	3,522	4,234

3. Energy Use Patterns

When the AN/MTC-1 is outfitted with a photovoltaic/battery power system, many of the usual load elements listed in Table VII-1 are disconnected. This is because the amount of solar cells necessary to provide sufficient power for the ancillary equipment would be too large to effectively deploy on the trucks that comprise the system. The two 3,000-watt electric heaters are disconnected for photovoltaic operation. This, of course, limits the use of the unit to the more temperate climate and warm seasons of the year. The intercom is disconnected since the units are usually set up end-on-end to provide direct communication between operators. The fans are also disconnected, so operation during warm spells requires that shelter doors be left open.

The lighting, battery fan, and power distribution panel are the only loads that are supplied when the unit is powered by a photovoltaic array. The unit is usually powered by a diesel generator which is sized to supply the power demand of all the load elements listed in Table VII-I. For this reason, no detailed load profile data on the unit are available from the Signal Battalions at Fort Hood or Fort Bragg. However, personnel at MERADCOM (Mobility Equipment Research and Development Command) at Fort Belvoir in Virginia have estimated that power demand of the loads connected for photovoltaic use will average 300 watts 24 hours a day 7 days a week (3). Figure VII-1 shows the load profile of the AN/MTC-1. Figure VII-2 shows the monthly energy use of the AN/MTC-1, based on the assumption that the station is used on three months of maneuvers during the summer.

B. Sizing of the Array and the Battery

The military field telephone office is a mobile system with a constant electrical load of 300 W direct current. The photovoltaic power system for this scenario is assumed to be backed up by a diesel-electrical generator. Since the operation site is not specified, it is assumed that the PV system would have to be sized to supply the power requirements of the field telephone office for a range of solar radiation conditions.

The average daily solar radiation in the contiguous 48 states ranges from 4 kWh/m^2-day to 6 kWh/m^2-day (averaged over a year). The array will be sized for a daily solar radiation of 4 kWh/m^2. Required array size is estimated by the formula:

$$A = \left[\frac{0.3 \text{ kW}}{\bar{I} \cdot \eta_p \cdot T} \right] \cdot \left[8 \text{ hours} + \frac{16 \text{ hrs}}{\eta_B} \right]$$

Where:

A = array size in kW peak

η_B = round trip battery energy efficiency

η_p = power conditioner efficiency

$\bar{I}$ = average solar radiation (4 kWh per m^2 per day)

T = average tilt factor, averaged over the year, defined as the ratio of average daily solar radiation intercepted by tilted array (tilt angle is set at the sun's zenith at noon) to average daily solar radiation on a horizontal surface.

This formula is based on the assumption that load is supplied directly by array output for an average eight hours per day, and by the battery 16 hours per day.

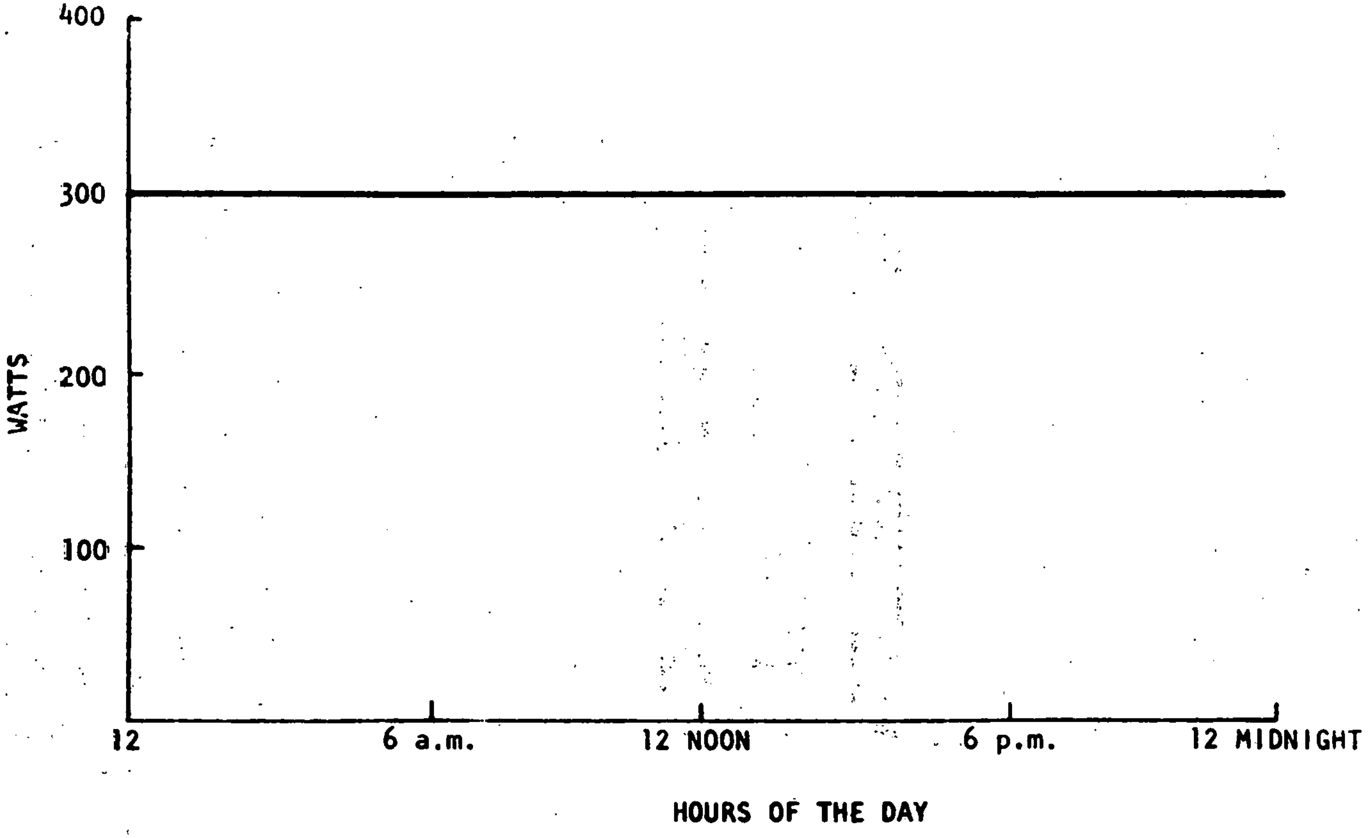

Figure VII-1. Load Profile for AN/MTC-1 Telephone Station on a Typical Day

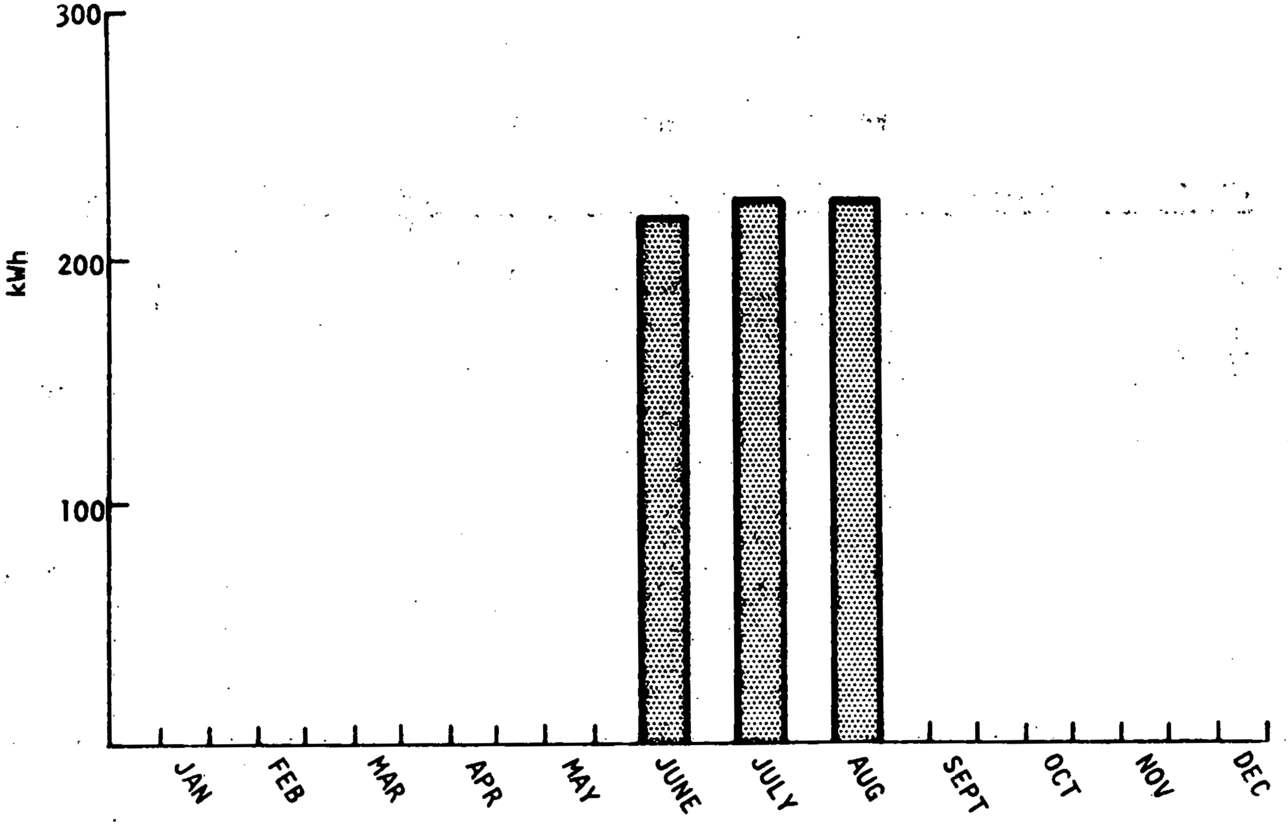

Figure VII-2. Energy Usage by Month of the AN/MTC-1 Telephone Station

Using $\eta_B = 0.80$ and $\eta_p = 0.90$, the required array size is found to be 2.5 kWp.

The battery must have an adequate capacity to supply the load for a continuous period of 18 hours. In winter, the array output is only available for about six hours. Battery effective capacity must be:

$$\frac{(18 \times 0.3)}{\eta_p = 0.90} = 6 \text{ kWh}$$

The maximum battery discharge rate is 330 watts. If the system were operated in areas with very high solar radiation (e.g., desert areas in the Southwest, where midday insolation is over 800 W/m^2), the array output power would be as high as 2 kW. The battery would then be charged at a rate of 1.67 kW (2 kW minus 300 W/0.90). Since this high charging rate (28 percent of battery capacity) is likely to damage the battery when it is near full charge, a battery charging controller is particularly important for this application.

C. Sizing of the Power Conditioner

Figure VII-3 is a simplified block diagram of the photovoltaic system for the military field telephone office application.

The photovoltaic array will supply all power up to its maximum capacity and the remainder will be supplied by the battery and DC generator.

The power conditioner chosen is a DC/DC type. Figure VII-4 is a block diagram of the unit. The converter operates like an automatically controlled "DC Variac." The control circuitry selects the ratio of the input voltage to the output voltage. The control circuitry includes controls for peak power tracking. When the power available from the array exceeds the load demand and the battery is charged to its full capacity, the controls automatically increase the array voltage and reduce array power output, thus preventing overvoltage of the battery. The filters function to reduce the ripple on the array and the battery.

Specifications of the DC/DC power conditioner follow:

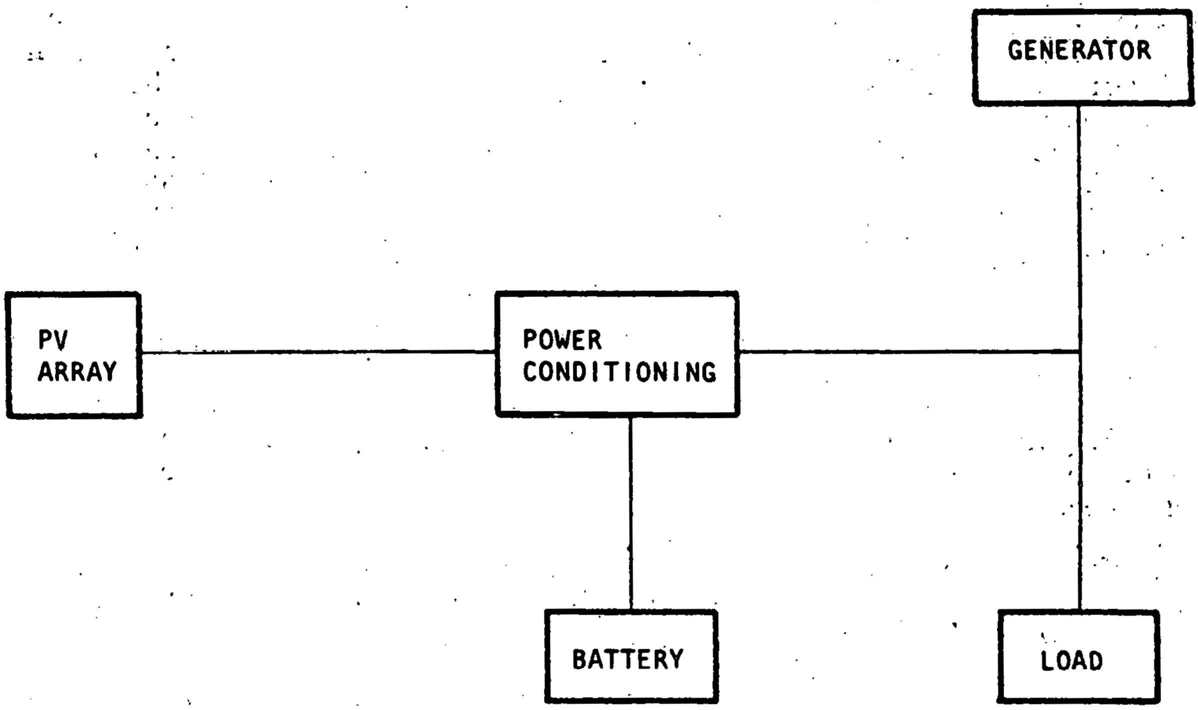

Figure VII-3. Photovoltaic System for the Military Field Telephone Office Application

