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Evaluation of International Photovoltaic Projects

Volume II: Technical Report

D. Eskenazi, D. Kerner, L. Slominski
Meridian Corporation
Falls Church, VA 22041

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Abstract

This report provides a comprehensive review and financial analysis of photovoltaic power systems for remote applications in developing countries. Volume I, the Executive Summary, provides an overview of all findings; Volume II, the Technical Report, covers the methods of analysis used and the results obtained. Five application areas are included: water pumping, communications, vaccine refrigeration, lighting and home power, and multi-use systems. Findings are based on qualitative reviews of more than 2700 systems in 45 countries. Information was collected from published reports, questionaires, and interviews with key experts Site visits were not within the scope of this evaluation. The intended audience of this report are development agency officials, manufacturers, and users. Based on "lessions learned" from past projects, recommendations are provided for project implementation. In addition, financial analyses allow decision makers to use their own assumptions to obtain a first-order indication of the financial attractiveness of photovoltaic systems for each application. This report also provides industry with an assessment of product performance and suggested areas for additional improvements.

ACKNOWLEDGEMENTS

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One subcontractor and two consultants provided technical inputs. I.T. Power, Incorporated, of Washington, D.C., provided most of the technical information on vaccine refrigeration systems. Matt Buresch and Barry Welch developed the system sizing and financial models used in the analysis.

This report could not have been completed in a credible manner without the unselfish input and support of many experts. Among those who provided substantial assistance are Anthony Ratajczak of NASA-Lewis Research Center, Bill Kaszeta of Solavolt International, Alfonso Zavala of the World Bank, Derek Lovejoy of the United Nations, and John Eckel of A.Y. McDonald.

The authors would like to thank Hal Post of Sandia National Laboratories for his endless patience and strong technical direction in monitoring this work. Special recognition is also in order for those who had the foresight to sponsor this report. Jack Vanderryn of the U.S. Agency for International Development provided the initial sponsorship of this report; Bud Annan, Director of the Photovoltaic Energy Technology Division of the U.S. Department of Energy, provided both the financial and moral support necessary to complete this project.

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LIST OF ACRONYMS

AC - Alternating current

CDC - Centers for Disease Control

CIF - Cost, insurance, and freight

DC - Direct current

EPI - Expanded Programme on Immunization

FOB - Free on board

HED - Hydraulic energy demand

kWh - Kilowatt-hour

LDC - Lesser developed countries

NPV - Net present value

O&M - Operation and maintenance

PV - Photovoltaic

SNLA - Sandia National Laboratories - Albuquerque

SPEC - South Pacific Bureau for Economic Cooperation

USAID - U.S. Agency for International Development

USDOE - U.S. Department of Energy

UNDP - United Nations Development Programme

WHO - World Health Organization

W_p - Peak watt (power output under standard rating conditions - 1,000 W/m^2 insolation at 25°C cell temperature)

CHAPTER 1

INTRODUCTION

1.1 Background

Photovoltaic (PV) systems use solar cells to generate clean, reliable electricity directly from sunlight. These systems can be used for a large variety of applications that require electrical power ranging from a fraction of a watt to several megawatts.

In the past 10 years, PV-powered systems have been installed in developing countries to provide power for water pumping, communications, refrigeration, lighting, and other basic necessities. These systems have brought electricity to people and areas that have never had power before. Photovoltaic projects have been principally sponsored by governments, donor agencies, and nonprofit organizations to test, evaluate, and demonstrate the performance of PV as an energy technology for remote areas of the developing world.

Despite the increased use of PV-powered systems, no attempt has been made to systematically collect and analyze the performance data and experience of PV systems across all predominant developing country applications. Similarly, comprehensive financial assessments of PV-powered systems have not previously been performed. Therefore, a comprehensive and objective evaluation of the viability of PV systems for various applications in developing countries was deemed appropriate. Officials in industry, development agencies, and developing countries, many of whom have sponsored past PV projects, requested such an assessment (References 1-1, 1-2 and 1-3). It is toward this end that this evaluation was conducted.

The evaluation is based on a review of the experience associated with over 2,700 systems in 45 countries. Information was collected from published reports and articles, questionnaires, and interviews with key experts in the application of photovoltaics in developing countries. Site visits were not within the scope of this evaluation.

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A Round Table Meeting was held on November 20, 1985 to review interim study findings. The 48 participants of this review included industry representatives, applications experts, and development agency officials (see Appendix C). Discussion was directed toward validating technical and financial findings and identifying the broader institutional factors that impact PV system implementation. Following the meeting, additional technical and financial analyses were performed in response to reviewer recommendations. Institutional issues raised during the course of the meeting have been incorporated into Chapter 14, "Institutional Factors."

This work was performed for Sandia National Laboratories (SNLA) and was supported by the U.S. Agency for International Development (USAID) and the U.S. Department of Energy (USDOE). The report was prepared by Meridian Corporation with the assistance of IT Power, Inc., which performed a separate evaluation of refrigeration systems for vaccine storage.

1.2 Purpose

The purpose of this report is twofold:

(1) To review the qualitative experience associated with PV-powered systems in developing country applications.

(2) To educate decision-makers on the viability of PV systems for various developing country applications.

In meeting this dual purpose, the report provides the following:

- A summary of the field experience of PV power/load systems, including the identification of key factors that affect system implementation.
- Current technical and cost data for PV power/load systems as well as data for competitive technologies (e.g., diesel, gasoline, and kerosene power systems). While this report contains basic system configurations and sizing procedures, it is not intended to serve as a design manual.
- Financial analyses comparing the life-cycle costs of PV- and conventional-powered systems on an application by application basis. These analyses are based on the financial assumptions typical of development agency projects.

1.3 Approach

The primary audience of this report is officials from federal (USAID) and multilateral development agencies. This report is also directed at users and manufacturers of photovoltaic equipment and systems throughout the world.

The World Bank is the primary source of world development funds and most developing country loans tend to follow World Bank standards. Therefore, this report provides the typical information required by the World Bank decision process. World Bank project appraisals involve six areas of analysis listed in Exhibit 1-1 (Reference 1-4).

EXHIBIT 1-1. World Bank Project Appraisal Analysis Steps

1. **ANALYSIS OF THE SECTORAL FRAMEWORK**
2. **MARKET ANALYSIS**
3. **TECHNICAL OR ENGINEERING ANALYSIS** ⇨ **<u>SECTION II</u>**
4. **MANAGEMENT, MANPOWER AND ORGANIZATIONAL ASPECTS** ⇨ **<u>SECTION IV</u>**
5. **FINANCIAL APPRAISAL** ⇨ **<u>SECTION III</u>**
6. **ECONOMIC APPRAISAL**

This report focuses on the technical and financial aspects of systems implementation and briefly addresses the institutional concerns of project management, planning, and training. These areas correspond to steps 3, 4, and 5 as noted in Exhibit 1-1. Steps 1, 2, and 6 are not within the scope of this report.

The evaluation was conducted in three phases:

- Review of field experience with PV systems in developing countries.
- Identification of current designs and costs for both PV- and conventional-powered systems.
- Performance of life-cycle cost analyses for comparing PV systems to conventional alternatives.

1.3.1 Review of Field Experience

The initial phase of this evaluation involved selecting the PV applications to be examined. It was decided that those selected must be significant stand-alone applications for developing countries, as determined by the number of systems installed, recommendations by applications experts, and the availability of data. Based on these criteria, the following applications were selected for evaluation: water pumping; communications; vaccine refrigeration; lighting and home power; and multi-use (e.g., load centers and mini-utilities) systems. Each of these applications is described in detail and analyzed individually in both the technical and financial sections of this report.

The experience associated with more than 2,700 PV power/load systems was incorporated into this evaluation. (A PV power/load system is defined to include the array, power conditioning equipment, energy storage, and end-use devices.) From these 2,700 systems, 29 specific projects were selected for detailed review based on their representative nature, the amount of available data, and/or their importance to understanding the key factors of PV system performance in particular applications. (In some cases, a "project" consists of many similar systems; for example, the NASA-Lewis refrigerator field tests total 28 systems, but they are treated as one project.) Performance summaries and lessons learned from these 29 projects are provided in later sections of this report.

Performance information was collected from three principal sources: project reports and articles, end-users and/or participating in-country personnel; and manufacturers and other key individuals. Questionnaires were sent to over 300 organizations and individuals to obtain field performance data and end-user perceptions about the viability of PV in developing countries. Twenty percent of those receiving questionnaires responded. This evaluation was conducted with the understanding that quantitative field performance data are limited, and what little data exist are of questionable accuracy.

Systems chosen for detailed review were evaluated on the basis of the following performance parameters:

- **Technical:** operating reliability, ability to meet demand, and ease of operation, maintenance, and repair.
- **Institutional:** demand for specific product/service, match between operator skill level and that required, and existence and performance of technical and administrative support.
- **Financial:** capital cost, operation and maintenance cost, life-cycle cost/benefit, and competitiveness with conventional-powered systems.

1.3.2 Identifying Current Designs and Costs

Because photovoltaic systems have been rapidly improving in both performance and cost, past systems may not be completely representative of today's technology. To facilitate a comparison of PV to other systems for possible future projects, it was necessary to identify recent system improvements and current costs. Toward this end, this report identifies base-case conceptual system designs in each application area for both PV and the most likely conventional alternative. Current costs were obtained directly from selected manufacturers and system suppliers.

1.3.3 Financial Analyses

The last phase of the evaluation was the performance of financial analyses. First, a methodology was developed for estimating the net present value life-cycle cost of remote power systems. The methodology and its attendant assumptions are based on World Bank standards and are representative of a typical developing country loan. Next, this methodology was applied to each selected application (see Exhibit 1-2) to compare PV systems to the most likely conventional alternative using "base-case" assumptions (see Exhibit 1-3). Third, sensitivity analyses were conducted to demonstrate the impact key parameters have on system life-cycle cost. (A graphic depiction of these

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EXHIBIT 1-2. Technologies Compared in Life-Cycle Analyses

APPLICATION	POWER SOURCE			
	PV	DIESEL	KEROSENE	BATTERIES
Water Pumping	X	X		
Communications	X	X		
Vaccine Refrigeration	X		X	
Lighting and Home Power	X		X	X
Multi-Use	X	X		

EXHIBIT 1-3. Load Specifications for Base-Case Analyses

APPLICATION	SPECIFICATION
Water Pumping	• Village drinking water system • 50 m^3/day annual average water demand • 25-meter head
Communications	• Microwave repeater application • 7.2 kWh/day constant, continuous load
Vaccine Refrigeration	• Vaccine Refrigeration • Two cases: - Small (24 liters) - Large (68-80 liters)
Lighting and Home Power	Three case: • Small - one light • Medium - two lights • Large - two lights and a radio
Multi-Use	• 10 kWh/day annual average electricity demand over a period of 12 to 15 hours

sensitivity analyses is provided to allow readers to make a first-order estimate of PV system viability over a range of loads.) Finally, best- and worst-case analyses were conducted to show a range of financial viability for PV systems.

A distinction should be made between financial and economic analyses. Financial analyses address the costs and benefits of one project. Economic analyses address the broader impacts of technology use on developing countries using such quantitative methods as shadow pricing. The assessments in this evaluation are restricted to financial analyses.

1.4 Report Organization

The body of the report is divided into the following sections:

- Section I, Introduction, provides background information.
- Section II, Technical Review, individually examines each of the applications under consideration, covering current system designs (both for PV and comparative technologies) and field experience. It also includes basic sizing considerations for each application.
- Section III, Financial Analyses, consists of life-cycle cost analyses that compare PV to competing technologies using base-case system designs for each application. Sensitivity analyses are also included to show the effect of varying assumptions.
- Section IV, Institutional Factors, discusses institutional considerations, including the broader infrastructural factors related to the implementation of PV power/load systems.
- Section V, Conclusions, presents the conclusions of this evaluation.
- Section VI, Appendices, provides backup data and information on the questionnaire responses, significant projects, and the technical and financial models used to perform the evaluation.

CHAPTER 2

PV SYSTEMS OVERVIEW

2.1 Introduction

This is the first of six chapters pertaining to the technical aspects of PV power systems. It provides a brief outline of the types, applications and components of PV power systems.

The five chapters that follow focus on each of the applications reviewed for this evaluation. The significance, current designs and field experience associated with PV-powered water pumping, communications, vaccine refrigeration, lighting and home power, and multi-use systems are presented. Current designs for the most common conventional power sources for each of the applications are also described. The review of field experience was based on questionnaire responses, published reports and articles, and interviews with key experts in the application of PV in developing countries.

In many instances, photovoltaic power systems have been shown to be an appropriate technology solution to rural electrification, resolving fuel supply uncertainties and maintenance problems associated with remote engine generators. They offer the advantages of high reliability, low maintenance, short construction periods, modularity and environmental acceptability.

2.2 Photovoltaic-Powered Applications

Photovoltaics (PV) is a solar energy technology that converts sunlight directly into electricity. PV power systems are capable of supplying electrical loads ranging from a fraction of a watt to several megawatts. PV power has been proven feasible and reliable for a variety of applications. These applications can be categorized by three system types:

- Stand-alone systems
- Grid-connected systems
- Consumer products.

Stand-alone systems are those systems not linked to utility grids. These can be remote applications where power is otherwise unavailable or unreliable. Remote applications include navigational aids, communications, vaccine refrigeration, cathodic protection, central village power, lighting, home power and water pumping.

In grid-connected systems, power generated by the PV array is conditioned to operate parallel to the electric utility. Applications range from small residential systems to multi-megawatt central-station generation plants for utilities.

Photovoltaics has been effectively used in consumer product applications as replacements for batteries and as battery chargers. In these applications, PV is used to power watches, calculators, small toys and trickle-chargers for rechargeable batteries.

This evaluation focused on systems that have the greatest significance for developing countries--remote, stand-alone systems. In particular, water pumping, communications, vaccine refrigeration, lighting and home power, and multi-use systems were selected for analysis. Multi-use systems include load centers (power for agricultural product processing, medical clinics, schools, etc.) and miniutilities. These applications were selected based on the number of systems installed in developing countries, the recommendations of application experts and the availability of data.

2.3 Photovoltaic Power System Components

A stand-alone PV power system generally consists of the following components:

- PV array
- Support structure for the modules
- Battery storage
- Power conditioning.

The following sections describe these components.

2.3.1 PV Array

The basic building block of a PV array is a photovoltaic module. When light strikes the modules, a direct electric current is generated. The modules are wired in series and parallel configurations to achieve the voltage and current needed to meet the load requirements.

This evaluation considered only flat-plate systems made using crystalline silicon technology, since they are the type most commonly found in developing country applications. Flat-plate modules can use both direct and diffuse radiation and are available in sizes ranging from about 5 to 180 peak watts. For most applications, modules in the 30-to-50-watt range are used. (A peak watt is defined to be the power output of a PV module under standard rating conditions--1000 W/m^2 insolation at 25°C cell temperature.)

2.3.2 Support Structures

The selection of an array support structure depends on the module type chosen and the intended application. Flat-plate modules are generally mounted on fixed structures. In remote applications, simple, easily erected rack structures made from aluminum, steel, wood and/or concrete have typically been used.

2.3.3 Battery Storage

Secondary batteries are used for PV applications as energy storage devices to offset periods of low insolation or peak energy demands. Batteries also provide the high starting currents required by some motors. Batteries can be classified as having deep or shallow discharge characteristics. Deep discharge batteries are designed specifically for large usable capacities (approximately 80%), whereas shallow discharge batteries are designed for about 20% discharge. Discharging the battery beyond these capacities can result in permanent damage. Either type can be used for PV applications, but deep discharge batteries are the predominant type used based on their charging/ discharging characteristics and larger capacity. Shallow discharge batteries have usually been used in conventional-powered systems.

Battery life is generally identified through a cycle life, where a cycle is designated as the discharge and subsequent recharge of battery capacity to its initial level. Cycle life (i.e., the number of cycles a battery can undergo before failure) is a strong function of the percentage of discharge that occurs in each cycle.

Batteries are available in both sealed and vented designs. Sealed batteries do not require a significant amount of maintenance. Vented batteries, although less expensive than sealed, require the regular addition of water (approximately every 3 to 6 months in average humidity environments). To minimize the concentration of gases discharged from vented batteries during charging, outside air circulation must be maintained.

2.3.4 Power Conditioning Subsystem

In stand-alone applications, the power conditioning subsystem controls, matches and, in some cases, manages the distribution of power to the loads and batteries. This control function maybe performed by voltage regulators, maximum power tracking devices or other similar components. A maximum power point tracker is a sophisticated piece of equipment relative to other PV system components. It continually samples and adjusts PV array power output to ensure that it is maximized. The type of power conditioning needed in a system depends on the intended application.

In a DC system, the power conditioning subsystem may consist only of a voltage regulator. In addition, many small DC pumping systems without battery storage do not use or require a voltage regulator (i.e. the array is directly connected to the pump motor). In an AC system with storage, the subsystem consists of a DC-to-AC inverter and a charge controller. Power conditioning subsystems can be designed to any level of sophistication. However, a PV power system should be kept as simple as possible since each step in the power conditioning process reduces system efficiency and each degree of sophistication increases cost and risk of failure.

Voltage Regulators/Charge Controllers

Voltage regulators provide constant voltage to the loads/batteries. Charge controllers regulate power output and have array management capabilities to control power supplied to the batteries. The controller manages the array output by dropping array strings (parallel array circuits) to reduce power going to the batteries as they reach a full state-of-charge. As an option, controllers can also include load management functions that allow the user to prioritize loads so that when the batteries are at low state-of-charge, the system powers only the most critical loads.

Inverters

An inverter is used to convert DC power to AC power so that it can interact with AC loads. The precision with which this conversion takes place dictates the cost of the equipment. The precision required by the system is determined by the loads.

The primary indication of the quality of the power output is its wave form. Perfect AC is in the form of a sine wave. Inverters produce a quasi-sine wave or sine-wave AC. The selection of a wave form depends on the loads. For resistive elements and some motors, simple square-wave AC is acceptable. For turntable motors and precision equipment, sine-wave AC is necessary. In cases where the user wants to link to a utility grid, only sine-wave quality AC is acceptable. Because the prices associated with the inverters that produce these wave forms vary significantly, it is important for purchasers to recognize the minimum acceptable quality of power for their loads.

Manufacturers often offer specialized circuits and switches for their inverters. For example, some manufacturers offer circuits designed for motor start-ups, applications that often require high peak currents. Others offer automatic on/off switches that eliminate power consumption when not in use. Control functions and maximum power tracking may also be offered.

DC-to-DC Converters

A DC-to-DC converter is used to step DC voltage up or down. For example, if the PV array produces 12 volts DC but the load requires 24 volts DC, a DC-to-DC converter can be used. In general, a PV power system should be designed (through the series-parallel configuration of its modules) so that a converter is not necessary since it adds to cost and detracts from efficiency.

CHAPTER 3

WATER PUMPING

3.1 Overview

Water is a basic development need for a large portion of the world's rural population. The majority of this population lives in remote sunny areas with relatively shallow water resources. They need potable water for human and animal consumption and for irrigation. The development and application of photovoltaic-powered water pumping systems have been supported by many donor agencies and governments as a technology with a strong potential for meeting this need.

The principal power sources for rural water pumping systems in developing countries have been diesel generators, human labor and animals. PV-powered systems can provide the same amount of power as these sources without requiring any fuel, the principal cost element of a diesel system, or extensive maintenance, another major diesel cost element. Another advantage of using a PV-powered system is that in situations where human labor or animals are the principal source of power, it may allow people time to pursue more productive activities and may avoid the so-called "milk and meat loss" associated with the use of farm animals as a power source.

Photovoltaic-powered water pumping systems have been developed and field tested for the past 10 years. A benchmark study on PV-powered pumping systems from 1979 through 1982 was performed for the United Nations Development Programme (UNDP) and World Bank. The study (Reference 3-1), which is reviewed in this report, concluded that PV-powered pumping is cost-competitive to conventional sources under low-flow and low-head conditions. These conditions imply water demands of 250 m^4/day and 150 m^4/day for rural water supply and irrigation systems, respectively (where m^4/day refers to the product of the volume demand and head). A 250 m^4/day demand is equivalent to a rural water supply of 10 m^3/day, through a 25 meter head, for up to 500 people (20 liters/day per person). Experiences with PV-powered pumping systems in Mali and Botswana have also been reviewed for this evaluation through interviews with key engineering managers from projects in those countries. These two field-based projects alone represent over 5 years of test experience with over 100 PV pumping systems.

It is estimated that there are more than 2000 PV-powered pumping systems installed worldwide (Reference 3-2). Review of the project experience associated with approximately 200 of these PV-powered pumping systems led to the identification of key factors that influence the performance and, ultimately, the viability of such systems. Successful PV-powered pumping systems have incorporated reliable subsystems, such as the power control equipment, pumps and motors. The availability and proper use of solar and water resource data for the sites were also key to successful system implementation. Other important factors for successful PV-powered pumping systems included a high level of end-user participation and the availability of technical support. The simplicity of PV and the standard technology of pumps have been shown to be easily understood by involved users and host-country technical organizations. Many users have found PV-powered pumping systems to be cost-competitive to diesel-powered systems, particularly in low-flow, low-head applications.

3.2 Current Designs

The following sections describe basic design considerations for PV- and conventional-powered water pumping systems. Typical system configurations, component options, operation and maintenance requirements, and rough sizing procedures are discussed.

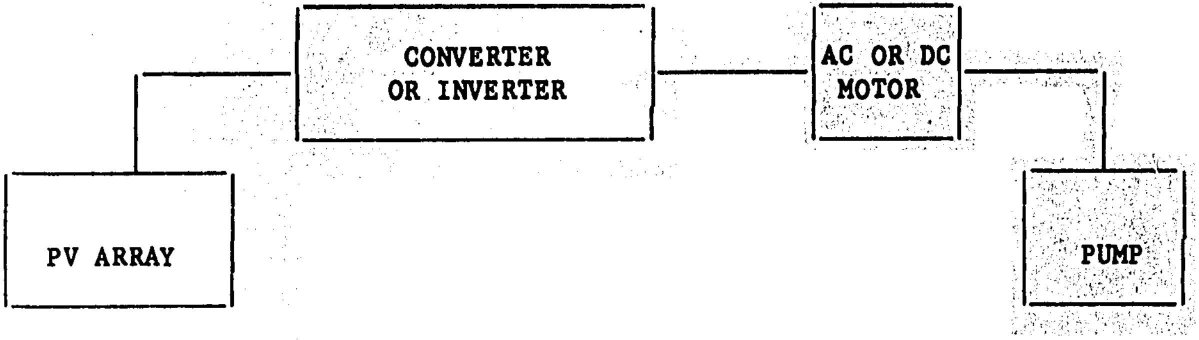
3.2.1 PV-Powered Systems

PV-powered pumping systems have been used for irrigation and for providing clean and safe water for human and animal consumption and washing. This section describes basic design features and considerations for such systems and presents a basic system sizing procedure.

The design of a system and the choice of components is determined as a function of the water demand and the characteristics of the solar and water resources. In general, well depth and water demand determine pump and motor choice. Energy demand, motor design and solar resource determine array size and power conditioning requirements. The maximum ratio of energy demand to insolation over the year indicates the array size required for highest availability (approaching 100%). PV array size may be reduced from this "peak size" by using adequate water storage, conservation or by tolerating short periods of reduced water supply.

The simplest PV power/load systems for water pumping applications consist of two basic components: the PV array and a motor/pump set. When a DC motor/pump set is used, power conditioning is not required, although a DC-DC converter can increase efficiency. If an AC motor is used, an inverter must also be provided. Battery storage is seldom considered for this application because storage of water is normally more economical than storage of electrical energy. Battery storage is sometimes used for motor start-ups. Exhibit 3-1 illustrates the configuration of a typical system.

EXHIBIT 3-1. Configuration of a PV-Powered Pumping System



Pumps

Pumps used in photovoltaic-powered systems can be divided into two major types (References 3-3 and 3-4):

(1) Centrifugal Pumps: water enters the center of a rotating impeller, and centrifugal force then discharges the water through diffuser blades. Pumps with more than one impeller are referred to as multi-staged. These pumps are designed for specified heads, with flow increasing with rotational speed. They have been shown to be most efficient at flow rates greater than 25 m^3/day and lifts of up to approximately 50 meters.

(2) Positive Displacement Pumps: also referred to as volumetric pumps, they come in two types: rotary and reciprocating. The most common type used in PV applications has been the jack pump (reciprocating). Jack pumps operate on a piston system that displaces a volume of water almost equal to the piston displacement. Because positive displacement pumps are cyclical loads that do not match well with the constant PV power supply, they require more complex power conditioning equipment than centrifugal pumps. Positive displacement pumps are good for low-flow applications with lifts from approximately 15 to 300 meters.

Motors

There are three types of motors available for PV-powered pumping systems: DC brush, DC brushless and AC. Because PV arrays produce DC power, there are certain benefits to using a DC motor; namely, no inverter is required. However, DC motors with brushes, the predominant type of DC motor, do require brush replacement at certain intervals (Reference 3-5). While DC brushless motors do exist, they have a higher initial cost and are available only in the smaller size range. Despite these cost and availability limitations, the use of brushless motors is appealing particularly in cases that require submersible motors. These motors are becoming more reliable, less expensive and available in larger sizes. The use of these motors is expected to increase over time. If DC brush motors are used in these situations, the motor must be periodically pulled from the well to replace the brushes. AC motors do not have brushes, but they require the use of an inverter to convert the DC power produced by the array.

System Configuration and Sizing

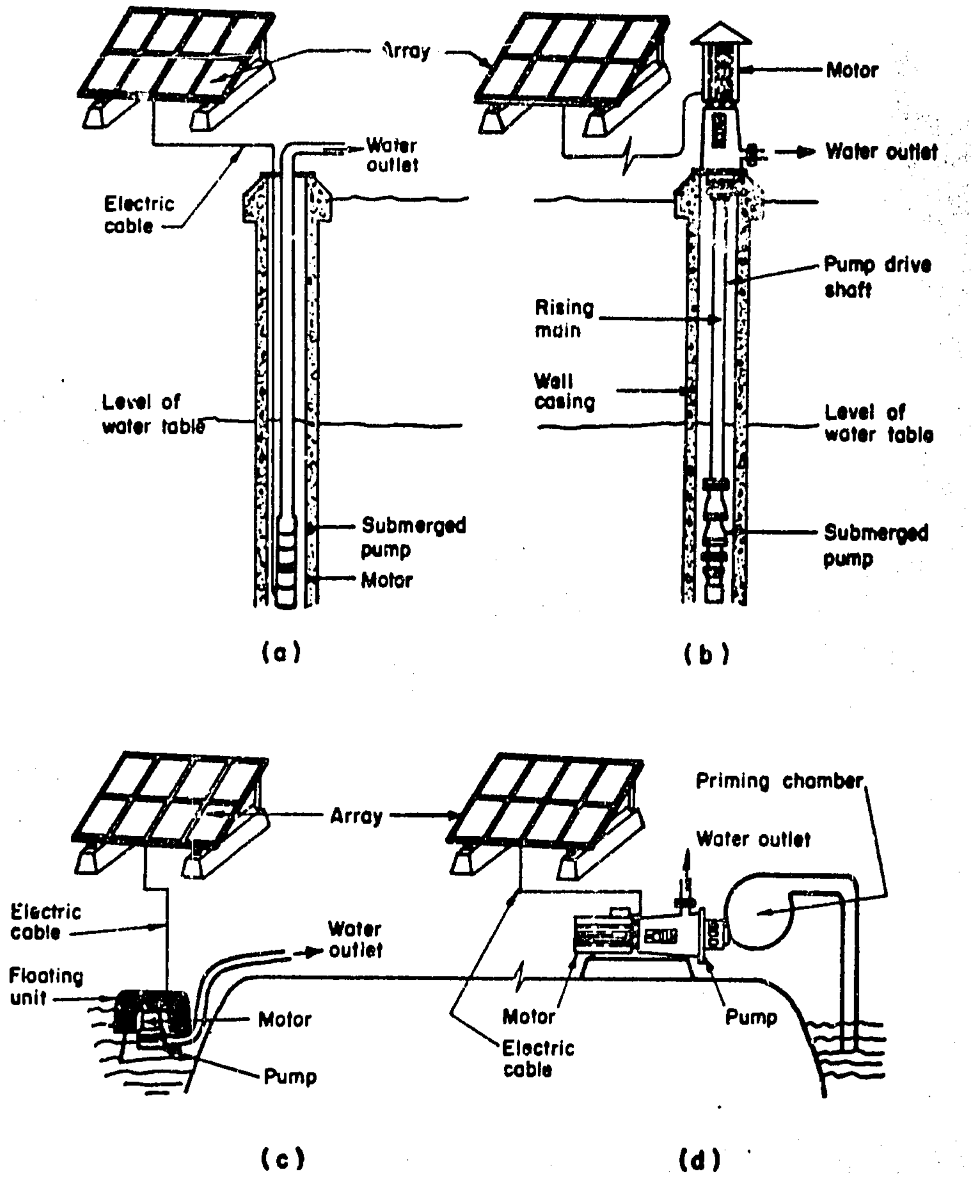
Exhibit 3-2 outlines four basic configurations for PV-powered motor/pump systems. Approximate sizing of a PV-powered pumping system can be determined from Exhibit 3-3. The model from which these graphs were generated is included in Appendix D. Exhibit 3-3 can be used as follows: assuming an average water demand of 50 m^3/day and a head of 25 meters, it can be seen from (a) that the average hydraulic energy demand is 3.4 kWh/day.

A peaking factor of 1.5 times the average hydraulic energy demand is used to size the PV array. This is based on considering the maximum ratio of hydraulic energy demand to insolation to be 1.5 times the average ratio over the year. Based on the average hydraulic energy demand from (a) and an average insolation of 5 kwh/m^2-day, it can be seen from (b) that a PV array size of approximately 2.3 kWp is required.

Operation and Maintenance

Operation and maintenance (O&M) items for PV-powered pumping applications are minimal. Assuming the system is designed for automatic starting (a

EXHIBIT 3-2. Typical Pump/Motor Configurations (Reference 3-1)



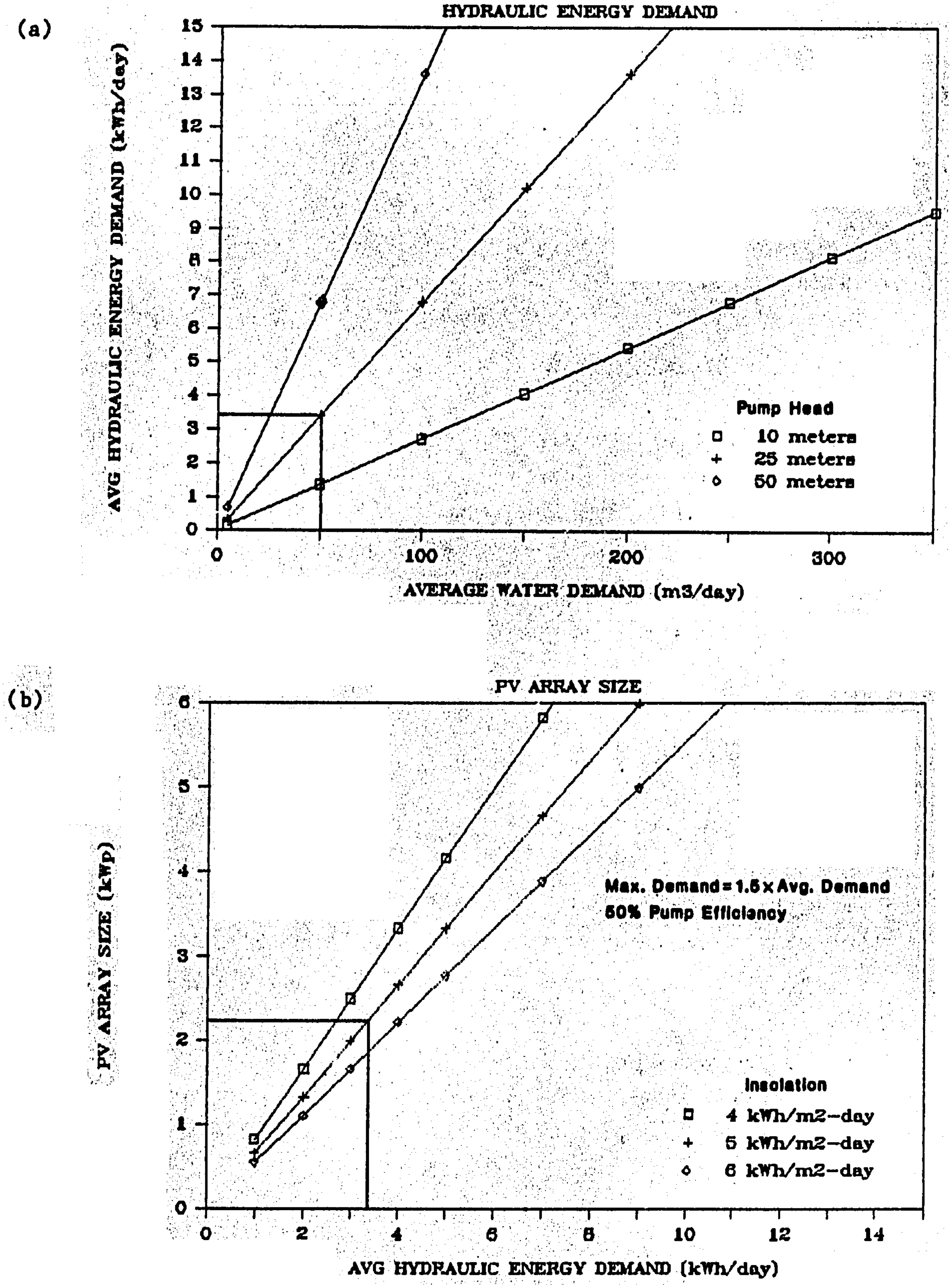
a. Submerged centrifugal pump and motor. Often the pump is multistaged.

b. Submerged pump with surface-mounted motor. Although this figure depicts a centrifugal pump, a positive displacement pump could also be used.

c. Floating pump and motor using a centrifugal pump.

d. Surface-mounted pump with a self-priming tank. Positive displacement pumps have better self-priming characteristics than centrifugal pumps.

EXHIBIT 3-3. Sizing of a PV-Powered Pumping System



common feature), no operator is required. Maintenance is necessary only on the motor/pump set and batteries (if they are provided). Maintenance for the motor/pump set includes such items as the lubrication of parts and brush replacement (if a DC brush motor is used). Batteries are provided only in the case of motors requiring high starting current. If the batteries are sealed, no maintenance is required; if they are vented batteries, regular addition of water is necessary.

The costs of PV-powered pumping systems (both initial and recurring) are presented in Chapter 9.

3.2.2 Conventional-Powered Systems

Traditionally, pumping systems in developing countries have been powered by motorized pump sets, human labor and animals. Comparing PV-powered systems to the use of humans and animals must take into account the value of human time and the "milk and meat loss" associated with using animals for labor. It is not within the scope of this evaluation to address these issues; thus, the comparative analyses focuses on the use of engines to power pumping systems.

System Configuration

There are two basic configurations for engine-powered pumping systems:

- Mechanically coupled: the engine is connected directly to the pump. Mechanical power generated by the engine is used to drive the pump.

- Engine-generator sets: the engine is linked with a generator, forming a "gen-set." The generator converts the mechanical power of the engine into electricity, which feeds into a motor used to drive a pump.