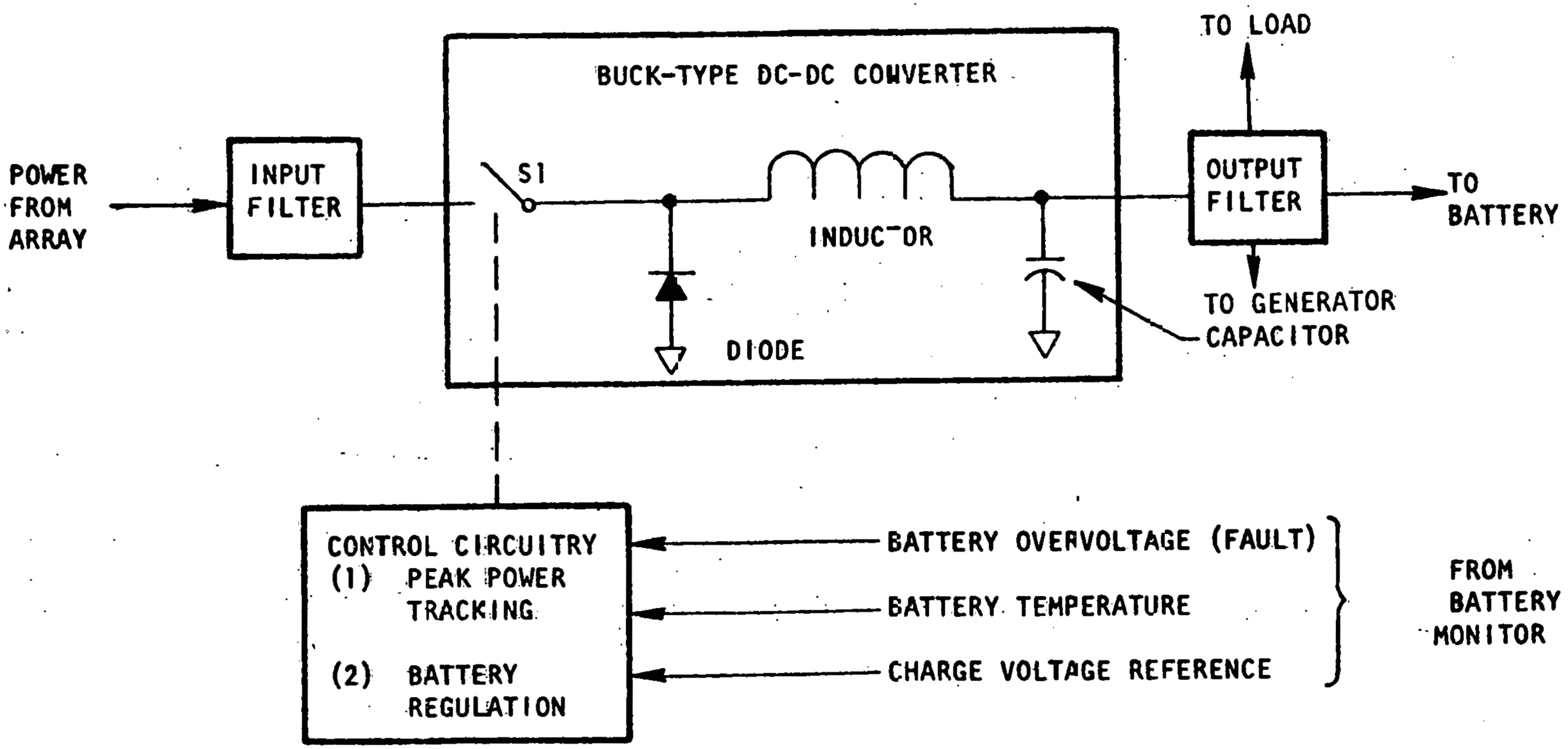

Figure VII-4. DC/DC Power Conditioning Unit Used for a Military Application (1)

Input	Specification
Operating range	50-70V DC
Output	
Voltage	48 volts DC
Power	300 watts
Short-term rating	450 watts for 10 seconds
Efficiency	90% from half to full load
Physical Characteristics	
Life	20 years
Reliability (MTBF)	20,000 hours
Environment	
Temperature	-10 to 50°C (14 to 122°F)
Humidity	0-95%
Protection	Input fuses Output current limiter Automatic starting and self protection Automatic shutdown for input voltages greater than 70 and less than 50 volts DC Over temperature Over/undervoltage

	Specification
Metering	Input voltage Output voltage Output frequency Output watt-hours Output power
Operation Mode	Stand-alone and generator

D. Summary of Battery Requirements

The following is a summary of battery requirements for the military field telephone office:

System voltage:	~60 volts, to provide 48V DC
Effective capacity:	6 kWh
Maximum discharge rate:	0.33 kW
Maximum charge rate:	1.67 kW
Duty cycle:	Daily deep discharge cycle, rapid fluctuations in rate and shifts between charge and discharge mode (shallow cycles)
Self-discharge rate:	Not critical
Health & safety:	Battery will be enclosed in a truck trailer.
Maintenance:	Should have minimal maintenance requirements for extended periods (several weeks).
Reliability:	Very high reliability is needed.

E. References

1. Faehn, Donald D. DOD/ERDA Terrestrial Photovoltaic Systems Demonstration Program. Twelfth IEEE Photovoltaic Specialists Conference, November 1976.

2. Private communication with Fort Bragg, Signal Battalion.

3. Private communication with Donald Faehn, MERADCOM, July 1979.

VIII. COST ANALYSIS OF BATTERY SYSTEMS

A. Introduction

This chapter presents the methodology and results of the analysis of life-cycle costs for the battery systems studied. Sections B through G of this chapter describe the analysis of projected selling prices for six battery types: lead-acid, Redox flow, nickel-hydrogen, lithium-metal sulfide, zinc-bromine, and calcium-metal sulfide. Section H shows how life-cycle costs were estimated.

The primary purpose of this analysis was to make a high and low projection of the selling prices of these batteries. The assumptions on which these projections were based are cited, and the factors of greatest uncertainty are identified.

For each battery, the materials and purchased components are first listed, along with the quantities required per kWh of battery capacity. This information was obtained from the battery developer or manufacturer, and from appropriate literature. Wherever possible, the current market prices were obtained for materials that are commercially available. Chemical prices were obtained from the *Chemical Marketing Reporter*, while metals prices were obtained from *Metals Week*, and *Iron Age* periodicals. Industrial suppliers were contacted for prices of materials not listed in these publications. From these quantities and prices, a total materials and purchased components cost was computed.

Other inputs to battery production are labor, production equipment, and factory space. Indirect costs such as federal, state, and local taxes and return on investment must also be considered in estimating the battery selling price. The recently revised Standard Costing Methodology developed for the Electric Power Research Institute provides a reasonable method for incorporating these factors to derive an estimated battery selling price (1). It is based on a manufacturing plant with an annual battery production of 2500 MWh. This costing methodology requires as inputs:

(1) Materials and purchased components cost

(2) Number of direct employees required by the plant

(3) Cost of battery manufacturing equipment

(4) Factory floorspace required.

The EPRI methodology is based on the following assumptions and standard rates:

(1) The standard labor rate is \$10 per hour (or \$20,800 per man year)

(2) Overhead rates are 150 percent on direct labor, and 10 percent on purchased materials and components

(3) Equipment cost is marked up by 25 percent to account for installation

(4) Installed equipment capital cost is depreciated at 10 percent per year

(5) The factory is leased at \$5 per square foot (\$50 per m^2) per year. This includes normal utility costs

(6) Federal, state, and local taxes per year are 15 percent of investment

(7) After tax return on investment is 15 percent of investment

(8) Investment is computed as installed equipment cost plus 30 percent of the annual value of production at factory cost (i.e., materials, labor, overhead, equipment depreciation, and annual factory rental cost)

(9) All costs are expressed in mid-1980 dollars.

The following formula for selling price was derived from the assumptions listed above:

Battery Selling Price per kWh =

(Materials and Components Cost per kWh) x 1.19

\+ (Labor hours per kWh) x 27.2

\+ (Installed equipment cost per annual kWh) x 0.4

\+ (Factory floorspace in m^2 per annual kWh) x 54.

B. Lead-Acid Battery

Two types of lead-acid batteries were identified in the analysis of photovoltaic power system applications. The remote-village scenario (stand-alone system) requires a battery capable of remaining in a standby mode at partial charge for several weeks at a time. This type of battery would experience only a shallow daily discharge cycle. Its duty cycle is similar to "float-service" batteries except that it experiences an annual deep discharge cycle due to lower solar radiation in winter. The other scenarios for which the lead-acid battery was deemed suitable -- utility, dairy, farm, and military -- are characterized by deep daily discharges.

Both float-service and deep-discharge batteries are currently manufactured for use in photovoltaic applications. Current selling prices are taken as the "high price" projections for lead-acid batteries. C&D Eltra sells its QP series, deep-discharge, photovoltaic battery for $189/kWh (in the largest cell size, 1.8 kWh cells). This battery is guaranteed to last 1,800 cycles. It may be discharged to an 80 percent depth of discharge. The C&D Eltra LCPSA series lead-acid batteries, designed for float service (or shallow daily discharge) sell for $116/kWh in the largest cell sizes (5.78 kWh/cell). The manufacturer recommends that the float-service batteries not be left to stand for more than a day at below a 50 percent depth of discharge. (This battery would therefore be unsuitable for a remote, stand-alone application.)

The technology underlying lead-acid batteries is well established, and innovative developments are not expected to significantly reduce their costs in the future. However, mass-production of lead-acid batteries for photovoltaic applications can greatly reduce the production cost. Automobile starting-lighting-ignition (SLI) batteries, which are mass-produced, now sell for $50 to $70/kWh. The SLI battery is similar to the float-service photovoltaic battery.

The Westinghouse R&D Center performed a study of the manufacturing costs of lead-acid batteries for utility load leveling (2). This study postulated a vertically integrated assembly-line battery plant manufacturing 25 to 40 MWh batteries annually. HAI has revised the production costs estimates to reflect June 1980 prices for raw materials, equipment, and labor. The EPRI Standard Costing Methodology was used to estimate selling price. The cost analysis is shown in Table VIII-1.

C. Redox Flow Battery

The system price of the chromium-iron Redox flow battery is expressed as the cost for power-related components ($/kW) and the cost for energy storage-related components ($/kWh).

TABLE VIII-1. LEAD-ACID BATTERY MANUFACTURE - SELLING PRICE CALCULATION

(in 1980 dollars)

Materials		
Lead		
Positive & Negative Grids Positive & Negative oxide Straps & cell connectors	32 kg/kWh at $0.88/kg =	$28.28/kWh
Positive plate wrap		$ 3.70
Separators and protectors		$ 3.70
Case, cover, sideplates, base		$ 3.00
Electrolyte		$ 0.22
Total Materials Cost per kWh		$38.90

Installed equipment:	$3,750,000
Floorspace required:	13,000 square meters
Labor:	150 operating personnel
Annual production:	1,000,000 kWh in 5 kWh cells
Selling price: (based on EPRI Standard Costing Methodology)	$57/kWh

*Lead prices have fluctuated considerably in the last two years. The average price in 1978 was $0.75/kg. In 1979 the price increased from $0.88 to $1.25/kg. The price in February 1980 was $1.10/kg, but in early June it had fallen to $0.75/kg. The price, used in this analysis, $0.88/kg, is an estimate of the long-term average market price, expressed in 1980 dollars. The selling price of mass-produced lead-acid batteries for utility load leveling may be expressed as a function of the cost of lead by the formula:

$$\text{Selling price} = \$23.3 + 38.2 \times P_L$$

where P_L = cost of lead in $/kg.

The power-related cost component is primarily dependent on current density, expressed in amps/m^2. The higher the current density, the less electrode and membrane area required. Membrane costs also vary. The pumps filters, and storage tank capacities, and thus their costs, are inversely proportional to the concentration of reactants. Storage-related costs are influenced primarily by the cost of chromium trichloride.

The assumptions listed in Table VIII-2 were used to make high and low price projections for Redox flow batteries. Table VIII-3 presents these two price projections for the Redox battery.

A production cost/selling price study for the Redox flow battery is currently being performed by United Technologies, Inc. The preliminary finding of this study is that production costs for Redox flow batteries will range from $150/kW, $25/kWh (low) to $400/kW, $50/kWh (high). These estimates appear to agree with the projections in Table VIII-3, $615/kW, $40 kWh (high) to $300/kW, $14/kWh (low).

D. Nickel-Hydrogen Battery

A detailed process engineering study has not yet been conducted on the manufacture of nickel-hydrogen batteries for terrestrial applications. Therefore, the materials and components have been specified primarily on the basis of descriptions of the COMSAT satellite batteries that are currently fabricated by Eagle Picher Industries. Table VIII-4 shows the materials and components of the nickel-hydrogen battery. The material and component requirements of this battery differ from those of the satellite battery in several ways:

(1) A chemically impregnated nickel electrode is specified which is similar to that being developed by ERC for the nickel-zinc EV battery. State-of-the-art nickel-hydrogen batteries use a sintered nickel electrode which costs approximately $200/kWh to produce. Nickel-cadmium batteries now use a pocket nickel electrode which is about half this cost.

(2) The catalyst loading on the hydrogen electrode is assumed to be 0.5 mg/cm^2, rather than 5 mg/cm^2.

(3) A steel pressure tank 1,380 kilopascal (200 psi) working pressure is assumed for containment, rather than the much more expensive Inconel pressure vessel.

TABLE VIII-2. PRICE PROJECTION ASSUMPTIONS FOR THE REDOX BATTERY

High Price Projections (4)

(1) Current density = 463 amps/m^2 (achieved)
Since cell voltage is 0.9 V, power density is 420 W/m^2. Thus, 2.4 m^2 of cell are required per kW output

(2) $CrCl_3 \cdot 6H_2O$ price at \$2.64/kg (Since 11 kg are needed per kWh, this results in a storage-related cost for the chromium reactant, of \$28/kWh)

(3) Reactant Concentration = 1 Molar.

Low Price Projection (3)

(1) Current density = 592 A/m^2
Power Density = 484 W/m^2
Thus, 2 m^2 of cell required per kW output

(2) Chromium chloride reactant is assumed to be produced at a cost of \$7 per kWh of storage capacity

(3) Reactant Concentration = 1 Molar.

TABLE VIII-3. MATERIALS AND COMPONENTS OF THE REDOX BATTERY

Element	High Cost Projection	Low Cost Projection
Power-Related Cost		
Electrodes (catalyzed carbon)	$ 28/m^2	$ 28/m^2
Cell Frames	$ 10.80/m^2	$ 10.80/m^2
Cell Stack Total	$ 38.70/m^2	$ 38.70/m^2
Cell Area per kW	2.4 m^2	2.0 m^2
Pumps, heat exchangers, filters, piping	215/m^2 cell area	$108/$m^2$ cell area
Total Power-Related Cost	$615	$300/kW
Storage-Related Cost		
Tanks (69 liter volume required per kWh)	$12/kWh*	$ 7.50/kWh**
Chromium chloride reactants and iron chloride	$28/kWh	$ 7/kWh
Total Storage Related Cost:	$40/kWh	$14/kWh

Based on a 3,785 liter (1,000 gallon) stainless steel tank for chemical storage, priced at $650.00.

***Based on a plastic-lined carbon steel or concrete tank.*

TABLE VIII-4. MATERIALS AND COMPONENTS OF THE NICKEL-HYDROGEN BATTERY

Anode*	Quantity	Price	Cost per kW
Platinum (@ 0.5 mg/cm^2 loading)	16.5 g	\$14.25/g	\$235
Nickel screen	3.3 m^2	\$20.00/m^2	66
Teflon backing and gas diffusion screen	3.3 m^2	\$10.00/m^2	33
Separator (Polypropylene)	3.3 m^2	\$16.00/m^2	53
			\$387/kW
Cathode	**Quantity/kWh**	**Price**	**Cost per kWh**
$NiSO_4 \cdot 6H_2O$	10 kg	\$ 2.30/kg	\$23
Graphite and Plastic binder	23 kg	\$ 2.20/kg	5
Nickel-plated steel current collector	0.45 kg	\$ 6.60/kg	3
Pressure Tank (200 psia working pressure)			\$35/kWh
Hydrogen gas	27 g per kWh		<1
Potassium hydroxide	2 kg/kWh		<1
			\$70/kWh

TOTAL: \$387/kW, \$70/kWh

**Anode area determines the power level of the Ni-*H_2 *battery. Assuming a current density of 25* mA/cm^2 *and a cell voltage of 1.2 volts, 3.3* m^2 *of anode area and separator area are required per kW of battery output.*

These modifications were suggested by engineers at Eagle-Picher Industries who are involved with nickel-hydrogen battery fabrication.

Clearly, the most expensive cost element is the platinum, which is used to catalyze the hydrogen electrode. One cost reduction route that has been considered is substituting palladium for platinum. The producer price for palladium is \$175/Troy oz; for platinum, the producer price (June 1980) is \$450/Troy oz. Assuming the same catalyst loading, 0.5 mg/cm^2, and current density, 25 mA/cm^2, the use of palladium in place of platinum would reduce the materials cost per kW from \$387 to \$243.

To estimate selling price for the Ni-H_2 battery, annual production rate, equipment cost, labor, and factory floorspace requirements must be assumed (a manufacturing plan has not been developed at this time). For the purpose of this analysis, the equipment, labor, and floorspace requirements were assumed to be the same as those estimated for the lithium-metal sulfide battery. Assumed values are:

(1) Equipment - \$4.40 per annual kWh produced

(2) Labor - 0.246 man-hours per kWh produced

(3) Floorspace - 184,400 m^2 for an annual production of 2,500,000 kWh.