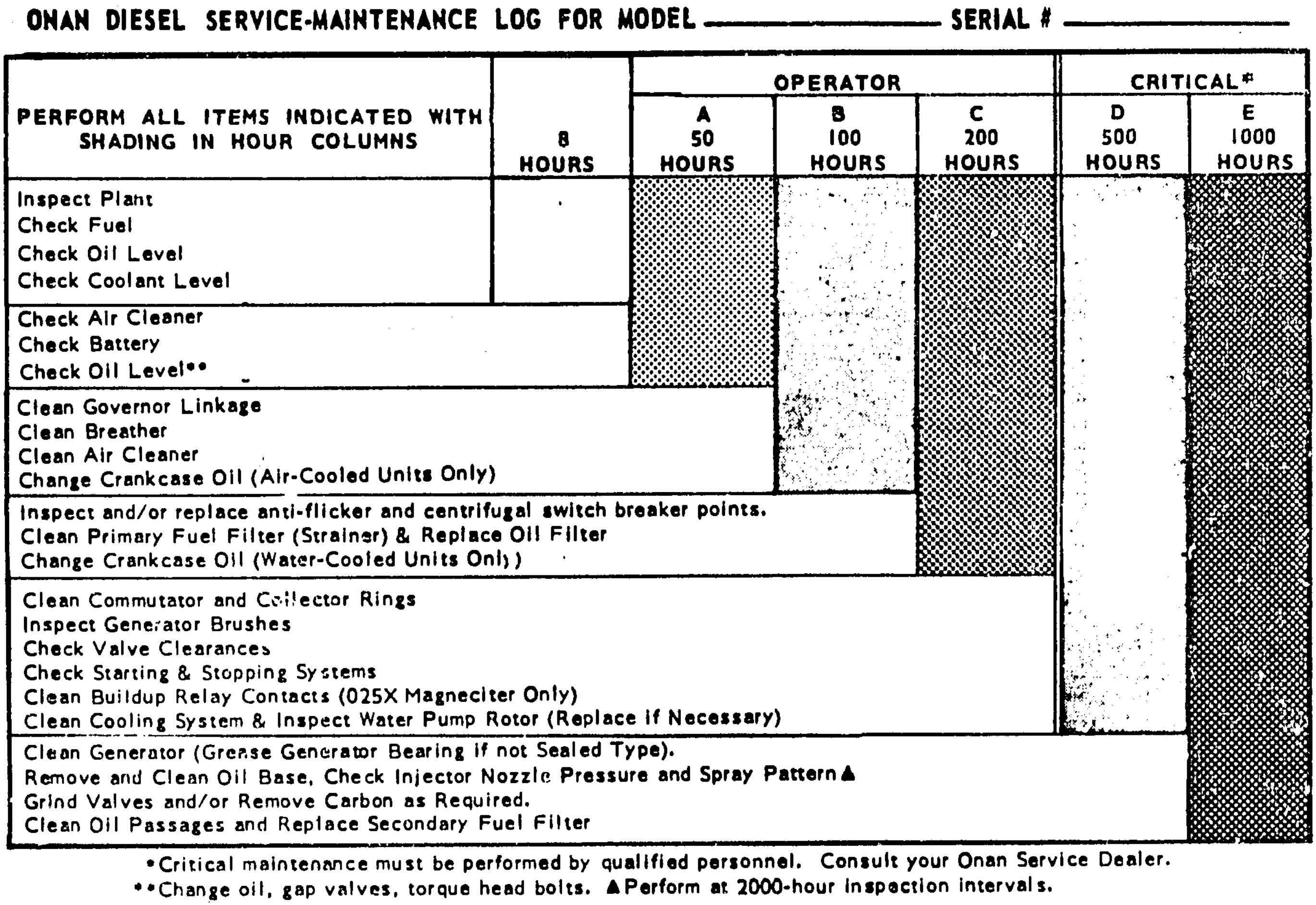
This evaluation concentrates on the gen-set configuration, reported to be commonly encountered in the field (Reference 3-6). The output of a gen-set is AC power, so a typical engine-powered pumping system incorporates both an AC motor and pump.

System Sizing

Exhibit 3-4 provides an example of the sizing of an engine-powered pumping system. The sizing model used to generate these graphs is presented in Appendix D. The graphs are used as follows: using an average water demand of 50 m^3/day and a head of 25 meters it can be seen from (a) that the maximum hydraulic energy demand (HED) is 5 kWh/day. Using this HED value, it can be seen from (b) that the engine size required is 6.4 kW.

A maintenance schedule for diesel engines is outlined in Exhibit 3-5. Similarly to the PV-powered system, motor/pump set maintenance, such as lubrication of parts, is also required. Brush-related maintenance is not a factor in the diesel-powered systems, because AC motors are used. The costs associated with the items required for maintenance and repair are outlined in Chapter 9.

EXHIBIT 3-5. Maintenance Schedule for Diesel Gen-Sets (Reference 3-7)

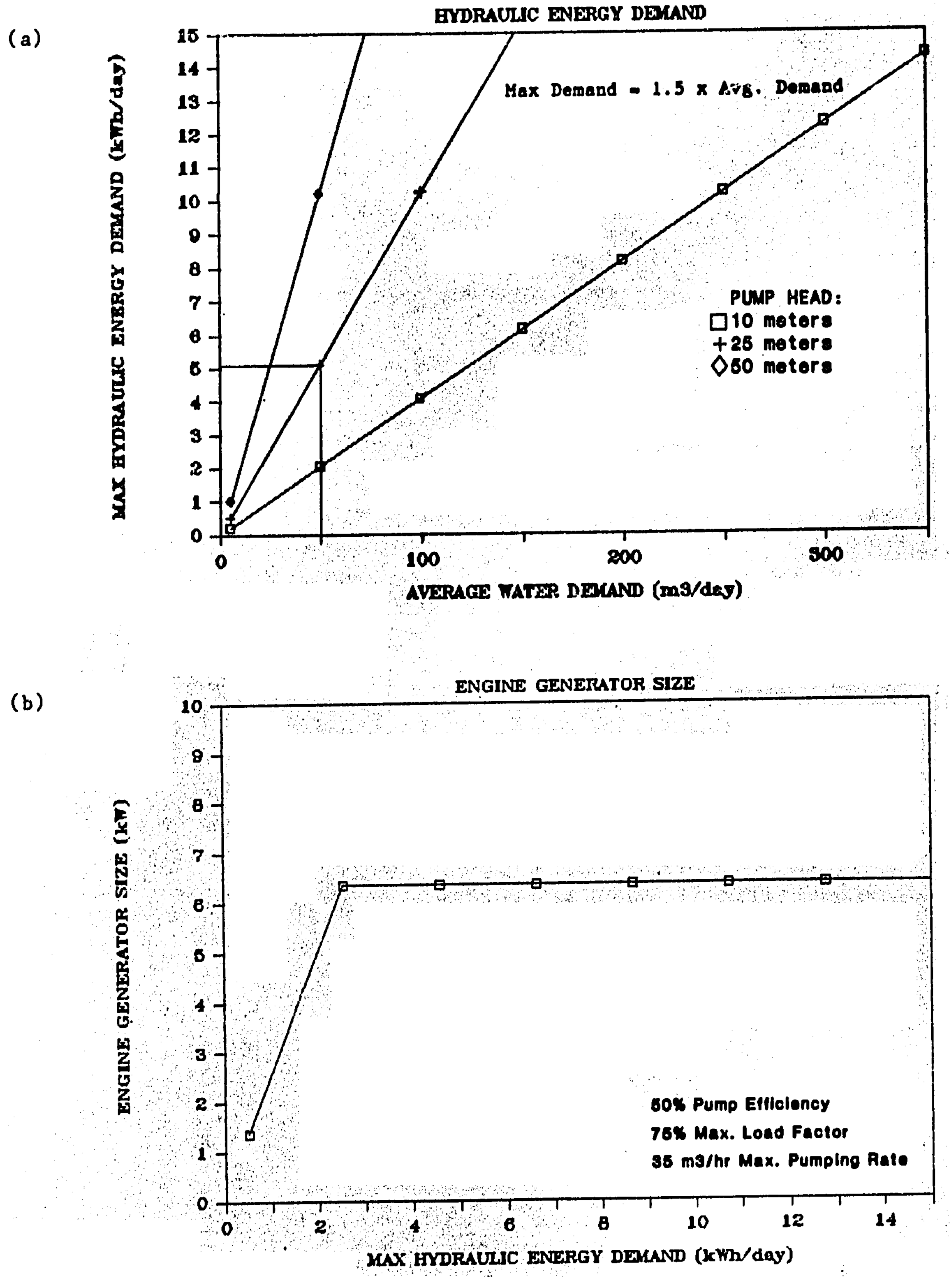


ONAN DIESEL SERVICE-MAINTENANCE LOG FOR MODEL ______________ SERIAL # ______________

PERFORM ALL ITEMS INDICATED WITH SHADING IN HOUR COLUMNS		OPERATOR			CRITICAL*	
	8 HOURS	A 50 HOURS	B 100 HOURS	C 200 HOURS	D 500 HOURS	E 1000 HOURS
Inspect Plant Check Fuel Check Oil Level Check Coolant Level		▨	▨	▨	▨	▨
Check Air Cleaner Check Battery Check Oil Level**		▨	▨	▨	▨	▨
Clean Governor Linkage Clean Breather Clean Air Cleaner Change Crankcase Oil (Air-Cooled Units Only)			▨	▨	▨	▨
Inspect and/or replace anti-flicker and centrifugal switch breaker points. Clean Primary Fuel Filter (Strainer) & Replace Oil Filter Change Crankcase Oil (Water-Cooled Units Only)				▨	▨	▨
Clean Commutator and Collector Rings Inspect Generator Brushes Check Valve Clearances Check Starting & Stopping Systems Clean Buildup Relay Contacts (025X Magneciter Only) Clean Cooling System & Inspect Water Pump Rotor (Replace if Necessary)					▨	▨
Clean Generator (Grease Generator Bearing if not Sealed Type). Remove and Clean Oil Base, Check Injector Nozzle Pressure and Spray Pattern ▲ Grind Valves and/or Remove Carbon as Required. Clean Oil Passages and Replace Secondary Fuel Filter						▨

•Critical maintenance must be performed by qualified personnel. Consult your Onan Service Dealer.
••Change oil, gap valves, torque head bolts. ▲Perform at 2000-hour inspection intervals.

EXHIBIT 3-4. Sizing of Engine Gen-Sets for Water Pumping



3.3 Field Experience

A detailed review of the field experience associated with more than 34 PV-powered pumping systems was conducted for this evaluation. A summary of these water pumping projects is presented in Exhibit 3-6. As part of the evaluation, questionnaires were mailed to over 300 organizations and individuals. Responses from the questionnaires addressed more than 160 pumping systems. Exhibit 3-7 provides a summary of the questionnaire responses. More detailed information on the significant projects and systems referenced in the questionnaires can be found in Appendices A and B.

Many of the PV-powered pumping systems reviewed have performed well in the field. Evaluation of these systems led to the identification of factors common to successful system implementation. These common factors are as follows:

- Reliability and performance of subsystems, particularly, the control electronics and pumps
- Availability and credibility of solar and water resource data
- End-user participation
- Infrastructure to provide technical support and spare parts.

3.3.1 Reliability and Performance of Subsystems

The use of field-proven pumps and simple controls (if any) has been common to most successful systems. Despite the fact that several different types of pumps/motors have been designed for use with PV, these components have been the weakest link of the system. Reduced system performance has commonly occurred with bearings, seals, push rods and packings. These failures have been caused by four major factors:

- Poor quality control of the equipment and/or installation.
- Misapplication of the pump.
- Insufficient well yield. For directly coupled arrays and pumps, the highest draw from a well generally occurs at solar noon. Well capacity must be capable of matching this demand; otherwise, pumps can lose suction, causing the motors to overspeed or overheat.

EXHIBIT 3-6. PV-Powered Water Pumping System Significant Projects

PROJECT TITLE AND LOCATION	APPLICATION	NUMBER AND/OR CAPACITY OF SYSTEMS	COMMENTS	REF # (DATE OF REF.)
Pumping Systems Mali	Centrifugal pumping systems to provide water.	>80 systems	• Most performance difficulties have come from the pumps and electronics. • Data on the peak yield of the well and low-level water controls are important design requirements. • Trained engineers are needed to perform troubleshooting, repair, and maintenance management. • Choice of PV was necessary because of the unavailability of any other fuel.	3-8 (1985) 3-9 (1985) 3-10(1985)
Desert Development Egypt	Systems have provided power for renewable energy/agricultural development work since 1981	2 systems (10 kW, 3 kW)	• Pump failures resulted from mechanical vibrations in the drive shaft of the pump. Additional drive shaft stabilizing bearings were added, and the pump operates with an average of 60% efficiency. • Array has performed reliably. • Battery maintenance must be tended to with unfailing regularity.	3-11 3-12(1985) 3-13(1983) 3-14(1983)
PV versus Diesel for Water Supply Botswana	PV versus diesel pumping field study.	>1 system	• Well peak yields may be a significant limiting factor to the application of PV systems. • Use of existing pumps and wells to capitalize on any equipment infrastructure is another design factor. • A "continuous discounting" life-cycle cost analysis (2% real discount rate, 20-yr life), showed that PV is economically competitive with diesel engine systems at the present time.	3-15(1984) 3-16(1984)
Water Pumping India	PV-powered water pumping system for remote village installed from 1979-1982.	1 system	• Many important socio-economic issues were raised: bureaucratic and administrative problems, the need for integral participation by villagers and the ownership and management of facility and water. • Choice of PV was based on the past experience and technical limits of other water pumping technologies (diesels had high incidence of breakdown and irregular fuel availability). • By consensus, a solar water management committee came into being for the distribution of water. It has managed to satisfy contradictory needs.	3-17(1983)
Mali Aqua Viva Program Mali	PV water pumping systems installed in 1984	30 systems 39 kW total	• Cost of PV pump was six times that of the manual pump, but it yields almost six times the volume of water. • For the size of a 5.2-kW system, PV water pumped from 10 meters depth costs 0.09 \$/m^3 at a rate of 350 m^3/hr. The level of maintenance was not included in the comparison. • For the PV pumping systems, 536 \$/year/pump was the cost of maintenance and operation for 30 pumps. The costs are expected to be able to be reduced to 330 \$/year/pump.	3-18(1985)
UNDP Pump Test	Evaluation performed (1980-1983) on PV-powered water pumps.		• Solar pumping systems for irrigation are beginning to become cost-competitive with diesel pumps in situations where peak daily water requirements are less than about 150 m^4/day and where the minimum monthly average solar irradiation is greater than about 15 MJ/m^2 per day. • Solar pumping systems for rural water supply are becoming cost-competitive with diesel pumps where the average daily water requirements are less than about 250 m^4/day and where the monthly average solar irradiation is greater than 10 MJ/m^2 per day.	3-1 (1983) 3-5 (1984)

EXHIBIT 3-7. Summary of Questionnaire Responses

	Technical			Institutional		Financial
	PV	Controls/Electronics	Pumps	Maintenance and Repair	Management	
Field Questionnaire						
Antigua (CARDI)	• Moisture in modules caused imbalance		• Impeller needed refitting	• Full local participation		
Botswana (BRET)	• PV panels seem reliable	• One controller out of service	• Problems with pump control components		• Potential problems with jurisdiction and responsibility	
Djibouti (ISERST/VITA)	• Good reliability			• Trained technicians available		• Smaller systems are more competitive
Haiti (USAID/CARE)	• Systems extremely reliable			• Installation by local engineers		
Indonesia	• Good reliability			• Conceptual design, installation start-up done by Indonesia personnel • Operation by villagers		• Maintenance cost lower than conventional technologies • High capital cost
Mali (LESO)	• No problems with solar panels		• Problems with pump bearings	• Trained technicians available	• Problem with transport and access to remote sites	
Senegal (CERER)	• Array is very reliable	• Maximum power controller and inverter are less reliable	• One pump is not working	• Maintenance & repair company available • Sufficient training lacking	• Problems often administrative and logistical	
Thailand (NEA)	• Works very well		• Only a carbon brush pole replaced	• Almost all activities performed by in-country personnel		• No operating costs • PV system cost is greater than diesel pump cost by more than 30%
Yemen Arab Republic	• Performed exceedingly well			• No breakdowns or technical difficulties • Only maintenance is bi-weekly cleaning of panels • Government does not have technical, commercial, nor conceptual background to maintain PV systems		
Zimbabwe (Ministry of Energy)	• No problem with PV array					• Competitive with diesel systems (4-year payback)
Project Questionnaire						
A.Y. McDonald	• Maintenance-free PV modules		• Surface centrifugal pumps are most reliable • Moving parts are minimal and accessible	• Minimal technical expertise required		
Associates in Rural Development[1]	• No problems with modules • Occasional vandalism	• One controller initially undersized • Problems with pump controllers	• One motor replaced because of calcium deposits • Pump output less than predicted	• No components locally repairable • No local technical expertise		• No systems locally financed
GRUNDFOS	• Operating performance very good	• Inverters used are 100% OK • One inverter failed when user applied excessive voltage				
Kyocera	• Performance and reliability of PV modules is excellent			• Installation material not thoroughly read • Modules are not cleaned regularly		• High initial cost
Solar Electric Int'l	• J-Boxes became detached • Performance of all modules is excellent	• At first, frequent system/electronic failures in MPC's due to dampness	• No mechanical difficulties • Few moving parts • Low level maintenance • Early pumps had no over-temperature or over-speed cutouts; failures due to clogged impellers and dry wells resulted	• No operational repair capability • Special training program available • Installation and operation no problem with instruction manual • Repairs easily made, even in the field	• Problems with good servicing and spare parts • Spare pumps/modules available in Nairobi/Malta	
Solar Voltaics	• No problems with PV array			• Local participation in system installation and start-up		
Solec International	• PV module reliability excellent			• Technical support by distributors		

1. Comments are relative to same systems as referenced in Botswana (BRET) response.

Thus, accurate and PV-specific well-yield tests should be performed in situations where systems are designed to operate near well peak-yield rates. While protection options for low water yields have not been offered as a standard part of pumping systems, they should be considered when site preparations are performed.

- Motor overloading. This condition is caused by sediments or other restrictions that increase the load on the motor. It results in broken components, overheating and motor burnout. Increasingly, manufacturers are providing overload and high-temperature protection on pump motors.

Actual pump performance has often not met manufacturers' claims. According to recent experience in Mali and Botswana (References 3-8, 3-19), performance has been 10 to 20 percent below pump curves provided by the manufacturers in some instances. Such findings are not unique to pumps used in PV-powered systems; they also typify field performance of pumps powered by conventional power sources. These findings may indicate that relative adjustments in pump size are required in order to achieve necessary field performance. However, pump field performance data must be carefully evaluated because it is difficult to duplicate manufacturer performance rating tests under field conditions.

Another factor common to successful PV systems is the simplicity of controls. Low-head centrifugal pumps that are directly connected to the array have performed well. Comments have been made about the sophistication of power conditioning electronics used with jack pumps to match the array to the motor. According to one particular source (Reference 3-9), current maximum power devices represent too high a reliability risk and are too costly to warrant wide usage. However, another investigation (Reference 3-15) showed that a maximum power point tracker (typically used with jack pumps) is financially justified on a life-cycle cost basis.

3.3.2 Solar and Water Resource Character

The performance of a PV-powered pumping system depends heavily on the character of the solar and water resources. The relation between solar insolation, the dynamic and static water levels of the well, and the water demand determines the cost and production of a pumping system.

Array sizing is a function of credible solar data. It represents a key factor in the viability of PV pumping systems. Erroneous estimates of insolation have resulted in underpowered or overpowered systems, causing some systems to fail to meet water demand or to be excessively (and unnecessarily) costly.

Predicting the performance of a PV-powered pumping system and evaluating manufacturers' claims are difficult tasks. Performance claims are best evaluated against actual country-specific operating data. An example of where this has been done is in Mali, where a considerable amount of PV-powered pumping performance data have been collected and now serve as a performance data base to specify and evaluate systems.

3.3.3 User Participation and Expectations

The involvement of the end-user has proven to be an important factor in the maintenance, troubleshooting, and water management of PV-powered water pumping systems. Feelings of ownership and responsibility are key to successful systems. "Experience shows that the more the local community can be involved in the installation and running of a system, the more committed it is likely to become to the project's success (Reference 3-20)."

The user's expectations are also a key factor in the success or failure of a system. For example, the use of drip irrigation versus flood irrigation requires the user to adjust to both new irrigation methods and a new technology. The distinction between the two types of irrigation is often not understood by the user (the fact that water is dripping and not flooding is perceived as a failure of the PV system, not as an alternate irrigation method). The effective management of PV energy requires the user to understand the limits of its supply. The use of pumped water for irrigation or village water supply is a socio-political issue for any installation.

3.3.4 Management and Communications Infrastructure

The ownership and organization of a new facility requires cooperation, especially in communities with little history of "managing communal projects....

Sufficient time should be allowed to work out a scheme that will assist the community to deal with issues of implementation and management (Reference 3-20)."

Management of technical support and spare parts is the predominant factor for successful, continued operation of remote power systems. PV-powered pumping systems experience the same infrastructure problems as other remote power technologies. However, under an equally poor infrastructure, PV-powered systems are likely to be more reliable than conventional systems because of the small amount of maintenance required and the reliability of PV-powered arrays (Reference 3-21).

Communications from the system site to technical support personnel are crucial. In some cases, incorrect, inadequate or unresponsive technical support caused by poor communication between system suppliers and the user or field technicians has resulted in significant downtimes.

CHAPTER 4

COMMUNICATIONS

4.1 Overview

PV-powered communications systems have a proven commercial record of technical and financial success throughout the world. The total number of new PV-powered communications installations worldwide is now approaching 10,000 per year (Reference 4-1). Their applications range from relatively large telecommunications systems (operated by governments or private companies) to small (one-module, one-battery) radio systems used in health care communications networks. Typical applications are outlined in Exhibit 4-1.

EXHIBIT 4-1. Typical Telecommunications Applications (Reference 4-2)

EQUIPMENT TYPE	TYPICAL APPLICATION
VHF/UHF Microwave Repeaters	High-capacity radio over 50 MHz for TV/phones
Radiophones VHF/UHF	Single-channel radio with PABX interface
Cablephones	PV powers subscriber unit in mountains
HF Radio	Inexpensive low-quality rural radio
TV Translators	Redirect TV broadcasts into valley areas
Fiber-Optic Cable System	Data transmission
Mobile Radio VHF/UHF	Personal, vehicle or cellular radio

While this chapter addresses the full-range of communications applications, Chapter 10 (communications financial analysis) concentrates on the larger loads. It is assumed that small loads (e.g., high-frequency radios, televisions, etc.) would be incorporated as part of a home power or multi-use system.

Traditionally, communications systems in developing countries have been powered by grid electricity, stand-alone generators (e.g., diesel and gasoline engines) or primary batteries. These systems have been plagued by

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unreliable fuel/parts supply, poor quality power and/or high costs. These factors have severely impacted the performance and expansion of telecommunications networks and restricted the implementation of small systems.

As a result of advancements in electronics and in the design of transmission systems, power requirements for telecommunications equipment have decreased significantly over the years. A system that may have consumed 500 continuous watts in 1970, today requires less than 100 watts (Reference 4-2). However, at the same time, networks are requiring more capacity to meet expanding demands.

This evaluation reviewed information on over 1100 PV-powered communications systems in more than a dozen countries to determine the key factors affecting system performance. Designs of successful systems have incorporated reliable charge controllers as well as field-proven radio equipment. Because of the simplicity and reliability of small systems, there are no technical barriers to their implementation. Larger, more complex systems are generally handled by telecommunications organizations, which have extensive experience in power electronics. The reliability of these larger systems has also been high.

4.2 Current Designs

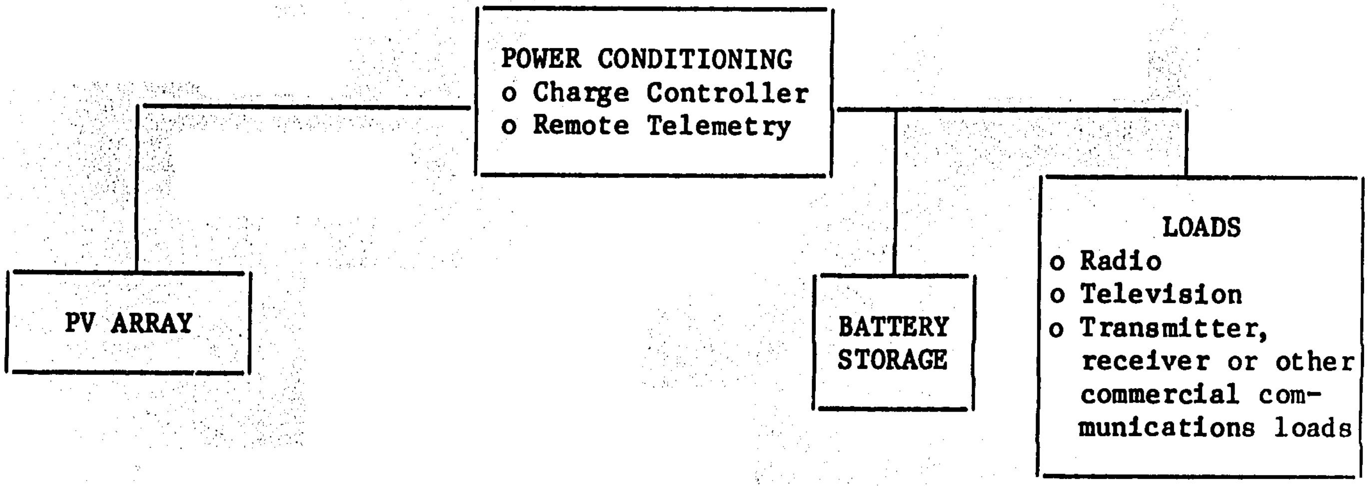
In most communications systems, one cannot afford to have the system fail. Reliability is critical due to the difficulty and cost involved in frequenting the site and/or the intangible costs of not having a communications link Therefore, most systems are designed for high reliability, often incorporating redundant components. The following sections describe the basic configurations of PV- and conventional-powered communications systems.

4.2.1 PV-Powered Systems

Photovoltaic-powered communications systems have been regarded as a viable alternative to conventional systems. A typical example is Guyana where some repeater stations have both grid and diesel power, but the poor quality of the grid and the unreliable supply of diesel fuel have resulted in the decision to use PV (Reference 4-3).

A photovoltaic power system for communications applications operates as a simple battery charging system (Exhibit 4-2). The basic components are the PV array, battery storage and power conditioning. The power conditioning may vary from a simple voltage regulator (as in some single-module, small-load systems) to controls that optimize system performance. The more complex systems may also include remote telemetry, allowing for control and monitoring from a distance.

EXHIBIT 4-2. Basic PV-Powered Communications System



Some telecommunications systems are hybrids of PV, diesel, battery and/or wind technologies. The technical advantages of hybrid systems are the ability to reduce array and battery capacity and to operate equipment at optimal loading (e.g., running a diesel infrequently but at full load). Hybrid designs reduce both maintenance and fuel requirements. The relative sizes of the PV array, battery storage and diesel depend on the cost of the PV, batteries and fuel and on the character of the loads. Hybrid systems were not within the scope of this evaluation and, therefore, will not be discussed in further detail.

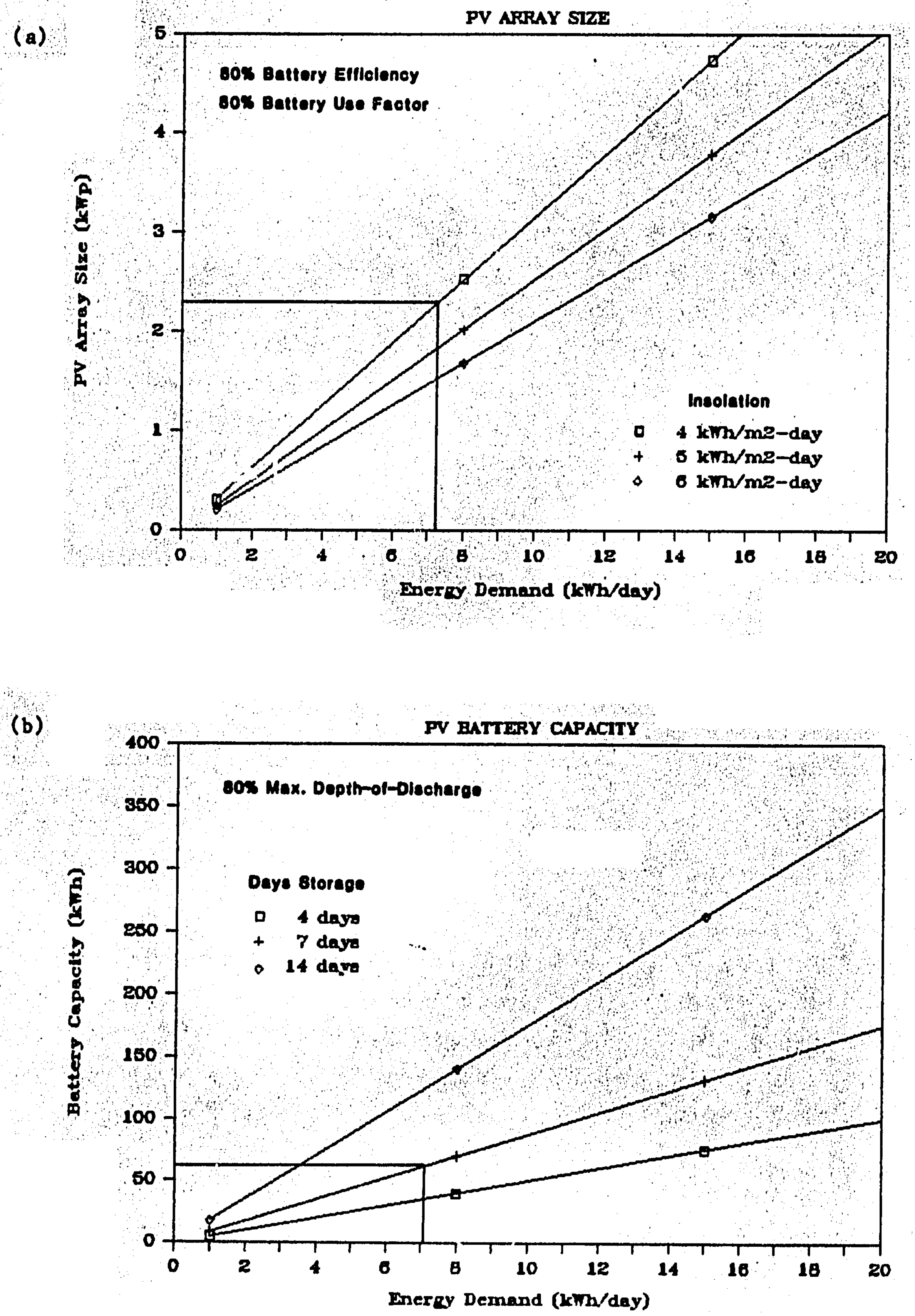
In order to perform a comparative cost analysis, a system size must be obtained. Exhibit 4-3 can be used to determine PV array size and required battery storage capacity, given a certain load and insolation. The choice of load and insolation should be such that the ratio of these parameters is the maximum experienced over the year. Assuming a constant load of 7.2 kWh/day and a lowest month daily insolation of 4 kWh/m^2-day, it can be seen from (a) that a 2.3-kWp PV array is needed. Using the same energy demand and 7 days of battery storage, it can be seen from (b) that 63 kWh of battery capacity is needed. The model used to construct these graphs can be found in Appendix D.

Because most remote PV-powered communications systems are designed to be unattended, they are designed for minimal maintenance and repair. This requirement often leads to the use of sealed batteries (to eliminate the periodic addition of water and to increase safety). If vented batteries are used, maintenance includes checking and adjusting battery electrolyte level. The costs associated with maintenance activities are provided in Chapter 10.

4.2.2 Conventional-Powered Systems

Grid electricity is the principal power source used for telecommunications applications. However, diesel generator systems have been used in remote locations of developing countries with loads of more than 200 continuous watts. In some situations, two and sometimes three diesels are run in tandem. For the smaller size range, diesel engines, gasoline engines, primary batteries, thermoelectric generators, and closed-cycle vapor turbines have been considered (Reference 4-2).

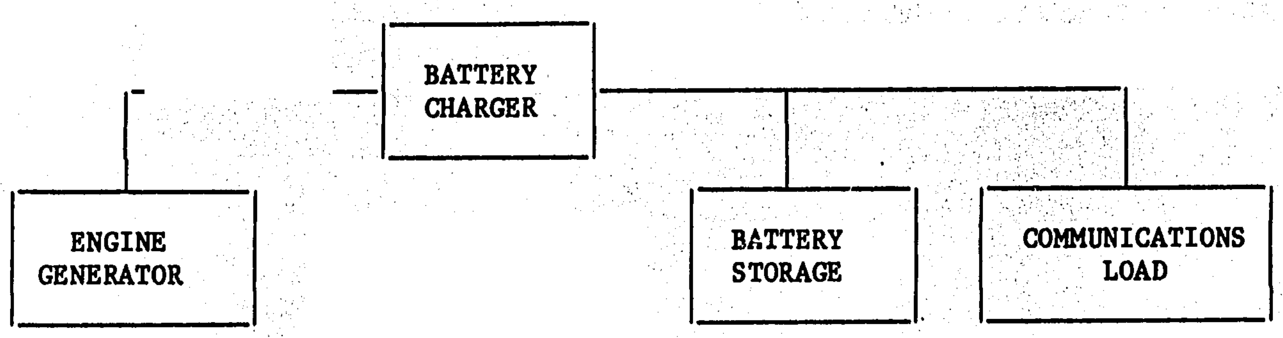
EXHIBIT 4-3. Sizing of PV-Powered Communications Systems



Comparative analyses (Chapter 10) focus on the diesel generators because diesels are used over a broad load range; however, it is important to point out a few considerations regarding the other technologies. Primary batteries cannot be recharged, so regular replacement is necessary. The associated costs of replacement can be significant especially at remote sites accessible only by helicopter. The use of thermoelectric generators and closed-cycle vapor turbines is hampered by the fact that the necessary bottled gas is often difficult to transport to the system site.

The basic configuration of an engine-powered generator is outlined in Exhibit 4-4. Battery storage is included for use during short periods of generator downtime. The engine can recharge the batteries when they are at a low state-of-charge through the use of a battery charger. A battery charger is basically a charge controller and rectifier that allows AC produced by the generator to charge the batteries, which require DC. Systems with two or three engines sometimes use redundant battery chargers and battery banks, depending on the required reliability.