To determine material cost per kWh, a battery discharge time of three hours was assumed. This short discharge time results in a higher estimate for cost per kWh. The high estimate for materials cost is thus \$200 per kWh (\$387/3 + \$70). This estimate assumes that the nickel electrode can be made for \$31/kWh. The low estimate is \$150 per kWh (243/3 + 70). Applying the EPRI Standard Costing Methodology, the high projected selling price is \$250 per kWh and the low projected selling price is \$180 per kWh, for a three-hour nickel-hydrogen battery.

E. Lithium Silicon-Iron Sulfide Battery

The Atomics International Division of Rockwell has performed cost analyses on the mass production of lithium-metal sulfide cells for load-leveling batteries (5). Cost estimates for this battery have also been made by Argonne National Laboratory and Eagle-Picher Industries (6). From these studies, two designs have been selected, a baseline design for the high cost projection, and an advanced design for the low-cost projection. Both designs list the material and component requirements for a 2.5 kWh cell. These material and component requirements are shown in Tables VIII-5 and VIII-6. The prices in the two tables were obtained in June 1980, from industrial suppliers whenever possible.

For those items for which a price estimate could not be obtained, the Atomic International or Eagle-Picher Industries estimates were used.

The baseline design is proposed for the initial mass production of load-leveling cells (400,000 cells/year). The advanced design is proposed for a second generation manufacturing plant producing one million cells per year. The major differences between the two designs are:

(1) The baseline design employs solid-nickel, ribbed structures and porous nickel for the containment of the positive active material. The advanced cell uses nickel-coated steel structures and nickel-coated steel screens, which are considerably less expensive

(2) The baseline cell design uses Si_3N_4 (silicon nitride) powder for the separator, a material that is not commonly used in industry. The advanced cell calls for calcium oxide, an inexpensive material, for the separator

(3) Both designs require Li_2S (lithium sulfide), a substance which is not currently used in industry. The price assumed for Li_2S in the baseline design is $15.45/kg, based on the Eagle-Picher Industries production plan for 1982. A price of $8.80/kg was assumed in the advanced cell design, based on eventual large-scale production. The feedstock for the Li_2S and LiCl (used in the electrolyte) is Li_2CO_3 (lithium carbonate), which currently sells for $2.56/kg.

The following estimates by Atomic International are based on the assumption of a factory producing one million lithium-metal sulfide cells per year (annual production of 2.5×10^6 kWh).

(1) Equipment (installed) - $4.30 per annual kWh production

(2) Labor - 0.26 man-hours per kWh produced

(3) Floorspace - 18,400 square meters for annual production of 2.5×10^6 kWh.

TABLE VIII-5. MATERIALS AND COMPONENTS FOR LiSi-FeS 2.5 kWh CELL

(Baseline Design)

	Material Weight (kg)	Price/kg	Cost
Positive			
Nickel ribbed structure	3.00	\$ 6.63	\$ 19.90
Porous nickel containment	.68	22.00	15.00
Nickel-plated copper current collector and tabs			.50
Li_2S	2.25	15.45	36.00
Fe	2.75	.25	1.51
Negative			
Carbon steel-shelved structure	4.80	.55	2.64
Carbon steel-electrode rime	.24	.55	.13
80 mesh stainless steel	$0.7\ m^2$	$\$20/m^2$	14.00
Nickel-plated copper current collector and tabs			.30
Electrolyte			
LiCl	2.32	\$4.95	11.47
kCl	2.95	.84	2.47
Separator (Si_3N_4 Powder)	2.18	11.00	24.00
Terminals (Ni-Plated Copper)	.35	3.30	1.14
Feedthrough (Bonded Ceramic)			2.00
Case (Carbon Steel)	.48	.55	.27
Total Material Cost for 2.5 kWh cell			\$132.00
Cost per kWh			53.00/kWh

TABLE VIII-6. MATERIALS AND COMPONENTS 2.5 kWh LiSi-FeS Cell

(Advanced Design)

	Weight (kg)	\$/kg	Cost
<u>Positive</u>			
Ni-coated steel structure	3.00	\$ 1.10	\$ 3.31
Ni-coated steel screens (containment)	0.68	13.20	9.00
Copper tabs and Ni-plated current collector			.50
Li_2S	2.25	8.80	19.80
Fe	2.75	.55	1.51
<u>Negative</u>			
Carbon steel structure	4.80	.55	2.64
Carbon steel electrode rims	.24	.55	.13
Stainless steel screen	0.7 m^2	\$20/m^2	14.00
Ni-plated copper current collector and tabs			.30
$FeSi_2$	1.50	1.01	1.51
<u>Electrolyte</u>			
LiCl	2.32	4.95	11.47
kCl	2.95	0.84	2.47
<u>Separator</u> (CaO or MgO)	2.18	.33	.72
<u>Terminals</u>	.35	3.30	1.14
<u>Feedthrough</u>			2.00
<u>Case</u>	0.48	.55	.27
Total Materials Cost for 2.5 kWh cell			\$71.00
Materials Cost per kWh			\$28/kWh

On the basis of the EPRI Standard Costing Methdology, the high projected selling price for LiSi-FeS cells is $72/kWh. The low projected selling price is $42/kWh. The primary area of uncertainty in the selling price of LiSi-FeS cells is the price of lithium sulfide. The life-cycle cost of this battery is quite sensitive to the assumed battery cycle life, which is also a major element of uncertainty. Section H illustrates the relationship between life-cycle cost (present value of a 20-year project life) and assumed cycle life.

F. Zinc-Bromine Battery

A 20 kWh zinc-bromine battery is being developed by Exxon Research and Engineering for electric vehicle propulsion. The Gould Corporation is working on the development of a 20 MW/100 MWh zinc-bromine utility load-leveling battery, based on an 8 kWh cell design. Both developers have made preliminary production cost estimates.

Like the Redox flow battery, the cost of a zinc-bromine battery may be expressed as the cost for power-related components (in $/kW) and the cost for storage-related components ($/kWh). However, the electrode, which represents a major cost component, is both power-related and storage-related; therefore, the two cost terms are not really independent.

Gould has estimated a range of selling prices for two utility battery designs, a mod 0, which is based on a 40 kWh cell, and a mod 1, which is based on an 8 kWh cell. For each design, two values were estimated for the cell capacity density (i.e., the quantity of electric charge which can be stored per unit area of electrode surface). The high cost projection is based on a capacity density of 2,000 Ah/m^2. At a cell voltage of 1.6 V/cell, 0.31 m^2 of positive electrode surface is required per kWh of energy storage. The low cost projection is based on a capacity density of 3,000 Ah/m^2 (.21 m^2 of electrode surface per kWh). The Gould estimates of projected selling price (based on the EPRI methodology) of a 20 MW/100 MWh utility load-leveling battery are:

	2,000 Ah/m^2	3,000 Ah/m^2
Mod 0	$109/kWh	$77/kWh
Mod 1	70/kWh	50/kWh

Two designs for zinc-bromine EV batteries are being investigated by Exxon Research Engineering. One design uses a selective membrane for the separator; the other uses a much less expensive microporous separator. Both Exxon designs use carbon-plastic electrodes, and an organic complexing agent for bromine storage. Table VIII-7 presents the component costs for the two Exxon battery designs.

Equipment, labor, and factory floorspace requirements have not been reported by Exxon for their EV battery. Assuming that fabrication of zinc-bromine batteries would include the same basic facilities and labor costs as those for zinc-chlorine, the following estimates are used:

(1) Equipment - \$6.50 per annual kWh of production

(2) Labor - 0.16 man-hours per kWh

(3) Floorspace - 20,000 square meters for 2,500,000 kWh of annual production.

The cost of materials and components for a five-hour discharge rate battery using the Exxon selective membrane design is \$33 per kWh. The cost of materials and components for the microporous membrane design (five-hour battery) is \$18 per kWh. Based on the EPRI Standard Costing Methodology, the high projected selling price for the Exxon Zn-Br_2 battery is \$50/kWh, and the low projected selling price is \$30/kWh.

G. Calcium Silicon-Metal Sulfide Battery

The calcium silicon-iron sulfide cell is being developed by the Chemical Engineering Division of Argonne National Laboratory. Research on this battery has not yet progressed to the point where a detailed production cost analysis has been merited. According to researchers at the ANL, the construction of the CaSi-FeS battery will be similar to that of the LiAl-FeS battery (also under development at ANL), with the following exceptions:

(1) The electrolyte of the CaSi-FeS battery will consist of an eutectric salt whose composition is 13 weight percent LiCl, 12 weight percent NaCl, 40 weight percent $CaCl_2$, and 35 weight percent $BaCl_2$. Total electrolyte weight will be 3.2 kg pounds per kWh.

(2) Calcium sulfide (CaS) will be substituted for lithium sulfide (Li_2S). The quantity required will be 1.6 kg per kWh.

TABLE VIII-7. ZINC-BROMINE BATTERY COMPONENTS COSTS

Selective Membrane Design	
Power Related	
Electrodes	$ 15/kW
Circulation System (pumps, controls, piping, valves)	9/kW
Membranes (2.1 m^2 required per kW, assumed price \$50/m^2*)	105/kW
Total Power-Related Cost	$129/kW
Storage Related	
Tanks, Electrolyte, Reactants, Complexing Agent	$ 7/kWh
Microporous Separator	
Power Related	
Electrodes	$ 11/kW
Circulation System	10/kW
Membranes (1.95 m^2 per kW, assumed price \$10/m^2	21/kW
Total Power-Related Cost	$ 42/kW
Storage-Related Cost	$ 9/kWh

**Currently ion selective membranes, costing \$108/m^2, are used in prototype batteries.*

An alloy composed of 75 weight-percent aluminum -25 weight percent silicon will be substituted for aluminum in the negative electrode.

The total material requirements and costs for calcium-metal sulfide cells are displayed in Table VIII-8. These figures are based on June 1980 prices for these materials, and the assumption that calcium sulfide can be synthesized from lime and hydrogen sulfide at a cost of about $.22 per kg.

TABLE VIII-8. CALCIUM-METAL SULFIDE BATTERY MATERIALS

Materials	Quantity (kg/kWh)	Price ($/kg)	Cost ($/kWh)
Molybdenum	0.95	9.68	9.25
CaS	1.60	0.22	0.35
$LiCl/NaCl/CaCl_2/BaCl_2$	3.18	0.66	2.10
MgO	0.89	0.55	0.50
Al/Si	1.15	2.20	2.52
Cell Can (Carbon Steel)	1.60	0.73	1.15
Feedthrough	---	2.40	2.40
Total Materials Cost			$18.27

The manufacturing equipment, labor, and factory space requirements for producing calcium-metal sulfide cells are assumed to be similar to those specified for the lithium aluminum-iron sulfide battery.

The manufacturing equipment cost was estimated at $3 to $5 per annual kWh. Direct labor was projected at 0.34 to 0.56 man-hours per kWh produced, and factory floorspace was estimated at 10 m^2 per annual MWh of battery production. On the basis of the EPRI Standard Costing Methodology, the selling price for calcium-metal sulfide cells is projected to range from $32 to $40 per kWh. The most expensive element in this battery is molybdenum used in the current collectors. If a less expensive substitute can be found, the low price projection would be reduced considerably.

H. Summary of Detailed Cost Analysis

Table VIII-9 summarizes the high and low price projections for the six batteries analyzed. Table VIII-10 lists the major uncertainty factors which affect these price projections.

TABLE VIII-9. SUMMARY OF HIGH AND LOW BATTERY PRICE PROJECTIONS

	High	Low
Lead-Acid	$125/kWh	$ 57/kWh
Redox	$615/kW $ 40/kWh	$300/kW $ 14/kWh
Nickel-Hydrogen	$250/kWh	$180/kWh
Lithium-Metal Sulfide	$ 72/kWh	$ 42/kWh
Zinc-Bromine	$70/kWh	$ 30/kWh
Calcium-Metal Sulfide	$ 40/kWh	$ 32/kWh

I. Life-Cycle Cost Analysis

1. Definition of Life-Cycle Cost

The life-cycle cost of a battery is defined as the present value of all costs incurred by the user over the course of the project life (20 years, for the purposes of this study). It is equal to the sum of first cost (purchase price), the present value of battery replacement costs over the project life, and the present value of operation and maintenance costs over the project life. For the purpose of this study, battery operation and maintenance costs were not considered. (See subsection i of the following discussion.)

2. Assumptions

In performing the life-cycle cost analysis, a number of specific assumptions were made:

TABLE VIII-10. SUMMARY OF COST-INFLUENCING VARIABLES OF GREATEST UNCERTAINTY

Battery		Variable
Lead-Acid	●	Price of lead
	●	Cycle life
Redox Flow	●	Current density
	●	Membrane cost
	●	Cost of chromium chloride
Nickel-Hydrogen	●	Feasibility of substituting cheaper material for platinum
	●	Feasibility of significantly reducing catalyst loading on hydrogen electrode
	●	Feasibility of fabricating a cheaper nickel electrode
Lithium Silicon-Iron Sulfide	●	Price of lithium sulfide
	●	Substitution of a less expensive current collector
	●	Cycle life
Zinc-Bromine	●	Membrane separator material and price
	●	Electrode material and fabrication
Calcium-Metal Sulfide	●	Molybdenum current collectors
	●	Cycle life not yet established.

(a) Base year for cost analysis

(b) Conversion of cycle life to calendar life

(c) Project life

(d) Battery selling price

(e) Discount rate

(f) Annualization rate

(g) Inflation rate

(h) Salvage values of batteries

(i) Operating and maintenance costs.

Each of these assumptions is discussed in detail below.

a. Base year for cost analysis. For purposes of cost comparisons, all results of this cost analysis are given in 1980 dollars. In cases where cost estimates used data from previous studies, costs had to be updated to 1980 dollars. The Bureau of Labor Statistics Producer Price Index was used for this purpose. The commodity group figure used was Storage Batteries (Code No. 1179-01). Cost in 1980$ = 1.43 x Cost in 1976$, 1.30 x Cost in 1977$, 1.21 x Cost in 1978$, 1.11 x Cost in 1979$.

b. Conversion of cycle life to calendar life. To calculate the life cycle of the batteries, calendar life of each battery was used. For batteries for which data had been obtained on cycle life only, a conversion from cycle life to calendar life was required. The conversion factor assumed was 365 cycles per year, (i.e., battery is discharged once each day). It should be noted that this conversion factor does not require that the battery be fully discharged each day. This assumption is conservative in that batteries in real photovoltaic applications will probably undergo fewer annual deep discharges.

c. Project life. To calculate a comparative life-cycle cost of the batteries, a project life of 20 years was used.

d. Battery selling price. The battery system costs calculated in this analysis are based on the selling price of each battery. Battery selling price projections for six of the 14 batteries are derived in Sections B through G of this chapter. They are summarized in Table VIII-9. For the remaining batteries, estimates of production cost were obtained from battery developers. Selling prices were approximated by applying tax and profit rates of 7.5% to estimated production cost. These profit and tax rates were approximately equivalent to the rates which resulted from the EPRI methodology when the selling price rather than invested capital was used. In addition, the 7.5 percent rate was judged to be a reasonable rate of return on overall costs of production.

e. Discount rate. In order to calculate the total present value life-cycle cost of each battery over the 20-year project life, a nominal discount rate of 10 percent was used. The choice of this rate was based on discussions which took place at a Department of Energy Battery and Electrochemical Contractors' Conference in Arlington, Virginia (December 10-12, 1979). This rate was assumed to reflect the cost of alternative investment opportunities over a long period of time.

f. Inflation rate. A general rate of price inflation has not been considered in detail in this cost analysis. The price escalation for each battery depends largely on the type of materials used in its construction.

g. Salvage value. For most of the batteries, the 20-year project life is not an integral multiple of battery life. Thus, an end-of-project salvage value was estimated and its present value equivalent (at the beginning of the project) was subtracted from the initial cost. The end-of-project salvage value was computed as battery selling price times the fraction of cycle life remaining.

h. Replacement cost. For 11 of the 14 batteries, replacement cost was assumed to be equivalent to purchase price. For the other three, Pb-acid (current), Pb-acid (projected), and Ni-Fe, a materials recycling credit was deducted from the purchase prices of replacements to estimate replacement costs. The values of the material recycling credit for lead and nickel were based on data supplied by battery manufacturers and current market prices for these metals. The potential for recovering and reusing materials from the other 11 batteries is very uncertain at this time.

i. Operating and maintenance costs. Operating and maintenance costs have been excluded from this cost analysis for the following reasons:

(1) Data on these costs were available for only 6 of the 14 batteries analyzed.