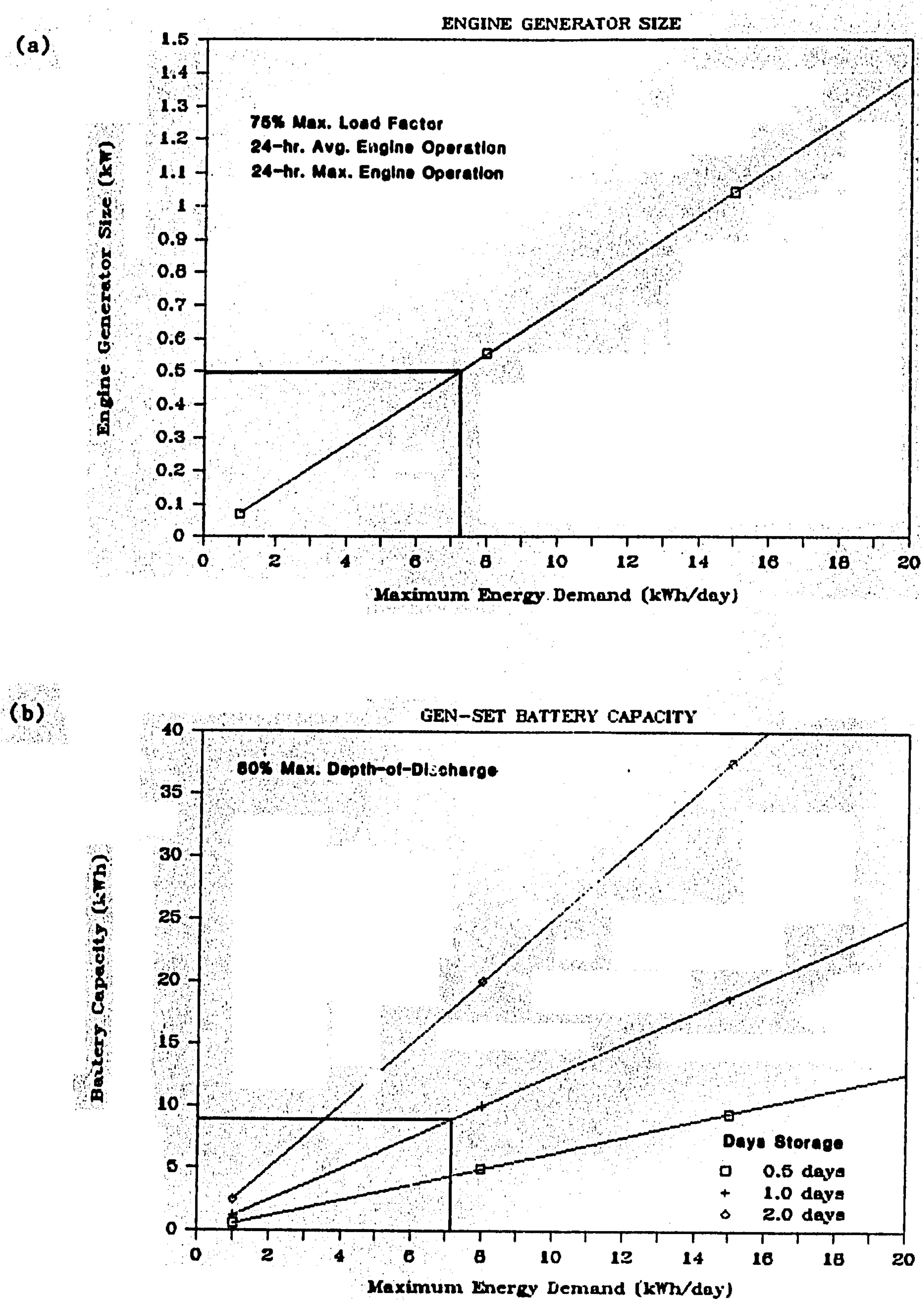
EXHIBIT 4-4. Basic Configuration of an Engine-Powered Communications System



The sizing of an engine generator system based on the maximum energy demand is shown in Exhibit 4-5. Assuming a maximum energy demand of 7.2 kWh/m^2-day, it can be seen from (a) that a 0.5-kW engine generator is needed. From (b), it can be seen that for the same energy demand and 1 day of storage, a battery bank of 9 kWh is needed.

The smallest diesel generators available off-the-shelf today are rated at about 3 kW. Thus, for the example given above illustrating the use of Exhibit 4-5, although a 0.5-kW generator is required, it would be necessary to use a 3-kW diesel

EXHIBIT 4-5. Sizing of an Engine Generator System for Communications



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because that is the smallest size available. These generators are large for typical telecommunications systems; however, because they are all that are available, they are being used in these mismatched applications. "Due to the light loads involved, high maintenance and operating costs become the rule rather than the exception (Reference 4-2)."

For systems that require the use of tandem generators (for reliability purposes), each gen-set must be capable of meeting the maximum energy demand. Thus, in the sizing example provided on page 4-6, two 0.5-kW gen-sets would be needed for a tandem system.

Diesel and gasoline engines require a constant supply of fuel and spare parts. The costs of these items are very site- and country-specific. Batteries in these systems are frequently discharged due to engine downtime resulting from unreliable fuel supply and/or equipment failure/maintenance. This frequent discharging significantly decreases the lifetime of the batteries. This is not a problem with PV-powered systems since they are designed specifically to charge the batteries, and thus have protection measures against overdischarge. The operation and maintenance schedule for diesel gen-sets used in communications applications is the same as that outlined for pumping systems (Exhibit 3-6).

4.3 Field Experience

Key factors impacting system implementation were identified based on the review of past projects. In total, the experience associated with more than 1,100 systems was examined. The experience associated with significant projects is summarized in Exhibit 4-6. More specific information regarding these projects can be found in Appendix B. The experience associated with other systems, as ascertained through the questionnaire responses, is summarized in Exhibit 4-7. Additional information on the questionnaire responses can be found in Appendix A.

In general, the performance of remote PV-powered communications systems, as compared to other remote technologies, has been found to be reliable and cost effective. While there have been failures of voltage regulators, charge controllers, other control electronics and radios, the failure rate of these components is not significant. Successful PV-powered communications system designs have taken the following into account:

- Charge controller reliability
- Radio equipment durability
- Battery life.

4.3.1 Charge Controller Reliability

The selection of reliable charge controllers is critical to successful system implementation. While early systems experienced performance difficulties resulting from environmental conditions, the fourth and fifth generation equipment currently being placed in the field has been much less susceptible to failure. Because the charge controller is usually a small percentage of the system capital cost, but potentially a high maintenance item, purchasers of successful systems have been willing to pay a higher price for reliable, field-proven equipment. Commercial communications companies have been particularly successful in implementing PV-powered systems, due to purchasers' familiarity with electronic equipment.

EXHIBIT 4-6. Communications Systems Significant Projects

PROJECT TITLE /LOCATION	APPLICATION	NUMBER AND/OR CAPACITY OF SYSTEMS	COMMENTS	REF. # (DATE OF REF.)
Microwave Telecommunications Papua New Guinea (PNG)	PV-powered repeater system installed in 1976.	one 234-W system	• Traditionally, repeaters in PNG have been powered by primary batteries. • PV system functions well. • Maintenance was nonexistent. • No institutional difficulties. • Cost analysis shows 1-1/2 to 2 year payback versus primary batteries. • Six more telecommunication routes were to have been installed by 1981.	4-4 (1978)
PV-Powered Televisions Niger	Educational tool.	>1000 sets	• PV technology was chosen because of its compatibility with rural village conditions. • The systems have been successful • The program is continually expanding.	4-5 (1985)
Telecommunications Relay Gabon	Pilot PV-powered relay system, installed in 1981, replacing a kerosene or gasoline generator.	one 650-watt system	• In 1982, conclusion was that this power level represents upper limit of use in isolated villages. • The costs of the PV system were 2 times that of a comparable thermogenerator. • System has run satisfactorily since its installation.	4-5 (1985)
PV-Powered Medical System Radios Guyana, Kenya	Two-way radios installed as part of the NASA-Lewis medical systems	three 1.5-kW systems (radios represent a small portion of load)	• Radios in Guyana performed without difficulty across distances of more than 200 km. • Radio frequencies in Kenya systems (50 km apart) not matched to each other. Kenya radios were sent to Nairobi for corrections, but transmission improved only slightly. • Conclusion about problems with the Kenya radios was that interference from terrain and other local transmissions were at fault.	4-6 (1983)
Health Care Communications Africa and Guyana	Two-way radio communications for medical programs.		• Common power source for 2-way radios is a car battery charged by a small diesel generator. • Costs and logistics of transporting fuel for a conventional system can be the highest cost of a radio system. • PV systems require little maintenance until it is necessary to replace components. • Field tests have not revealed major problems with PV, but it is too early for a definitive statement.	4-7 (1980)
Telecommunications Systems Australia (Although not a developing country, its experience with remote communications systems is relevant)	PV-powered repeaters installed since the 1970s.	75 to 100 systems of up to 2000 W_p each (300-W continuous load)	• No system failures among the major systems in over 10 years. • PV proven reliable and cost-effective for loads up to 300 watts continuous. • For systems with loads greater than 300 W, they plan to use hybrid systems of PV and wind or diesel.	4-8 (1985)

EXHIBIT 4-7. Summary of Questionnaire Responses

	TECHNICAL			INSTITUTIONAL		FINANCIAL
	PV	CONTROL/ELECTRONICS	BATTERIES	OPERATIONAL/MAINTENANCE & REPAIR	MANAGEMENT	COST
Belize (Robert Nicolait & Assoc.)	• Reliability exceptionally good			• Isolated instances of deterioration of steel mounting equipment		• PV is viable—present equipment for communication and transportation systems are inadequate and outdated
Djibouti (ISERST/VITA)	• PV is well suited for communication field					• PVs are least-cost energy source for remote communications applications • Government budget can't afford PV systems because of high cost
Dominican Republic (CODETEL)	• 100% reliability—No service interruption since installation			• Very low maintenance cost		• PV is currently viable only where commercial power is not available • Initial installation cost extremely high
Dominican Republic (Direccion General de Telecomns.)	• 100% excellent performance	• Only problems detected were at block circuit relay				
Lesotho (ATS)	• Systems are very reliable		• Good PV potential to charge batteries, as throw-away dry cells are bought in large quantities in Lesotho	• Performance is good		• PV systems are cost effective in remote areas for low-power applications
Lesotho (Swedish Telecomms. Int'l)	• Excellent reliability • Vandelism damage(rocks) • With full moon and cloudless sky the array powers the 2x2 way repeater			• Japanese engineer will assist and train during first yr. Local staff to operate and maintain system		• For low-load telecom. purposes PV is cheaper on per watt basis compared to diesel generators in both investment maintenance and fuel costs
ARCO Solar, Inc. (G. Zahnstecher)	• PV power supply is very reliable • Quality and reliability of AC power was poor; now it is very good	• Balance of system components are much improved now (controllers, inverters batteries), and the latest inverters and controllers should be used	• With new sealed batteries, minimal maintenance is required	• Few operating difficulties • In Chile, site visits were cut from monthly to twice yearly		• Intial cost is high
Solarex Pty. Ltd.	• PV systems are very reliable	• Faulty installation and wire sizing • Defective regulator • Regulator failure after lightning strike • Typhoon damaged antenna		• Regulator repair is troublesome in remote areas—technical expertise is not available	• Delays in procurement of replacements	
United Nations	• Reliability has been good					

4.3.2 Radio Equipment Durability

Like power electronics, radios and other load equipment must be capable of operating under site-specific environmental conditions. While the durability of load equipment for PV-powered telecommunications applications is no different from that for conventional-powered systems, attention must be given to selecting field-proven components.

4.3.3 Battery Life

Batteries are a major cost in PV-powered telecommunications systems. In systems where reliability is critical, as is the case in most telecommunications applications, the technical performance of the batteries is crucial to system success. Because batteries are the only component requiring maintenance, user awareness of the state-of-charge and electrolyte level is important to ensure maximum battery life and reliability. The use of low-maintenance (e.g., sealed) and deep-discharge batteries is encouraged.

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CHAPTER 5

VACCINE REFRIGERATION

5.1 Overview

Refrigeration is a vital component of health care in the developing world. It is needed for storing vaccines and freezing ice packs in hospitals and health centers.

> The need for solar refrigerators is greatest at peripheral health centres serving populations of 20,000 to 100,000 with about 150 live births per month on the average. The volume of packed vaccine needed to fully immunize 150 infants and their mothers is approximately 4 litres (Reference 5-1).

These refrigerators serve as the final link in the Cold Chain, which is identified as the transport and storage of vaccines from the time and place of manufacture to several months later actually vaccinating someone thousands of miles away.

Generally, there is no electricity in the rural areas where these hospitals and health centers are located, or, at best, fuel and power supplies are erratic and unreliable. It has been claimed that photovoltaic-powered refrigerators offer better performance, lower operating costs, better reliability and longer working life than those fueled by kerosene or bottled gas. In the past 7 years, the U.S. Agency for International Development (USAID), the World Health Organization (WHO), the Centers for Disease Control (CDC) and other government and health agencies have sponsored PV-powered refrigeration projects in order to analyze these claims. To date, approximately 600-800 PV-powered refrigeration systems have been installed around the world (Reference 5-2).

A review of significant PV-powered refrigeration projects, representing more than 105 installations in 43 countries, was performed for this evaluation. Early system reliability averaged approximately 80 to 85 percent (Reference 5-2). Systems recently installed were found to be more reliable (95 to 99%), particularly those from suppliers with previous experience (Reference 5-2). The successful performance of such systems was shown to depend on the use of proven equipment suitably matched to the location and, more importantly, to the end-user's understanding of the operation (i.e., proper loading) of the system.

5.2 Current Designs

There are two main types of refrigerators: compression and absorption. These refrigerators produce a cooling effect as a result of heat being absorbed by a liquid (the refrigerant) as it evaporates. The two refrigerator types differ in the way they condense the refrigerant gas after the evaporation process.

Electrically-driven refrigerators use a vapor compression cycle to mechanically compress the refrigerant gas, thereby raising its temperature. As it cools back to ambient temperature, the gas condenses.

With vapor absorption refrigerators, the refrigerant is absorbed by a liquid (or sometimes a solid) called the absorbent. The refrigerant is eventually boiled off the absorbent (and subsequently condensed) using heat produced by a generator. The generator produces heat through the burning of kerosene or propane or the use of an electrical heater. There is also a solar-powered refrigerator that uses heat generated by the sun.

A wide range of refrigerator sizes are available, from 3.6 to 200 liters. While WHO states that only about 4 liters of packed vaccines are needed per month in villages with approximately 150 births per month, there are other biologicals that health centers need to store (Reference 5-1). Thus, the optimum refrigerator size is still somewhat under debate.

It is important that the system be capable of freezing ice packs. These are used in transporting vaccines from the health center to the field for immunization. This requirement represents a significant load on the system.

5.2.1 PV-Powered Systems

PV-powered refrigeration systems consist of a PV array, a charge controller, batteries and a refrigerator unit. Exhibit 5-1 shows a schematic of a typical system. Exhibit 5-2 is a cut-away diagram of a vaccine refrigeration unit used in PV applications. Currently, the only type of PV-powered refrigerator commercially available and suitable for vaccine storage is a compression refrigerator.

EXHIBIT 5-1. Schematic of a PV-Powered Refrigeration System

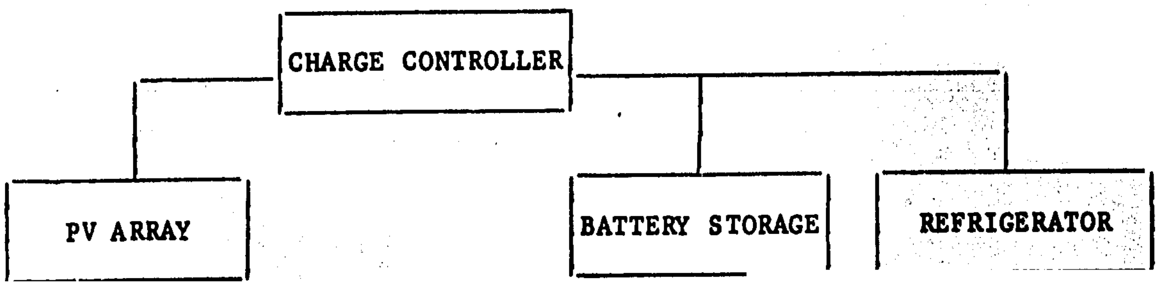
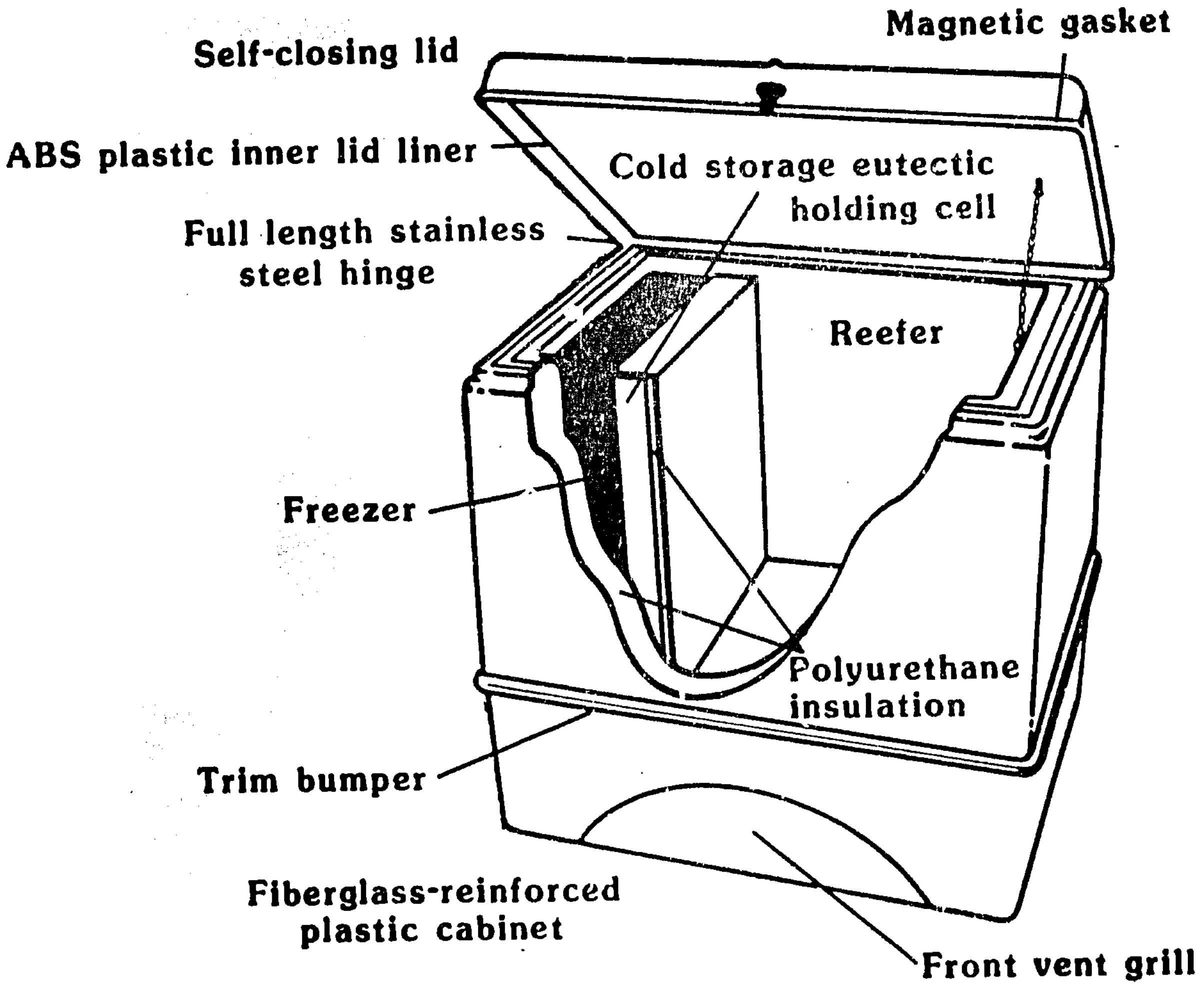


EXHIBIT 5-2. Vaccine Refrigerator Used in PV Applications



The WHO Expanded Program on Immunization (EPI) issues technical specifications for Cold Chain equipment and subsequently tests equipment that is submitted to it. Based on test results, EPI regularly publishes product information sheets. An example of one of the product information sheets is presented in Exhibit 5-3. Inclusion of a product in these sheets means that based on the information and experience available to EPI, the product is considered suitable for the Cold Chain. Institutional purchasers generally select equipment from these product information sheets. PV-powered refrigeration systems considered by EPI to be suitable for the Cold Chain must meet the specifications outlined in Exhibit 5-4.

The 1985 edition of the product information sheets (Reference 5-3) includes the PV-powered refrigerators and suppliers listed in Exhibit 5-5. The suppliers offer complete packaged systems. Two of the suppliers (Solarex and Solavolt) offer the choice of two refrigerator models. Until others have passed the specifications outlined in Exhibit 5-3, WHO recommends only those systems and suppliers listed in Exhibit 5-5 for vaccine storage.

There are many other 12-volt DC-powered refrigerators available and in use. However, these systems, although easily adaptable to PV, have been used only for recreational purposes and are not suitable for vaccine storage due to internal temperature variations. A summary of the characteristics of PV-powered refrigeration systems accepted by WHO is given in Exhibit 5-6. In an effort to identify additional systems that meet its refrigeration criteria, WHO is continuing refrigerator testing in Colombia.

The reliability of PV-powered refrigeration systems has improved with increased field experience. Reliability can be quantified in terms of availability, where the availability is defined as the percentage of time that the refrigerator operates within technical specifications. Early installations had an availability of 80 to 85%, while recent installations have been 95 to 99% available (Reference 5-2). In terms of vaccine refrigeration, availability is critical. Not operating within technical specifications means the temperature is not maintained within the proper range, which results in the loss of vaccines.

EXHIBIT 5-3. Example of a WHO EPI Product Information Sheet (Reference 5-3)

UNIPAC/

DESCRIPTION **P.I.S 83/08**

Photovoltaic solar system
Refrigerator & freezer solar system

COMPANY NAME & ADDRESS

SOLAREX

1335 Piccard Drive
Rockville
MD 20850

USA

Tel/Tex: 301 948 0202 / 248369 solx ur

SIZE **Refrigerator:** **Freezer:**

Manufacturers gross volume.	93	Lts	Manufacturers gross volume.	18	Lts
Vaccine storage capacity...	80	Lts	Vaccine storage capacity...	10	Lts

External dimensions of refrigerator/freezer...HxWxL... 91 x 82 x 67 Cm

PERFORMANCE at................32degC....43degC

		32degC		43degC	
Icepack freezing, kgs. per /No. hours..........		2.1/24	Kgs/hr	2.1/24	Kgs/hr
Internal refrigerator temperatures,	minimum....	5	DegC	-2	DegC
	maximum....	8	DegC	8	DegC
Holdover time during power cut..................		20	Hours	16	Hours
Power consumption per 24 hours.....	electricity.	0.53	Kwh	0.93	Kwh
(with icepack freezing)	kerosene....	NA	Litres	NA	Litres
	LP gas......	NA	Kgs	NA	Kgs

Minimum C and Maximum C recorded during day/night (43/15C) tests

SYSTEM COMPONENTS

	A	B		MODEL
Refrigerator/freezer.........	1	1	Qty	Marvel RTD 4
Photovoltaic panels..........	5	4	Qty	Solarex model SX-42 @ 44Wp
Battery systems..............	8	5	Qty	GNB Absolyte 1260 @ 60Ah
Power regulator..............	1	1	Qty	Included with 4 RTD
Array cable..................	20	20	m	#6 AWG, 2 cond.type S20
No. shipping packages........	3	3		
Overall volume...............	1.4	1.1	m3	
Overall weight...............	305	235	Kgs	
Accessories..................				

COMPLETE SYSTEM PRICES $US **Qty: 1-9 10-99 100+**

	1-9	10-99	100+
System A : Areas receiving 3.5-4.7 Kwh/m2/day 8 days no-sun security........................	5507	4782	4292
System B : Areas receiving 5.8-7.0 Kwh/m2/day 5 days no-sun security........................	4781	4115	3674

Both systems normal operation with icemaking, no-sun period without icemaking
Note: 1 Kwh/m2/day = 86 Langleys = 86 gm cal/cm2/day= 3.6 ml.Joules/sq.m/day

COMMENTS **Revision date: 22/05/85**

Report references: CCIS/85.4

Countries where this company has installed refrigerator/freezer systems: United States, Australia, Guyana, Ecuador, Kenya, Zimbabwe, Zaire, Nigeria and Sierra Leone.
Worldwide Solarex distributor, contact above address for further information.

EXHIBIT 5-4. WHO EPI Specifications (Reference 5-3)

- System. The system is sized to enable continuous operation of the refrigerator and freezer (loaded and includes ice-pack freezing) during the lowest periods of insolation. It is designed to allow a minimum of 5 days, continuous operation when the battery is fully charged and the PV array is disconnected. During this time, with the external temperature at a minimum of +32°C, the internal temperature of the refrigerator will be maintained between 0°C and +8°C.

- Refrigerator/Freezer. In continuous ambient temperatures of 20°C, 32°C and 43°C, the internal temperature of the refrigerator, when stabilized and fully loaded with empty vaccine vials, will not exceed the range 0°C to +8°C. In an ambient temperature of +32°C, this range will be maintained when the maximum recommended load of ice packs containing water at +32°C is placed in the freezer and frozen solid without adjustment of the thermostat. The recommended load of ice packs should freeze in less than 24 hours and will weigh at least 2 kg, excluding the pack material.

- Photovoltaic Array. The PV modules meet the latest applicable specifications of the Jet Propulsion Laboratory (USA) or ISPRA (Italy). Array structures are designed for either ground or roof mounting and will withstand wind loads of 20 kg/m^2. Appropriate photovoltaic-type sealed connectors, incorporating proper strain relief, will be provided for the array cable. Lightning protection devices will also be provided.

- Battery Set. Either sealed, low water-loss, or nonliquid electrolyte deep-discharge batteries are used (minimum 1000 cycles to 50% discharge). Automotive batteries are unacceptable for this application. The batteries are housed within the refrigerator/freezer cabinet or in a separate cabinet. In either case, the cabinet is lockable. Dry cell batteries should not be used to power instruments and controls.

- Charge Controller. The charge controller meets the charge/temperature requirements of the selected battery and will cut off the loads when the battery has reached a state-of-charge that can be repeated to a minimum of 1000 cycles. The load will be automatically reconnected when the system voltage recovers. Lightning protection is provided.

- Instrumentation

  - An LED alarm warns the user when power to the compressor has been cut by the controller. An expanded scale voltmeter or LED alarm warns the user when the battery is at an unusually low state-of-charge, giving adequate advance warning. The minimum voltage warning light should be clearly labeled "DO NOT FREEZE ICE PACKS" in the appropriate local language. If an external reading thermometer is provided for the refrigerator, it should be clearly marked in green between 0°C and +8°C.

  - A thermostat or a defrost switch is provided; no other power switches should be installed.

  - Circuit breakers or cartridge fuse holders are fitted with a polyethylene bag holding 10 spare fuses. Special attention should be given to corrosion of fuse mountings.

EXHIBIT 5-5. PV-Powered Refrigerators and Suppliers Approved by WHO (Reference 5-3)

SYSTEM SUPPLIER	REFRIGERATOR
AEG (W. Germany)	Polar Products RR2
BP Solar (UK)	LEC EV
Leroy Somer (France)	Leroy Somer 40
Polar Products (USA)	Polar Products RR2
Solarex (USA)	(a) Marvel 4RTD (b) Polar Products RR2
Solavolt International (USA)	(a) Marvel 4RTD (b) Polar Products RR2

5.2.2 Conventional-Powered Systems

Traditionally, refrigeration in developing countries has been achieved using kerosene or bottled gas to fuel absorption refrigerators. It is estimated that in rural areas of developing countries, 75% of the refrigerators are kerosene-fueled and 25% are gas-fueled (Reference 5-5). The reliability of these conventional systems has been a serious concern. According to a recent report from the WHO (Reference 5-4), whose product information sheets (Reference 5-3) include conventional-powered refrigerators,

> Absorption refrigerators using kerosene or bottled gas have not proved to be the viable, or the reliable answer for vaccine storage they were once thought to be. The logistical problems of maintaining a continuous fuel supply are so great that for most of these units that have been purchased for use in outlying regions, continuous operation over any extended period of time is extremely difficult to impossible. The reliability of these systems has been further hampered by the lack of spare parts and by maintenance problems, especially in the case of kerosene-fueled units, due to the poor quality of the kerosene available in most of the countries of the developing world.

WHO's concern with reliability can be quantified in terms of the availability (percentage of time that the refrigerator is in the correct temperature range) of kerosene-fueled refrigerators. The availability has varied widely, from 20% to 80%. An availability of 50% has typically been experienced (Reference 5-5).

EXHIBIT 5-6. Characteristics of PV-Powered Refrigeration Systems Approved by WHO (References 5-3 and 5-4)

SUPPLIER	VACCINE STORAGE CAPACITY (Liters)		HOLD-OVER TIME[1] (Hours)	SYSTEM A[2]		SYSTEM B[3]		POWER CONSUMPTION[4]	
	REFRIGERATOR	FREEZER		ARRAY (Wp)	BATTERY (kWh)	ARRAY (Wp)	BATTERY (kWh)	NO ICE-PACK	ICE-PACK
AEG	90	33	4	312	3.6	195	2.4	0.5	0.62
BP Solar	24	6	6	297	5.5	198	5.5	0.35	NA
Leroy Somer	16	16	6	400	5.3	320	3.0	0.82	NA
Polar Products	90	33	4	215	3.6	172	2.4	0.5	0.62
Solarex	(a) 80 (b) 90	(a) 10 (b) 33	(a) 20 (b) 4	220	5.8	168	3.6	(a) 0.43 (b) 0.5	(a) 0.53 (b) 0.62
Solavolt International	(a) 80 (b) 90	(a) 10 (b) 33	(a) 20 (b) 4	280	8.8	200	5.1	(a) 0.43 (b) 0.5	(a) 0.53 (b) 0.62

1. Time refrigerator will hold internal temperature when power is cut, given ambient temperature of 32°C.
2. System A applies to areas receiving 3.5-4.7 kWh/m^2-day. Includes 8 days of no-sun security. Assumes no icemaking during periods of no sun.
3. System B applies to areas receiving 5.8-7.0 kWh/m^2-day. Includes 5 days of no-sun security. Assumes no icemaking during periods of no sun.
4. Power consumption in kWh per 24 hours, with and without ice-pack freezing, given an ambient temperature of 32°C.

NA - Data not available.

Exhibit 5-7 shows a schematic of a kerosene-fueled refrigerator. Exhibit 5-8 summarizes the characteristics of kerosene-fueled refrigerators.

EXHIBIT 5-7. SCHEMATIC OF A KEROSENE-FUELED VACCINE REFRIGERATOR

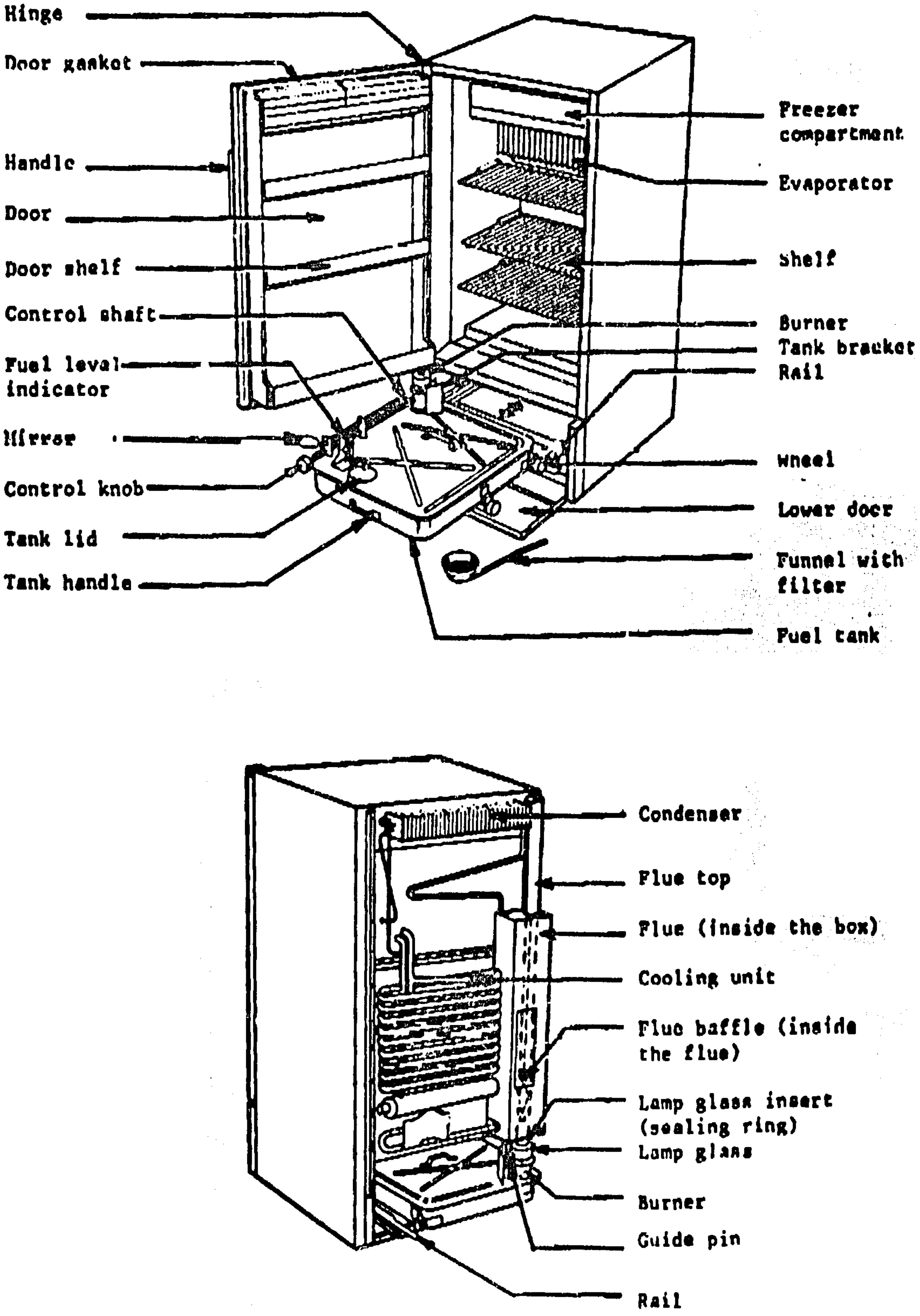


EXHIBIT 5-8. Characteristics of Kerosene-Fueled Refrigeration Systems (Reference 5-3)

REFRIGERATOR MODEL	VACCINE STORAGE CAPACITY (Liters)		HOLD-OVER TIME[1] (Hours)	FUEL CONSUMPTION[2] (Liters/day)
	REFRIGERATOR	FREEZER		
Electrolux RC 65	142[3]	142[3]	5.0	1.8
Electrolux RCW 65	32	0	14.0	1.8
Electrolux RCW 42 EK	24	0	12.5	0.2
Electrolux RCW 42 EKG	21	0	16.0	0.2
Sibir S2325	68	30	10.5	0.7

1. Time refrigerator will maintain internal temperature when power is cut, given ambient temperature of +32°C.

2. Fuel consumption per 24 hours, given an ambient temperature of +32°C.

3. Model can be used either as a refrigerator <u>or</u> as a freezer.

5.3 Field Experience

The project reviews conducted for this evaluation reflect the experience associated with more than 105 systems in 43 countries. The most significant work to date has been that performed under the direction of WHO and that conducted by NASA. The formal development and field demonstration programs conducted by these organizations have led to increased operating knowledge and, subsequently, improved system designs. Exhibit 5-9 summarizes the significant projects reviewed for this evaluation. Detailed reviews can be found in Appendix B. Exhibit 5-10 presents responses from questionnaires completed in the course of this effort. Additional information on the questionnaires is provided in Appendix A.

In reviewing past project experience, certain factors emerged as being essential to successful project implementation. They are:

- Accurate array and battery sizing
- User training and support
- Coordination with end-use organization.

5.3.1 Accurate Array and Battery Sizing

Successful systems have generally been implemented by suppliers with previous experience with PV-powered refrigeration systems, particularly in a specific region. Specific operating experience with a number of systems in a given environment has provided valuable design information for later applications. This experience has allowed such suppliers to avoid costly systems resulting from overdesign and poor performance due to underdesign.

Underdesign has been one of the major reasons for systems experiencing internal operating temperatures outside the acceptable range. Tenders submitted for the supply of 23 solar refrigerators/freezers to the South Pacific Bureau for Economic Cooperation (SPEC) exhibited significant variance in photovoltaic array sizes and battery capacities (Reference 5-2).