(2) For those batteries for which these data were available, annual operating and maintenance costs ranged from less than $.20 to $.75 per

kWh of rated capacity. These costs are approximately one percent of the annual total amount of the respective battery costs. It was judged that the addition of this cost, while not a significant component of annual total cost, would still somewhat distort the annual total cost figures for comparison with those batteries for which no estimates of operating and maintenance costs are available. Operation and maintenance costs will undoubtedly vary by battery type.

3. Analysis

The following procedure was used to compute battery life-cycle costs for the fifteen batteries.

(a) Determined battery life in years. For applications where the battery undergoes only shallow daily cycle (i.e., remote stand-alone), battery calendar life was used. For applications involving daily deep discharge cycling, battery life was found by dividing cycle life by 365 (a "worst-case" assumption).

(b) Determined the required number of replacements over a 20-year project life.

(c) Determined the fraction of battery life left at the end of the 20th year.

(d) Determined the present value of battery life cycle cost (BLCC) (in \$/kWh)* by the formula:

$$\text{BLCC} = \left[C1 + C2 \cdot \sum_{N=1}^{K} \frac{1}{(1+i)^{N \cdot L}} \right] - \left[C1 \cdot \frac{1}{(1+i)^{20}} \cdot F \right]$$

Where: C1 = battery first cost, \$/kWh*

C2 = battery replacement cost, \$/kWh* (C1 minus materials recycling credit)

K = number of replacements required over 20 years

L = battery life in years

**For flow batteries, all battery costs are expressed as an energy-dependent component, \$/kWh, and a power-dependent component, \$/kW.*

i = discount rate, expressed as decimal

F = fraction of battery life left at end of 20th year

To illustrate this procedure, the life-cycle cost for the state-of-the-art lead-acid battery is computed: Battery first cost, C1, is $125/kWh. Recycling credit is $12/kWh. Therefore, replacement cost, C2, is $113. A discount rate, i, of 10 percent is used. This battery has a cycle life of 1,800 cycles. Assuming the application will involve deep discharge, battery life is 1,800/365 = 4.9 years. Therefore, four replacements are needed, the first at 4.9 years, the second after 9.8 years, the third after 14.7 years, and the fourth after 19.6 years. At the end of the twentieth year, the fraction of battery cycles left is 1 - 0.4/4.9 = 0.9.

The present value of life-cycle cost is therefore:

$$\$125 + \$113 \cdot \left[\frac{1}{1.59} + \frac{1}{2.54} + \frac{1}{4.06} + \frac{1}{6.47} \right] - \left[\$125 \cdot (0.148) \cdot 0.9 \right] = \$269/\text{kWh}$$

4. Results

The results of the battery cost analysis are shown in Table VIII-11. The uncertainty ranges in Table VIII-11 were derived using the method described in Chaper IX, Section F.

The cycle lives shown are what the developers believe will be achieved when the battery technology reaches maturity. The exceptions are current lead-acid batteries, which have already achieved 1,800 cycles and nickel-iron (2,000 cycles).

J. References

1. George, J.H.B. Revised Guidelines for Estimating the Capital Costs of Advanced Battery Systems for Utility Energy Storage. Report 1198-2. Electric Power Research Institute, September 1979.
2. Westinghouse R&D Center. Study of Manufacturing Costs of Lead-Acid Batteries for Peaking Power. October 1976.
3. Thaller, Lawrence H. Recent Advances in Redox Flow Cell Storage Systems, presented at the 14th Intersociety Energy Conversion Engineering Conference, August 5-10, 1979.

TABLE VIII-11. BATTERY LIFE-CYCLE COSTS PRESENT VALUE (1980$)

(20-year project life, 10 percent discount rate)

Battery	Estimated Selling Price $/kWh	Cycle Life (Projected)	Present Value Cost ($/kWh)	Uncertainty in Present Value Cost ($/kWh)
Pb-Acid (Current)	$125	1,800**	$269	0
Pb-Acid (Advanced)	72	4,000	91	±37
Ni-Fe	82	2,000**	168	±66
Ni-Zn	55	1,000	202	±153
Ni-H_2*	215	30,000	215	±33
LiAl-FeS	57	2,000	120	±61
LiSi-FeS*	57	3,000	90	†
Na-S (Glass)	40	2,500	71	†
Na-S (β Alumina)	48	2,500	85	±23
CaSi-FeS*	36	2,500	65	†
Zn-Br*	50	5,000	60	†
Redox*	$450/kW + $27/kWh	10,000	$450/kW + $27/kWh	†
$ZnCl_2$	$128/kW + $14/kWh	5,000	$152/kW + $17/kWh	†
Zn-$FeCN_6$	$230/kW + $32/kWh	5,000	$274/kW + $38/kWh	†

**Selling price estimates for these batteries are the average of the low and high battery price projections shown in Table VIII-10.*

***Achieved.*

† *Computed uncertainty exceeds estimate value.*

4. Warshory, M., and Lyle O. Wright. "Cost and Size Estimates for a Redox Bulk Energy Storage Concept." Journal of Electrochemical Society, February 1977.

5. Sudan, S., L.A. Heredy, and L. McCoy. Development of Lithium-Metal Sulfide Batteries for Load Leveling, September 30, 1977, Rockwell Int., Conoga Park, California, EPRI EM-716, June 1978.

6. Chilenskas, A.A., J.C. Schaefer, W.L. Towle, and D.L. Barney. A Preliminary Estimate of the Manufacturing Cost for Lithium/Metal Sulfide Cells for Stationary and Mobile Applications, ANL 79-59. January 1980.

7. Putt, R. "A Zinc Bromine Battery for Energy Storage," presented at the 14th Intersociety Energy Conversion Engineering Conference, August 5-10, 1979.

8. Grimes, Patrick. "Zinc Bromine Battery Development." Presentation at DOE Flow Battery Project Review, July 17, 1979.

9. Private communication with Mike Roche, Chemical Engineering Division, Argonne National Laboratory, July 3, 1980.

10. Interim Cost Esimates for Advanced Battery Systems. EPRI Research Project 787-2, Interim Report. July 1978.

11. Proposed Criteria for Estimating the Capital Costs of Advanced Battery Systems for Utility Energy Storage. EPRI Research Project 787-1, Interim Report. November 1978.

IX. BATTERY SYSTEM EVALUATION AND SCREENING

A. Methodology

The following battery attributes were considered in the selection of battery systems.

(1) Cost

- (a) Battery production cost
- (b) Battery auxiliary cost
- (c) Operation and maintenance cost
- (d) Cycle life
- (e) Energy efficiency.

(2) Health and Safety

- (a) Health effects
- (b) Safety

(3) Reliability/maintainability

- (a) Reliability
- (b) Operating temperature range
- (c) Ability to withstand overcharge and overdischarge

(4) Suitability for the application

- (a) Self-discharge rate
- (b) Special requirements (ability to be maintained in standby mode for long periods).

Since the relative importance of the first three criteria depends upon the application, a different set of weighting factors was developed for each of the six application scenarios. These weighting factors were jointly developed with the program managers from DOE and Sandia Laboratories. Table IX-1 illustrates the weighting factors chosen. The last criterion, suitability for the application, carried the most weight in selection decisions.

TABLE IX-1. WEIGHTING FACTORS

	Application					
Criterion	Residential*	Commercial	Military	Agricultural	Utility	Remote
Cost	0.75	0.60	0.20	0.50	0.50	0.20
Reliability/ Maintainability	0.20	0.25	0.70	0.40	0.40	0.70
Environmental/ Health/Safety	0.05	0.15	0.10	0.10	0.10	0.10

**The values of these weighting factors are based on the assumption that the batteries meet environmental, health, and safety requirements for each application. Thus, batteries which present substantial hazards were not considered for residential application.*

Total cost data were developed for the candidate batteries. The total cost includes the battery cost, auxiliary cost, and inefficiency cost penalty. The total cost was converted into a dimensionless number by taking the ratio of the cost of the least expensive battery to the cost of each alternative battery. The ratio was then multiplied by 10 so that relative cost values fall on the same scale as ratings for the other two criteria.

The rating of reliability and health and safety factors is subjective. A number between 0 and 10 was assigned to each sector, 10 being the highest rating. The batteries were ranked for each of the six application scenarios. Each rating value for a battery was multiplied by the weighting factor associated with that criterion. The products for the three criteria were then summed to give a single number that scores the battery for that application. The two top-scoring batteries for each application were then selected.

The figure of merit of each battery can be expressed as follows:

$$\text{FOM} = \sum_{i=1}^{3} W_i A_i$$

Where:

FOM = Figure of merit
W_i = Weighting factor
A_i = Relative rating of each battery attribute.

The six tables in the appendix to this volume contain the attribute rating values for the batteries evaluated for each of the six applications. Some of the batteries were considered unsuitable for particular applications, and were not included in the ranking analysis for those applications.

For the remote village stand-alone application, only four types of batteries were considered suitable: lead-acid, Redox, zinc-ferricyanide, and zinc-bromine. The nickel-iron and nickel-zinc batteries have too high a self-discharge rate for a stand-alone photovoltaic application. The lithium, calcium, and sodium-sulfur batteries are not suitable because they require auxiliary heating during long standby periods. Nickel-zinc and zinc-chlorine batteries are not suitable for such applications because they must be completely discharged periodically.

For the residential application, the lithium, calcium, sodium-sulfur, and zinc-chlorine batteries are considered unsuitable due to their potential safety hazard.

For the military application, the four flow batteries, (Redox, zinc-ferricyanide, zinc-bromine, and zinc-chlorine) are not suitable because this application requires a battery capacity smaller than is practical for flow batteries.

B. Evaluation of Cost

The cost of batteries includes estimated battery selling price auxiliary cost, cycle life, and energy efficiency. All of the four factors were combined into a present catalog of life-cycle cost. Battery selling price estimates are discussed in detail in Chapter VIII.

The battery auxiliary cost includes the cost of the hardware and systems necessary for control of the batteries, and the safety and protection of the installation and personnel. The battery auxiliaries consist of the following:

(1) Operational
    (a) Ventilation
    (b) Temperature control
    (c) Monitoring
    (d) Charge/discharge control
    (e) Bus wiring
    (f) Maintenance requirements
    (g) Enclosure
(2) Safety and protection
    (a) Electrical protection
    (b) Electrolyte containment
    (c) Fire protection equipment
    (d) Gas detection.

Tables IX-2 through IX-6 show the battery auxiliary costs for the various applications. At present, no firm guidelines exist on the auxiliary cost of batteries. The

TABLE IX-2. BATTERY AUXILIARY COSTS, RESIDENTIAL APPLICATION

(15 kWh Capacity, 1980 $)

Battery Type	Cost Estimate	Reference
Improved Pb-Acid	$ 240*	1
Ni-Fe	240*	2
Ni-Zn	240*	3
$Ni-H_2$	180**	4
Redox	432**	6
$Zn-Fe(CN)_6$	540**	7
$Zn-Br_2$	540**	8

**Uncertainty is ±20 percent (10).*

***Uncertainty is ±30 percent (10). Cost estimates are provided only for those batteries considered appropriate for this application.*

TABLE IX-3. BATTERY AUXILIARY COSTS, DAIRY FARM APPLICATION*

(50 kWh Battery, 1979 $)

Battery Type	Cost Estimate	Reference
Improved Pb-Acid	$ 800**	1
Ni-Fe	800**	2
Ni-Zn	800**	3
$Ni-H_2$	600†	4
LiAl-FeS	900†	1
LiSi-FeS	900†	1
CaSi-FeS	900†	5
Na-S (Glass)	1,440†	1
Na-S (β-Alumina)	1,340†	1
Redox	1,440†	6
$Zn-Fe(CN)_6$	1,800†	7
$Zn-Cl_2$	1,800†	1
$Zn-Br_2$	1,800†	8

**Battery is 3.33 times the capacity required for residential application.*

****Estimate uncertainty is ±20 percent (10).*

†*Estimate uncertainty is ±30 percent (10).*

TABLE IX-4. BATTERY AUXILIARY COSTS, REMOTE STAND-ALONE APPLICATION*

(125 kWh Battery, 1979 $)

Battery Type	Cost Estimate	Reference
Improved Pb-Acid	$ 2,000**	1
Redox	3,600†	6
$Zn-Fe(CN)_6$	4,500†	7
$Zn-Br_2$	4,500†	8

**Battery is 8.33 times the capacity required for residential application.*

***Estimate uncertainty is ±20 percent (10).*

†Estimate uncertainty is ±30 percent (10).

TABLE IX-5. BATTERY AUXILIARY COSTS, MILITARY APPLICATION*

(6 kWh Battery, 1979 $)

Battery Type	Cost Estimate	Reference
Improved Pb-Acid	$ 240**	1
Ni-Fe	240**	2
Ni-Zn	240**	3
$Ni-H_2$	180†	4
LiAl-FeS	270†	1
LiSi-FeS	270†	1
CaSi-FeS	270†	5
Na-S (Glass)	430†	1
Na-S (β-Alumina)	370†	1

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*Auxiliary cost is assumed to be fixed below 15 kWh capacity.
** Estimate uncertainty is ±20 percent (10).
†Estimate uncertainty is ±30 percent (10).

TABLE IX-6. BATTERY AUXILIARY COSTS, UTILITY APPLICATION

(37.5 MWh Battery, 1979 $)

Battery Type	Cost Estimate	Reference
Improved Pb-Acid	$ 620,000**	9
Ni-Fe	620,000**	9
Ni-Zn	620,000†	9
Ni-H_2	460,000†	4
LiAl-FeS	700,000†	2
LiSi-FeS	700,000†	2
CaSi-FeS	700,000†	5
Na-S (Glass)*	2,175,000†	9
Na-S (β-Alumina)	940,000†	9
Redox	1,120,000†	6
Zn-Fe$(CN)_6$	1,390,000†	7
Zn-Cl_2	1,390,000†	9
Zn-Br_2	1,390,000†	8

**The auxiliary cost for Na-S (glass) utility battery is high because of the projected small cell size and the resultant high cost of monitoring a large number of cells.*

***Estimate uncertainty is ±20 percent (10).*

†Estimate uncertainty is ±30 percent (10).

auxiliary costs were obtained from a study entitled "Westinghouse Energy Storage for Photovoltaic Conversion," prepared for the USNSF, September 30, 1977. There is a wide margin for error in the determination of the auxiliary cost of batteries.

The cycle life used in the determination of the present value of the cost is the projected value for each battery, not the presently achieved cycle life.