EXHIBIT 5-9. Refrigeration Systems Significant Projects

PROJECT TITLE AND LOCATION	APPLICATION	NUMBER AND/OR CAPACITY OF SYSTEMS	COMMENTS	REF # (DATE OF REF.)
NASA-Lewis R/F Systems 23 Countries	PV-powered refrigerators for vaccine storage were installed from 1981 to 1983.	28 systems	• The refrigerator/freezers (R/Fs) have maintained internal temperatures within the required temperature range for slightly more than 80% of the time. This level of reliability is comparable with that of kerosene refrigerators. All the problems experienced are believed to be avoidable in future installations. • Of the various component failures encountered, none occurred consistently across the systems, and most were not considered serious. • There have been no known PV power system problems. • The R/Fs have been relatively problem free with no compressor problems. • A few problems were encountered with the compressor electronic control module. • Instrumentation has been a major problem (in particular, with pyranometers and amp-hours meters—instruments that have been used successfully in many other projects). • Misuse of R/Fs (e.g., for cold drinks, meat storage, etc.) has been observed in several systems. • Some R/Fs have yet to be used for vaccines because the health programs or the vaccines themselves are not available. • The cost of current PV R/F systems ranges from $3500-6500 and is dependent on the location, system design and supply point of the R/F.	5-2 (1985) 5-6 (1984) 5-7 (1982) 5-8 (1983) 5-9 (1984) 5-10(1983) 5-11(1982) 5-12(1985) 5-13(1985)
World Health Organization (WHO) Field Trials Ghana, Kenya Tanzania, Columbia, Yemen Arab Republic, India, the Phillippines, and the South Pacific Islands	Laboratory tests (1980-1983) and field trials (Installed in 1983 and 1984) of PV-powered refrigerators for vaccines.	20 field trials	• Four refrigerator models have been approved by WHO for vaccines (Polar Products RR2, LEC EV 570, Frigesol 40 and Marvel 4RTD). • Others were rejected due to characteristics such as high energy consumption, lack of ice-making capability and unacceptable holdover time. • Improper sizing of the array/battery and instrumentation failures were encountered. • Energy consumption in the field does not match that anticipated based on laboratory tests (strictly controlled laboratory tests did not account for misuse of equipment in the field).	5-1 (1981) 5-2 (1985) 5-3 (1985) 5-4 (1985) 5-14(1982)
PV versus Kerosene Refrigerators The Gambia	An immunization program financial analysis of PV-powered vaccine refrigerator versus kerosene refrigerators.	Approx. 28 systems	• Results of life-cycle cost analysis for PV and kerosene refrigerators indicate that the total cost per dose ranges from $0.62 to $1.19 with a kerosene refrigerator and $0.53 to $1.14 using the more reliable solar units. • The benefit consists of improved cost-effectiveness rather than reduced costs. • Analysis assumes that the solar vaccine refrigerator will be 90-100% reliable, compared with kerosene refrigerators being only 85% reliable.	5-15(1985)

EXHIBIT 5-10. Summary of Questionnaire Responses

	TECHNICAL					INSTITUTIONAL		FINANCIAL
	PV	BATTERIES	CONTROLS	REFRIGERATOR	OTHER	OPERATION/MAINTENANCE AND REPAIR	MANAGEMENT	COST
Dominican Republic (Regional Office of Health)	• System has worked well	• Battery for the controls was replaced		Replacement of worn out fan motor brushes not available locally	• Thermostat is damaged	• Maintenance support by AID discontinued • Users have indifferent attitude towards system		
Ecuador (INE)						• Local participation 100% in installation start-up and maintenance	• Some local participation in design and manufacture	• PV is the only economically and socially profitable alternative in some locations
Indonesia	• Good reliability					• Good institutional capability		• High capital cost
Liberia (USAID) [1]			• Voltage regulator inoperable	Compressor inoperable		• Local engineer is making repairs	• System was in storage for two years	
Mali (LESO)				Problems with fridge fuses				
Zaire (Samuteb Mem. Hospital)							• Refrigerator was lost in transport--when arrived after 2 yr had no refrigerant left (not replaced as yet)	• PV systems are viable due to lack of kerosene
Zaire (USAID)		• One battery out of six stolen in transit	• Fuses and wiring to electric module burnt after 1-1/2 years • Spare electronic module left by SPC technician was wrong model	Three out of ten refrigerators completely broken down Four other units do not maintain sufficiently cool temperatures	• Scaffolding to support solar modules stolen • Fan cooling the compressor in one broken-down unit consumed too much energy	• Technician from local electrical construction firm available to perform routine maintenance for first 1-1/2 years • Technician moved--no assistance available • Solar equipment available locally	• Health workers require more training and monitoring	
Zimbabwe (Ministry of Energy)	• No problems with PV array	• No problems with batteries			• Data collection instrumentation never worked satisfactorily			

1. Equipment environmental damage due to exceptionally long storage period near ocean.

In some instances, countries that planned to install a number of refrigeration systems initially purchased only a fraction of the units. These sample systems have been used for training purposes and/or to ensure the appropriate sizing of the system under the particular field conditions in which it will operate. For example, in Zaire, a program is currently underway to install 100 PV-powered refrigeration systems. Twenty are being installed initially. Once they have performed to the satisfaction of the Health Ministry, the remaining systems will be purchased and installed (Reference 5-2).

5.3.2 User Training and Support

Successful systems have been those with user training that provides the user with an understanding of the operation (i.e., proper loading) of the system. Ineffective training programs have resulted in system misuse--users have often placed large amounts of warm material into the refrigerator at the end of the day, causing the internal temperature to rise above the acceptable limit.

Reports from the field indicate that improved user training in maintenance and trouble-shooting, coupled with adequate documentation and spare parts, could reduce the downtime in a number of installations. Back-up support has varied from project to project. While some suppliers have been thorough in providing this support, others have caused users to wait for instruction manuals after system installation. Thus, for vaccine refrigeration, which requires a highly reliable power system, using a supplier who will provide adequate training and support is critical.

5.3.3 Coordination with End-Use Organizations

Working with appropriate host-country organizations and implementation agencies is an important element of successful system implementation. The WHO field trials, which involved working with donor agencies, regional offices and local health authorities, are an excellent example of a successful network for reporting field data. Similarly, the success of the NASA-Lewis program can be tied to their identification of appropriate host-country organizations in their field trials sponsored by the CDC and USAID. While these programs were successful, a number of lesser projects failed to meet their objectives because the responsible agencies in the field were not familiar with the end-use. Often, there is a tendency to work with academic or energy-related organizations rather than with those organizations familiar with rural health care.

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CHAPTER 6

LIGHTING AND HOME POWER SYSTEMS

6.1 Overview

Photovoltaic power for area lighting and home power systems is emerging as a significant technology in the developing world. For example, in French Polynesia, more than 1,000 of these systems were installed over a three-year period. This application includes one-to-two-module systems used in individual households as well as systems used to provide area lighting. The small household systems have been primarily dedicated to lighting, but they can also be used to power radios, televisions, refrigerators and/or water pumps. Area lighting systems have been used for community, street and security lighting purposes.

The demand for lighting in rural areas of developing countries has typically been supplied by kerosene, candles or primary batteries. Lighting from these sources is often expensive and of poor quality. For example, a kerosene pressure lamp provides about 12 lux of light, while a 20-watt fluorescent tube with reflectors will provide 100 lux (Reference 6-1). Lighting is used for evening activities such as cooking, reading, simple work and social activities. During the night, a lamp is often kept lit for security and safety reasons.

This evaluation's review of PV-powered lighting and home power systems in developing countries was based on projects referenced in the questionnaires and on significant projects being conducted in Papua New Guinea, Zimbabwe and French Polynesia for a total of more than 1,260 systems in 14 countries. Successful PV-powered lighting and home power systems used both reliable charge controllers and DC ballasts and/or ensured adequate availability of spare parts and technical support. PV-powered lighting and home power systems were shown to be technically reliable. Many users also found such PV-powered systems to be cost-competitive with kerosene-fueled lamps, the predominant technology currently employed.

6.2 Current Designs

6.2.1 PV-Powered Systems

As discussed in Section 6.1, lighting and home power systems include area lighting systems and one-to-two-module systems primarily dedicated to home lighting. This section describes the design of such systems.

A light consists of three major components: a luminaire (or bulb or tube), a ballast and a fixture. Lighting applications identified for developing countries use gas vapor lamps (e.g., fluorescent, low-pressure sodium, mercury vapor and metal halide). These lamps require a high-voltage electric charge to excite the gas molecules, thus producing light. Once initiated, lighting can be maintained with lower voltages. The charge is sparked and the operating frequency is regulated by a ballast--a high frequency inverter and transformer that controls the current flow into the lamp. The ballast and lamp are mounted in a fixture. The only difference between an AC and DC light is the ballast design.

Exhibit 6-1 depicts a typical area lighting system. These systems consist of one or two PV modules, battery storage, a simple charge controller, timing controls and a light. Several companies offer self-contained units (the type depicted in Exhibit 6-1) equipped with light poles and weatherproof containers for battery storage and electronics. Area lighting systems represent a relatively new product in the developing world.

Home power systems are typically one-to-two-module systems operating two-to-four fluorescent lights (10 to 40 watts each) in a private household. This type of lighting is usually combined with other end-use devices (such as refrigerators, radios, televisions, fans, etc.) operated from the same PV power system. The basic configuration of such a system is outlined in Exhibit 6-2.

EXHIBIT 6-1. Area Lighting System

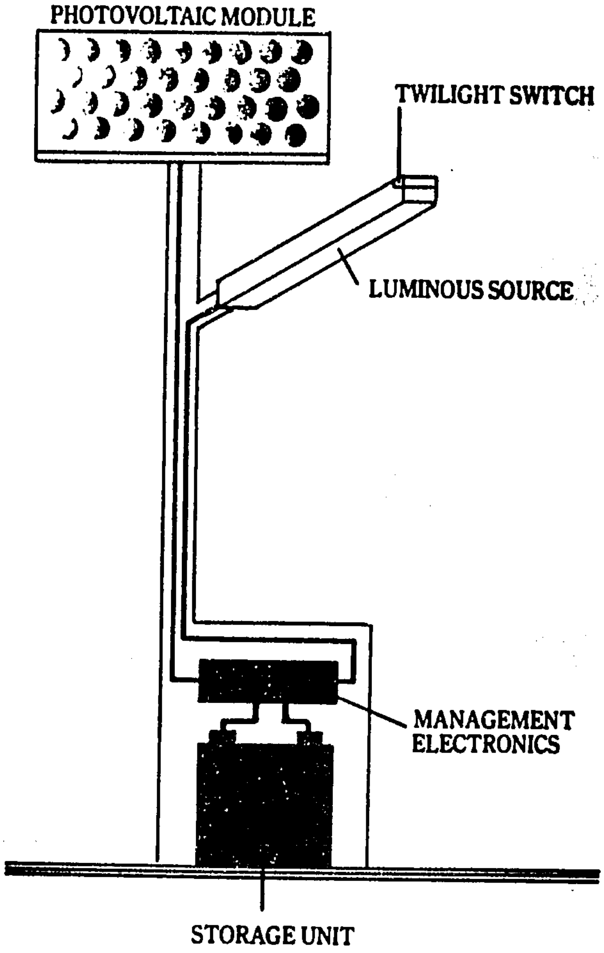
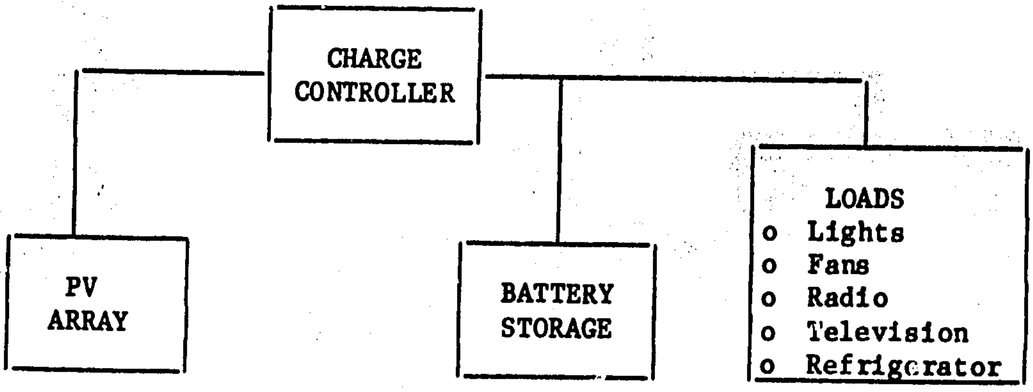


EXHIBIT 6-2. Configuration of a Home Power System



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In rural areas of developing countries, kerosene-fueled lamps are used both indoors and outdoors. Therefore, an important design aspect of small lighting systems can be portability. In Papua New Guinea, this issue has been addressed by using PV to charge nickel-cadmium batteries for fluorescent lanterns (Exhibit 6-3). These systems have been developed and tested to compete with kerosene-fueled lanterns.

Exhibit 6-4 presents sizing graphs for a PV home power system. The choice of energy demand and insolation should be such that the ratio of these parameters is the maximum experienced over the year. Given a maximum energy demand of 0.24 kWh/day and a respective insolation of 4 kWh/m^2-day, it can be seen from (a) that an 0.078 kWp PV array is needed. Using the same energy demand and 2 days of battery storage, it can be seen from (b) that a battery capacity of 0.6 kWh is needed. The model used to generate these graphs is described in Appendix D.

Maintenance on the system is restricted to the batteries and loads. If the batteries are vented, distilled water must be added on regular basis. Fluorescent tubes must be replaced as they burn out. Ballasts must be replaced approximately every 3 years. The costs associated with these items are provided in Chapter 12.

6.2.2 Conventional-Powered Systems

Conventional lighting practices in rural areas of developing countries usually involve the use of kerosene-fueled lamps. A typical household may have one or more hurricane lamps or lanterns (wick lamps with a capacity of 0.5 to 1 liter of kerosene), and sometimes a pressurized lamp (e.g., the Coleman variety). Electrical loads, such as radios, are powered by automotive batteries that are recharged by engine generators. Primary batteries (e.g., throw-away batteries) have also been used to power electrical loads, but they will not be discussed in this evaluation.

Conventional-powered systems can be sized in terms of the number and type of kerosene lamps and the number of automotive batteries. Socio-economic data and fuel consumption information from Papua New Guinea were used as the basis for the conceptual design of three conventional home power systems. These systems

EXHIBIT 6-3. Portable PV-Powered Lantern (Reference 6-2)

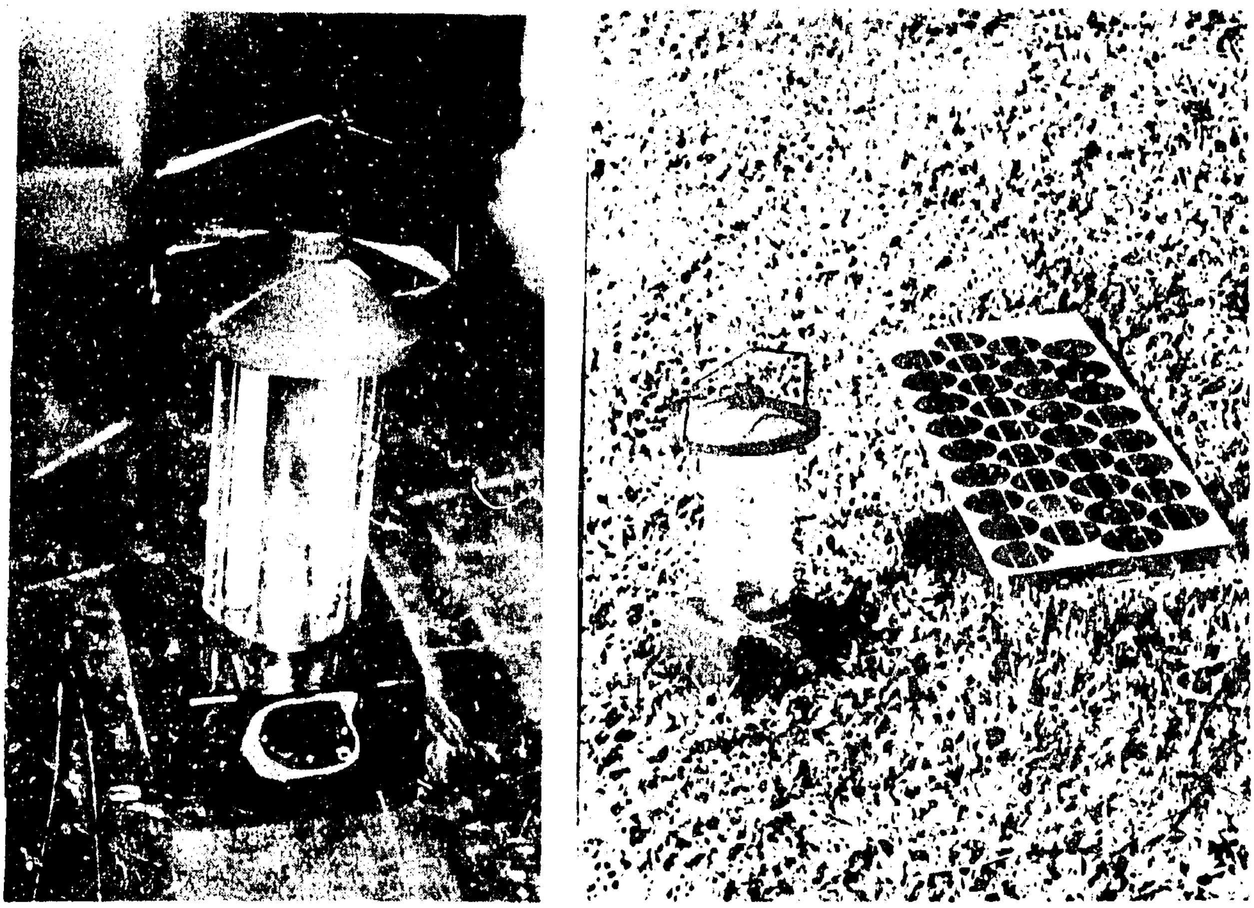
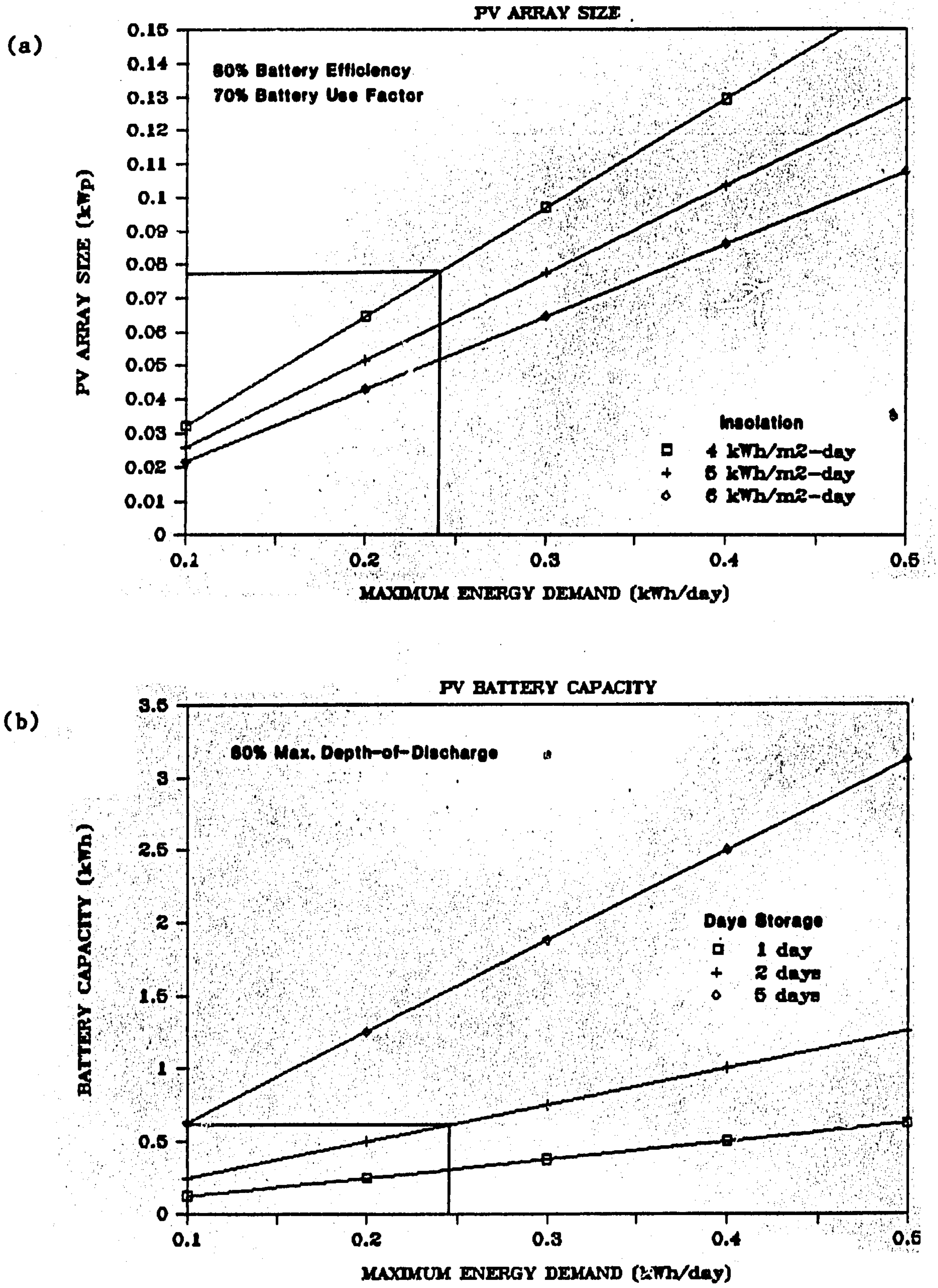


EXHIBIT 6-4. Sizing of PV-Powered Home Power Systems



are outlined in Exhibit 6-5. Technical assumptions for the components of such systems are outlined in Exhibit 6-6. While these data were comprehensive in characterizing lighting and home power fuel and cost requirements, no additional information was available to determine how typical these systems are in developing countries.

Operation and maintenance of the kerosene lamps requires regular cleaning, fuel addition and replacement of parts. In Papua New Guinea, standard operating procedure for a kerosene pressure lamp is described as follows (Reference 6-1):

> ...it takes at least 5 minutes to refuel the tank, clean the glass and then actually light it. When there is no alcohol to heat the generator and the mantle, one would have to use kerosene. In this case it takes longer to light. The pressure in the lamp frequently runs low (hence low lux) and would require repumping at least once every half hour.

Replacement of parts was shown (Reference 6-1) to be necessary at intervals ranging from every month to every 3 years, depending on the part. The generator of a pressure lamp has been shown to be the most frequently replaced part. Costs associated with fuel consumption and parts replacement are outlined in Chapter 12.

EXHIBIT 6-5. Typical Conventional-Powered Home Power Systems

COMPONENTS	SYSTEM SIZE		
	SMALL	MEDIUM	LARGE
Kerosene-Fueled Hurricane Lamp	-	1	1
Kerosene-Fueled Pressure Lamp	1	1	1
12-Volt Automotive Battery*	-	-	1

* Battery is used to power electrical loads such as a radio, television or other lights.

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EXHIBIT 6-6. Technical Assumptions for Components of Conventional-Powered Home Power Systems

COMPONENTS	LIFE (Years)	FUEL CONSUMPTION (Liters/year)
Kerosene-Fueled Hurricane Lamp*	3	40
Kerosene-Fueled Pressure Lamp*	3	115
12-Volt Automotive Battery	2	—

* Reference 6-1

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6.3 Field Experience

In conducting this evaluation, the experience associated with more than 1,260 lighting and home power systems was reviewed. This number includes systems, or groups of systems, categorized as significant projects and systems discussed in the questionnaires. The experience associated with the significant projects is summarized in Exhibit 6-7. More detailed information on these systems can be found in Appendix B. Responses from the questionnaires are tabulated in Exhibit 6-8. Appendix A contains more extensive information on the questionnaire responses.

Based on the review of past projects, certain factors emerged as being critical to the implementation of successful projects. These factors are:

- Reliable charge controllers
- Available spare parts and distribution system
- Customer financing policy.

6.3.1 Reliable Charge Controllers

A range of experience has been encountered with charge controllers. In early systems, charge controllers were often a weak link in system performance. However, as product development has progressed, increased precaution has been taken by the manufacturers to protect components from environmental conditions. As a result, improved performance has been experienced.

While the charge controller is often the least cost of a system and improved products are available, care should be taken to select a reliable, field-proven component. Successful implementation of large numbers of systems has also been made possible through the availability of replacement charge controllers.

EXHIBIT 6-7. Lighting and Home Power System Significant Projects

PROJECT TITLE AND LOCATION	APPLICATION	NUMBER AND/OR CAPACITY OF SYSTEMS	COMMENTS	REF. # (DATE OF REF.)
Rural Lighting Papua New Guinea (PNG)	1-to-2-module systems for patrol posts and village lighting kits.	2.5 kW total	• PNG established policy to use PV for patrol post lighting. • Two-to-four-year payback from PV lighting kits. • Estimated potential of 17.5 MW for PV lighting kits by 1992. • Fluorescent lanterns powered by Ni-Cad batteries charged by PV are being developed and tested.	6-3 (1982)
PV versus Kerosene Lighting Survey Papua New Guinea	1-module PV system versus two kerosene lamps for rural villages	35-W system	• Less than 5-year payback for PV lighting. • Quality of PV lighting is at least five times better than from kerosene. • PV kit provides light instantaneously. For kerosene pressure lamp, it takes at least 5 minutes to get light. • Reference suggests Papua New Guinea Government should finance or encourage lending institutions to provide loan opportunities to pay for PV kits.	6-1 (1981)
PV versus Conventional Lighting Zimbabwe	1-module system versus candles, gas or paraffin.	30-40-W system	• Portability of lamps stressed as important design parameter • Six to seven year paybacks were noted for PV versus conventional lighting. • When compared to petrol generator, PV showed payback of less than 2 years.	6-4 (1983)
School Lighting Mali	Fluorescent lighting installed in 1980 to provide light for evening.		• Competing alternative is gas lamps. • Despite risk of bottled gas, use of PV could only be regarded as interesting experience • Need substantial reduction in PV cost and/or increase in rural education budget.	6-5 (1985)
Traffic Lighting United Arab Emirates	PV-powered street lighting systems; installed in 1983.	o 21 70-watts systems o 1 15-kW system	• Customer pleasantly surprised at the illumination delivered by PV. • Initially, problems were encountered operating high-pressure sodium vapor lamps from modified square wave inverters. Once corrected, system has performed reliably. • High-efficiency, high-powered DC ballasts were mentioned as vital to optimizing PV lighting systems.	6-6 (1984)
Home Power Systems French Polynesia	Systems to provide lighting, television and fans for individual houses installed since about 1980.	>1000 systems	• PV-powered rural electrification program subsidized by the French Atomic Energy Commission, French Agency for Energy Management and Government of French Polynesia. • Program developed based on studies that it would be more cost-effective to introduce PV than to extend grid. PV justified where user is more than 200 meters from grid.	6-7 (1985) 6-8 (1985)

EXHIBIT 6-8. Summary of Questionnaire Responses

	TECHNICAL				INSTITUTIONAL		FINANCIAL
	PV	CONTROL/ELECTRONICS	BATTERIES	LAMPS	OPERATION/MAINTENANCE & REPAIR	MANAGEMENT	COST
Belize (Robert Nicolait & Assoc.)	• Reliability exceptionally good			• Problems in navigational light systems with bird droppings • Problems minimized with anti-bird nesting rods	• Understanding of limits of PV systems is lacking • Operators are competent		• Systems are privately owned • Restrictive lending/borrowing conditions exist • PV lighting and TV lifetime costs are competitive at low power levels
Botswana ([illegible])	• PV panels seem reliable			• Problems with outdoor lights	• Substantial local participation with installation & start up	• Potential administrative problems with jurisdiction and responsibility	
Indonesia (Gov't. Official)	• Good reliability • All PV systems are running well				• No special maintenance is needed except for batteries • No problems with in-country institutional capability • Conceptual design, installation, and start-up done by Indonesian personnel • Operated by villagers		• Lower maintenance cost than conventional energy technologies • High capital cost
Lesotho ([illegible] Solar Systems)	• Reliability generally excellent—PV is better than estimated		• Worst problems are with electro-mechanical load shedding type regulators—Best regulator is educated consumer	• Users lack understanding of end-use energy consumption and how this affects system sizing and behavior	• Virtually no maintenance • Trained local staff	• No unsolvable problems to date	• Cost of getting to remote locations is a problem • Small systems are very viable • No data on life-cycle cost
Mali (LESO)			• User problems with battery discharge	• Problems with replacing fluorescent tubes		• Problems with transport and access to remote sites	
Nigeria	• Reliability is excellent • Panels have higher output if rinsed off with water during harmattan season						• No operating costs • PV appears to compare favorably on a life-cycle basis to gasoline and diesel engines due to the latter's short life and poor maintenance
Thailand (NEA)			• Problems due to battery life	• Fluorescent lamp has durability problems	• Almost all activities performed by in-country personnel—no problems with capability	• Plans to test acceptance	• PV lighting is competitive with conventional technologies
Yemen Arab Republic	• Some problems with user acceptance due to belief in mountain areas that solar panels attract lightning • System does provide light	• Difficulties with voltage regulators	• Difficulties with battery protectors		• Requires monthly on-site check-up and monitoring due to faulty battery protectors • Government does not have technical, commercial, nor conceptual background to maintain PV systems		
Zaire ([illegible] Memorial Hospital)	• System has worked well	• No presence of voltage regulator in system	• Replaced one battery	• Replacements obtained	• Small maternity lighting systems well received		• PV systems are viable due to absence of conventional energy sources
Zimbabwe (Ministry of Energy)	• No problem with PV array			• Defective ballast	• Problems with meeting user demand for extra lights		• Competitive with conventional systems (6-yr payback)
ARCO Solar Inc. (G. Shushnar)	• PV system has been very reliable	• Only one inverter failure in 3 years of system operation • No control system failures	• Problems with lack of battery maintenance (Saudi Arabia)		• Almost no maintenance and repair required • Battery watering has been irregular	• Very little in-country personnel participation in system design, installation, and start-up, although repeatedly requested (Saudi Arabia)	
Solar Electric International	• Excellent performance			• 12-V fluorescent lights are extremely reliable			• Kerosene supply is not reliable—PV is most viable

6.3.2 Available Spare Parts and Distribution System

Essential to the successful implementation of PV-powered lighting systems is ensuring an adequate supply of spare lamps and ballasts. An infrastructure of this type is necessary for the widespread application of any technology.

6.3.3 Customer Financing Policy

In 1980, PV-powered lighting was determined to be cost-competitive with kerosene in Papua New Guinea (Reference 6-1). As a result of government policies, conditions for the viability of PV-powered lighting exist in many other countries as well. At least two governments, French Polynesia and Spain (although not a developing country, Spain's experience with home power systems is applicable to this evaluation), have established policies that subsidize the use of PV for rural electrification in remote areas (References 6-7, 6-8, 6-9, and 6-10). (These policies involve either direct subsidy or low-interest loans. French Polynesia and Spain have successfully encouraged the implementation of thousands of PV-powered home power systems in the last few years.

CHAPTER 7

MULTI-USE SYSTEMS

7.1 Overview

Multi-use systems are considered an important application for PV because of the large number of unelectrified villages in remote locations of the developing world. Traditionally, needs for power in developing countries have been met through conventional means such as diesel- and gasoline-fueled engines, kerosene-fueled refrigerators and lights, and batteries.

Multi-use systems include mini-utility systems and load centers. A mini-utility system consists of a centralized generator that provides service to an entire community through a distribution network. A load center system is designed to power a variety of loads at the site of application. Load centers include medical clinics, agri-processing centers (e.g., for grain grinding), and educational facilities.

The concepts of mini-utilities and load centers represent two different strategies for rural electrification: using one centralized system (PV-powered or a conventional system) and forming a grid network versus using many dispersed systems at points of power demand. This latter concept can be extended to home power systems, which were discussed in Chapter 6.

Key factors of performance were developed based on a review of more than 42 systems in 22 countries. The reliability of power conditioning equipment, principally inverters, was shown to be critical to the success of such systems. Another factor affecting the implementation of multi-use systems is the policy decision concerning whether centralized or dispersed systems are preferable.

7.2 Current Designs

7.2.1 PV-Powered Systems

PV-powered multi-use systems range in size from a few hundred watts to over 25 kilowatts. As discussed in Section 7.1, multi-use systems are categorized in two ways: mini-utilities and load centers. The major differences between these two system types lie in the magnitude of the array, the complexity of the power conditioning subsystem and the need for an administrative infrastructure. These distinctions are detailed in Exhibit 7-1. Schematics of typical multi-use systems are outlined in Exhibit 7-2 and 7-3.

EXHIBIT 7-1. Distinctions between PV-Powered Multi-Use Systems

CHARACTERISTIC	MULTI-USE SYSTEM TYPE	
	LOAD CENTERS	MINI-UTILITIES
Array Size	< 5 kW	> 5 kW (up to about 30 kW)
Type of Power Output	AC or DC	AC
Power Conditioning	● Charge controller (with load-shedding capabilities) ● Inverter (if AC loads)	● Charge controller ● Inverter (with load-shedding capabilities) ● Metering
Power Distribution System	Only within one facility	● Throughout entire village ● Metering
Infrastructure	● Supply of spare parts ● System repair	● Supply of spare parts ● System repair ● Billing system ● Power management

EXHIBIT 7-2. Schematic of a PV-Powered Load Center System
(Centralized Loads)

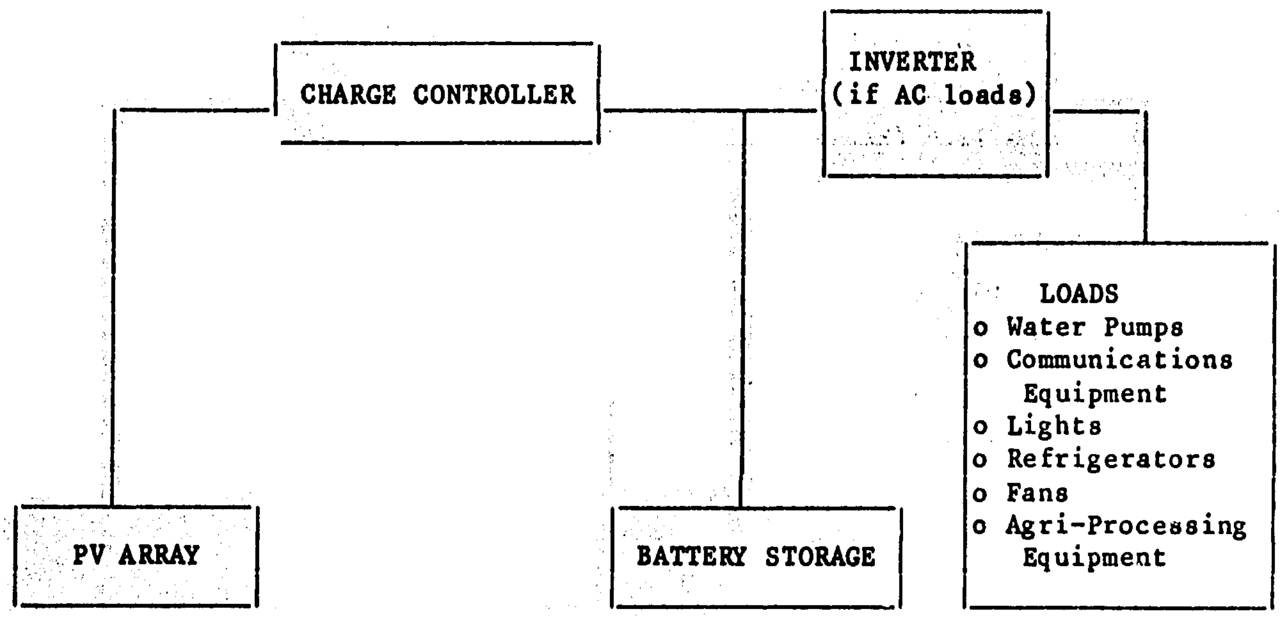
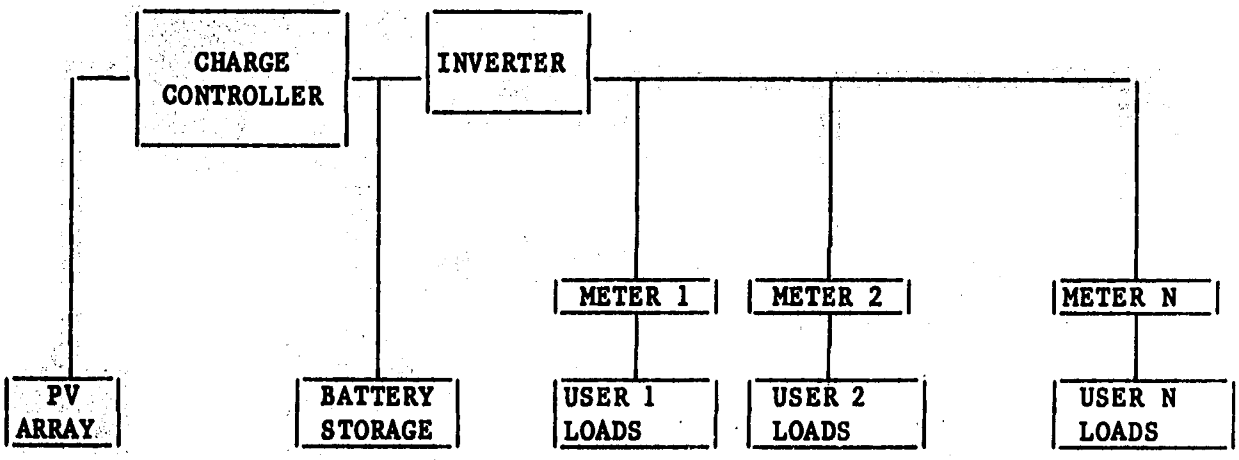


EXHIBIT 7-3. Schematic of a PV-Powered Mini-Utility System
(Decentralized Loads)



PV-powered multi-use systems can be designed to produce AC or DC power. Mini-utilities are traditionally AC since AC is a more efficient means of distributing power over large distances. Both AC and DC systems have been designed for the load centers. Applications experts have agreed (Reference 7-1) that systems should be designed to be DC whenever possible. The basis for this consensus is the fact that using an inverter increases system complexity and hence the risk of system failure. Load availability is the critical factor in determining the viability of designing a DC system, as DC loads are currently available only for specialty markets. Items such as lights, fans, refrigerators and some audio-visual equipment are available in DC, making DC power systems appropriate for load centers such as schools and remote health clinics. However, for multi-use systems with a mixture of appliances, such as stereos, televisions, small hand tools, and more complex medical equipment (for centralized health centers), AC power systems are the only real option.

A peaking factor of 1.5 times the average energy demand is used to size the array. Exhibit 7-4 presents sizing curves for PV-powered AC multi-use systems. Using an average energy demand during the year of 10 kWh/day and an insolation of 5 kWh/m^2-day, it can be seen from (a) that a 3.9-kWp PV array is needed. Using the same energy demand, and 2 days of battery storage in (b), the required battery capacity can be seen to be 38 kWh. The model used to develop these curves is described in Appendix D. The inverter is sized according to the maximum power demand and rounded up to the next kilowatt size rating. Maximum power demand is set at 1.8 times the average power demand where average power demand is equal to the average energy demand divided by 12 hours.

7.2.2 Conventional-Powered Systems

Mini-utilities have traditionally been powered by engine generator sets (gen-sets) that produce AC electricity. Back-up power for these systems have generally been in the form of another engine generator (i.e., a dual-engine system). Load centers have typically been powered by diesel- or gasoline-fueled generators, often in combination with kerosene for vaccine refrigeration at health centers or with manual labor for water pumping, grain grinding or other mechanical work.

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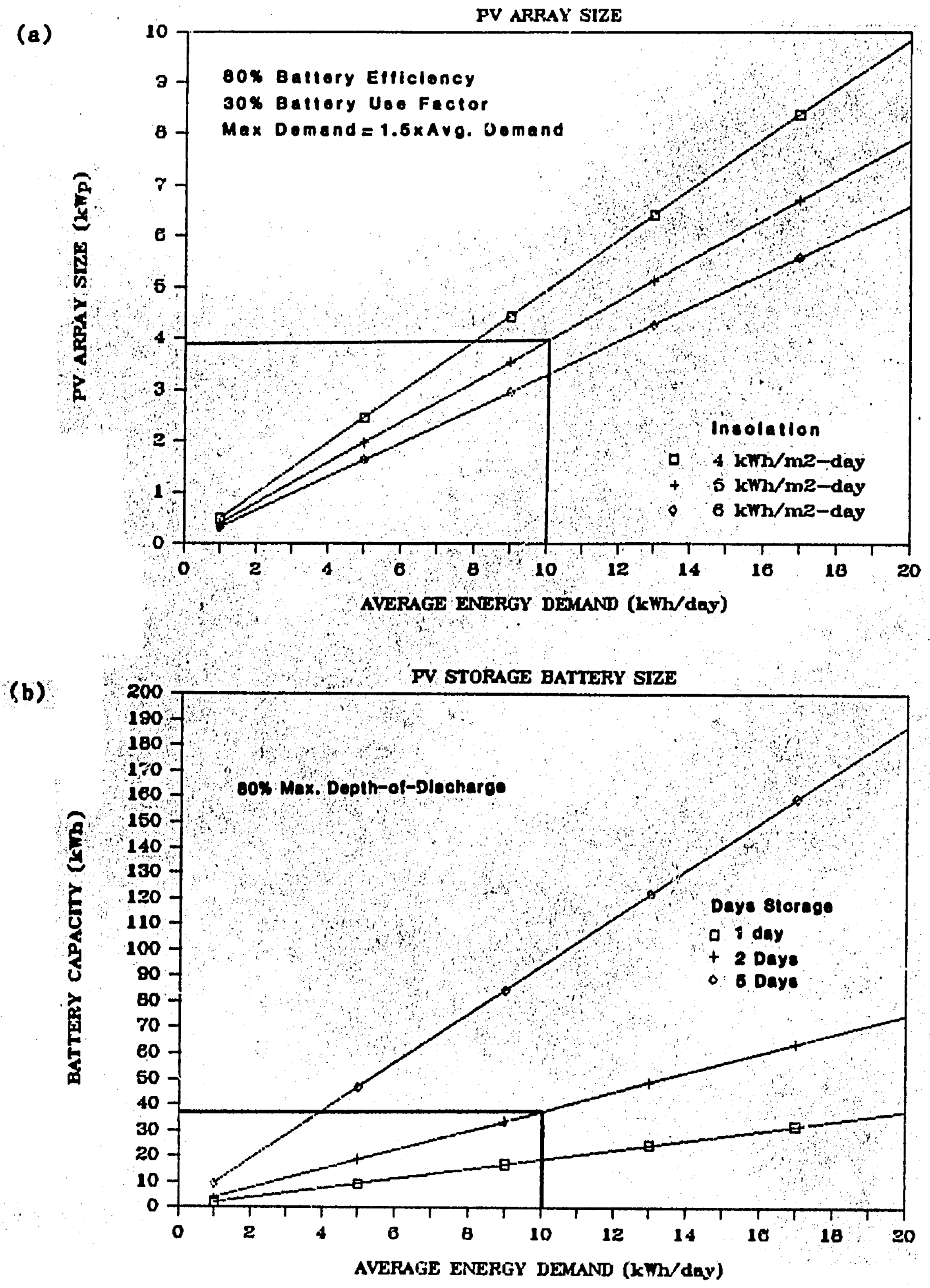
EXHIBIT 7-4. Sizing of a PV-Powered AC Multi-Use System



Typical engine-powered multi-use systems are depicted in Exhibits 7-5 and 7-6. Using the average energy demand, the size of an engine-powered system can be determined from Exhibit 7-7. For an average energy demand of 10 kWh/day, it can be seen from this exhibit that a generator size of 1.5 kW is needed.

EXHIBIT 7-5. Schematic of an Engine-Powered Load Center System

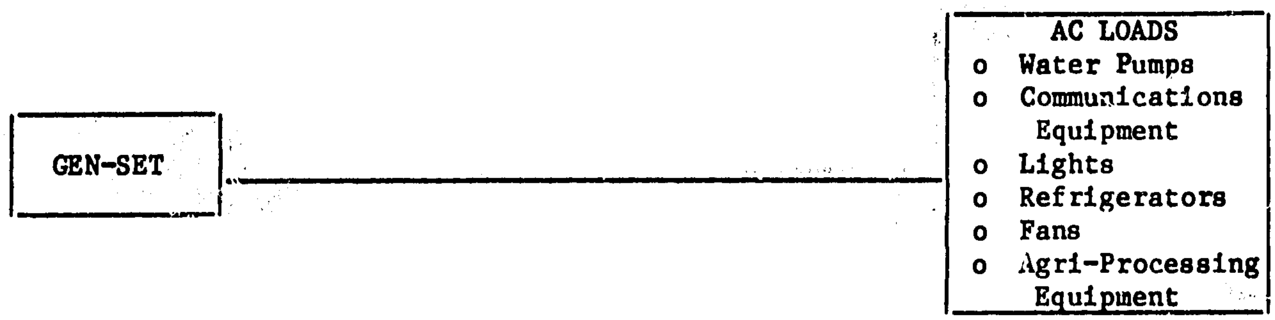


EXHIBIT 7-6. Schematic of an Engine-Powered Mini-Utility System

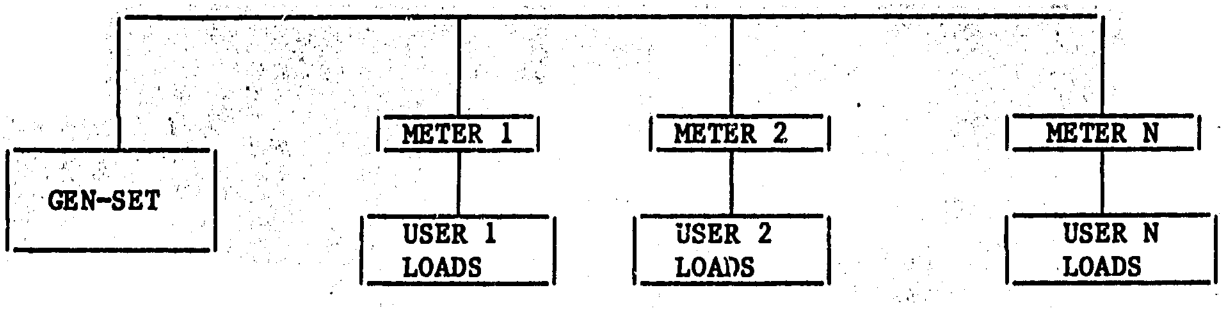
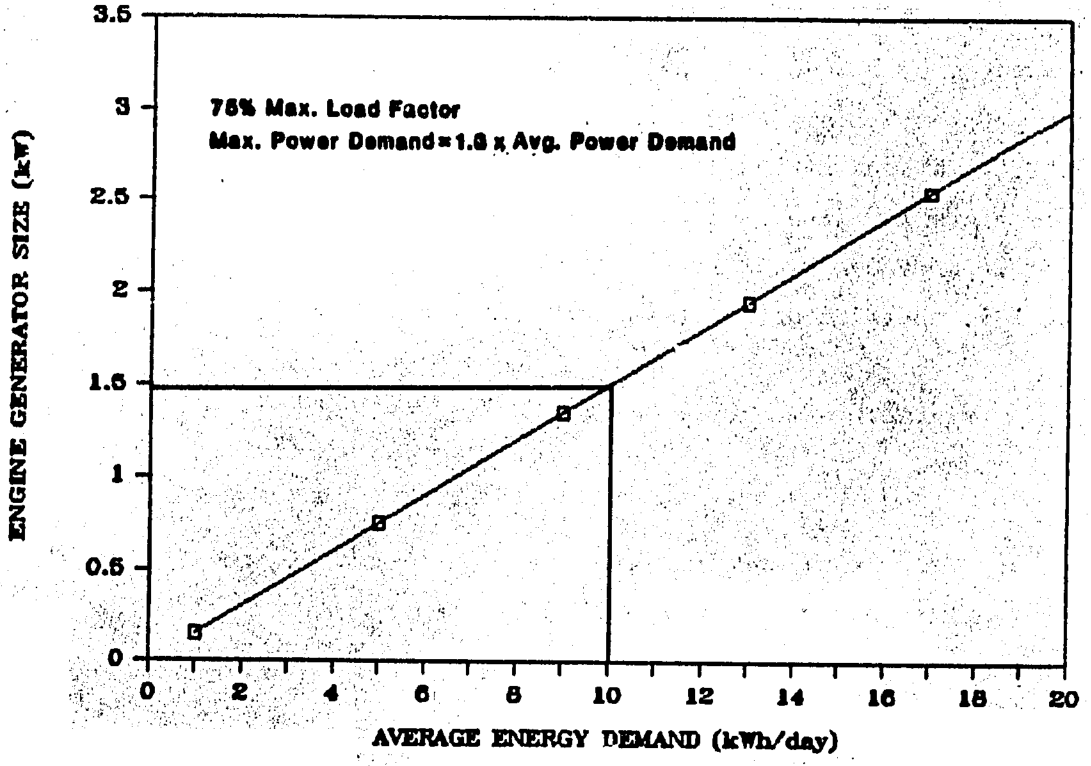


EXHIBIT 7-7. Sizing of an Engine-Powered Multi-Use System



Diesel gen-sets are only available above 3 kW. If the loads require engines below that size (as in the example above) and a diesel gen-set is desired, a 3-kW diesel engine operating at a lower load factor must be used. This graph was constructed based on the model presented in Appendix D.

Maintenance must be regularly performed on conventional-powered multi-use systems. The operation and maintenance schedule for the multi-use gen-set is the same as that for the pumping and communications applications (See Exhibit 3-6).

7.3 Field Experience

In performing this evaluation, the experience associated with approximately 42 systems was reviewed. Projects of particular interest include those managed by NASA-Lewis: the grain mill project in Tangaye, Bourkina Fasso (formerly Upper Volta), five medical clinics in four developing countries and a mini-utility system in Tunisia. The findings from these and other significant projects are summarized in Exhibit 7-8. More detailed project descriptions are provided in Appendix B. Responses from the questionnaires are tabulated in Exhibit 7-9. Supplementary questionnaire information can be found in Appendix A.

Key factors in the implementation of PV-powered multi-use systems were determined to be:

- Reliability and Complexity of Power Conditioning Equipment
- Infrastructure for System Management
- Rural Electrification Policy.

Since multi-use systems have a combination of various end-uses, the key factors affecting the system implementation of the individual applications (as outlined in Chapters 3 through 6) should also be taken into account.

7.3.1 Reliability and Complexity of Power Conditioning Equipment

Field experience has shown that the reliability of power conditioning equipment is critical to successful systems. While both inverters and charge controllers have been identified as potentially weak links in the PV-powered systems, charge controllers are considered further along in the product development process (Reference 7-1). Some system problems have been related to quality control and most likely would have been discovered had "burn-in" testing been performed. Other problems have been related to environmental factors (e.g., heat and humidity) or user operating errors. Only proven equipment should be selected for all inverters and controllers. Factory testing should be included as part of the purchase specifications.

EXHIBIT 7-8. Multi-Use Systems Significant Projects

PROJECT TITLE AND LOCATION	APPLICATION	NUMBER AND/OR CAPACITY OF SYSTEMS	COMMENTS	REF # (DATE OF REF.)
Village Power and Farm House Tunisia	One system (29 kW) installed in 1983 serves village of 120 persons. Additionally, a farm house system and two drip irrigation systems were installed.	4 systems: 29 kW 1.4 kW 1.4 kW 1.4 kW	• Operation and evaluation of the systems is the responsibility of an in-country organization. • Users are billed for specific consumption. • Down-time of 29-kW system was the result of operations error that resulted in an inverter failure (improper switch sequencing during manual start-up). • Numerous problems with 1-kW inverter of farm-system and extensive time required for repairs.	7-2 (1983) 7-3 (1984) 7-4 (1985) 7-5 (1985)
Village Electrification Gabon and the Marshall Islands	A PV-powered water pump, school system, community light, and health dispensary were installed in each of 4 remote Gabonese villages from Nov. '84 to Feb. '85. The Utirik Atoll system for village electrification became operational in 1984.	17 systems for a total of 12 kW (Gabon) 1 8-kW system (Utirik Atoll, Marshall Islands)	• So far, both PV village electrification projects have had 100 percent availability. • The integral inverter for each fluorescent lamp in the Gabonese community service systems has experienced a failure rate proportional to outdoor storage time in the moist tropic environment before installation (inverters that were installed directly in fixtures have not had any failures).	7-6 (1985) 7-7 (1980) 7-8
Village Electrification Basaisa Village, Egypt	The PV system installed 1977-1981, powers audio visual equipment, a light, and water pumps for irrigation.	1 system (6kW not including power for water pumps)	• The village has established a community cooperative, community club, technical center and community clinic. There is a fee for memberships in these. Members must pay rent for the pumps and audio visual equipment during times of use. • Operation, maintenance and repairs are performed by volunteers in the community (the project team only intervenes if the villagers cannot fix the system in the case of breakdowns). • The energy cooperative not only provides for the basic energy needs of the community, but it also establishes an educational atmosphere and a type of community spirit. • There has not been much conflict over the use (and scheduling of the use) of the various equipment.	7-9 (1983) 7-10(1984) 7-11(1983)
Community Center and Irrigation Project West Bengal, India	In 1980 a PV system was installed to power a community center. In 1981, a 300W water pumping system was installed for irrigation.	200 W and 300 W	• Although some modules failed after 3 years due to cracking of cell interconnections and motor-pump set problems were encountered (mainly with the carbon seals and commutators), the system seemed to be operating smoothly as of 1984. • In 1984, the community center was economically viable. • BOS costs (per peak watt) are less in India than in the U.S. due to cheap labor. • This project has generated tremendous enthusiasm. • The villagers manage security, operation and maintenance on a cooperative basis.	7-12(1984)
Niaga Wolof Energy Centre Senegal	The PV-Wind hybrid system, installed 1983-1984, powers lighting, a water pump, and refrigerators.	5 kW PV	• No problems with the PV portion of the system. • A full-time system operator is not necessary. • The system is close to technical support. • Users of the system are billed according to an established tariff structure.	7-13(1984)
Agricultural Product Processing Bourkina Fasso	PV-powered water pump and grain mill installed in 1979.	3.6 kW	• System had over 90% performance reliability in first 4 years. • Proceeds from milling are used to pay an operator and for maintenance and special operational support and other village development projects. • The complexity of the original controller (although very reliable) intimidated in-country technical support staff and was replaced with a simple packaged control module. • Local cooperative formed to manage the PV system was a major factor contributing to the success of the system (genuine interest and concern for the project's success were exhibited by villagers). • Infrastructure needed to supply technical support and spare parts. • The village, which was dispersed, is now centralized around the service points of water pumping and grain milling.	7-14(1985) 7-15(1982) 7-16(1982) 7-17(1982) 7-18(1979) 7-19(1985)
NASA-Lewis Medical Systems Guyana, Ecuador, Kenya, Zimbabwe	PV medical systems supply power for R/F, lights, sterilizers, and radio and were installed in 1983	5 systems ranging in size from 1.5 to 3 kW	• All five systems have functioned reliably regarding array, battery, and control functions. • Automatic data acquisition systems did not work. • The sterilizer (electrochemical) never performed properly in all the systems (no health problems resulted, however). • Spare light tubes are not available beyond those supplied with the system. • With total loads of 1.5 to 2 kW, the current price, including end-use components, would be $25,000-30,000 installed.	7-20(1985) 7-21(1985)
Medical Systems Senegal	PV system installed in 1982, powers refrigerators, lighting, fans, and laboratory instruments.	670 W	• Each dispensary deals with 10,000 inhabitants, providing 100 to 150 consultations per day. • The system cost US $20,000 (price includes R&D work). • The system was oversized as a result of overestimation of the load.	7-22(1985)

EXHIBIT 7-9. Questionnaire Responses - Multi-Use Systems

	TECHNICAL				INSTITUTIONAL			
	PV	BATTERIES	POWER CONTROL UNITS	END-USE DEVICES	OPERATION/MAINTENANCE & REPAIR	MANAGEMENT	COST	OTHER
Botswana				• Reliability problems with fridges		• Clinics seem reluctant to abandon old fridges		
Djibouti (ISERT/VISTA)[1]	• Good reliability		• Inverter problems		• Limited repair expertise with inverter			
Ecuador					• 100% local participation in installation, start-up and maintenance • Some local participation in design and manufacture of system		• PV systems are more viable than other technologies especially for low-power applications (< 2 kW) and in sites far from public electrical energy sources	
Kenya	• Very reliable			• Sterilizer does not work	• Little maintenance required • Few local technicians	• No spares available		
Senegal (CERER)	• PV array is very reliable							
Zaire (Samuteb Memorial Hospital)	• System has worked well	• Replaced one battery	• No presence of voltage regulator in system	• Lamp replacements obtained			• PV systems are viable due to absence of conventional energy sources	
Zimbabwe (Ministry of Energy)	• No problem with PV array	• No problems with batteries		• Defective light ballast • Sterilizer at one clinic never worked • Problems with freezer due to electronic module/compressor malfunction	• Repairs for clinic made by suppliers (covered by guaranty) • In-country personnel participated in design, site selection, installation and start-up of PV systems	• Problems with meeting user demand for extra lights	• PV lighting system is competitive with conventional systems (6-yr payback)	• Automatic data acquisition system at one clinic never worked
ARCO Solar Inc. (G. Zahnstecher)	• Working very well to date		• Inverters and controllers are much improved now	• Water pumping system is very successful	• Systems are difficult to repair in remote or primitive locations		• Initial cost is high	• Quality and reliability of AC power was poor • Now it is very good
Kyocera International	• Performance and reliability of PV modules are excellent	• Performance and reliability of batteries are excellent			• Problems with good servicing and spare parts • No in-country capability to operate and repair			• Problems with poor foundation construction performed by local contractor
ecours Leroy Somer			• Problems occurred with inverter, back-up generating set measurement system (data logging)		• Impossible to repair a PWM inverter locally			
Senegal (not indicated)	• In good functioning order • System performance satisfactory	• Two battery elements exploded	• Problem with power used of inverter		• Installation done by Senegalese organization, SINAES[2] • SENELEC responsible for use and maintenance • Maintenance only consists of cleaning modules & equalizing charge of batteries every 6 months • No problems with in-country institutional capability	• No problem with acceptance	• No operating costs (i.e., no operator is required)	
Solarex Pty. Ltd.	• PV systems are very reliable	• Electrolyte replacement is required in the battery bank after 2 yrs. in operation • Battery is weakest portion of PV system	• Minor problem developed in the inverter working voltage supply due to heat and humidity	• End-use devices powered satisfactorily since installation	• Repairing inverters is a problem in remote areas--technical expertise is not available • Problems with replacement delays		• Initial cost and rates of return on investment are still unacceptable	
United Nations	• Reliability has been good							

1. Building power system (5.3 kW)
2. Industrial Society for Application of Solar Energy (SINAES)

At the Round Table Meeting held in November 1985, applications experts agreed that low power inverters present a weak link in a multi-use system (both in terms of reliability and efficiency losses). Inverter problems have driven system designers to install DC systems whenever possible. Since mini-utilities are traditionally AC (AC is a more efficient means of distributing power over large distances), the applications experts agreed that PV-powered mini-utilities offer limited viability at this time.

Complex operating procedures and over-sophistication of equipment and documentation have caused system implementation problems in developing countries. For example, in the grain mill and water pumping system in Tangaye, Bourkina Fasso, it was observed that the complexity of the original control system intimidated the technical support staffs of the in-country participating institutions (Reference 7-14). Although state-of-the-art equipment is moving to simpler designs, there is still room for improvement.

7.3.2 Infrastructure for System Management

The most important factor impacting the success of a multi-use system is the effectiveness of local management in operating the system. A sense of "ownership" results in a commitment to system success, ensuring an adequate supply of spare parts and availability of technical support.

As the systems get larger in size and/or consist of a larger variety of loads, effective management becomes more critical since the interests of a larger number of people must be integrated.

7.3.2 Rural Electrification Policy

The decision to procure one centralized system as opposed to many dispersed systems is a key policy issue (Reference 7-23). Traditionally, centralized systems have been preferred by funding organizations since their performance is more easily monitored. However, some governments, such as Papua New Guinea and French Polynesia, have made commitments to promote small individual systems (as discussed in Chapter 5). Although these government policies referred to home power systems (mini-load centers), the trade-offs also apply to the load centers discussed in this chapter.

Load centers do not require a distribution system throughout the village or metering systems. Also system failures impact a smaller sector of the population (e.g., sometimes only one household) than would be the case of a large centralized system. In the case of home power and other small systems, the PV modules can be mounted on roofs rather than dedicating valuable land to a large system. The management of power is much more complex in a centralized system since the interests of the entire community must be integrated and administrative support must also be available to coordinate a billing system.

CHAPTER 8

OVERVIEW OF FINANCIAL ANALYSES

8.1 Introduction

This section presents life-cycle cost comparisons of PV-powered systems and the most likely conventional alternative system in each of the five application areas (water pumping, communications, vaccine refrigeration, lighting and home power, and multi-use). These comparisons are intended to give the reader a first-order indication of when a PV-powered system should be considered for a particular application. The financial analyses are tailored to the decision-making perspective of development bank or borrowing country project officers. Thus, the financing parameters used in the analyses (amount financed, debt term, discount, and interest rate) are consistent with those for development bank loans, as opposed to those for commercial loans.

The cost comparisons are presented on two basic levels. First, detailed net present value life-cycle cost analyses are presented as 20-year cash flows comparing the conventional alternative to PV using specific base-case assumptions. Next, sensitivity analyses are presented that explore system comparisons as certain base-case assumptions are varied. In each case, the sensitivity analyses cover a range of possible application loads. A graphic presentation of these sensitivity analyses allows readers to estimate the comparative viability of PV versus conventional alternatives based on particular country-specific parameters.

8.2 Methodology

In each application area, conceptual designs are developed for PV- and conventional-powered systems to meet "base-case" load requirements. Each base case is intended to be representative of a typical application for which PV systems might be used. These two base-case systems are compared using a 20-year life-cycle cost analysis, whose output is the net present value (NPV) of the system's total capital and operating costs over the period. The NPV cost is presented as the annualized cost for each system. In cases where the same load(s) can be used for the PV- and conventional-powered systems, only the power systems are compared (i.e., load costs are not included). This is the case for communications, multi-use and the radio load in home power systems. Where different loads are required (pumping, refrigeration and home power system lights), comparisons are made between power/load systems. The assumptions used in each analysis are detailed in the following sections.

Sensitivity analyses were performed to determine how the NPV cost varies from the base case as the following key parameters changed:

- Equipment capital cost
- Conventional fuel cost (diesel or kerosene)
- Discount and interest rate
- Expected lifetime for conventional equipment (diesel)
- Insolation.

In some applications, additional sensitivities were examined, such as the variation in refrigeration life-cycle cost as a function of the number of vaccine doses per year or the operating availability of kerosene-fueled refrigerators. The results of these analyses are presented in graphic form in Chapters 9 through 13. These graphs provide the reader with an initial level of comparison between PV- and conventional-powered alternatives.

Finally, graphs were constructed for each application to show overall PV best- and worst-case viability over the given load range. These graphs were developed by compounding the extreme sensitivity parameters as follows: for the best-case PV viability, a curve was generated using the lowest discount and interest rate, highest fuel cost, shortest conventional system lifetime and highest insolation of the sensitivity parameter range. The worst-case curve was developed using the other extreme of the range.

8.2.1 Common Base-Case Assumptions

This section outlines the assumptions that are common to the base-case analyses in all five application areas. Assumptions unique to a particular application are detailed in the appropriate analysis chapter (Chapters 9 through 13).

Financial Assumptions

Common financial assumptions are outlined in Exhibit 8-1, and explanations of each parameter are provided below.

EXHIBIT 8-1. Common Base-Case Financial Assumptions

PARAMETER	ASSUMPTION
Debt Service	● 100% of system initial capital CIF cost ● capitalize CIF cost ● 20-year term ● 10% per year (compounded at the end of the year)
Salvage Value	● included
Installation Costs	● not included
Operating Labor	● not included
Diesel Fuel Cost	● $0.50 per liter
Kerosene Fuel Cost	● $0.70 per liter
General Inflation	● 5% per year
Nominal Discount and Interest Rate	● 10%

All costs for customs, insurance and freight are capitalized in the total system cost. The CIF value (cost, insurance and freight) is assumed to be 25% more than the FOB (Free on Board) manufacturer system cost (Reference 8-1). Installation costs are not included since these costs vary widely, according to the country and specific site. It is assumed that all systems are 100% financed for a debt term of 20 years at an interest rate of 10% per year, compounded at the end of each year (this is typical of a developing country loan). This assumption is made even for cases where expected equipment lifetimes may be much shorter than 20 years, such as diesel engine generator sets ("gen-sets"). Because the common analysis period of 20 years is desired, the initial capital cost in such instances is assumed to be 100% financed by the development loan; any subsequent capital replacement costs are represented as pure cash outlays at the end of each estimated equipment lifetime.

Maintenance parts costs are generally specified as a percentage of the initial capital cost. For the most part, maintenance costs appear as recurring annual costs, although some systems such as diesel gen-sets also require periodic major maintenance overhaul. These overhaul costs are estimated as a percentage of the original capital cost and are assumed to occur at a specified frequency throughout the 20-year analysis. Operating labor is not included as a recurring project cost because this cost varies widely, even within the same country.

Nominal fuel costs are assumed to be $0.50 per liter for diesel and $0.70 per liter for kerosene. These numbers are based on values cited in the questionnaire responses (15 citations for diesel fuel costs and 13 for kerosene fuel costs), values listed in the World Bank's Domestic Petroleum Product Prices (Reference 8-2) and discussions with principals from major refrigeration programs (Reference 8-3).

All operating costs (including fuel) are escalated at a general inflation rate of 5% per year for all base-case life-cycle analyses. In addition, recurring costs are appropriately inflated for the year of their occurrence. A 10% nominal discount rate was used to obtain the net present value (NPV) costs of all base-case cash flows.

Technical Assumptions

Specifications such as the power system size required for the typical system in each application area were developed as part of this evaluation. These specifications are discussed in Chapters 3 through 7 of this report. The key technical assumptions common to the base-case analyses are identified in Exhibit 8-2.

EXHIBIT 8-2. Common Base-Case Technical Assumptions
(References 8-3, 8-4, 8-5 and 8-6)

	SYSTEM TYPE		
SPECIFICATION	PV	DIESEL	KEROSENE
Component Life (Years)			
- Array	20	NA	NA
- Gen-Set	NA	6	NA
- Power Conditioning	10	10	NA
- Batteries	5	5	2*
- Loads	5	5	10 - refrig. 3 - lights
Major Maintenance			
- Engine Overhaul	NA	every 3 years	NA

NA - Not applicable
* - Batteries used in conventional home power systems

The availability of power/load systems is defined as the percentage of time the system operates within technical specifications. Potential causes of system unavailability include:

- Scheduled downtime and regular maintenance
- Downtime for repair (including unavailability of spare parts)
- No fuel
- No sun
- Operating outside of specifications (e.g., a refrigerator operating outside the appropriate temperature range or a power system providing energy to the loads outside the voltage range at which the loads can function).

The availability values that were chosen for the PV- and conventional-powered systems in each application are outlined in Exhibit 8-3. These values are discussed in more detail in the individual analysis sections (Chapters 9 through 13). The values are based on an uninterrupted supply of fuel (except in the case of kerosene refrigeration). This is an optimistic assumption, particularly for conventional power systems. If, for example, there is no diesel fuel for 1 month out of the year, diesel system availability would decrease by an additional 8%, raising the NPV cost for diesel-powered systems approximately 9%.

EXHIBIT 8-3. System Availability

APPLICATION	AVAILABILITY (%)	
	PV	CONVENTIONAL
Pumping[1]	95	95
Communications[2]	99.9	99.9 (2 diesels @ 97.5)
Refrigeration[1]	95	50*
Home Power	NA	NA
Multi-Use[2]	97.5	97.5

1. Availability of power/load system.
2. Availability of power system.

* - Includes unavailability of fuel.
NA - Not applicable (i.e., system-specific availability not determined but assumed to be equal).

The availability values also do not quantify the availability of spare parts and operation, maintenance and repair services. Clearly, all analyses depend on the reasonable availability of parts and service; otherwise, the assumptions of system lifetime and availability should be adjusted downwards accordingly.

Gasoline gen-sets are not examined in the comparative cost analyses. However, the following information is provided as reference material (Reference 8-5):

- Gasoline gen-sets are available in sizes ranging from 300 watts to 100 kilowatts, although systems in the low end of that spectrum (< 3 kW) are predominantly used.

- Gasoline gen-sets in the low size range offer the advantage of increased portability.

- Gasoline gen-sets have lower initial capital costs than diesel gen-sets. In the less than 3-kW range, gasoline gen-sets cost $400 to $900 per kW.

The minimum size diesel gen-set is approximately 3 kW and costs approximatly $1800 per kW.

- Gasoline fuel is more expensive (by approximately 50% to 100%) on a $/liter basis than diesel fuel. For example, in Sudan, diesel fuel costs $0.51/liter, while gasoline costs $1.02/liter.

- Gasoline gen-sets have a higher fuel consumption rate than diesel gen-sets. Full-load fuel consumptions were determined to be 1 liter/kW/hour (in the 0.5 to 3-kW range) and 0.4 liter/kW/hour (in the 3 to 25-kW range) for gasoline and diesel gen-sets, respectively.

- Gasoline gen-sets have a much shorter lifetime than diesel gen-sets (3000-5000 hours versus 20,000 hours).

Chapters 9 through 13 present the financial analyses performed for each of the applications. The models used to perform the technical sizing and life-cycle cost comparisons are described in Appendix D.

Credibility of Financial Analyses Assumptions

This discussion addresses whether the financial assumptions used in this evaluation result in conservative or optimistic assessments of PV system financial attractiveness. Overall, it is believed that the assumptions balance each other out, resulting in an unbiased analysis for the development loan scenario.

Conservative assessments of PV financial viability resulted from the following assumptions:

- The analyses do not include the labor costs associated with operation, maintenance and repair because they are country- and site-specific. This assumption is considered conservative because conventional systems generally require more of these services than PV-powered systems.

- The supply of spare parts and fuel is assumed to be uninterrupted. Field reports indicate that the unreliable supply of these items has been a major cause of conventional-powered system unavailability.

- No price reductions are assumed for system components. Because the conventional power systems represent a stabilized market, price reductions are not anticipated. However, because PV power systems involve developing technologies and little mass production, component prices are expected to decline over the years, thus making the replacement costs used in the analyses high.

Optimistic assessments of PV financial viability resulted from the following assumptions:

- No system design costs are included. PV-powered systems generally involve more costly design phases, since packaged systems and standard designs are not yet available across all applications.

For some assumptions, it is uncertain whether they have a conservative, optimistic or neutral effect on PV system financial viability. These assumptions include:

- Because the evaluation involved a financial analysis, macroeconomic considerations such as shadow pricing and tax revenue are not addressed.

- The implication of tax benefits to the system owner is unclear.

- Most costs are based on the purchase of one system. It is recognized that the block purchases typical of institutional procurements result in significant system cost reductions for PV systems. Data on the effect of conventional system block purchases was unavailable.

- A 20-year PV array life is assumed. While accelerated life testing indicates that current PV arrays have lifetimes greater than 20 years, these arrays have not yet been in the field for 20 years.