A cost penalty was computed for batteries with lower energy efficiencies. This cost penalty is to be added to the battery cost and battery auxiliary cost in order to incorporate the impact of photovoltaic power system costs attributable to battery efficiency. A separate set of cost penalties was computed for each application scenario. For the remote stand-alone, military, and utility scenarios, the inefficiency cost penalty was computed as the cost of additional photovoltaic arrays necessary to provide the same system energy output as a system using a battery with 85 percent energy efficiency (the value of the most energy-efficient batteries considered). For the commercial, dairy farm, and residential systems, the cost penalty was set equal to the present value cost of added auxiliary energy (over the 20-year project life) needed to make up the loss due to a battery efficiency of less than 85 percent. Table IX-8 is a summary of cost penalties for battery efficiencies less than 85 percent. Tables IX-9 through IX-14 show the life-cycle cost of the energy storage subsystem for the various applications.

C. Evaluation of Health and Safety Factors

1. Redox

This battery possesses the least health and safety problems. It is an ambient temperature battery and does not contain any hazardous substances. A value of 9 was assigned to this battery.

2. Pb-Acid, Ni-Fe, Ni-Zn, $Zn\text{-}Fe(CN)_6$

These batteries operate at ambient temperatures. The Pb-Acid, Ni-Fe, and Ni-Zn have been proven to be safe. The only safety hazard associated with the $Zn\text{-}Fe(CN)_6$ battery is the possibility of spillage of potassium hydroxide electrolyte.

TABLE IX-7. BATTERY AUXILIARY COSTS, COMMERCIAL APPLICATION

(700 kWh Battery, 1979 $)

Battery Type	Cost Estimate	Reference
Improved Pb-Acid	$ 11,500	9
Ni-Fe	11,500	9
Ni-Zn	11,500	9
Ni-H_2	8,600	4
LiAl-FeS	12,900	2
LiSi-FeS	12,900	2
CaSi-FeS	12,900	5
Na-S (Glass)	40,600	9
Na-S (β-Alumina)	17,800	9
Redox	20,700	6
Zn-$Fe(CN)_6$	25,900	7
Zn-Cl_2	25,900	9
Zn-Br_2	25,900	8

NOTE: Estimate uncertainty is ±20 percent for Pb-acid, Ni-Fe, and N-Zn; ±30 percent for other batteries (10).

TABLE IX-8. SUMMARY OF COST PENALTIES FOR BATTERY EFFICIENCIES OF LESS THAN 85 PERCENT

(1979 $)

	Projected Energy Efficiency (%)	Remote Stand-alone	Dairy Farm	Commercial	Utility	Residential	Military
Improved Pb-Acid	80	800	200	4,000	400,000	100	800
Ni-Fe	65	NA	900	20,000	1,800,000	450	3,600
Ni-Zn	75	NA	400	8,600	900,000	200	1,600
Ni-H_2	63	NA	900	21,600	1,900,000	450	4,000
LiAl-FeS	83	NA	0	0	0	NA	0
LiSi-FeS	83	NA	0	0	0	NA	0
CaSi-FeS	85	NA	0	0	0	NA	
Na-S Glass	85	NA	0	0	0	NA	0
Na-S β-Alu.	75	NA	400	8,600	900,000	NA	1,600
Redox	70	2,000	600	13,000	1,300,000	300	NA
Zn-$Fe(CN)_6$	84	0	0	0	0	0	NA
Zn-Cl_2	65	NA	900	20,000	1,800,000	NA	NA
Zn-Br_2	73	1,600	400	8,600	900,000	200	NA

NA = Not Applicable.

TABLE IX-9. ENERGY STORAGE SUBSYSTEM, RESIDENTIAL APPLICATION

Life-Cycle Cost (Present Value)

Battery Type	Battery Cost	Auxiliary Cost	Inefficiency Cost Penalty	Total Cost*
Improved Pb-Acid	$ 1,365	240	100	1,705
Ni-Fe	2,520	240	450	3,210
Ni-Zn	3,030	240	200	3,470
Ni-H_2	3,225	180	450	3,855
Redox	1,785	432	300	2,517
Zn-$Fe(CN)_6$	1,390	540	--	1,930
Zn-Br_2	750	540	200	1,490

**See Section F for discussion of uncertainty in total cost.*

TABLE IX-10. ENERGY STORAGE SUBSYSTEM, REMOTE VILLAGE (STAND-ALONE) APPLICATION

Life-Cycle Cost (Present Value)

Battery Type	Battery Cost	Auxiliary Cost	Inefficiency Cost Penalty	Total Cost*
Improved Pb-Acid	$ 11,375	2,000	800	14,175
Redox	4,890	3,600	2,000	10,490
$Zn-Fe(CN)_6$	5,650	4,500	0	10,150
$Zn-Br_2$	7,250	4,500	1,600	13,350

**See Section F for discussion of uncertainty in total cost.*

TABLE IX-11. ENERGY STORAGE SUBSYSTEM, DAIRY FARM APPLICATION

Life-Cycle Cost (Present Value)

Battery Type	Battery Cost	Auxiliary Cost	Inefficiency Cost Penalty	Total Cost*
Improved Pb-Acid	$ 4,550	800	200	5,550
Ni-Fe	8,400	800	900	10,100
Ni-Zn	10,100	800	400	11,300
Ni-H_2	10,750	600	900	12,250
LiAl-FeS	6,000	900	0	6,900
LiSi-FeS	4,500	900	0	5,400
CaSi-FeS	3,250	900	0	4,150
Na-S (Glass)	3,550	1,440	0	4,990
Na-S (β-Alumina)	4,250	1,340	400	5,990
Redox	8,550	1,440	600	10,590
Zn-$Fe(CN)_6$	3,130	1,800	0	4,930
Zn-Cl_2	3,130	1,800	900	5,830
Zn-Br_2	2,900	1,800	400	5,100

**See Section F for discussion of uncertainty in total cost.*

TABLE IX-12. ENERGY STORAGE SUBSYSTEM, DEDICATED UTILITY APPLICATION

Life-Cycle Cost (Present Value in Thousands)

Battery Type	Battery Cost	Auxiliary Cost	Inefficiency Cost Penalty	Total Cost*
Improved Pb-Acid	$ 3,412	620	400	4,432
Ni-Fe	6,300	620	1,800	8,720
Ni-Zn	7,575	620	900	9,095
Ni-H_2	8,060	460	1,900	10,420
LiAl-FeS	4,500	700	0	5,200
LiSi-FeS	3,375	700	0	4,075
CaSi-FeS	2,437	700	0	3,137
Na-S (Glass)	2,662	2,175	0	4,837
Na-S (β-Alumina)	3,187	940	900	5,027
Redox	4,160	1,120	1,200	6,480
Zn-Fe$(CN)_6$	3,343	1,390	0	4,733
Zn-Cl_2	1,701	1,390	1,800	4,891
Zn-Br_2	2,175	1,390	900	4,465

**See Section F for discussion of uncertainty in total cost.*

TABLE IX-13. ENERGY STORAGE SUBSYSTEM, COMMERCIAL OFFICE BUILDING APPLICATION

Life-Cycle Cost (Present Value)

Battery Type	Battery Cost	Auxiliary Cost	Inefficiency Cost Penalty	Total Cost*
Improved Pb-Acid	$ 63,700	11,500	4,000	79,200
Ni-Fe	117,600	11,500	20,000	149,100
Ni-Zn	141,400	11,500	8,600	161,500
Ni-H_2	150,500	8,600	21,600	180,700
LiAl-FeS	84,000	12,900	0	96,900
LiSi-FeS	63,000	12,900	0	75,900
CaSi-FeS	45,500	12,900	0	58,400
Na-S (Glass)	49,700	40,600	0	90,300
Na-S (β-Alumina)	59,500	17,800	8,600	85,900
Redox	63,900	20,700	13,000	97,600
Zn-Fe$(CN)_6$	54,000	25,900	0	79,900
Zn-Cl_2	27,100	25,900	20,000	73,000
Zn-Br_2	40,600	25,900	8,600	75,100

**See Section F for discussion of uncertainty in total cost.*

TABLE IX-14. ENERGY STORAGE SUBSYSTEM, MILITARY FIELD TELEPHONE OFFICE APPLICATION

Life-Cycle Cost (Present Value)

Battery Type	Battery Cost	Auxiliary Cost	Inefficiency Cost Penalty	Total Cost*
Improved Pb-Acid	$ 550	240	800	1,590
Ni-Fe	1,010	240	3,600	4,850
Ni-Zn	1,210	240	1,600	3,050
Ni-H_2	1,290	180	4,000	5,470
LiAl-FeS	720	270	0	990
LiSi-FeS	540	270	0	810
CaSi-FeS	390	270	0	660
Na-S (Glass)	430	430	0	860
Na-S (β-Alumina)	510	370	1,600	2,480

**See Section F for discussion of uncertainty in total cost.*

Should the battery short-circuit or overheat, it could create a rupture which could lead to a fire. The only safety hazard associated with the Pb-Acid battery is the possibility of spillage of H_2SO_4 in case of battery rupture. A value of 8 was assigned to these batteries.

3. $\underline{Ni\text{-}H_2,\ Zn\text{-}Br_2}$

These batteries operate at ambient temperatures. The $Ni\text{-}H_2$ battery contains pressurized hydrogen at about 200 psi. The $Zn\text{-}Br_2$ battery contains bromine gas which is toxic in the free state. The zinc-bromine battery uses approximately 2 kg of Br_2 per kWh of battery capacity; however, most of the bromine is stored in the polybromide phase, where it is relatively innocuous. Moreover, the volatility at room temperature is relatively low. A value of 7 was assigned to these batteries.

4. LiAl-FeS, LiSi-FeS, CaSi-FeS, Na-S (Glass), Na-S (β-Alumina), $Zn\text{-}Cl_2$

All of the batteries, with the exception of the $Zn\text{-}Cl_2$ battery, operate at high temperatures. The high operating temperatures pose a possibility of fire hazards in the event of battery housing rupture. The $Zn\text{-}Cl_2$ battery contains chlorine, which is toxic. The worst possible accident associated with the $Zn\text{-}Cl_2$ battery would be chlorine gas leakage from the chlorine hydrate storage vessel. The rate of chlorine release would depend on the ambient temperature. Only 1 ppm of chlorine in the atmosphere is needed to reach a toxic level. Another toxic substance contained in the electrolyte is thallium chloride; however, only about 2 g are used per kWh of battery capacity.

These batteries would have the lowest relative rating for health and safety acceptability. A value of 6 was assigned to these batteries.

D. Evaluation of Reliability/Maintainability

1. $\underline{Ni\text{-}H_2}$

The $Ni\text{-}H_2$ battery operates at ambient temperatures. The fact that nickel-hydrogen batteries are now being used for satellite missions of several years attests to this battery's high reliability. A value of 10 was assigned to this battery.

2. Pb-Acid, Ni-Fe

These batteries operate at ambient temperatures. The long record of reliable operation of Pb-Acid batteries in automobiles, telephone systems, and emergency lighting provides proof that this battery is highly reliable. Overcharging and overdischarging damage the battery systems. A value of 9 was assigned to these batteries.

3. Redox

The Redox battery operates at ambient temperatures. The reliability is limited to a certain extent by the complexity of the plumbing and control systems. A value of 8 was assigned to this battery.

4. $Zn\text{-}Fe(CN)_6$, $Zn\text{-}Cl_2$, $Zn\text{-}Br_2$

These batteries operate at ambient temperatures. The reliability is limited to a certain extent by the complexity of the plumbing and control systems. Due to the problem with zinc electrodes in these batteries, a slightly lower value has been assigned to these batteries than the Redox. A value of 7 was assigned to these batteries.

5. Ni-Zn

The Ni-Zn battery operates at ambient temperatures. There are two failure mechanisms:

(a) Separator failure due to breakdown at high temperature, or penetration by zinc dendrites

(b) Loss of capacity at the zinc electrode due to redistribution of the zinc during cycling.

E. Summary of Results

Table IX-15 lists the batteries with the highest figures of merit for each of the six applications. These batteries were selected as most promising on the basis of their figures of merit (FOMs). It must be noted, however, that differences between their FOMs are smaller than the ranges of uncertainty in most of the FOMs. The right hand column of each table in the appendix displays these uncertainty ranges. Section F of this chapter explains the computation of uncertainty ranges for battery life-cycle cost estimates.

TABLE IX-15. TOP-RANKING BATTERIES

Application	Batteries
Remote Village (Stand-alone PV system)	Pb-Acid, Redox
Residential	$Zn-Br_2$, Pb-Acid
Dairy Farm	Pb-Acid, $Zn-Fe(CN)_6$, $Zn-Br_2$
Office Building	CaSi-FeS, Pb-Acid, $Zn-Br_2$, $Zn-Cl_2$
Utility	Pb-Acid, CaSi-FeS
Military	Pb-Acid, $Ni-H_2$

An important finding of this study is that the distinction between several battery types with regard to suitability for photovoltaic energy storage is somewhat obscured by the uncertainty in estimated battery cost and life expectancy.

F. Uncertainty

There is a considerable degree of uncertainty in the rating estimates for all three attributes used in the ranking analysis. The reliability and health/safety attributes were rated subjectively using available information about the batteries. Most of this information is qualitative. A range of uncertainty of 25 percent is inherent in the process of assigning quantitative ratings (i.e., 0 to 10) on the basis of entirely qualitative information.

A quantitative uncertainty analysis was performed on the estimates for life-cycle costs. The life-cycle cost for a battery system is computed by the formula:

$$LCC = A + F \cdot R$$

Where:

LCC = estimated battery system life cycle cost

A = estimated auxiliary system cost

F = estimated first cost (or battery selling price)

R = ratio of the present value of battery purchases over the 20-year project life to the first cost. R is actually a function of estimated battery life and interest rate. The relationship between R and battery life is depicted in Figure IX-1.

An uncertainty analysis for an estimate that is a function of several independent variables [i.e., $LCC = f(A,F,R)$] requires that an uncertainty be expressed for each independent variable, and that these uncertainties all have the same probability level. The uncertainty in an estimated value can be expressed in absolute terms (e.g., \$50 ± \$20), as a percentage of the estimated value (e.g., \$50 ± 40%), or as a confidence interval (\$30 to \$70).

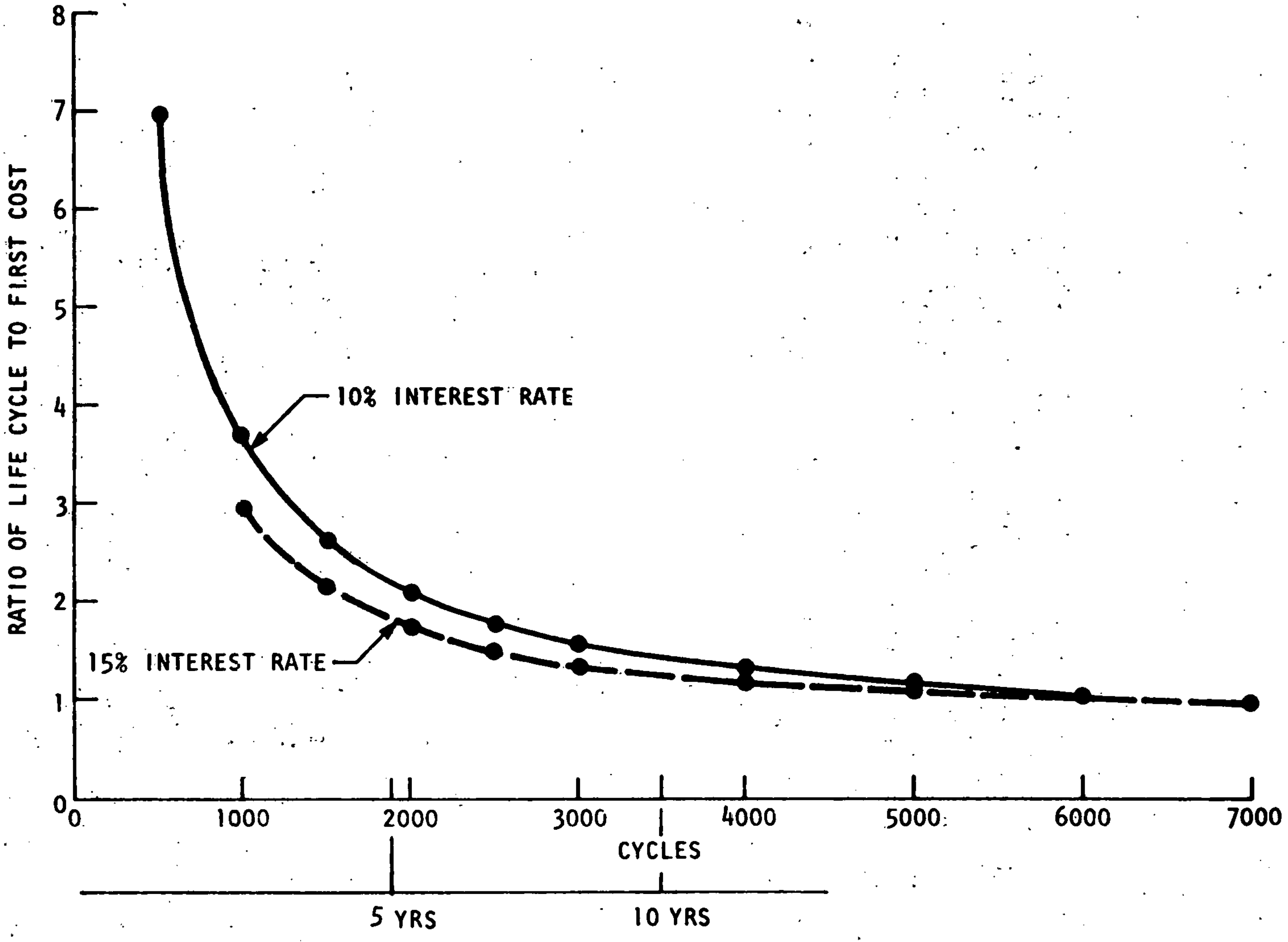

Figure IX-1. Relationship Between R and Battery Life

Tables A-1 through A-6 in the appendix contain uncertainty values for total FOMs. The uncertainty for battery first cost was computed using the interval between the low and high projected selling price as the confidence interval. The midpoint between low and high projected selling price was used as the estimate for first cost.

The uncertainty in R was derived by evaluating the function R = f(L) at the low and high estimates for battery cycle life, L, and using this interval as the confidence interval. The function was also evaluated at the midpoint between low and high cycle life to obtain the estimate for R. The probability associated with all three estimates (i.e., A, F and R) is assumed to be approximately 80 percent.

$$R = 1 + \sum_{N=1}^{K} \frac{1}{(1+i)^{N.L.}}$$

i = interest rate

K = number of battery replacements over 20 years

The uncertainty in an estimated value, which is a function of n variables, is given by the formula:

$$U_y = \pm \left[\sum_{i=1}^{n} \left(\frac{\partial Y}{\partial X_i} \cdot W_i \right)^2 \right]^{1/2}$$

Where: U_y = uncertainty in estimated value of y (expressed as an absolute term)

y = function of X_1, X_2, X_3 ... X_n

$\pm W_i$ = uncertainty in variable X_i, (expressed as absolute terms).

This formula is predicated on the uncertainties, W_i, having a uniform probability.

Applying this formula to the equation for life cycle cost, the uncertainty in the estimate for life-cycle cost, U_{LCC}, is derived:

$$U_{LCC} = \pm \left[a^2 + R^2 \cdot f^2 + F^2 \cdot r^2 \right]^{1/2}$$

Where: ±a = uncertainty in auxiliary system costs

R and F defined as above

±f = uncertainty in F

±r = uncertainty in R

Uncertainties, expressed as percentages of the estimated values for auxiliary costs, first costs, and present value/first cost ratio (R) are listed in Table IX-16. These uncertainties were applied to the values for life-cycle costs in Tables A-1 through A-6 in the appendix. The uncertainties were used in the evaluation and ranking matrices in the appendix.

TABLE IX-16. UNCERTAINTIES

(Expressed as percentage of estimated value)

Battery	Auxiliary Cost ±%	First Cost ±%	Present Value Ratio, R ±%	Total Life-Cycle Cost ±%
Pb-Acid	20	20	23	40
Ni-Fe	20	40	5	39
Ni-Zn	30	30	38	76
Ni-H_2	30	16	0	15
LiAl-FeS	30	25	27	51
LiSi-FeS	30	25	70	*
CaSi-FeS	30	11	55	*
NaS (Glass)	30	15	55	*
NaS (β Alumina)	30	10	20	27
Redox	30	35	0	*
Zn-Fc$(CN)_6$	30	30	70	*
Zn-Cl_2	30	15	55	*
Zn-Br_2	30	40	70	*

**Uncertainties exceed estimate value.*

G. References

1. Feduska, et al. Energy Storage for Photovoltaic Conversion - Residential Systems. Westinghouse R&D Center, 1977.

2. Personal communication with Ed Broglio, Eagle-Picher, March 1980, indicated that auxiliary requirements for Ni-Fe are similar to lead-acid.

3. Personal communication with Robert A. Brown, Eagle-Picher, March 1980, indicated that auxiliary requirements for Ni-Zn batteries are similar to those for lead-acid.

4. Personal communication with Lee E. Miller, Eagle-Picher, March 1980, indicated that Ni-H_2 batteries have auxiliary requirements similar to those of lead-acid batteries, with the exception that Ni-H_2 does not require H_2 venting, H_2 detection, or spill containment. Therefore, an auxiliary cost 25 percent less than for lead-acid batteries is assumed.

5. Personal communication with M.F. Roche, Argonne National Laboratory, March 1980, indicated that auxiliary requirements of CaSi-FeS batteries are similar to those of lead-acid batteries.

6. Personal communication with H. Thaller, NASA-LeRC, March 1980, indicated that auxiliary requirements for Redox batteries are similar to those of Zn-Cl_2 batteries, except that Redox flow batteries do not require toxic gas detection and venting.

7. Personal communication with George B. Adams, Lockheed Missile and Space Co., Inc., March 1980, indicated that auxiliary requirements for Zn-$Fe(CN)_6$ are similar to Zn-Br_2 batteries.

8. Personal communication with Ronald A. Putt, Gould, March 1980, indicated that the auxiliary cost for a Zn-Br_2 battery is approximately $36/kWh. The battery requires a more sophisticated toxic gas detection and ventilation system than is needed for lead-acid batteries.

9. Feduska, et al. Energy Storage for Photovoltaic Conversion - Utility Systems. Westinghouse R&D Center, September 1977.

10. Personal communication with E.F. Federmann, Westinghouse Electric Corporation, January 1981.

X. FINAL SIZING OF PHOTOVOLTAIC SYSTEMS

A. Dairy Farm

The most promising battery types identified for this scenario were the lead-acid, zinc-bromine, and zinc-ferricyanide. The PV system contains a 20 kWp array, a battery with 50 kWh effective capacity, and a 15 kW generator. The lead-acid battery would be sized at 63 kWh (due to the 80 percent maximum depth of discharge restriction). The zinc-bromine battery can be sized at 50 kWh. The required power rating of the battery is 15 kW. Since the round-trip energy efficiency of the zinc-bromine battery (about 70 percent) is less than the energy efficiency of the lead-acid battery (about 80 percent), the zinc-bromine battery would use more auxiliary generator energy or would require a larger array. The lead-acid system would supply about 18,000 kWh from the photovoltaic array and draw approximately 20,000 kWh from the generator. The zinc-bromine system would supply about 16,000 kWh from the PV array, and 22,000 kWh from the generator. The 15 kW power conditioner design will meet the specifications indicated in Section III.

B. Commercial Office Building

Four types of batteries were identified as being equally promising for this application. The PV system contains a 500 kWp array, and a storage battery with an effective capacity of 700 kWh and a power rating of 100 kW. The zinc-bromine battery, which can be discharged 100 percent, would be sized at 700 kWh. The PV system would supply approximately 550 MWh of the 636 MWh required annually. The balance would be supplied by the auxiliary generator. The 225 kW power conditioner design will meet the specifications outlined in Section IV.

C. Residence

Two batteries were identified as most promising for the residential scenario: lead-acid and zinc-bromine.

The PV system for this scenario contains a 4 kWp array and a 15 kWh effective capacity storage battery. This photovoltaic system would supply approximately 4,750 kWh per year. The balance, 3,300 kWh, would be purchased from the electric utility through the utility interconnection. Due to the lower energy efficiency of the zinc-bromine battery, the PV systems for this battery requires that more energy be purchased from the utility than does the lead-acid battery. An alternative would be to increase the PV array size by approximately 10 percent to compensate for the lower battery efficiency. The 10 kW power conditioner design will meet the specifications outlined in Section V.

D. Remote Village

The two most promising battery types identified for this scenario were the lead-acid and Redox.

The effective capacity of the lead-acid battery must be 125 kWh. Since the maximum depth of discharge for lead-acid batteries is 80 percent (to prevent sulfation of the electrodes), the battery capacity must be 157 kWh. Array size is 1.6 kWp.

Since the Redox battery can be discharged to 90 percent of capacity, a Redox system sized at 139 kWh would suffice for this scenario. The required power rating of the Redox system is 2.2 kW. Since the round-trip energy efficiency of the Redox system is about 70 percent (compared to 80 percent for lead-acid), the minimum array size must be increased from 1.6 to 1.8 kWp. The 4 kW power conditioner design will be as indicated in Section VI.

E. Utility

The lead-acid and calcium-metal sulfide batteries were identified as most promising for this application. The system contains a 14.7 MWp PV array (assuming an 80 percent efficient battery) and a battery with an effective storage capacity of 37.5 MWh. The battery power rating is 7.0 MW. For the calcium-metal sulfide battery, which has a round-trip energy efficiency of 70 percent, the PV array must be increased to 15.5 kWp. The lead-acid battery should not be discharged below 80 percent of capacity; thus it must be sized at 46.9 MWh. The calcium-metal sulfide battery would be sized at 41.7 MWh to account for a 90 percent maximum depth of discharge. The 10 MW power conditioner design will meet the specifications outlined in Section VII.

F. Military Scenario

The lead-acid and nickel-hydrogen batteries were identified as most promising for this scenario. The system contains a 2.5 kWp PV array and a 6 kWh battery. As in the dairy farm scenario, the system with the less efficient nickel-hydrogen battery would require more auxiliary energy from the generator. The exact amount depends on the location and season for which the military field telephone system was used. The 300 watt power conditioner design will be as indicated in Section VIII.

XI. INTERFACING

A. Basic Interfacing Requirements

The power conversion system must meet certain basic requirements at the source interface, at the utility interface, if utility connected, and internal to the equipment.

At the utility interface, the power conversion system must (1):

(1) Operate within a specified power factor range under various loading conditions

(2) Tolerate normal ranges of line voltage unbalance and still operate within specifications

(3) Tolerate line, load, or generation faults on the network and not produce any additional fault condition

(4) Limit harmonic distortions so that network components and loads are not damaged and communications interference does not occur

(5) Operate within the normal ranges of network voltage and frequency tolerances.

At the source interface, the power conversion system must (1):

(1) Maintain ripple current and voltage burdens on the source within the system's capacity to bear them

(2) Clear DC faults without damaging the source

(3) Operate within a specified source voltage range.

In order for the power conversion equipment to function properly, the power conversion system must (1):

(1) Clear faults due to malfunction without damaging the source, equipment, and network

(2) Tolerate network disturbances without creating additional fault to the system

(3) Clear faults due to malfunction of the source without causing internal damage or damaging network components.

B. Power Quality

There exists a need for the development of power quality standards; there is no utility consensus in this matter. Harmonic distortions of 10 percent for current and 5 percent for voltage and a 0.9 lead/lag power factor are under consideration as a standard (2).

C. Safety

Safety is an area of concern in utility-connected systems. During repair of a distribution system, the circuit is usually de-energized. The linemen de-energize the disconnect switches at the utility substation. With onsite photovoltaic systems connected to a utility grid, it will be absolutely necessary to disconnect all onsite photovoltaic system feeders connected to the utility line. Voltage control problems might arise during restoration of service. To remedy this situation, a DC circuit breaker can be provided to block the power conditioner from the array side. Utility management of power system control may be necessary to protect utility personnel while servicing electrical equipment. Another solution may be to develop automatic, fail-safe disconnect switches. Grounding the line at the point of repair will also be necessary to guard utility personnel against shock.

D. Fault Protection

Fault protection is a major problem in interfacing. The conversion equipment should not make any significant contribution to fault current due to a network fault. Hence, power conversion equipment should either shut down or operate in current-limited operation during abnormal operation.

In general, DC faults are created by malfunction of equipment and failures of internal components. DC faults, in turn, create AC faults. If the DC fault is cleared, whether inherent or engendered, it will clear the AC fault. The DC fault should, however, be cleared rapidly to prevent equipment damage. High-speed DC interrupters are required for this purpose.

E. Effect on Utility Networks

In general, three types of problems must be considered when evaluating the impact of dispersed photovoltaic systems on the utility electrical distribution system (3,4).

1. Maintenance Problems

Utilities employ well-established procedures to isolate faults. Dispersed photovoltaic systems complicate the isolation procedure and, therefore, increase the cost.

2. Hardware Problems

During steady-state operation, harmonics and voltage flicker may be induced in the system, giving rise to hardware problems. Inverters can cause harmonics which, in turn, can cause interference with communication systems, TV, and telephone systems. The photovoltaic array may act as an antenna, picking up spurious signals which may be injected into the AC network. Proper protection is needed to prevent loadings due to overcurrent, overvoltage, and frequency changes. Protective devices such as fuses, reclosers, protective relays, and sectionalizers must be properly sized to handle abnormal operation.

The voltage level of distribution system feeders is usually controlled by voltage regulators, which compensate for the line-drop characteristics of the particular feeder. Feedback from the photovoltaic system to the utility system may mislead the compensation circuit. Special controls need to be provided to remedy this situation. Due to the existence of power conditioners, the distribution system requires additional VAR (reactive volt-amps) supply. The amount of VAR needed is considerably higher than that needed for distribution systems. During low load periods when the photovoltaic system is not operating, a higher amount of VAR will be needed. The capacitors that are provided to produce the VAR must therefore be provided with switching devices.

Different types of interrupters are provided in utility distribution feeders to sectionalize a distribution system in case of a fault. This is done to minimize power interruption to users. The interrupters are energized by voltage and current signals which could be distorted by the photovoltaic power system. Some of these interrupters are able to automatically reclose to handle temporary faults. With the dispersed photovoltaic system, there may be a backfeed to the fault which prevents the automatic reclosers from operating. To remedy this situation, additional interrupters must be provided and new distribution systems designed.

If the utility system is interrupted because of a fault on the primary distribution system, the connected motors could operate as induction generators because of the capacitors on the system. This, in turn, could cause overspeed and overvoltage of the motors.

3. Post-Fault Protection

This problem relates to the protection of equipment after the distribution network is isolated due to a fault. Synchronous machines should be properly maintained. The inverter should maintain conversion of DC power to AC, and the photovoltaic system devices should follow the load fluctuations when isolated from the faulted distribution network. During isolation, the voltage and frequency may become unstable unless corrective measures are taken.

F. Batteries

Because batteries possess low internal resistance, the interfacing equipment must be able to withstand high short-circuit currents. The low internal resistance of the batteries creates problems for solid-state equipment connected to the battery.

Batteries interface with current-fed conversion equipment through a reactor. The reactor converts the source characteristic to a constant current feed under steady-state conditions. To do this, it must support any ripple voltage component at the DC terminals and limit the peak ripple current. Batteries cannot withstand the ripple current without generating excessive heat. Hence, the inductor must be sized properly to limit ripple current.

If the conversion equipment malfunctions, the inductor limits the rate of rise of fault current in the DC loop. However, the inductor makes the interruption of DC loop faults more difficult as interruption is engendered.