The assumptions used in the financial analyses were based on development bank loans. For commercial loans, the assumptions for loan term and percent of the loan financed are considered high. Thus, the financial results show greater PV viability than would exist under a commercial setting.

CHAPTER 9

WATER PUMPING ANALYSIS

9.1 Overview

The financial analysis presented in this chapter compares PV-powered water pumping systems to diesel-powered systems for rural water supply, assuming development agency financing. The analysis shows that PV-powered systems are the least-cost option at demands of up to 25 m^3/day at a head of 25 meters (625 m^4/day), even under unfavorable financial assumptions (see Exhibit 9-1). When the financial parameters are more favorable, PV-powered systems are competitive up to 550 m^3/day (13,750 m^4/day).

The graph in Exhibit 9-1 depicts the ratio of PV- to diesel-powered pumping system net present value costs for the best PV case and worst PV case scenarios. Both scenarios assume 20-year life-cycle costing and development agency financing. At an NPV cost ratio of 1.0, PV and diesel system life-cycle costs are equal. Under the best PV case scenario, the five parameters shown on the graph are adjusted to "reasonable extremes" that favor PV systems. An opposite adjustment is made under the worst PV case scenario. The area between the two curves represents a reasonable range of financial assumptions.

This range indicates that PV-powered pumping systems are the least-cost option at loads much greater than shown by a 1983 UNDP/World Bank study (Reference 9-1). It showed PV systems to be competitive up to 250 m^4/day as opposed to the 625 to 13,750 m^4/day demonstrated in this report. The major reasons for this difference are: (1) the assumption of 20-year development bank financing; (2) the consideration of diesel system inefficiencies when the system is operated substantially below rated capacity, and (3) recent improvements in the cost and performance of PV systems.

Exhibit 9-2 depicts the various cost elements of PV- and diesel-powered pumping systems. The sensitivity analyses presented in this chapter indicate that diesel lifetime, fuel cost, discount and interest rate, insolation, and pumping head all have a strong impact on the cost analysis.

EXHIBIT 9-1. Sensitivity of Water Pumping Costs to Best and Worst Conditions

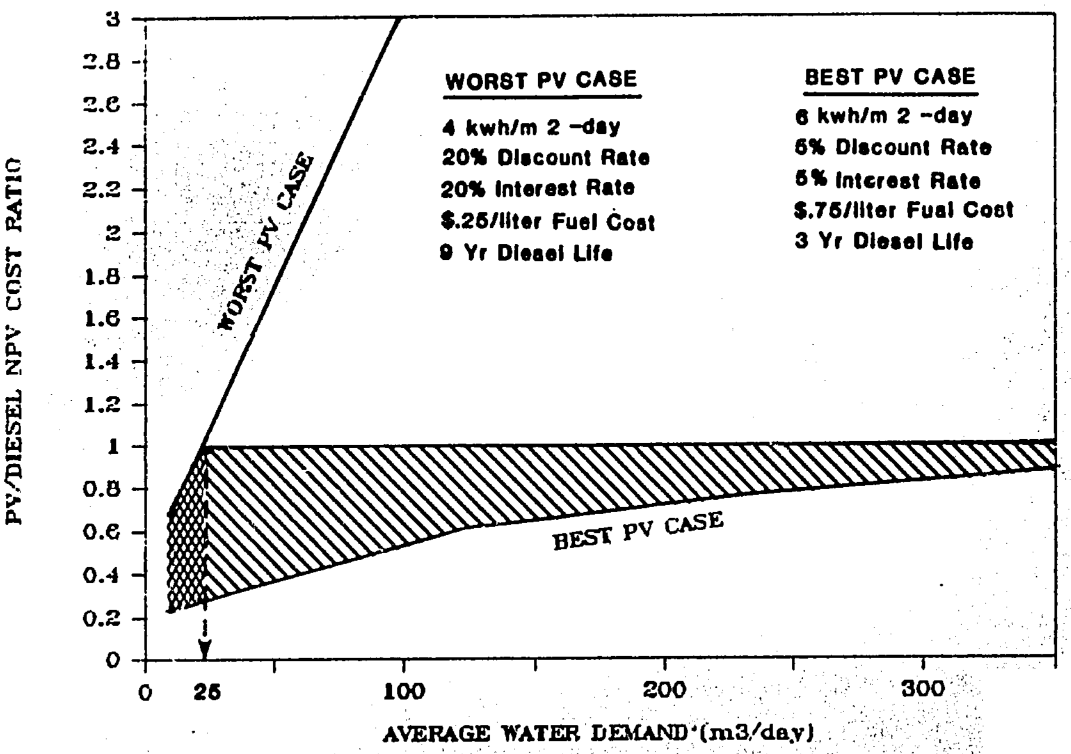
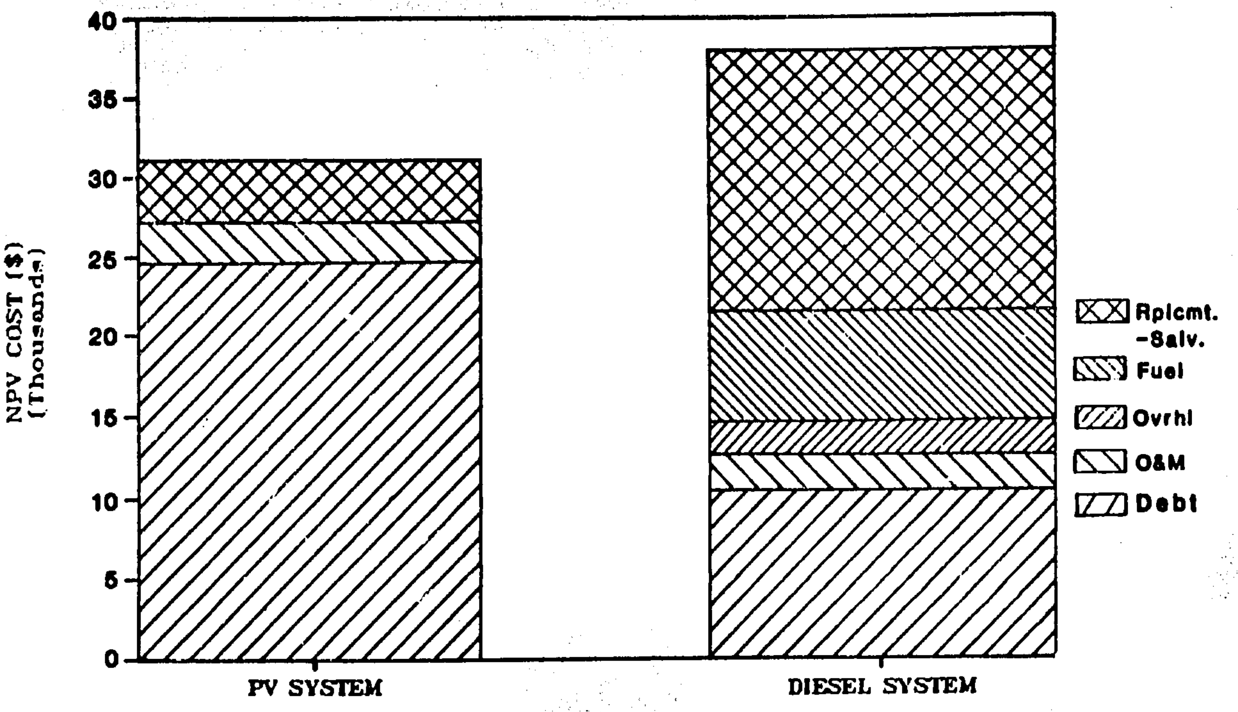


EXHIBIT 9-2. Base-Case Water Pumping System Cost Components



9.2 Description of the Base Case

Based on field experience with pumping applications, the base-case load requirement chosen for this analysis is an average daily water demand of 50 m^3 to be pumped through a 25-meter head. This load is representative of a village drinking water system that supplies water to approximately 1,250 to 2,500 people (based on 20 to 40 liters per person per day). It is assumed that the load varies throughout the year, reaching a maximum that is 50 percent higher than the average, or 75 m^3/day. It is further assumed that the well is capable of yielding the volume and the pump flow rate demanded of it.

The conventional alternative chosen for this analysis is a diesel engine with a generator set connected to an AC motor and pump. For both the PV- and conventional-powered systems, it is assumed that water is pumped into a storage tank. Thus, the total head included an assumption of some vertical distance to the tank height. Because the well and tank are considered to be the same for both systems, their costs are not included in the analysis. The PV and diesel systems are further described below, including discussions of system cost determinations.

The availability of both pumping systems is assumed to be 95%. This figure is considered conservative for the PV-powered system, and, since it does not include unavailability of fuel, it is optimistic for the diesel-powered system.

9.2.1 PV-Powered System Description

The PV-powered pumping system design chosen for the base-case analysis consisted of the following primary components:

- PV array (2.3 kWp)
- DC motor/centrifugal pump
- Voltage regulator
- Wiring, valves, etc.

No batteries were included because a low starting current for the motor is assumed and because storage for periods of low insolation can be inexpensively provided by a water tank sized for more than 1 day of storage. The average insolation incident on the array during the period of maximum demand is 5 kWh/m^2-day. It is assumed that the pump automatically starts with the sun (i.e., no operator). The system is sized according to the graphs presented in Section 3.2. Excess water pumping capacity beyond the annual demand is disregarded when performing cost calculations.

9.2.2 Diesel-Powered System Description

The diesel-powered pumping system chosen to meet the base-case pumping requirements consists of the following primary components:

- Diesel gen-set (6.4 kW)
- AC motor/pump
- Wiring, valves, etc.

The diesel-powered pumping system is specified to operate during one period of the day at a maximum load factor of 75%. This load factor is based on user and manufacturer recommendations for optimum use to ensure maximum diesel engine life. The duration of the daily pumping period is based on the time required to pump the average daily volume requirement into the storage tank at 75% diesel load factor. It is further specified that the diesel gen-set operate for at least 1 hour per day. Because diesel gen-sets are not commonly available in sizes less than 3 kW, a 3-kW diesel gen-set must operate at less than 75% load factor in cases of small pumping demands in order to meet the 1-hour requirement.

The pump has a maximum flow rate capability of 35 m^3/hour. This flow rate minimizes the time needed to operate the diesel over the range in demands analyzed.

9.3 System Costs

9.3.1 PV-Powered Pumping System Costs

The FOB manufacturer costs of PV-powered pumping systems have dropped dramatically from approximately $30/Wp in 1978 to less than $10/Wp in 1986 (Reference 9-2). Assuming several systems are purchased at a time, current installed system costs range from about $11/Wp to $14/Wp. Costs vary over this range as a function of the pump selected, site-specific conditions and other options. Exhibit 9-3 lists some of the PV-powered pumping system costs obtained during the course of this evaluation. The costs shown include CIF and installation costs.

EXHIBIT 9-3. PV-Powered Pumping System Costs[1]

PERFORMANCE REQUIREMENT (VOLUME, HEAD)	PUMP/MOTOR TYPE	ARRAY SIZE (Wp)	INSOLATION (kWh/m^2-day)	INSTALLED COSTS ($/Wp)	REFERENCE
230 m^3/day, 2 meters	Centrifugal, Single-Stage DC Brushless	516	6	13.7	9-3
13 m^3/day, 3 meters	Centrifugal, Single-Stage, DC Brushless, Floating	85	6	11.8	9-4
76 m^3/day 11 meters	Centrifugal, DC Motor Drive, Surface Mounted	770	5	11.7	9-5
70 m^3/day, 27 meters	Centrifugal, Multi-Stage, AC Submersible	1500	-	13.3	9-6
30 m^3/day, 65 meters	Centrifugal, Multi-Stage, AC Submersible	1500	-	13.3	9-6
25 m^3/day, 34 meters	Jack pump, DC driven	800	-	13.8	9-6
			Average	12.9	

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[1] Based on system prices from 1983 to 1985.

A summary of the costs assumed for the base-case PV-powered pumping system is presented in Exhibit 9-4. An initial capital cost of $10.5/Wp (not including installation costs) was selected for the base case. This value is considered consistent with the installed costs presented in Exhibit 9-3. It is assumed that the motor/pump set, voltage regulator and valves will be replaced during the 20-year financial analysis period. These components are assumed to have a 5-year life and an FOB manufacturer cost of approximately $1,635 in year one (Reference 9-7). In the cash flow, this cost is escalated 5% per year (the assumed general inflation rate for all the base cases) to the year of replacement. The only other cost assumed for PV-powered pumping systems is the annual maintenance and repair cost. This cost is for items not included in the regular replacement of components (e.g., lubrication of pump parts, replacement of brushes if necessary, etc.). For the base case, these costs amount to 1% of the initial capital cost (Reference 9-7).

EXHIBIT 9-4. Base-Case PV-Powered Pumping System Costs

SPECIFICATION	COST
Initial Capital Costs (FOB manufacturer)	
- PV Array (2.3 kWp)	$18,149
- Pump/Regulator/Valves	1,635
Total Capital Cost	$19,784
Recurring Capital Costs (FOB manufacturer)	
- Pump/Regulator/Valve Replacement	$1635 every 5 years*
Other Recurring Costs (% Initial Capital Costs)	
- Maintenance and Repair	1%/year*

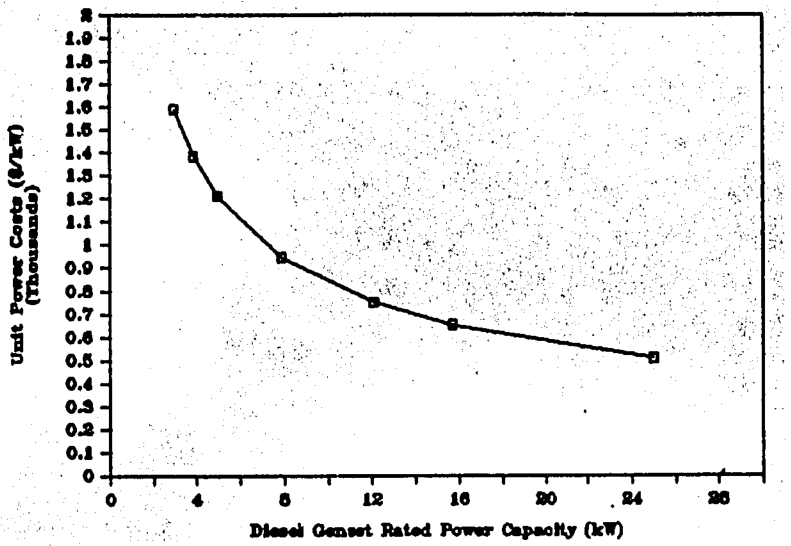
* Plus the appropriate escalation due to general inflation.

9.3.2 Diesel-Powered Pumping System Costs

Capital Costs

Initial capital costs (FOB manufacturer) for diesel gen-sets are provided for generators ranging in size from 3 to 25 kW (Reference 9-8). (Diesel gen-sets are not commonly available below 3 kW.) A regression analysis was performed on the available cost data to obtain a continuous curve of capital cost over the size range. Exhibit 9-5 presents this cost regression. It is assumed that the diesel gen-set will be replaced every 6 years.

EXHIBIT 9-5. Diesel Gen-Set Costs (Reference 9-7)



Initial costs (FOB manufacturer) for AC motor/pumps to be used in conjunction with the diesel gen-sets for various flow rates at different heads are provided in Exhibit 9-6 (Reference 9-8). It is assumed that the AC motor/pump and valves are replaced every 5 years. For this particular analysis, the cost for these items amounts to $1,564.

EXHIBIT 9-6. AC Pump Costs (Reference 9-8)

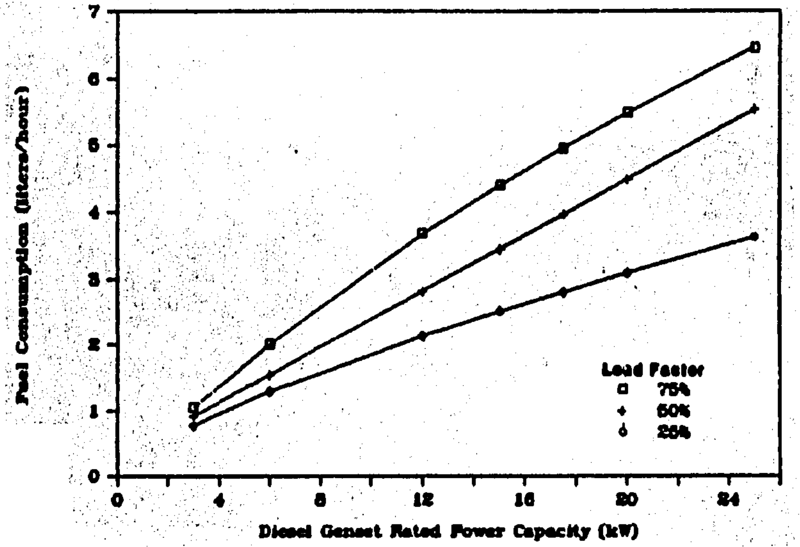
AC PUMP COSTS (Actual Data)		
Flow Rate (m^3/hr)	Head (m^3)	Cost ($)
0.6	10	325
0.6	25	325
0.6	40	359
3.0	10	325
3.0	25	325
3.0	40	550
12.0	10	822
12.0	25	822
12.0	40	1,713
35.0	10	1,564
35.0	25	1,564
35.0	40	1,983

Operating Costs

Operation, maintenance and repair costs are significant in diesel-powered pumping systems. These include the costs associated with fuel, engine overhauls, and miscellaneous maintenance and repair items.

Fuel consumption rates vary as a function of the size of the engine, the engine's efficiency, the number of hours the engine runs, and the load factor at which the engine operates. Exhibit 9-7 presents fuel consumption rates (in liters/hour) at 1/4-, 1/2- and 3/4-load for gen-sets ranging in size from 3 to 25 kW (Reference 9-9). For each comparative financial analysis, the average load factor is calculated, then the appropriate fuel consumption rate is selected. The average number of operating hours is also computed, which allows the total annual fuel cost to be determined.

EXHIBIT 9-7. Fuel Consumption Rates (Reference 9-9)



Engine overhauls were assumed to be performed every 3 years. The cost associated with an overhaul was estimated to be equivalent to 15% of the initial capital cost of the engine. Miscellaneous maintenance and repair for the system are assumed to be equivalent to 2% of the system capital cost (Reference 9-7).

The operating and capital costs associated with the base-case diesel-powered pumping system are outlined in Exhibit 9-8.

EXHIBIT 9-8. Base-Case Diesel-Powered Pumping System Costs

SPECIFICATION	COST
Initial Capital Costs (FOB manufacturer)	
- Diesel Gen-Set (6.4 kW)	$6,754
- Pump/Valves	1,564
Total Capital Cost	$8,318
Recurring Capital Costs (FOB manufacturer)	
- Diesel Gen-Set Replacement	$6,754 every 6 years*
- Pump/Valve Replacement	$1,564 every 5 years*
Other Recurring Costs	
- Engine Overhaul	15% of initial gen-set cost every 3 years*+
- Maintenance & Repair	2% of initial system cost per year*
- Fuel Cost (1,104 liters @ $0.50/liter)	$552/year*

* Plus appropriate escalation due to general inflation.
\+ Engine overhauls not performed during replacement years.

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9.4 Twenty-Year Life-Cycle Costs

Using the base-case assumptions, 20-year cash flows are estimated. The cash flows for the PV- and diesel-powered pumping systems are shown in Exhibits 9-9 and 9-10, respectively. The results of the cash flows are expressed as the total net present value cost for PV- and diesel-powered systems (assuming 50m^3/day pumping volume and a 25-meter head). For the base case, these cash flows demonstrate that PV is a slightly more cost-effective option: the NPV cost for PV was $31,166, and the NPV cost for diesel was $38,021.

The complete technical and financial model used to generate these cash flows and the sensitivity analyses presented in the following sections is provided in Appendix D.

EXHIBIT 9-9. PV-Powered Pumping System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$2,905	$24,729
Operating & Maintenance Expenses:																					
Annual Maintenance	$208	$218	$229	$240	$252	$265	$278	$292	$307	$322	$338	$355	$373	$392	$411	$432	$453	$476	$500	$525	$2,516
Recurring Capital Costs:																					
Pump, Reg, Valve Cost	$0	$0	$0	$0	$2,608	$0	$0	$0	$0	$3,329	$0	$0	$0	$0	$4,249	$0	$0	$0	$0	$0	$3,920
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Cash Outflow:	$3,112	$3,123	$3,134	$3,145	$5,766	$3,170	$3,183	$3,197	$3,212	$6,556	$3,243	$3,260	$3,278	$3,296	$7,565	$3,337	$3,358	$3,381	$3,405	$3,430	
Discount Factor (DF) DF = 1/((1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$2,829	$2,581	$2,354	$2,148	$3,580	$1,789	$1,633	$1,491	$1,362	$2,528	$1,137	$1,039	$949	$868	$1,811	$726	$664	$608	$557	$510	
TOTAL NPV OF CASH OUTFLOW	$31,166																				
Annual Water Pumped (m3)	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	

EXHIBIT 9-10. Diesel-Powered Pumping System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$1,221	$10,398
Operating & Maintenance Expenses:																					
Annual Maintenance	$175	$183	$193	$202	$212	$223	$234	$246	$258	$271	$285	$299	$314	$329	$346	$363	$381	$400	$420	$441	$2,116
Diesel Engine Overhaul	$0	$0	$1,173	$0	$0	$0	$0	$0	$1,572	$0	$0	$0	$0	$0	$2,106	$0	$0	$0	$0	$0	$2,052
Fuel	$580	$609	$639	$671	$705	$740	$777	$816	$856	$899	$944	$991	$1,041	$1,093	$1,148	$1,205	$1,265	$1,328	$1,395	$1,465	$7,020
Recurring Capital Replace Cost:																					
Pump, Reg, Valve Costs	$0	$0	$0	$0	$2,495	$0	$0	$0	$0	$3,184	$0	$0	$0	$0	$4,064	$0	$0	$0	$0	$0	$3,750
Diesel Gen Replace Cost	$0	$0	$0	$0	$0	$11,314	$0	$0	$0	$0	$0	$15,162	$0	$0	$0	$0	$0	$20,319	$0	$0	$14,372
Salvage	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$14,714	$2,187
Total Cash Outflow:	$1,976	$2,013	$3,226	$2,095	$4,633	$13,498	$2,232	$2,283	$3,907	$5,576	$2,450	$17,674	$2,576	$2,644	$8,885	$2,789	$2,868	$23,269	$3,037	($11,587)	
Discount Factor (DF) DF = 1/((1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$1,796	$1,664	$2,424	$1,431	$2,877	$7,619	$1,145	$1,065	$1,657	$2,150	$859	$5,631	$746	$696	$2,127	$607	$567	$4,185	$497	($1,722)	
TOTAL NPV OF CASH OUTFLOW	$38,021																				
Annual Water Pumped (m3)	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	17,338	

9.5 Sensitivity Analyses

The graphs on the following pages demonstrate the projected sensitivity of the net present value (NPV) life-cycle pumping cost as a function of changes in six key variables--capital cost, discount and interest rate, fuel cost, diesel system lifetime, insolation and pumping head. The general relationship shows diesel-powered systems becoming more cost-effective at larger demands. This relationship is due to the decreasing costs of diesel-powered systems versus the almost linear costs for PV-powered systems on a cost per unit volume basis.

The graphs present data in terms of the ratio between the PV- and diesel-powered system life-cycle costs. Therefore, when this ratio is less than 1.0, the PV-powered system is projected to provide lower life-cycle costs. For the capital cost sensitivity, the NPV costs are presented individually for PV and diesel (i.e., not in ratio form).

The base-case analysis assumes a head of 25 meters. NPV life-cycle costs are considered valid for systems where the average pump/motor efficiency is 50% and pump/motor costs are similar to that used in this analysis.

9.5.1 Sensitivity to Capital Cost

This section examines the effect of changing capital cost estimates for both diesel- and PV-powered systems. The effect is modeled as a "cost multiplier," which is examined at values of 0.75, 1.0 and 2.0, with 1.0 equaling the base-case estimate. The range of multipliers is intended to account for system capital cost variations. These variations can result from different cost, insurance, and freight (CIF) equipment costs and can account for installation costs, which are very country- and site-specific. This sensitivity is depicted individually for PV- and diesel-powered systems in terms of their NPV costs in Exhibits 9-11 and 9-12.

EXHIBIT 9-11. Sensitivity of PV-Powered Pumping Costs to Capital Cost

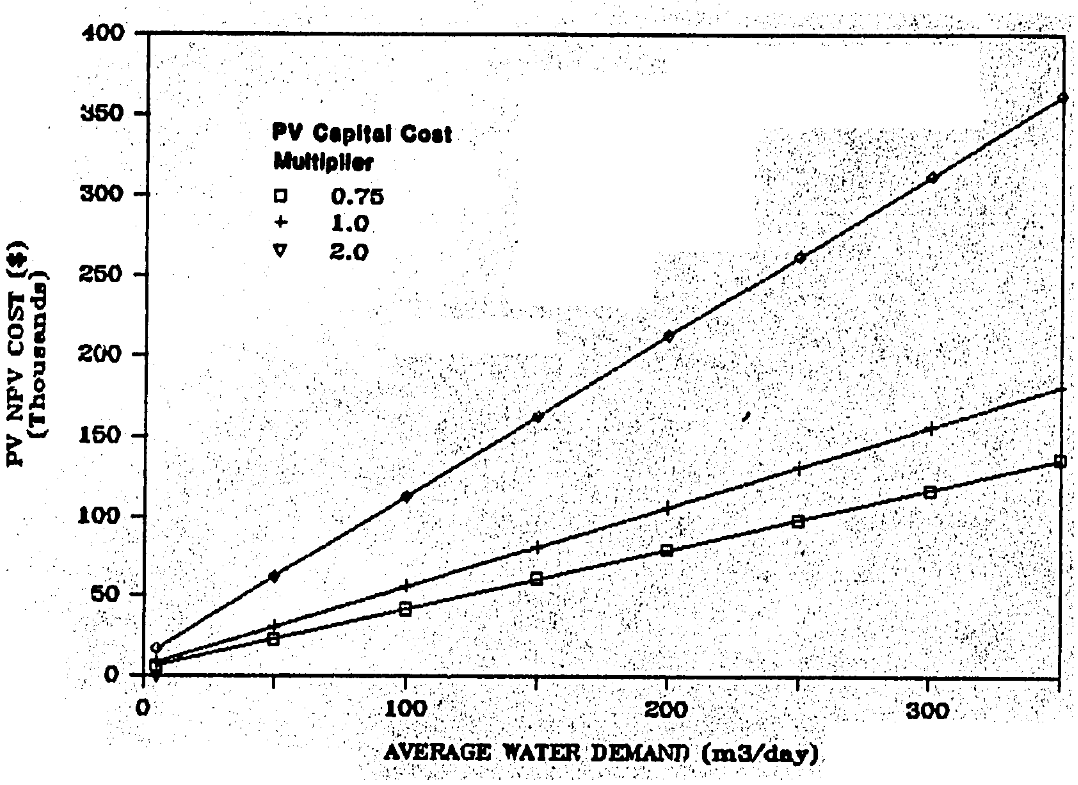

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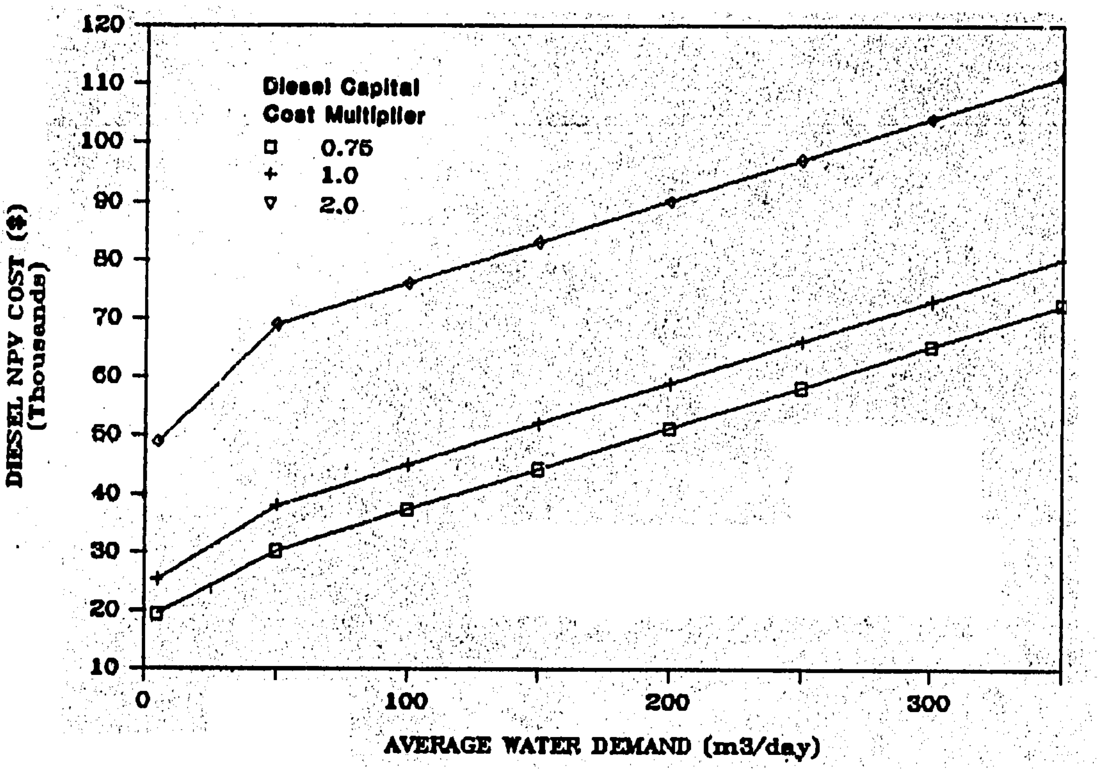
EXHIBIT 9-12. Sensitivity of Diesel-Powered Pumping Costs to Capital Cost



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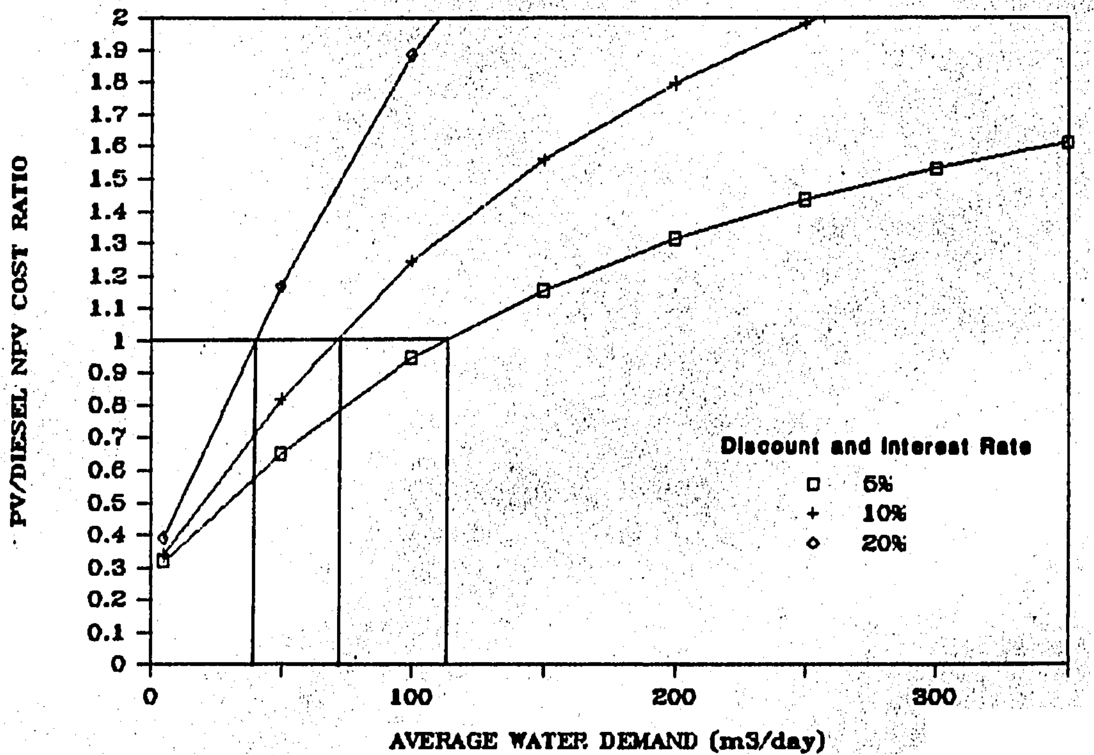
9.5.2 Sensitivity to Discount and Interest Rate

This analysis (Exhibit 9-13) examines the changes that occur in comparative life-cycle pumping costs as the discount and interest rate applied to each cash flow is varied between 5% and 20%. As the rate increases from the 10% base-case rate, the obvious effect on both systems is a decrease in overall life-cycle costs. However, the diesel pumping cost shows a greater decrease than that of the PV system. This occurs because the diesel cash flows have a higher proportion of escalating recurring costs versus the level payments for debt services. Therefore, the effective reduction of this escalating diesel cost burden at higher discount and interest rates produces a greater net present value cost reduction than in the PV cash flow, which is dominated by its large proportion of levelized debt service.

The graph in Exhibit 9-13 demonstrates this disproportionate impact. At a 20% discount and interest rate, PV systems hold an NPV cost advantage for pumping loads only up to 40 m^3/day, whereas at a 5% discount and interest rate, PV pumping systems appear to have an advantage up through approximately 112 m^3/day of pumping demand.

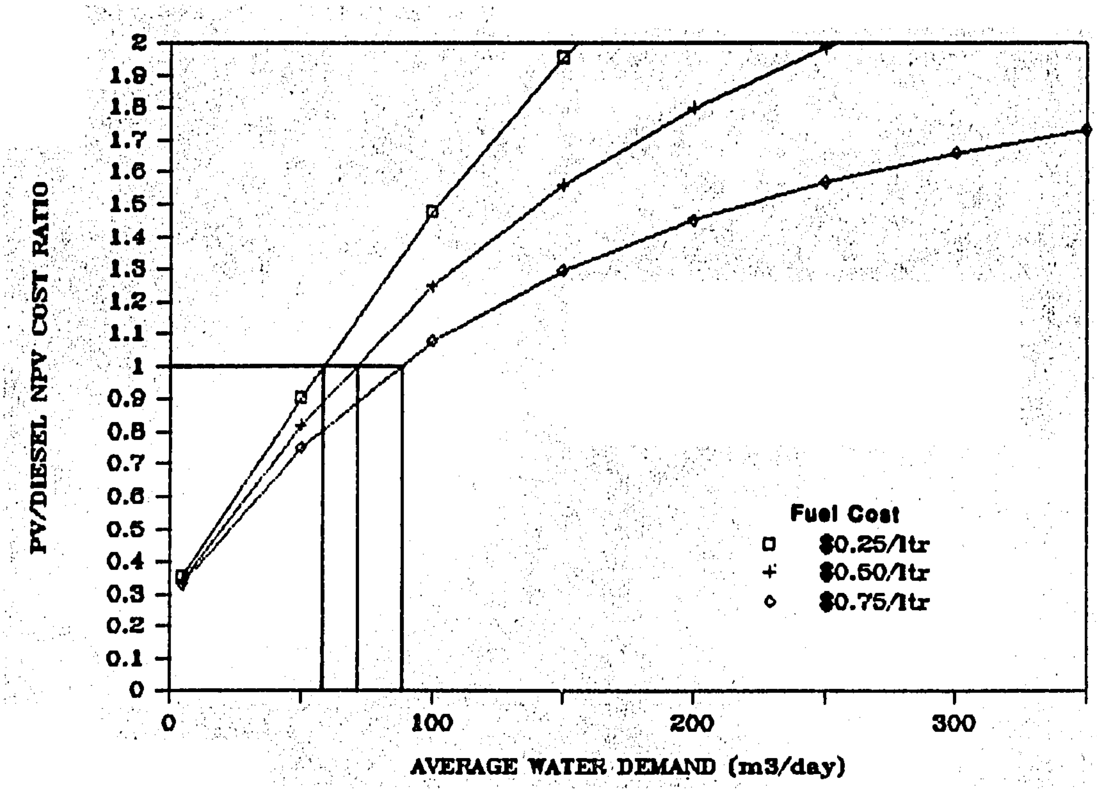
EXHIBIT 9-13. Sensitivity of Pumping Costs to Discount and Interest Rate



9.5.3 Sensitivity to Diesel Fuel Cost

This section examines the changes that occur in comparative life-cycle pumping costs as the cost of diesel fuel varies from $0.25 per liter to $0.75 per liter (i.e., 50% lower and 50% higher than the base-case price of $0.50 per liter). Exhibit 9-14 shows that for the base case of $0.50 per liter, diesel-powered life-cycle pumping costs become lower than PV-powered costs at pumping loads of approximately 70 m^3/day or higher. At $0.25 per liter, this crossover occurs at 57 m^3/day, and at $0.75 per liter, not until 90 m^3/day. Clearly, the higher the diesel fuel cost, the larger the pumping demand range over which PV-powered systems have a financial advantage.