Current-fed converters are unidirectional at the DC interface, so that changing from a discharge to charge mode, and vice versa, can be accomplished either by a reversing switchgear or by duplicating all or part of the converter. The first method is less expensive and mechanical disconnects or solid state switchgear may be used. The second method is more expensive, but the turnaround time is less, and there are no additional losses created by the thyristor switches. Control of the charging and discharging is very important; if the charging rate is high, the polarization and I^2R losses can result in excessive heating of the battery. Deep discharging beyond the rated capacity decreases cycle life.

G. Power Conditioner

The simplest combined DC interface floats the battery across the photovoltaic array (Figure XI-1). This system, however, cannot match the power of the array at all levels of insolation, and the maximum power point conditioner should be designed for the full DC voltage range of the battery. The optimum charging profile for the battery is not achievable with this type of system.

Figure XI-2 shows a photovoltaic array/battery/power conditioner using a full-rated DC/DC power conditioner. A DC/DC power conditioner is connected between the array and the battery, and a DC/AC power conditioner is connected directly to the battery. This system meets the requirement for continuous power matching of the array and optimizes battery charge/discharge conditions. The DC/DC power conditioner, however, contributes to extra losses and cost.

Figure XI-3 shows a photovoltaic array/battery/power conditioner using two power conditioners. Two DC/AC power conditioners are used for the battery and the array. This produces similar performance to the scheme shown in Figure XI-2, but is less efficient in charging the battery from the array-generated energy.

Figure XI-4 shows a photovoltaic array/battery/power conditioner using a reversible DC/DC power conditioner. A DC/AC power conditioner is provided between the array and the AC system. A reversible DC/DC power conditioner controls the flow of energy to and from the battery. This system may be more efficient than those shown in Figures XI-2 and XI-3.

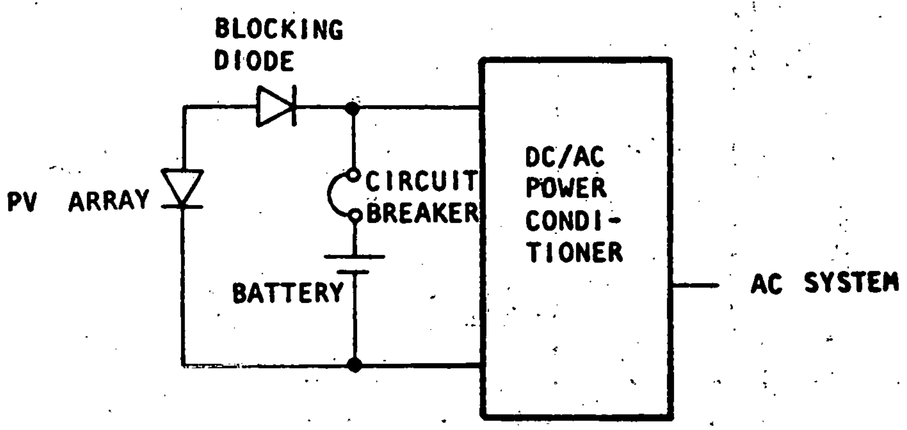

Figure XI-1. Simplest PV Array/Battery/Conversion Equipment Arrangement (5)

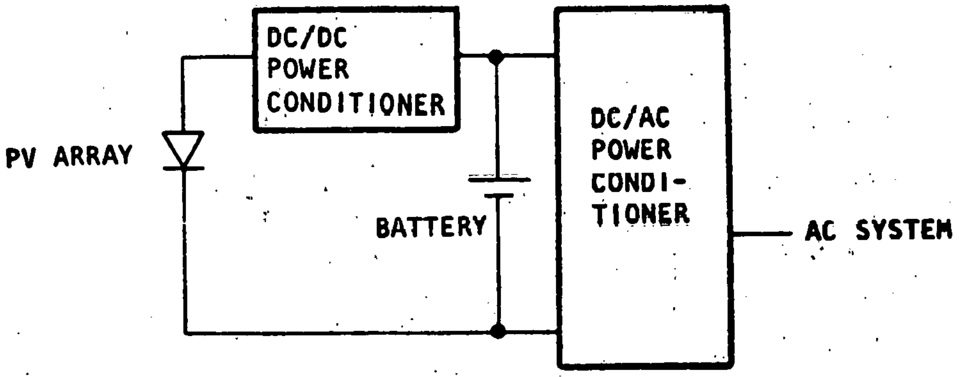

Figure XI-2. PV Array/Battery/Conversion Equipment Using Full Rated DC/DC Converter (5)

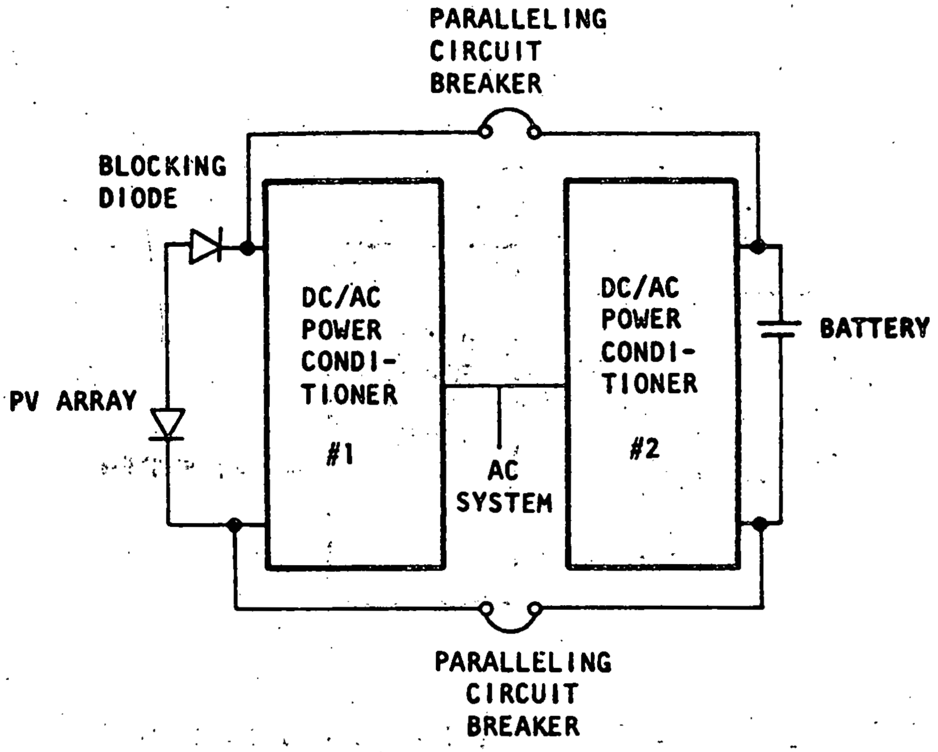

Figure XI-3. PV Array/Battery/Conversion Equipment Using Two Converters (5)

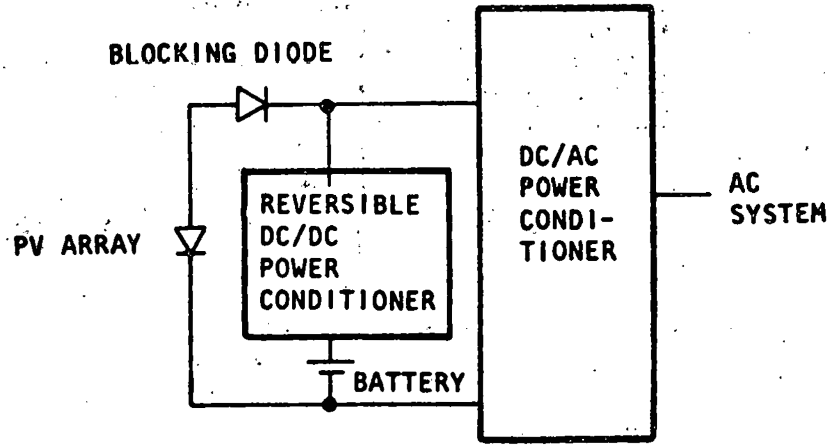

Figure XI-4. PV Array/Battery/Conversion Equipment Using Reversible DC/DC Converter (5)

H. References

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2. Smith, D. R., Sandia Laboratories. "Workshop on Power Conditioning for Alternative Energy Technologies, Executive Summary." Presented at the Workshop on Power Conditioning for Alternative Energy Technologies, Denver, Colorado, May 9-11, 1979.

3. Ma, Fred S., et al., Systems Control, Inc. "Interfacing Dispersed Solar and Wind Systems with Electric Distribution Systems." Proceedings of the International Solar Energy Society, Volume Three. Atlanta, Georgia, May 1979.

4. Marsh, W. D., General Electric Company. Requirements Assessment of Photovoltaic Power Plants in Electric Utility Systems, EPRI ER-685. Project 651-1. Technical Report. Volume I. June 1978.

5. Wood, Peter, Westinghouse Electric Corporation. "Power Conditioning for Solar Photovoltaic/Battery Storage Systems." Abstracts of Invited Papers. Presented at Workshop on Battery Storage for Solar-Photovoltaic Systems, Denver, Colorado, January 11-13, 1978.

XII. RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT

This chapter identifies required areas of battery research and development to satisfy the energy storage needs of photovoltaic power systems. Major battery development programs are already underway for electric vehicle propulsion and electric utility load leveling. Any additional DOE funding should be directed toward those battery requirements associated with photovoltaic power systems that differ from requirements on utility load-leveling and vehicle propulsion batteries.

To help identify these R&D needs, a panel discussion was held in July 1980 with representatives of several battery manufacturing companies and research and development organizations. Section D of this chapter lists the participants. An important issue emphasized by several of the panel members was that the potential market for photovoltaic batteries must be large enough to provide battery manufacturers with the incentive to participate in the development effort and eventually invest in the required production facilities.

A. Potential Markets

The potential market for photovoltaic power systems can be divided into four categories:

(1) Remote/continuous

(2) Remote/intermittent

(3) Stand-alone with onsite backup

(4) Utility-connected.

Remote/continuous power photovoltaic systems include radio and microwave repeaters, cathodic protection devices for bridges, wells, and pipelines, and navigational aids. This category comprises most of the existing terrestrial PV applications. In 1977 the installed capacity of such PV systems was approximately 650 kWp of solar array and between 40 and 60 MWh of storage batteries (1). However, the market has been increasing rapidly; the sales of PV modules in 1980 are expected to exceed 1 MWp. The potential market is much larger. The potential worldwide battery market for photovoltaic-powered radio and microwave repeaters is estimated to range from 125 to 350 MWh annually. The potential worldwide battery market for photovoltaic-powered cathodic protection systems ranges from 25 to 250 MWh annually (2).

Remote/intermittent applications include agricultural water pumping, remote village electric power systems, and forest ranger stations. The potential worldwide market for photovoltaic village power systems (40 MWp per year) would create a demand for 300 to 400 MWh of batteries per year (i.e., 7.5-hr to 10-hr storage cycle). The potential worldwide battery market for photovoltaic-powered, low-lift irrigation pumps is 750 MWh annually (2). These annual markets include replacement batteries.

The primary potential customer for stand-alone PV systems with generator backup is the U.S. Department of Defense, which already uses over 100 MW of small gasoline and diesel-powered mobile generators. The demand for batteries for such photovoltaic systems is estimated at 500 MWh annually (i.e., 5 hours of storage) (2).

Utility grid-connected photovoltaic systems may some day be used in the residential, commercial, and industrial sectors. Most studies have considered residential systems. One projection is that 600,000 homes will have PV power systems by 1990 (3). However, the potential role of energy storage in grid-connected PV systems is very uncertain. The need for energy storage would be affected by time-of-day electricity pricing, energy sell-back, and demand charges by the utility. Preliminary studies have indicated that the excess photovoltaic array output in such systems would best be supplied directly to the grid, and that if battery storage were found to be justified, the batteries should be charged using off-peak power. In other words, the storage should be general, system-wide, not dedicated to the photovoltaic array (4). This finding is predicated on a high electricity sell-back rate. The storage batteries in such a system would be designed to satisfy utility load-leveling specifications, but not photovoltaic power requirements. For this reason, it is recommended that an R&D program for photovoltaic batteries should concentrate on battery characteristics required for the first three categories, remote/continuous, remote/intermittent, and stand-alone with onsite backup.

A market assessment of PV power systems should be made. Such an assessment would provide realistic projections of the near-term and intermediate markets for batteries to meet the energy storage needs of the photovoltaic power market. The market assessment should project the number of batteries and their capacities and discharge rates. A decision should be made on whether or not development work should be directed toward utility batteries for co-located energy storage in utility grid-connected PV systems. Recent studies have suggested that such configurations are not always economical and that utility system-wide general storage is preferable to photovoltaic-dedicated storage (3). If this finding is confirmed, further battery development for photovoltaics should be directed toward stand-alone systems and load-leveling applications.

1. Remote/Continuous

Battery sizes for this application range from 5 to 40 kWh. Charge and discharge rates are generally between C/60 and C/100. The typical duty cycle is characterized by a shallow daily fluctuation in state of charge (about three percent) and a single annual cycle. The battery operates near full charge in summer months and near maximum discharge in winter months. Batteries used in these applications must be able to satisfy the following requirements:

(a) Ability to stand or operate in a float condition for long periods of time. Must be able to function in a deep discharged state at any ambient temperature.

(b) Ability to withstand adverse environment: seasonal temperature range of 55°C; some applications are in areas with ambient temperatures as high as 50°C; others are as low as -35°C. Systems sited in desert areas have to withstand very low humidity and dust storms; those sited near the ocean must be able to survive salt spray.

(c) Very low open-circuit standby loss (e.g., low parasitic power loss due to pumps, fans, and other auxiliary equipment).

(d) Very low self-discharge rate.

(e) Ability to accept low charging currents.

(f) Ability to operate without equalizing charges.

(g) Ability to operate unattended for over a year.

The current DOE goals for such batteries is a cost of $35 to $140/kWh and 4- to 10-year life (1). Lead-acid batteries that are now being used for PV-powered microwave repeaters and cathodic protection cost between $100/kWh and $200/kWh. However, to meet the performance requirements, these systems are generally sized so that the minimum state of charge never drops below 50 percent. Thus, the real storage cost is $200 to $400 or more per effective kWh.

2. Remote/Intermittent

Battery sizes for this category range from 100 to 200 kWh. Charge and discharge rates are C/30 to C/5. Most of the applications in this category would be attended, and the battery would be accessible to maintenance. Some of the applications would be characterized by a deep daily cycle, others by a shallower daily cycle (10 percent daily fluctuations in state of charge). For the deep cycling applications, it is important to know the relationship between battery life and maximum depth of discharge per cycle in order to optimally size the battery. It is also important to be able to monitor the battery's state of charge to prevent overcharge or overdischarge.

To aid battery development efforts, existing PV systems in this category should be monitored to record the actual state-of-charge versus time profile. These profiles should then be used in laboratory tests of battery performance. Such cycle testing would be analogous to the standard driving cycle tests being conducted on candidate EV batteries at the NBTL.

3. Stand-Alone Systems with Onsite Backup

A major near-term application for photovoltaic systems is to reduce the fuel requirements of small 3 to 25 KVA diesel and gasoline-powered electric generators. The batteries for such systems would be sized to provide from three to eight hours of storage, and they would range in size from 10 to 200 kWh. Their service would typically be a deep daily cycle, with several partial cycles per day.

B. General Requirements

Most of the photovoltaic applications discussed above will require batteries with small cells (several hundred amp-hours at most). This factor may limit the suitability of those types of batteries which exhibit large economies of scale in both capital cost and operating efficiency. For example, high temperature batteries may be impractical below a certain capacity because the thermal insulation required per unit capacity increases with decreased battery size. Flow batteries also have a minimum practical size, due to the decreasing efficiency of small pumps and auxiliary equipment. The question of minimum practical size for each candidate battery should be resolved before it is considered for further development for photovoltaic applications.

Another requirement which is imposed on batteries in some photovoltaic applications is the need to shift frequently between the charge and discharge mode and to be charged at a variable rate. This shifting is necessary to accommodate the intermittent and stochastic nature of insolation and the load. This requirement is similar to regenerative braking in an electric vehicle. The degree of shifting between charge and discharge in photovoltaics is uncertain; monitoring data from field tests of PV systems is needed to better clarify this requirement.

The auxiliary equipment required by candidate batteries must be determined for the types of photovoltaic applications discussed above. In many cases, this equipment will be required to perform functions not required of load-leveling or electric vehicle batteries.

More information is needed on the factors that are likely to limit reliability in batteries used in photovoltaic systems. Total battery reliability will have to be estimated. These data will be useful in designing cell interconnections and battery monitoring and control systems.

The relationships between cell voltage and state-of-charge, and between cell voltage and charge or discharge rate must be defined, and these data used in designing power conditioning systems for PV systems.

C. Battery-Specific R&D Needs

1. Lead-Acid Batteries

A better method is needed for protecting lead-acid cells from sulfation when the battery is at a low state of charge for long periods of time. Other development needs are already being addressed in the DOE/EPRI programs to develop load-leveling batteries for utilities.

2. Calcium-Iron Sulfide

Determine minimum practical cell size. Determine the effect of low charge/discharge rate operation. Other development needs are already being addressed in the load-leveling and electric vehicle battery programs.

3. Zinc-Bromine, Zinc-Chlorine, and Redox Flow Batteries

Determine minimum practical size (power and energy storage). Design low head pumps capable of very efficient operation at variable flow rate. Examine feasibility of automatic pump shutdown/startup.

Other development efforts, e.g., reducing membrane resistivity in Redox batteries, designing inexpensive reactant tanks, and cycle life testing, are already underway.

4. Nickel-Hydrogen Batteries

This battery is not currently under development by DOE or EPRI. Research on Ni-H_2 cells has been supported by the U.S. Air Force and by COMSAT. Because of their high reliability and long cycle life, Ni-H_2 batteries are beginning to replace nickel-cadmium batteries for energy storage in communication satellites. Cost is the key issue in assessing whether Ni-H_2 batteries can be competitive for terrestrial PV applications. Both electrodes, the sintered nickel cathode, and the hydrogen anode, are high-cost items in the state-of-the-art Ni-H_2 batteries. In deciding whether or not to initiate a full-scale development program for this battery, the following issues must be resolved:

(a) Can the quantity of platinum used to catalyze the hydrogen anode be substantially reduced or even replaced by a significantly cheaper material? What is the lowest-cost anode that still gives acceptable performance? (As determined by battery requirements listed above.)

(b) Can the sintered nickel cathode be replaced by a pocket-plate or pressed electrode?

(c) What would the self-discharge rate be if the maximum hydrogen pressure were reduced?

(d) What are the performance characteristics at reduced hydrogen pressures?

(e) What effect would the pressure vessel have on cost?

If there is a high probability that a redesigned Ni-H_2 battery that fulfills these requirements can be built for \$100 to \$150/kWh, a development program is recommended.

5. Zinc-Ferricyanide Batteries

The areas that will require research and development efforts are as follows:

(a) Evaluate alternative low-cost separator materials and determine specific resistance, iron and zinc permeation rates, as well as mechanical and chemical stabilities.

(b) Perform microscopic studies on the quality of zinc electrodeposition obtained using electrolyte additives and flow rate/flow distribution modification in half-cell cycling.

(c) Obtain additional information on the long-term stability of sodium ferricyanide electrolyte.

(d) Investigate the use of a lower-cost electrode substrate than the porous nickel plaque now used.

D. Participants in Panel Discussion on Batteries for Photovoltaic Energy Storage

The following individuals helped identify research and development needs for photovoltaic systems:

Jack Brill	Eagle-Picher Industries, Inc.
Lee Miller	Eagle-Picher Industries, Inc.
Pat Grimes	Exxon Research & Engineering Company
Frank J. Biondi	Consultant to Sandia National Laboratory
Ron Putt	Gould, Inc.
Al Chilenskas	Argonne National Laboratory
D.T. Ferrell, Jr.	Exide Engineering and Development Center
James Mayo	U.S. Department of Energy
Albert Landgrebe	U.S. Department of Energy

Dave Caskey	Sandia National Laboratory
W.R. Abel	Sandia National Laboratory
Rae Chudacer	Aerospace Corporation

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XIV. ABBREVIATIONS

battery energy efficiency (round trip)	η_B
calcium silicon-ferrisulfide	CaSi-FeS
degrees (Centrigrade)	°C
degrees (Fahrenheit)	°F
full load amperes	FLA
feet	ft
figure of merit	FOM
gallon	gal
hertz	Hz
iron-chromium	Fe-Cr
kilovolt-amperes	kVA
kilowatt-hour	kWh
kilowatt-hours per square meter	kWh/m^2
kilowatts per square meter	kW/m^2
kilowatt (peak)	kWp
lead-acid	Pb-Acid
liquified propane gas	LPG
lithium aluminum-ferrisulfide	LiAl-FeS
lithium silicon-ferrisulfide	LiSi-FeS
locked rotor amperes	LRA
megawatts	MW
natural gas	NG
nickel-iron	Ni-Fe
nickel-hydrogen	Ni-H_2

nickel-zinc	Ni-Zn
not applicable	NA
phase	ph, Ø
photovoltaic	PV
power conditioner efficiency energy	η_p
parts per million	ppm
quantity	Qty
running load amperes	RLA
sodium-sulfur	Na-S
volts	V
watts	W
watts per square meter	W/m^2
watt-hour	Wh
year	yr
zinc-bromine	$Zn\text{-}Br_2$
zinc-chlorine	$Zn\text{-}Cl_2$
zinc-ferricyanide	$Zn\text{-}Fe(CN)_6$

APPENDIX

RANKING TABLES

TABLE A-1. WEIGHTED EVALUATION OF BATTERIES FOR THE REMOTE VILLAGE APPLICATION

Battery System	Attributes						
	Cost Weighting Factor, W_1 = .20		Reliability Weighting Factor, W_2 = .70		Health & Safety Weighting Factor, W_3 = .10		Total Figure of Merit (Uncertainty)*
	Relative Rating A_1	Figure of Merit W_1A_1	Relative Rating A_2	Figure of Merit W_2A_2	Relative Rating A_3	Figure of Merit W_3A_3	$FOM = \sum_{i=1}^{3} W_iA_i$
Pb-Acid	7	1.4	9	6.3	8	0.8	8.5 (±0.6)
Redox	10	2.0	6	4.2	9	0.9	7.1 (±2.0)
$Zn\text{-}Fe(CN)_6$	10	2.0	5	3.5	8	0.8	6.3 (±2.0)
$Zn\text{-}Br_2$	8	1.6	5	3.5	7	0.7	5.8 (±1.6)

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*Uncertainty = U_{total} x W_1A_1, U_{total} = Total Cost Uncertainty

U_{total} from Table IX-16.

TABLE A-2. WEIGHTED EVALUATION OF BATTERIES FOR THE RESIDENTIAL APPLICATION

Battery System	Attributes: Cost Weighting Factor, $W_1 = .75$		Reliability Weighting Factor, $W_2 = .20$		Health & Safety Weighting Factor, $W_3 = .05$		Total Figure of Merit (Uncertainty)
	Relative Rating A_1	Figure of Merit W_1A_1	Relative Rating A_2	Figure of Merit W_2A_2	Relative Rating A_3	Figure of Merit W_3A_3	$FOM = \sum_{i=1}^{3} W_iA_i$
Pb-Acid	9	6.7	9	1.8	8	0.4	8.9 (±2.7)
Ni-Fe	5	3.7	9	1.8	8	0.4	5.9 (±1.4)
Ni-Zn	4	3.0	6	1.2	8	0.4	4.6 (±2.3)
$Ni-H_2$	4	3.0	10	2.0	7	0.4	5.4 (±0.5)
Redox	6	4.5	8	1.6	9	0.5	6.6 (±4.5)
$Zn-Fe(CN)_6$	8	6.0	7	1.4	8	0.4	7.8 (±6.0)
$Zn-Br_2$	10	7.5	7	1.4	7	0.4	9.3 (±7.5)

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*Uncertainty = $U_{total} \times W_1A_1$, U_{total} = Total Cost Uncertainty

U_{total} from Table IX-16.

TABLE A-3. WEIGHTED EVALUATION OF BATTERIES FOR THE DAIRY FARM APPLICATION

	Attributes						
Battery System	Cost Weighting Factor, $W_1 = 0.5$		Reliability Weighting Factor, $W_2 = 0.4$		Health & Safety Weighting Factor, $W_3 = 0.1$		Total Figure of Merit (Uncertainty)*
	Relative Rating A_1	Figure of Merit W_1A_1	Relative Rating A_2	Figure of Merit W_2A_2	Relative Rating A_3	Figure of Merit W_3A_3	$FOM = \sum_{i=1}^{3} W_iA_i$
Pb-Acid	9	4.5	9	3.6	8	0.8	8.9 (±1.2)
Ni-Fe	5	2.5	9	3.6	8	0.8	6.9 (±1.0)
Ni-Zn	4	2.0	6	2.4	8	0.8	5.2 (±1.5)
Ni-H_2	4	2.0	10	4.0	7	0.7	6.7 (±0.3)
LiAl-FeS	7	3.5	5	2.0	6	0.6	6.1 (±1.8)
LiSi-FeS	9	4.5	5	2.0	6	0.6	7.1 (±4.5)
CaSi-FeS	10	5.0	5	2.0	6	0.6	7.6 (±5.0)
Na-S (Glass)	10	5.0	5	2.0	6	0.6	7.6 (±5.0)
Na-S (β-Alumina)	9	4.5	5	2.0	6	0.6	7.1 (±1.2)
Redox	5	2.5	8	3.2	9	0.9	6.6 (±2.5)
Zn-Fe$(CN)_6$	10	5.0	7	2.8	8	0.8	8.6 (±5.0)
Zn-Cl_2	9	4.5	7	2.8	6	0.6	7.9 (±4.5)
Zn-Br_2	10	5.0	7	2.8	7	0.7	8.5 (±5.0)

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*Uncertainty = U_{total} x W_1A_1, U_{total} = Total Cost Uncertainty

U_{total} from Table IX-16

TABLE A-4. WEIGHTED EVALUATION OF BATTERIES FOR THE OFFICE BUILDING APPLICATION

Attributes

Battery System	Cost Weighting Factor, W_1 = .60		Reliability Weighting Factor, W_2 = .25		Health & Safety Weighting Factor, W_3 = .15		Total Figure of Merit (Uncertainty)*
	Relative Rating A_1	Figure of Merit W_1A_1	Relative Rating A_2	Figure of Merit W_2A_2	Relative Rating A_3	Figure of Merit W_3A_3	$FOM = \sum_{i=1}^{3} W_iA_i$
Pb-Acid	7	4.2	9	2.2	8	1.2	7.6 (±1.7)
Ni-Fe	4	2.4	9	2.2	8	1.2	5.6 (±1.0)
Ni-Zn	4	2.4	6	1.5	8	1.2	5.1 (±1.8)
$Ni-H_2$	3	1.8	10	2.5	7	1.0	5.3 (±0.3)
LiAl-FeS	6	3.6	5	1.2	6	0.9	5.7 (±1.8)
LiSi-FeS	8	4.8	5	1.2	6	0.9	6.9 (±4.8)
CaSi-FeS	10	6.0	5	1.2	6	0.9	8.1 (±6.0)
Na-S (Glass)	6	3.6	5	1.2	6	0.9	5.7 (±3.6)
Na-S (β-Alumina)	7	4.2	5	1.2	6	0.9	6.3 (±1.1)
Redox	6	3.6	8	2.0	9	1.3	6.9 (±3.6)
$Zn-Fe(CN)_6$	7	4.2	7	1.7	8	1.2	7.1 (±4.2)
$Zn-Cl_2$	8	4.8	7	1.7	6	0.9	7.4 (±4.8)
$Zn-Br_2$	8	4.8	7	1.7	7	1.0	7.5 (±4.8)

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*Uncertainty = $U_{total} \times W_1A_1$, U_{total} = Total Cost Uncertainty
U_{total} from Table IX-16.

TABLE A-5. WEIGHTED EVALUATION OF BATTERIES FOR THE UTILITY APPLICATION

	Attributes						
Battery System	Cost Weighting Factor, W_1 = .50		Reliability Weighting Factor, W_2 = .40		Health & Safety Weighting Factor, W_3 = .10		Total Figure of Merit (Uncertainty)*
	Relative Rating A_1	Figure of Merit W_1A_1	Relative Rating A_2	Figure of Merit W_2A_2	Relative Rating A_3	Figure of Merit W_3A_3	$FOM = \sum_{i=1}^{3}$
Pb-Acid	7	3.5	9	3.6	8	0.8	7.9 (±1.4)
Ni-Fe	4	2.0	9	3.6	8	0.8	6.4 (±0.8)
Ni-Zn	3	1.5	6	2.4	8	0.8	4.7 (±1.1)
Ni-H_2	3	1.5	10	4.0	7	0.7	6.2 (±0.2)
LiAl-FeS	6	3.0	5	2.0	6	0.6	5.6 (±1.5)
LiSi-FeS	8	4.0	5	2.0	6	0.6	6.6 (±4.0)
CaSi-FeS	10	5.0	5	2.0	6	0.6	7.6 (±5.0)
Na-S (Glass)	6	3.0	5	2.0	6	0.6	5.6 (±3.0)
Na-S (β-Alumina)	6	3.0	5	2.0	6	0.6	5.6 (±0.8)
Redox	5	2.5	8	3.2	9	0.9	5.6 (±2.5)
Zn-Fe$(CN)_6$	7	3.5	7	2.8	8	0.8	7.1 (±3.5)
Zn-Cl_2	6	3.0	7	2.8	6	0.6	6.4 (±3.0)
Zn-Br_2	7	3.5	7	2.8	7	0.7	7.0 (±3.5)

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*Uncertainty = $U_{total} \times W_1A_1$, U_{total} = Total Cost Uncertainty

U_{total} from Table IX-15.

TABLE A-6. WEIGHTED EVALUATION OF BATTERIES FOR THE MILITARY APPLICATION

Battery System	Attributes: Cost, Weighting Factor, W_1 = .20		Reliability, Weighting Factor, W_2 = .70		Health & Safety, Weighting Factor, W_3 = .10		Total Figure of Merit (Uncertainty)*
	Relative Rating A_1	Figure of Merit W_1A_1	Relative Rating A_2	Figure of Merit W_2A_2	Relative Rating A_3	Figure of Merit W_3A_3	$FOM = \sum_{i=1}^{3} W_iA_i$
Pb-Acid	4	0.8	9	6.3	8	0.8	7.9 (±0.3)
Ni-Fe	1	0.2	9	6.3	8	0.8	7.3 (±0.1)
Ni-Zn	2	0.4	6	4.2	8	0.8	5.4 (±0.3)
Ni-H_2	1	0.2	10	7.0	7	0.7	7.9 (±0.3)
LiAl-FeS	7	1.4	5	3.5	6	0.6	5.5 (±0.7)
LiSi-FeS	8	1.6	5	3.5	6	0.6	5.7 (±1.6)
CaSi-FeS	10	2.0	5	3.5	6	0.6	6.1 (±2.0)
Na-S (Glass)	8	1.6	5	3.5	6	0.6	5.7 (±1.6)
Na-S (β-Alumina)	3	0.6	5	3.5	6	0.6	4.7 (±0.2)

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*Uncertainty = [illegible] total [illegible] Cost Uncertainty

U_{total} from Table IX-16.

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