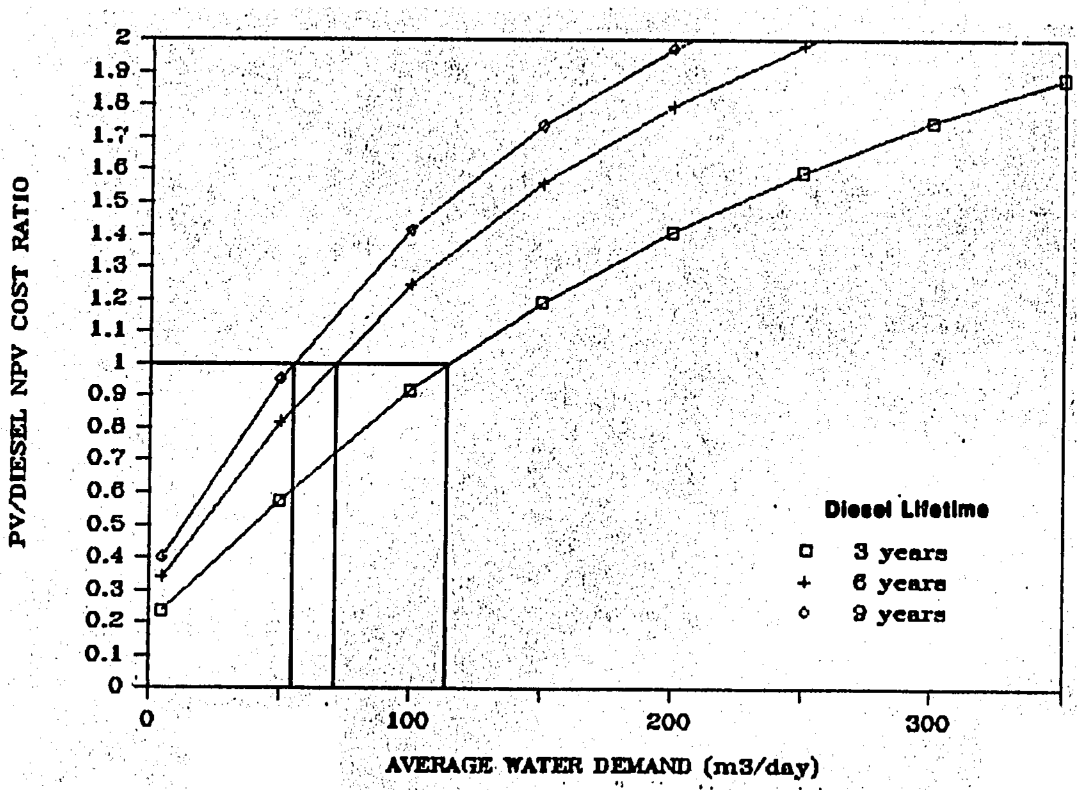
EXHIBIT 9-14. Sensitivity of Pumping Costs to Diesel Fuel Cost



9.5.4 Sensitivity to Diesel System Lifetime

It has been debated that the lifetime expectations for diesel power systems can vary widely as a function of the quality and frequency of maintenance in developing countries. This section explores the effect on pumping costs of assuming diesel lifetimes of 3 years and 9 years, as compared to the base-case assumption of 6 years. The financial impact of varying this assumption appears as more or less frequent diesel system replacement costs in the cash flow projections. While Exhibit 9-15 shows the base-case diesel system becoming less costly at pumping loads of approximately 71 m^3/day or higher, for a diesel life of 3 years, this crossover occurs at about 115 m^3/day, and at 9 years it occurs at only 54 m^3/day.

EXHIBIT 9-15. Sensitivity of Pumping Costs to Diesel Lifetime



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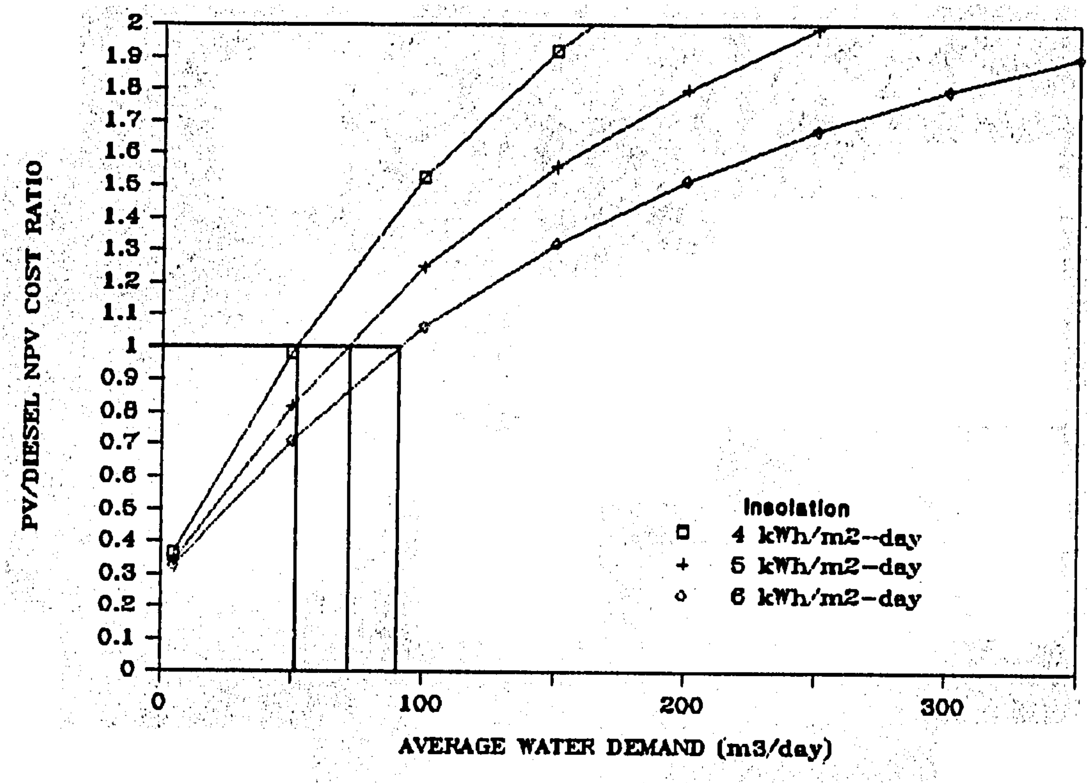
9.5.5 Sensitivity to Insolation

Exhibit 9-16 presents a graph comparing the life-cycle costs of PV- and diesel-powered systems over a range of pumping demands (m^3/day) and at varying insolation levels. For the base-case average daily insolation of 5 kWh/m^2-day, the break-even point between PV and diesel costs is about 70 m^3/day. By varying the insolation to as low as 4 kWh/m^2-day and as high as 6 kWh/m^2-day, the break-even points range from approximately 50 m^3/day to 90 m^3/day respectively.

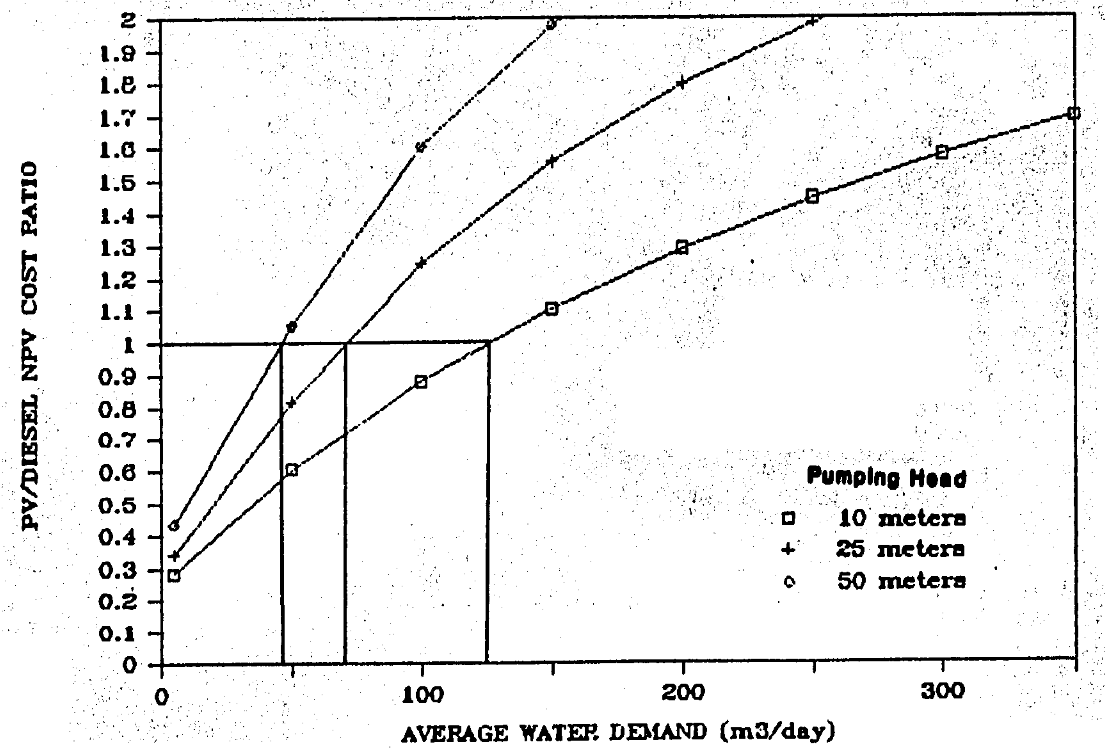
EXHIBIT 9-16. Sensitivity of Pumping Costs to Insolation



9.5.6 Sensitivity to Pumping Head

Exhibit 9-17 presents a graph comparing the life cycle costs of PV- and diesel-powered systems over a range of pumping demands (m^3/day) and at varying pumping heads (meters). For the base-case pumping head of 25 meters, the break-even point between PV and diesel costs is approximately 70 m^3/day. As pumping head is varied to as low as 10 meters and as high as 50 meters, the breakeven points range from approximately 125 m^3/day to 45 m^3/day, respectively. This sensitivity follows the general relation between energy demand and PV system financial viability since pumping head times volume is directly related to energy. PV system financial competitiveness compared to diesel increases with decreasing energy demand.

Exhibit 9-17. Sensitivity of Pumping Costs to Pumping Head.



CHAPTER 10

COMMUNICATIONS ANALYSIS

10.1 OVERVIEW

The financial analysis presented in this chapter compares PV- and diesel-powered microwave repeater systems assuming development agency financing. The analysis shows that PV-powered systems are the least-cost option at daily energy demands of up to 5 kWh, even under unfavorable financial assumptions (see Exhibit 10-1). When the financial parameters are more favorable, PV-powered systems are competitive up to 24 kWh per day. These results are consistent with the substantial number of commercial PV applications that are in place today.

The graph in Exhibit 10-1 depicts the ratio of PV- to diesel-powered communications life-cycle costs for the best PV case and worst PV case scenarios. Both scenarios assume 20-year life-cycle costing and development agency financing. At an NPV cost ratio of 1.0, PV and diesel system life-cycle costs are equal. Under the best PV case scenario, the five parameters shown on the graph are adjusted to "reasonable extremes" that favor PV systems. An opposite adjustment is made under the worst PV case scenario. The area between the two curves represents a reasonable range of financial assumptions.

Exhibit 10-2 depicts the various cost elements of PV- and diesel-powered microwave repeater systems. PV life-cycle costs are equally divided between debt service (initial system cost) and battery replacement, suggesting that battery life and cost are important parameters. The cost of diesel-powered systems is heavily dependent on fuel cost. Based on this information and the sensitivity analyses presented in this chapter, the major cost parameters in this analysis were determined to be battery life and cost, fuel cost, and diesel system lifetime.

The remainder of this chapter discusses the analyses and assumptions leading to Exhibits 10-1 and 10-2.

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EXHIBIT 10-1. Sensitivity of Communications Costs to Best and Worst Conditions

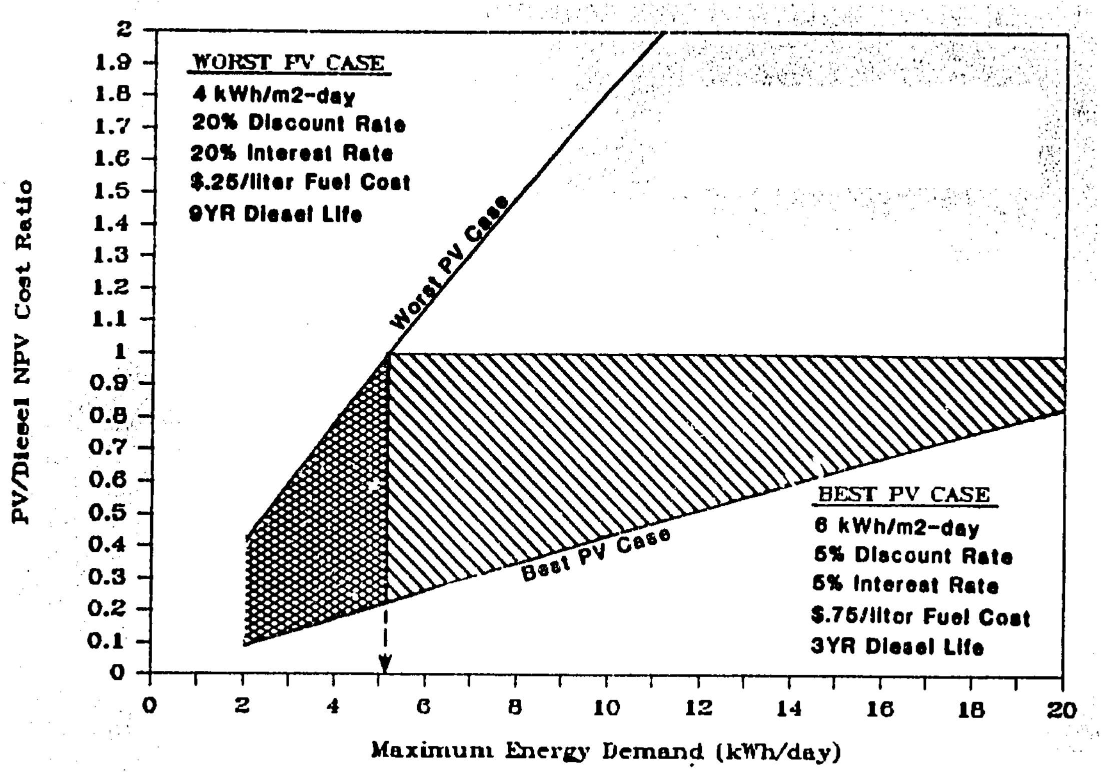
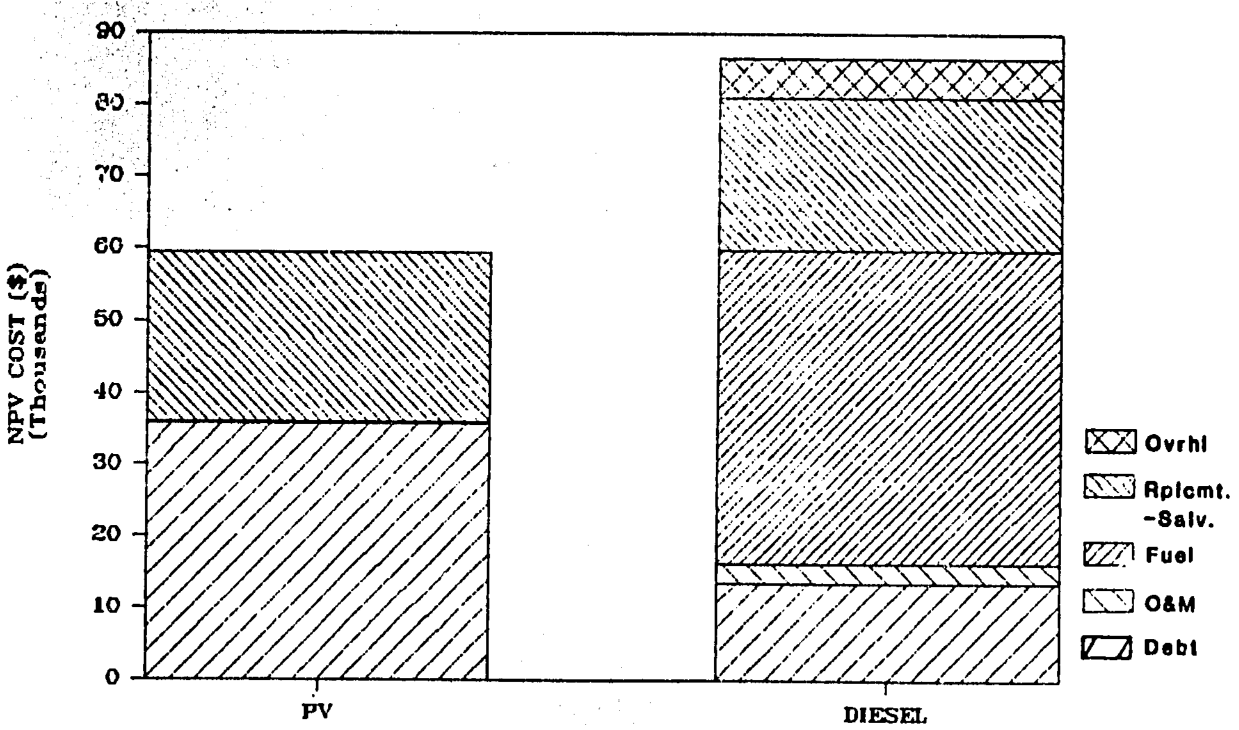


EXHIBIT 10-2. Base-Case Communications System Cost Components



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10.2 Description of the Base Case

The application considered for the base-case communications system was a DC-powered microwave repeater station. The repeater itself was assumed to be identical for both the PV- and conventional-powered systems. Therefore, the financial comparison is performed only between power systems, excluding any load costs. The base-case power requirement chosen for the typical load is a constant 7.2 kWh/day. Maximum daily load is equal to the constant daily load. Continuous 24-hour operation is assumed to be a critical design parameter.

The base-case conventional power system is a tandem diesel generator system. It is assumed that the supply of diesel fuel and PV and diesel spare parts is never interrupted. The PV and diesel power systems are discussed in detail in the following sections.

10.2.1 PV Power System Description

The components for the base-case PV power system for communications applications include:

- PV array (2.3 kWp)
- Charge controller
- Battery storage (63 kWh).

Battery storage is sized for 7 days. The lowest-month daily insolation incident on the array is 4 kWh/m^2-day. Availability of the PV power system is assumed to be 99.9% (Reference 10-1).

10.2.2 Diesel Power System Description

The diesel power system chosen to meet the base-case requirements comprises the following components:

- Two diesel gen-sets (@ 3 kW each)
- Battery charger
- Battery storage (9 kWh).

The two diesel gen-sets operate alternately for 12-hour periods. Battery storage is included for short periods of diesel downtime (1 day) caused by dual failure or time needed for maintenance.

Diesel power system availability, not including breaks in fuel supply, is assumed to be 99.9%. This high availability is the result of having a tandem generator set, where unavailability is the square of a single gen-set unavailability. Thus, assuming a 97.5% availability of one gen-set, the availability of a tandem set is $[1 - (0.025)^2]$, or 99.9%.

10.3 System Costs

10.3.1 PV Power System Costs

The initial capital cost for the PV power system represents three components--the array, batteries and electronics. Recurring costs are those associated with component replacement, maintenance and repair. The PV power system cost breakdown for the communications base case is summarized in Exhibit 10-3. All the costs presented in this chapter refer to FOB manufacturer.

EXHIBIT 10-3. PV Power System Costs for Communications Base Case

SPECIFICATION	COST
Initial Capital Cost (FOB Manufacturer)	
- PV Array (2.3 kWp)	$18,182
- Controller	909
- Battery (63 kWh)	9,450
Total Capital Cost	$28,541
Recurring Capital Costs (FOB Manufacturer)	
- Battery Replacement	$9,450 every 5 years*
- Controller Replacement	909 every 10 years*
Other Recurring Costs (% Initial Cap. Costs)	
- Maintenance and Repair	0.05%/year*

* Plus appropriate cost escalation due to general inflation.

PV module costs range from $6 to $8 per peak watt as a function of the magnitude of the order and the potential, in the eyes of the manufacturer, for future sales. Mounting hardware (e.g., support structure) and array wiring costs (area-related balance-of-system costs) amount to an additional $0.50 to $1 per peak watt. For the base case, a value of $8 per peak watt is used as the total of module and area-related balance-of-system costs (Reference 10-2).

The batteries used for communications applications are sealed, deep-discharge batteries. The cost for these batteries is approximately $150 per kWh and the cost of the electronics is approximately $0.40 per peak watt. (Ref. 10-4). The batteries are assumed to need replacement every 5 years and the control electronics every 10 years. The only additional recurring cost is for annual maintenance and repair, which is 0.05% of the total system initial capital cost (Reference 10-2).

10.3.2 Diesel Power System Costs

The capital cost of the diesel power system is based on the use of two diesel gen-sets, a battery charger and a battery bank. The cost breakdown for both initial and recurring costs is detailed in Exhibit 10-4. The costs presented are FOB manufacturer.

EXHIBIT 10-4. Diesel Power System Costs for Communications Base Case

SPECIFICATION	COSTS
Initial Capital Costs (FOB Manufacturer)	
- Diesel Gen-Sets (2 @ 3 kW)	$9,541
- Battery (9 kWh)/Charger	1,350
Total Capital Cost	$10,891
Recurring Capital Costs (FOB Manufacturer)	
- Diesel Gen-Sets Replacement	$9,541 every 6 years*
- Battery/Charger Replacement	$1,350 every 5 years*
Other Recurring Costs	
- Engine Overhaul	15% of engine cost every 3 years*+
- Maintenance and Repair	2% of system cost per year*
- Diesel Fuel (6816 liters @ $0.50/liter)	$3,408/year*

* Plus appropriate escalation due to general inflation.
\+ Overhauls not performed during engine replacement years.

Although the maximum load requirements can be met with 500-watt gen-sets, it is necessary to assume the use of 3-kW gen-sets since diesels are not commonly available below that size. Costs are based on the same data assumed in the diesel-powered pumping system (Exhibit 9-5 from the previous chapter). The engines need replacement every 6 years.

Batteries for the diesel power system are of the sealed, deep-discharge variety. The battery charger price is included in the battery price, for a total of $150 per kWh of battery capacity. These components are assumed to need replacement every 5 years.

Fuel consumption rates are based on the same figures outlined in Exhibit 9-6 of the pumping section (Chapter 9). Engine overhauls are assumed to require an expenditure equivalent to 15% of the engine capital cost every 3 years. Annual maintenance and repair costs are assumed to be equivalent to 2% of the capital cost of the system (Reference 10-3).

10.4 Twenty-Year Life-Cycle Costs

Using the assumptions outlined in the previous sections, 20-year cash flows are presented in Exhibits 10-5 and 10-6 for the base-case PV and diesel power systems, respectively. The results are expressed as the total net present value (NPV) cost for PV and diesel power systems to provide an average of 7.2 kWh/day over twenty years with 99.9% reliabiity. This base-case value is $59,230 for PV and $86,529 for diesel. These base-case values show that at the assumed energy demand, the cost of the PV power system is less than that of the diesel system. Thus, for communications loads less than 7.2 kWh/day (300 watts continuous), PV power systems are more cost effective than diesel power systems. (The model used to develop these NPV cost figures and the sensitivity analyses that follow is provided in Appendix D.)

EXHIBIT 10-5. PV-Powered Communications System Twenty-Year Cash Flow (Base Case)

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$4,191	$35,676
Operating & Maintenance Expenses:																					
Annual Maintenance	$15	$16	$17	$17	$18	$19	$20	$21	$22	$23	$24	$26	$27	$28	$30	$31	$33	$34	$36	$38	$181
Recurring Capital Costs:																					
Battery Replace Cost	$0	$0	$0	$0	$15,076	$0	$0	$0	$0	$19,241	$0	$0	$0	$0	$24,557	$0	$0	$0	$0	$0	$22,658
Controller Replace Cost	$0	$0	$0	$0	$0	$0	$0	$0	$9	$1,851	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$714
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Cash Outflow:	$4,205	$4,206	$4,207	$4,208	$19,285	$4,210	$4,211	$4,212	$4,213	$25,306	$4,215	$4,216	$4,217	$4,219	$28,778	$4,222	$4,223	$4,225	$4,227	$4,228	
Discount Factor (DF) DF = 1/((1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$3,823	$3,476	$3,161	$2,874	$11,974	$2,376	$2,161	$1,965	$1,787	$9,757	$1,477	$1,343	$1,222	$1,111	$6,889	$919	$836	$760	$691	$629	
TOTAL NPV OF CASH OUTFLOW	$59,230																				
PV System Generation(kWh/yr)	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	2,625	

HIBIT 10-6. Diesel-Powered Communications System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$1,599	$13,614
Operating & Maintenance Expenses:																					
Annual Maintenance	$229	$240	$252	$265	$278	$292	$307	$322	$338	$355	$373	$391	$411	$431	$453	$475	$499	$524	$550	$578	$2,770
Diesel Engine Overhaul	$0	$0	$1,657	$0	$0	$1,918	$0	$0	$2,220	$0	$0	$2,570	$0	$0	$2,975	$0	$0	$3,444	$0	$0	$5,420
Fuel	$3,578	$3,757	$3,945	$4,142	$4,350	$4,567	$4,795	$5,035	$5,287	$5,551	$5,829	$6,120	$6,426	$6,748	$7,085	$7,439	$7,811	$8,202	$8,612	$9,042	$43,342
Recurring Capital Replace Cost:																					
Battery Replace Cost	$0	$0	$0	$0	$2,154	$0	$0	$0	$0	$2,749	$0	$0	$0	$0	$3,508	$0	$0	$0	$0	$0	$3,237
Diesel Gen Replace Cos	$0	$0	$0	$0	$0	$15,983	$0	$0	$0	$0	$0	$21,419	$0	$0	$0	$0	$0	$28,783	$0	$0	$21,009
Salvage	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$19,265	$2,864
Total Cash Outflow:	$5,406	$5,597	$7,453	$6,006	$8,380	$24,359	$6,701	$6,956	$9,444	$10,254	$7,801	$32,100	$8,436	$8,778	$15,621	$9,514	$9,910	$42,473	$10,761	($8,046)	
Discount Factor (DF) DF = 1/((1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$4,915	$4,625	$5,600	$4,102	$5,204	$13,750	$3,439	$3,245	$4,005	$3,953	$2,734	$10,228	$2,444	$2,312	$3,739	$2,070	$1,961	$7,639	$1,760	($1,196)	
TOTAL NPV OF CASH OUTFLOW $86,529																					
Diesel Sys Gen (kWh/yr)	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	2,626	

10.5 Sensitivity Analyses

For communications systems, sensitivity analyses demonstrate the effect of varying the capital cost, discount and interest rate, diesel fuel cost, diesel lifetime and insolation on the life-cycle NPV cost comparisons between PV and diesel power systems. In each of the following sensitivity analyses except capital cost, the ratios of the life-cycle NPV costs for the two systems are plotted against a range of energy demands at several values for the sensitivity parameters. In the capital cost analysis, the actual NPV costs are individually presented for the PV and diesel power systems.

10.5.1 Sensitivity to Capital Costs

The sensitivity of the life-cycle costs of PV- and diesel-powered communications systems to the capital costs for equipment is compared using capital cost multipliers ranging from 0.75 to 2.0, where the base case is 1.0. The sensitivity of communications cost to PV and diesel power system capital costs is illustrated in Exhibits 10-7 and 10-8, respectively. For the PV power system, NPV cost is directly proportional to energy demand as shown in Exhibit 10-7. The NPV cost for the diesel power system is presented as a function of a load range (in kWh/day). The use of a multiplier represents the effect of different cost, insurance and freight (CIF) equipment costs and accounts for installation costs, which were not included in the base case.

EXHIBIT 10-7. Sensitivity of Communications Costs to PV Power System Capital Costs

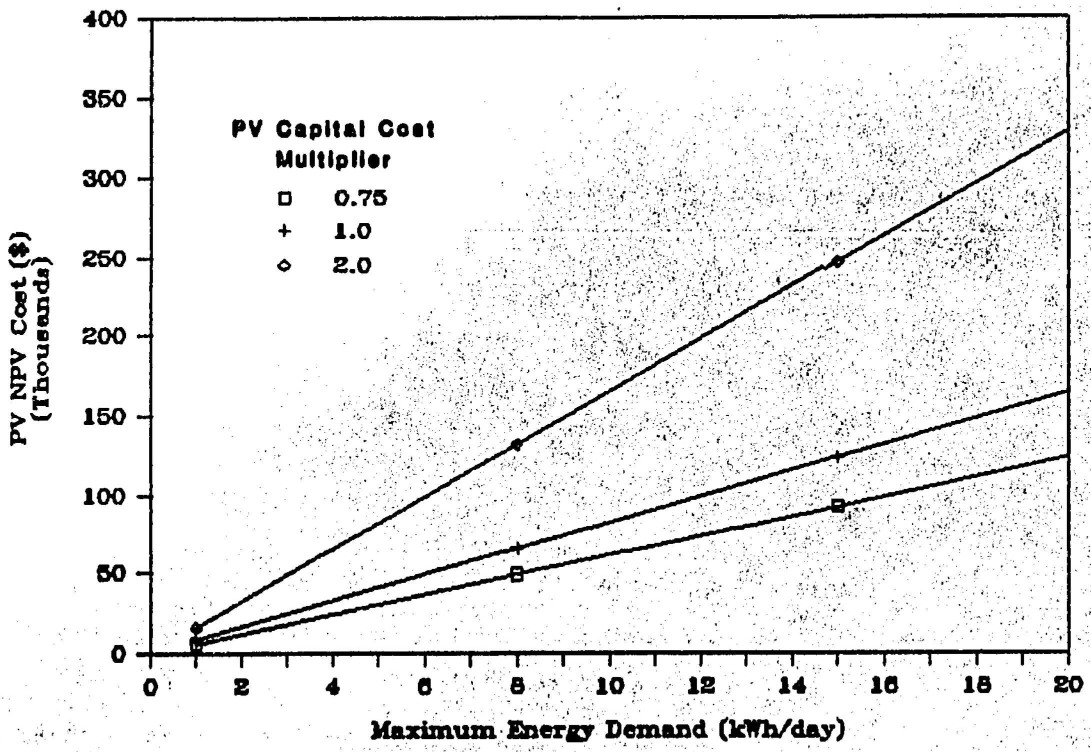
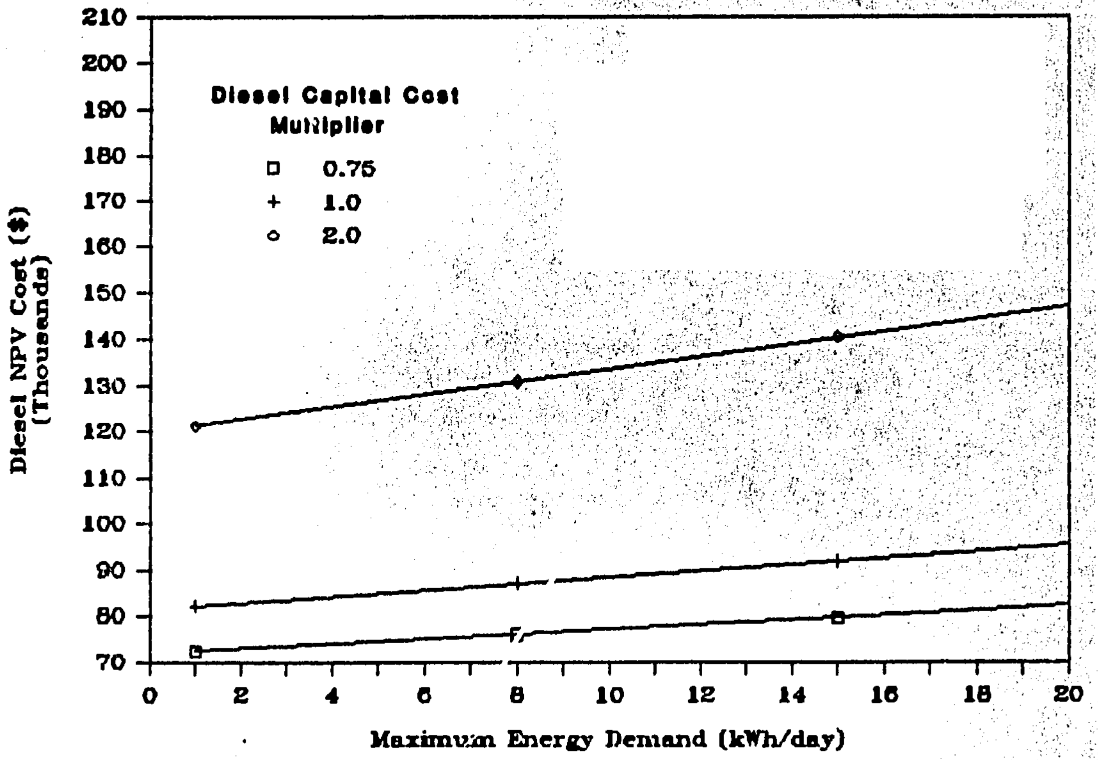


EXHIBIT 10-8. Sensitivity of Communications Costs to Diesel Power System Capital Costs



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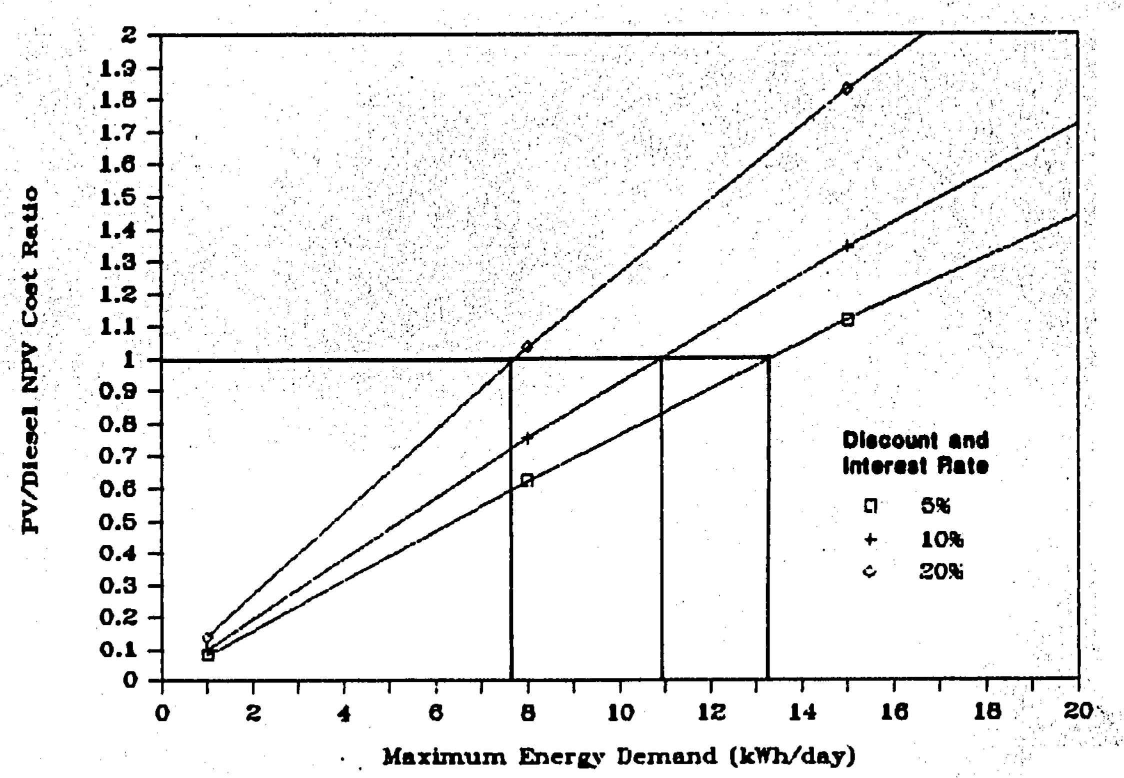
10.5.2 Sensitivity to Discount and Interest Rate

Exhibit 10-9 shows that as the discount and interest rate increases, the demand range over which PV power systems are financially favorable becomes smaller. The base case, with 10% discount and interest rates, shows the crossover between PV and diesel power systems to occur at about 11.0 kWh/day. At a rate of 5%, PV is financially more attractive up to 13.4 kWh/day, while at a 20% rate, the cross-over is at 7.8 kWh/day.

As discussed in the pumping analysis, this shift in the crossover occurs because of the nature of the PV and diesel cash flows, in terms of recurring versus capital costs. The diesel cash flow has a higher proportion of recurring costs that are subject to annual escalation. The base-case PV cash flow, on the other hand, is less affected by cost escalation since its proportionally larger debt service component is levelized over the entire 20-year life of the system. However, since the PV system also has large recurring costs due to battery replacement, the NPV cost ratio is less sensitive to discount and interest rate in this application than the others.

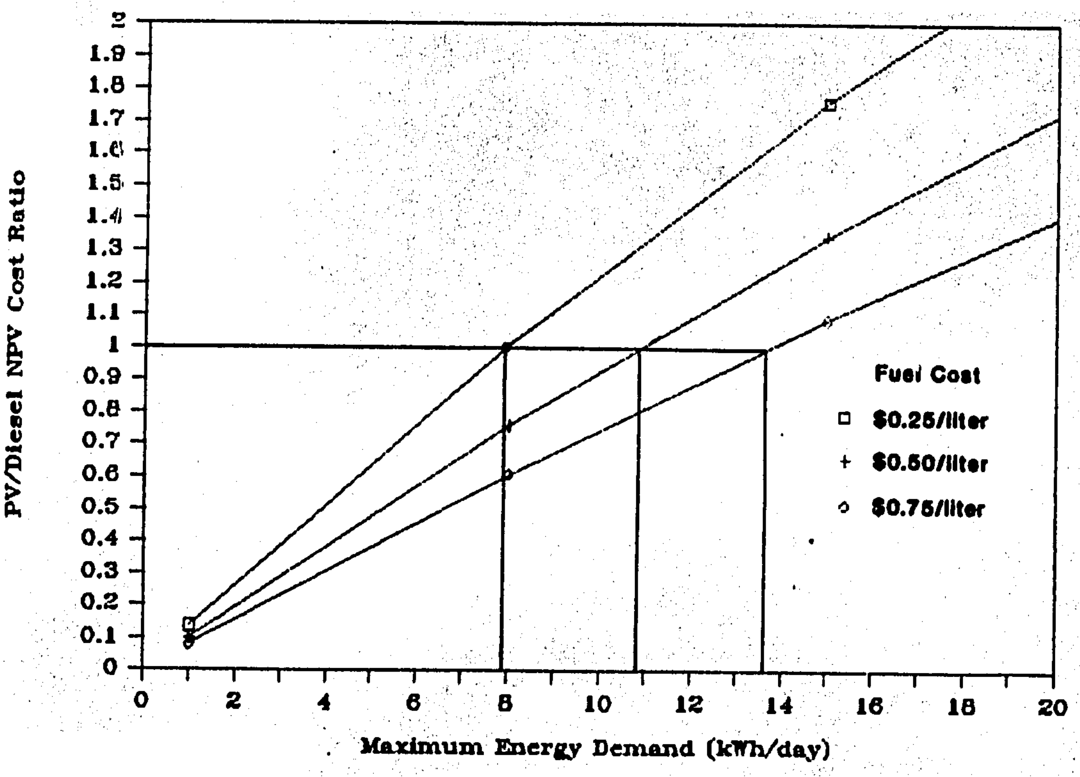
EXHIBIT 10-9. Sensitivity of Communications System Costs to Discount and Interest Rate



10.5.3 Sensitivity to Diesel Fuel Cost

This analysis examines the effect of varying fuel cost from the base-case value of $0.50 per liter. Exhibit 10-10 shows the impact of using fuel costs of $0.25, $0.50 and $0.75 per liter. While the base case of $0.50 per liter shows the PV system to be more cost-effective up to demands of 10.9 kWh/day, at $0.25 per liter, the crossover between PV and diesel occurs at about 7.9 kWh/day. When using the higher cost of $0.75 per liter, PV is the more cost-effective option up to demands of 13.8 kWh/day.

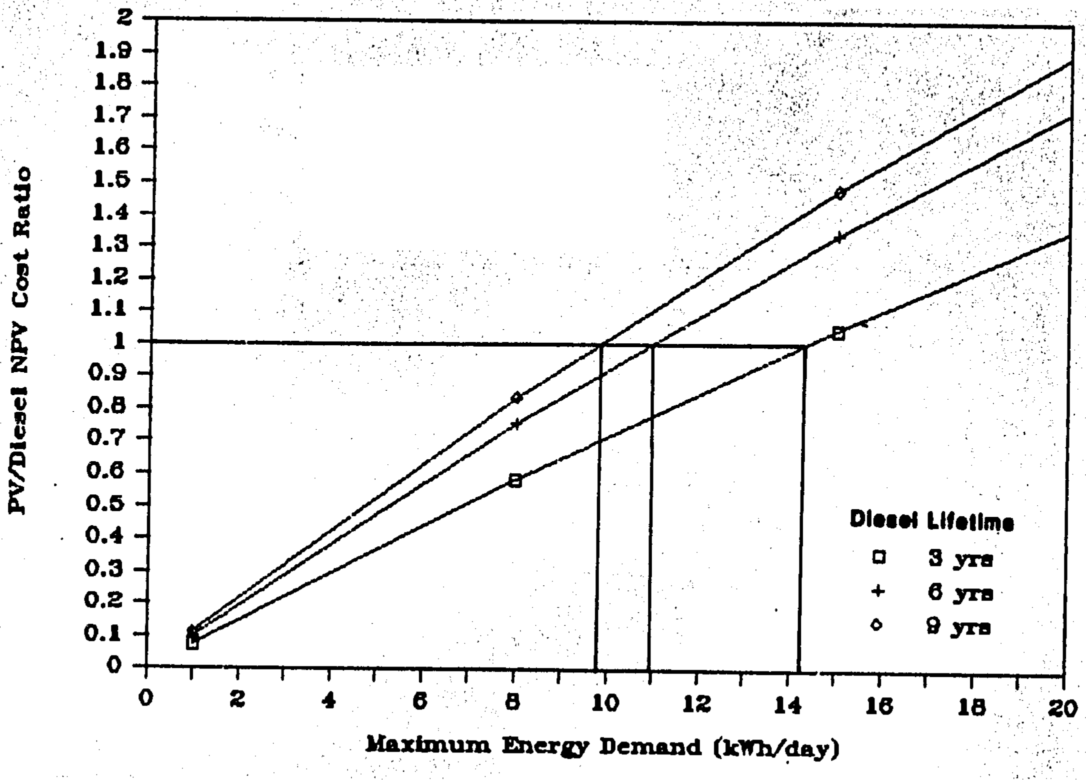
EXHIBIT 10-10. Sensitivity of Communications System Costs to Diesel Fuel Cost



10.5.4 Sensitivity to Diesel Lifetime

Exhibit 10-11 demonstrates the effect of using a 3-, 6- and 9-year diesel lifetime on communications system life-cycle costs (the base case uses 6 years). A diesel with a 3-year life results in the PV system showing a cost advantage up to demands of 14.2 kWh/day. With a 9-year life, this crossover occurs at 9.6 kWh/day.

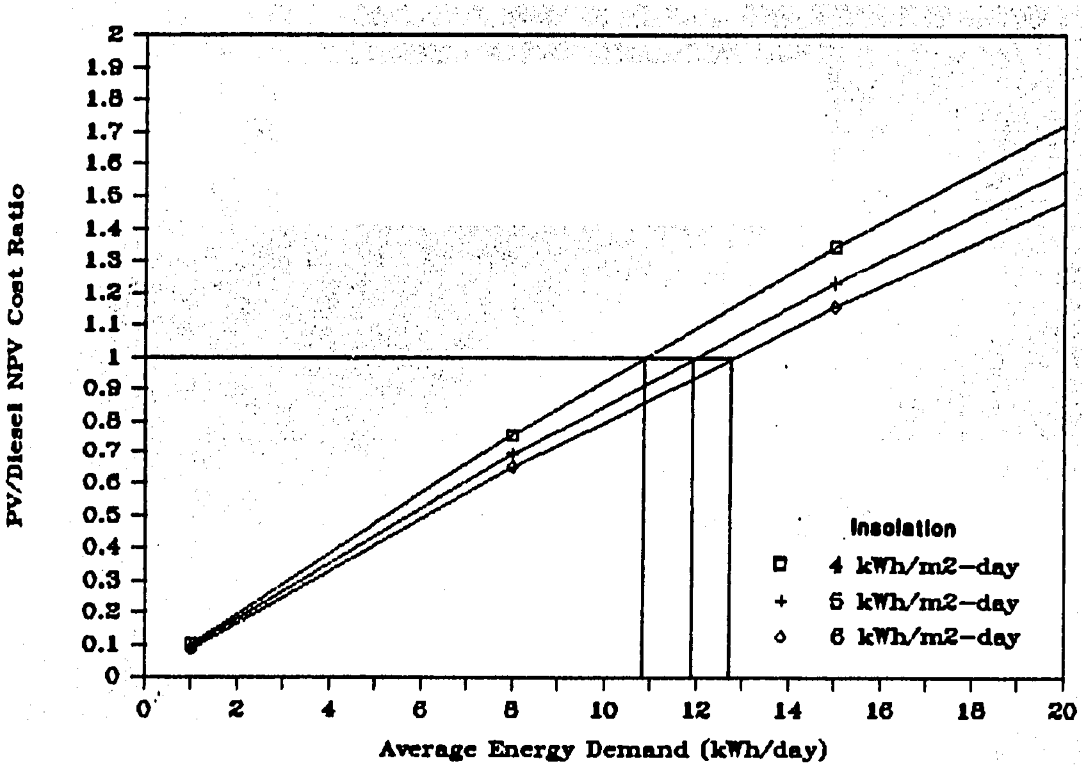
EXHIBIT 10-11. Sensitivity of Communications System Costs to Diesel Lifetime



10.5.5 Sensitivity to Insolation

The ratio of communications system costs is somewhat insensitive to changes in insolation. Exhibit 10-12 shows that by varying insolation from the base-case lowest-month daily insolation of 4 up to an insolation level of 6 kWh/m^2-day, the crossover between PV and diesel system attractiveness ranges from 10.8 to 12.6 kWh/day. This relatively low sensitivity to insolation variation is due to the fact that the PV power system costs for communications are heavily influenced by battery capacity, which is not directly related to insolation.

EXHIBIT 10-12. Sensitivity of Communications System Costs to Insolation



CHAPTER 11

VACCINE REFRIGERATION ANALYSIS

11.1 Overview

The financial analysis presented in this chapter compares PV-powered vaccine refrigeration systems to kerosene-fueled refrigerators, assuming development agency financing. The analysis shows that there is no clear-cut range of viability for either PV or kerosene systems (see Exhibit 11-1). PV-powered system viability, for both small and large systems, is always in the break-even range (or very dependent on case-specific parameters).

The bar charts in Exhibit 11-1 depict the ratio of PV- to kerosene-powered vaccine refrigerator life-cycle costs for the best PV case and worst PV case scenarios. Both scenarios assume 20-year life-cycle costing and development agency financing. At an NPV cost ratio of 1.0, PV and kerosene system life-cycle costs are equal. Under the best PV case scenario, the five parameters shown on the graph are adjusted to "reasonable extremes" that favor PV systems. An opposite adjustment is made under the worst PV case scenario.

The sensitivity analyses in this chapter, and the life-cycle cost elements illustrated in Exhibit 11-2, indicate which are the most important cost parameters when comparing PV-powered and kerosene-fueled refrigerators. The most critical assumptions are related to vaccine wastage, which is a function of the annual vaccine dose requirement and system operating availability (the percentage of time the system operates within the proper temperature range). It is assumed that because vaccines are a critical item, any vaccines lost due to system unavailability must be replaced through pure cash outlays. For the PV-powered systems, the most dominant costs are debt service and replacement costs, indicating that refrigerator and battery lifetimes are important parameters. For the kerosene-fueled refrigerators, the overwhelming cost is vaccine wastage, due to the low availability of kerosene units.

The remainder of this chapter discusses the analyses and assumptions leading to Exhibits 11-1 and 11-2.

EXHIBIT 11-1. Sensitivity of Refrigeration Costs to Best and Worst Conditions

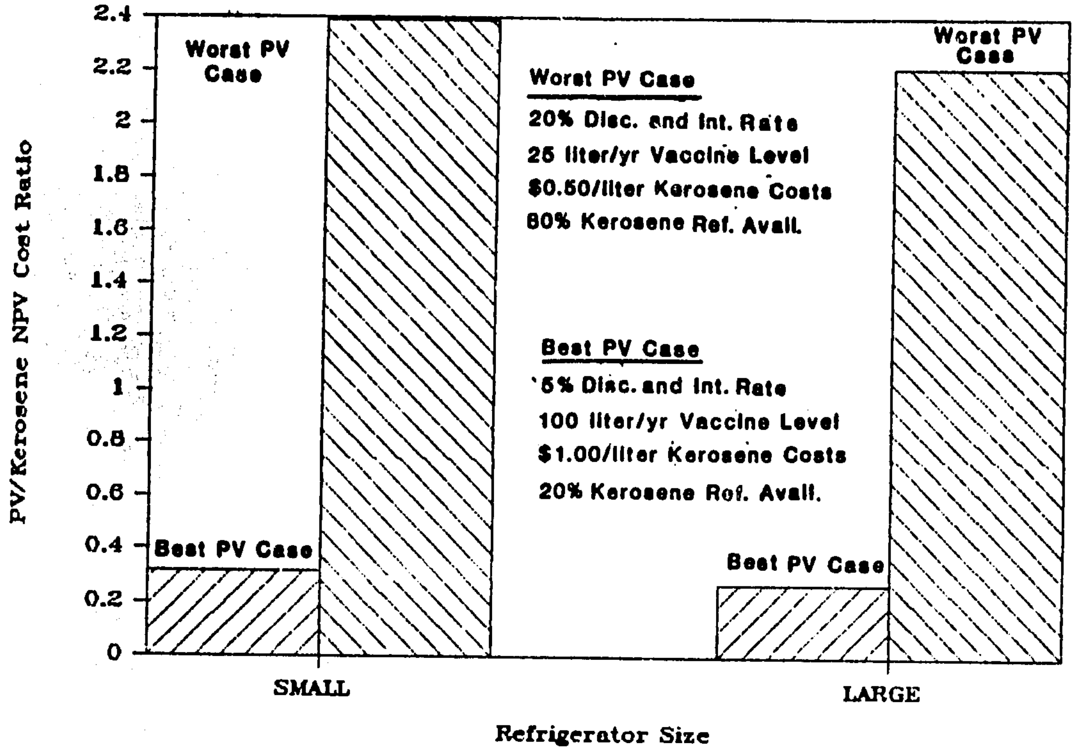
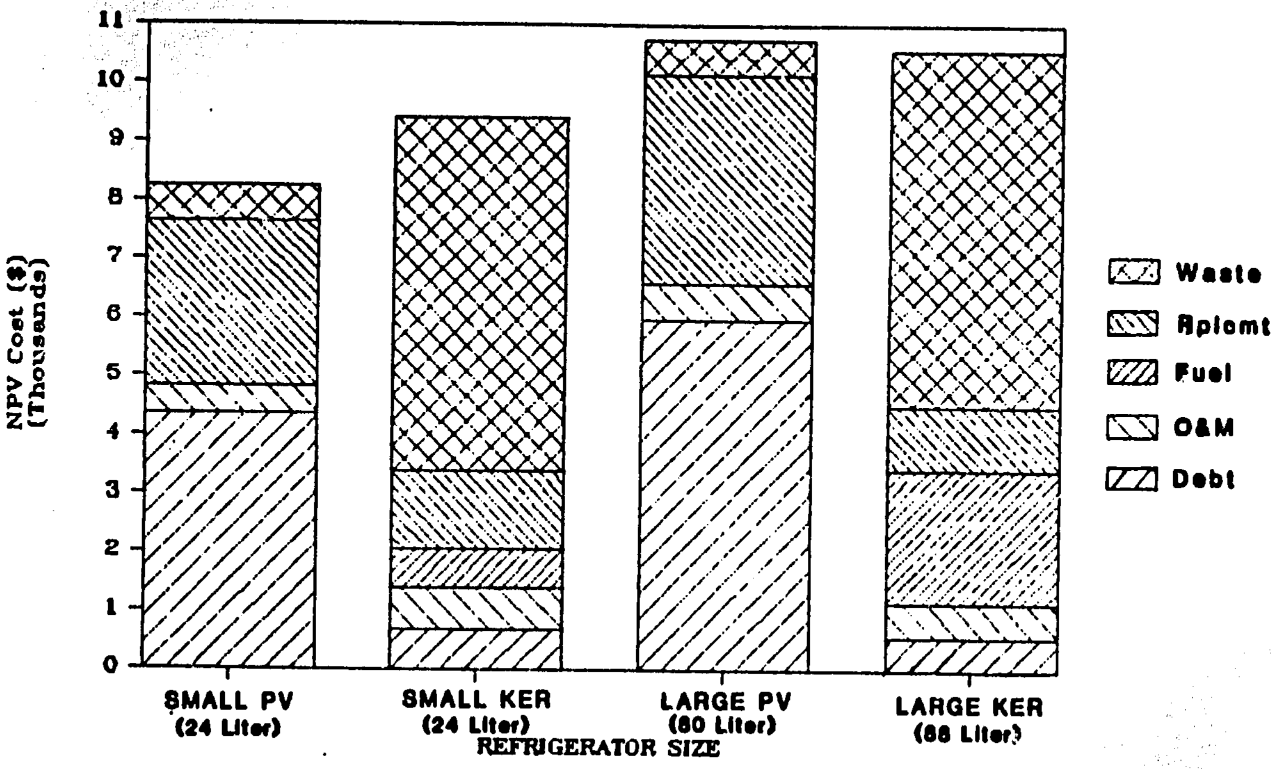


EXHIBIT 11-2. Base-Case Refrigeration System Cost Components



11.2 Description of the Base Case

The base-case vaccine refrigeration comparison is between PV- and kerosene-powered units. System specifications are taken directly from World Health Organization (WHO) product information sheets (References 11-1 and 11-2). The energy consumption estimates are based on test data at an ambient temperature of 32°C, with no ice-pack freezing. Although all of the units analyzed are capable of freezing, comparable energy consumption data with freezing were not available. While system specifications are based on test conditions, they are considered valid for field operation assuming that adequate user training is provided (Reference 11-3).

An important aspect of system performance is operating availability. For vaccine refrigeration, availability is the percentage of time the system is operating within the prescribed temperature range. When availability is less than 100%, there are both quantifiable and unquantifiable costs of lost vaccines. The quantifiable portion is the actual cost of the vaccines that are wasted. From WHO data (Reference 11-1), it was determined that an average liter of vaccine costs approximately $19. Section 11.3 compares the impact of this cost for both PV and diesel systems. The unquantifiable impact of lost vaccines is the potential human cost of not maintaining a reliable supply of vaccines in developing country health programs.

In the financial analysis, the cost of wasted vaccines was quantified based on the following assumptions:

- A liter of packed vaccines costs $19.
- Fifty liters of vaccines are needed per year. This figure is equivalent to vaccinating the children and mothers within a village of about 45,000 people (Reference 11-1). (It is important to keep in mind that remote health centers that serve 20,000 to 100,000 people have been identified as having the greatest need for solar-powered vaccine refrigeration (see page 5-1).)

The selected PV- and kerosene-powered refrigeration systems and their life-cycle cost comparisons are described in the following sections. The comparisons are made on the basis of the net present value (NPV) life-cycle cost in dollars per liter of refrigerated space.

11.2.1 PV-Powered System Description

The two PV-powered refrigeration systems used in the analysis are based on data provided by BP Solar Systems, assuming a LEC EV 5750 refrigerator, and Solarex Corporation, assuming a Marvel 4RTD refrigerator.

These suppliers have already sized systems for WHO vaccination program specifications. It is assumed that the average insolation incident on the PV array is between 5.8 and 7.0 kWh/m^2-day. Battery capacity is sized for 5 days of no sun. Both systems included the following components:

- PV Array
- Charge Controller
- Battery Storage
- Refrigerator.

Technical specifications for these two systems are outlined in Exhibit 11-3. The availability (i.e., the percentage of time operating within the required temperature range) of PV-powered refrigeration systems is assumed to be 95% (Reference 11-4).

EXHIBIT 11-3. Base-Case PV-Powered Refrigeration System Specifications* (References 11-1 and 11-2)

SYSTEM SUPPLIER	REFRIGERATOR VACCINE STORAGE (Liters)	ARRAY SIZE (Wp)	BATTERY SIZE (kWh)	POWER CONSUMPTION (kWh/24 hours)
BP Solar	24	198	5.47	0.35
Solarex	80	168	3.60	0.43

* Based on 32°C ambient temperature, an insolation of 5.8-7.0 kWh/m^2-day, 5 days no-sun security, and no freezing.

11.2.2 Kerosene-Powered System Description

Kerosene-powered refrigeration systems are self-contained units. The two units selected for this analysis are an Electrolux RCW 42 EK and Sibir S2325. The technical specifications for these two systems are outlined in Exhibit 11-4. The availability of these systems is assumed to be 50% (Reference 11-4).

EXHIBIT 11-4. Base-Case Kerosene-Fueled Refrigeration System Specifications* (Reference 11-1)

SYSTEM SUPPLIERS	REFRIGERATOR VACCINE STORAGE (Liters)	FUEL CONSUMPTION (Liters/24 Hours)
Electrolux	24	0.2
Siber	68	0.7

* Based on 32°C ambient temperature and no freezing.

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11.3 System Costs

11.3.1 PV-Powered Refrigeration System Costs

The costs for the PV-powered refrigeration systems were provided by their suppliers in the WHO product information sheets (Reference 11-1) and are outlined in Exhibit 11-5. The small PV-powered refrigerator unit (BP Solar) selected for analysis costs $3,500, while the large unit (Solarex) costs $4,781 (Reference 11-1).

EXHIBIT 11-5. PV-Powered Refrigeration System Costs (Reference 11-1)

SUPPLIER	REFRIGERATOR VACCINE STORAGE (Liters)	COST (FOB MANUFACTURER) (Based on the purchase of 1-9 units)	
		SYSTEM A*	SYSTEM B**
AEG	90	$5,800	$4,700
BP Solar	24	$4,300	$3,500
Leroy Somer	16	$9,628	$8,278
Polar Products	90	$5,675	$5,150
Solarex	(a) 80 (b) 90	(a) $5,507 (b) $6,458	(a) $4,781 (b) $5,732
Solavolt International	(a) 80 (b) 90	(a) $5,335 (b) $6,861	(a) $4,386 (b) $5,912

* System A applies to areas receiving 3.5-4.7 kWh/m^2-day. Includes 8 days of no-sun security. Assumes no ice-making during periods of no sun.

** System B applies to areas receiving 5.8-7.0 kWh/m^2-day. Includes 5 days of no-sun security. Assumes no ice-making during periods of no sun.

The PV array has a lifetime of 20 years. The batteries must be replaced every 5 years. The refrigerator and electronic controls are assumed to have a life of 10 years (Reference 11-4). To obtain replacement costs for these components, the array cost of $8 per peak watt and battery costs of $150/kWh are subtracted from the total system cost. Thus, values of $1,096 and $2,897 are assigned to the refrigerator and controls replacement costs for the BP Solar and Solarex systems, respectively. Annual maintenance and repair costs are equivalent to 1% of the total system cost. Exhibit 11-6 provides the cost breakdown for the PV-powered refrigeration systems. (Reference 11-5)

EXHIBIT 11-6. PV-Powered System Costs for Refrigeration Base Case

SPECIFICATION	COST	
	SMALL SYSTEM	LARGE SYSTEM
	BP Solar	Solarex (Marvel)
Initial Capital Costs (FOB Manufacturer)		
- System Cost	$3,500	$4,781
Recurring Capital Costs (FOB Manufacturer)		
- Battery Replacement	$821 every 5 years*	$540 every 5 years*
- Refrigerator/Controls Replacement	1,096 every 10 years*	$2,897 every 10 years*
Other Recurring Costs (% Initial System Cost)		
- Maintenance & Repair	1%/year*	1%/year*

*Plus appropriate escalation due to general inflation.

11.3.2 Kerosene-Fueled Refrigeration System Costs

Costs for these systems are provided by their manufacturers in the WHO product information sheets (Reference 11-1). System costs are outlined in Exhibit 11-7. Based on the purchase of one system, the Electrolux unit used in the analysis costs $552 and the Sibir unit costs $458. These entire units were assumed to need replacement every 5 years (Reference 11-4).

Fuel consumption rates are outlined in Exhibit 11-4. A fuel cost of $0.70 per liter is used, as outlined in Section 8.2.1. Annual maintenance and repair is equivalent to 10% of the initial system cost (Reference 11-4). Exhibit 11-8 outlines the kerosene-fueled system costs used in the comparative analysis.

EXHIBIT 11-7. Kerosene-Fueled Refrigerator System Costs* (Reference 11-1)

REFRIGERATOR MODEL	REFRIGERATOR VACCINE STORAGE (Liters)	COST (FOB Manufacturer)
Electrolux RC 65	142	725
Electrolux RCW 65	32	1213
Electrolux RCW 42 EK	24	552
Electrolux RCW 42 EKG	21	775
Siber S2325	68	458

*Based on the cost of one system.

EXHIBIT 11-8. Kerosene-Fueled System Costs for Refrigeration Base Case

SPECIFICATION	COST	
	SMALL SYSTEM	LARGE SYSTEM
	Elextrolux RCW 42 EK	Sibir
Initial Capital Costs (FOB Manufacturer) - System Cost	$552	$458
Recurring Capital Costs (FOB Manufacturer) - System Replacement	$552 every 5 years*	$458 every 5 years*
Other Recurring Costs - Maintenance & Repair - Kerosene Fuel (@ $0.70/liter)	 10%/year* $51/year*	 10%/year* $179/year*

*Plus appropriate escalation due to general inflation.

11.4 Twenty-Year Life-Cycle Costs

Twenty-year cash flows for the small and large PV- and kerosene-powered refrigeration systems are presented in Exhibits 11-9 through 11-12. In the small case, the NPV costs for the PV- and kerosene-powered systems are $8,252 and $9,406, respectively. The large units have NPV costs of $10,757 for the PV system and $10,569 for the kerosene system. Note that, for the large units, capacity is 80 liters for the PV system and 68 for the kerosene.

The significant financial impact of lost vaccines becomes clear upon examining the "vaccine wastage" line item in each of the cash flows. For the base case, 50 liters of good vaccines are required per year (i.e., for children and mothers within a village of approximately 45,000 people). If vaccines are wasted, they must be replaced at a cost of $19 per liter. In the first year, the PV systems' 95% availability results in losses of only $50. Alternatively, the kerosene systems' 50% availability produces a first-year vaccine wastage of $499.

It should be pointed out that the unquantifiable cost of lost vaccines (i.e., the human cost of not have vaccines when needed) is not included in this analysis. This cost could significantly alter the comparison of PV to kerosene. In this analysis, kerosene-fueled refrigerators are marginally less expensive in some of the sensitivity cases presented. However, the vaccine loss from kerosene systems is substantially greater (10 times higher) than that for PV systems. Therefore, if the unquantifable costs could be quantified, it would most likely sway many specific analyses in favor of PV systems.

EXHIBIT 11-9. Small PV-Powered Refrigeration System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$514	$4,375
Operating & Maintenance Expenses:																					
Annual Maintenance	$37	$39	$41	$43	$45	$47	$49	$52	$54	$57	$60	$63	$66	$69	$73	$76	$80	$84	$88	$93	$445
Recurring Capital Costs:																					
Battery Replacement	$0	$0	$0	$0	$1,309	$6	$0	$0	$0	$1,671	$0	$0	$0	$0	$2,132	$0	$0	$0	$0	$0	$1,967
Refrig/Contr Replacement	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,232	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$860
Vaccine Waste:	$50	$52	$55	$58	$61	$64	$67	$70	$74	$77	$81	$85	$90	$94	$99	$104	$109	$114	$120	$126	$604
Total Cash Outflow:	$601	$605	$609	$614	$1,928	$624	$630	$636	$642	$4,550	$655	$662	$669	$677	$2,818	$694	$703	$712	$722	$733	
Discount Factor (DF) DF = 1/(1+DR)^Y	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$546	$500	$458	$419	$1,197	$352	$323	$297	$272	$1,754	$230	$211	$194	$178	$675	$151	$139	$128	$118	$109	

TOTAL NPV OF CASH OUTFLOW (PVNPV) = $8,252

Refr Vaccine Storage Capacity (PVSC) = 24.0 liters

EXHIBIT 11-10. Small Kerosene-Fueled Refrigeration System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$690
Operating & Maintenance Expenses:																					
Annual Maintenance	$58	$61	$64	$67	$70	$74	$78	$82	$86	$90	$94	$99	$104	$109	$115	$120	$127	$133	$139	$146	$702
Fuel	$54	$56	$59	$62	$65	$68	$72	$75	$79	$83	$87	$92	$96	$101	$106	$112	$117	$123	$129	$136	$650
Recurring Capital Replace Cost:																					
Total System Replacement	$0	$0	$0	$0	$881	$0	$0	$0	$0	$1,124	$0	$0	$0	$0	$1,434	$0	$0	$0	$0	$0	$1,324
Vaccine Waste:	$499	$524	$550	$577	$606	$637	$668	$702	$737	$774	$812	$853	$896	$940	$987	$1,037	$1,089	$1,143	$1,200	$1,260	$6,041
Total Cash Outflow:	$691	$722	$754	$788	$1,704	$860	$899	$940	$983	$2,152	$1,075	$1,125	$1,177	$1,232	$2,724	$1,350	$1,413	$1,480	$1,550	$1,623	
Discount Factor (DF) DF = 1/(1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$629	$597	$566	$538	$1,058	$485	$461	$438	$417	$830	$377	$358	$341	$324	$652	$294	$280	$266	$253	$241	

TOTAL NPV OF CASH OUTFLOW (KNPV) = $9,406

Refriger Storage Capacity (KSC) = 24.0 liters Refrig Space

EXHIBIT 11-11. Large PV-Powered Refrigeration System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$702	$5,976
Operating & Maintenance Expenses:																					
Annual Maintenance	$50	$53	$55	$58	$61	$64	$67	$71	$74	$78	$82	$86	$90	$95	$99	$104	$110	$115	$121	$127	$608
Recurring Capital Costs:																					
Battery Replacement	$0	$0	$0	$0	$861	$0	$0	$0	$0	$1,100	$0	$0	$0	$0	$1,403	$0	$0	$0	$0	$0	$1,295
Ref/Contr Replacement	$0	$0	$0	$0	$0	$0	$0	$0	$0	$5,899	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,274
Vaccine Waste:	$50	$52	$55	$58	$61	$64	$67	$70	$74	$77	$81	$85	$90	$94	$99	$104	$109	$114	$120	$126	$604
Total Cash Outflow:	$802	$807	$812	$818	$1,685	$830	$836	$843	$850	$7,855	$865	$873	$882	$891	$2,303	$910	$920	$931	$943	$955	
Discount Factor (DF)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
DF = 1/(1+DR)^Y																					
NPV Stream	$729	$667	$610	$559	$1,046	$468	$429	$393	$360	$3,029	$303	$278	$255	$235	$551	$198	$182	$168	$154	$142	

TOTAL NPV OF CASH OUTFLOW (PVNPV)=$10,757

Refr Vacc Storage Capacity (PVSC)= 80.0 liters

EXHIBIT 11-12. Large Kerosene-Fueled Refrigeration System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$67	$573
Operating & Maintenance Expenses:																					
Annual Maintenance	$48	$50	$53	$56	$58	$61	$64	$68	$71	$75	$78	$82	$86	$91	$95	$100	$105	$110	$116	$122	$582
Fuel	$188	$197	$207	$217	$228	$240	$252	$264	$277	$291	$306	$321	$337	$354	$372	$390	$410	$430	$452	$475	$2,275
Recurring Capital Replace Cost:																					
Total System Replacement	$0	$0	$0	$0	$731	$0	$0	$0	$0	$933	$0	$0	$0	$0	$1,190	$0	$0	$0	$0	$0	$1,098
Vaccine Waste:	$499	$524	$550	$577	$606	$637	$668	$702	$737	$774	$812	$853	$896	$940	$987	$1,037	$1,089	$1,143	$1,200	$1,260	$6,041
Total Cash Outflow:	$802	$839	$877	$918	$1,691	$1,005	$1,052	$1,101	$1,153	$2,139	$1,264	$1,324	$1,387	$1,453	$2,712	$1,594	$1,671	$1,751	$1,835	$1,924	
Discount Factor (DF) DF = 1/(1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$729	$693	$659	$627	$1,050	$567	$540	$514	$489	$825	$443	$422	$402	$382	$649	$347	$331	$315	$300	$286	

TOTAL NPV OF CASH OUTFLOW (KNPV)= $10,569

Refriger Storage Capacity (KSC) = 60.0 liters Refrig Space

11.5 Sensitivity Analyses

Sensitivity analyses demonstrate the effect that varying certain parameters has on the life-cycle cost of refrigeration systems. The parameters include capital cost, discount and interest rate, kerosene fuel cost, liters of vaccines needed per year, and kerosene system operating availability. Sensitivity analyses are performed on the basis of NPV levelized annual cost per unit liter of capacity to account for different capacities in the large refrigerator system comparison. A sensitivity analysis was not performed on insolation because the system specifications were based on insolations ranging from 5.8 to 7.0 kWh/m^2-day.

11.5.1 Sensitivity to Capital Cost

The effect of varying the capital cost of PV and kerosene refrigeration systems is depicted in Exhibits 11-13 and 11-14, respectively. In each graph, the NPV cost is shown for variations in the capital cost of 0.75, 1.0, and 2.0 times the base case for both small and large refrigerator systems. The range of multipliers is intended to account for system CIF capital cost variations. These variations could result from different cost, insurance, and freight (CIF) equipment costs and can account for installation costs.

EXHIBIT 11-13. Sensitivity of PV-Powered Refrigeration Costs to Capital Cost

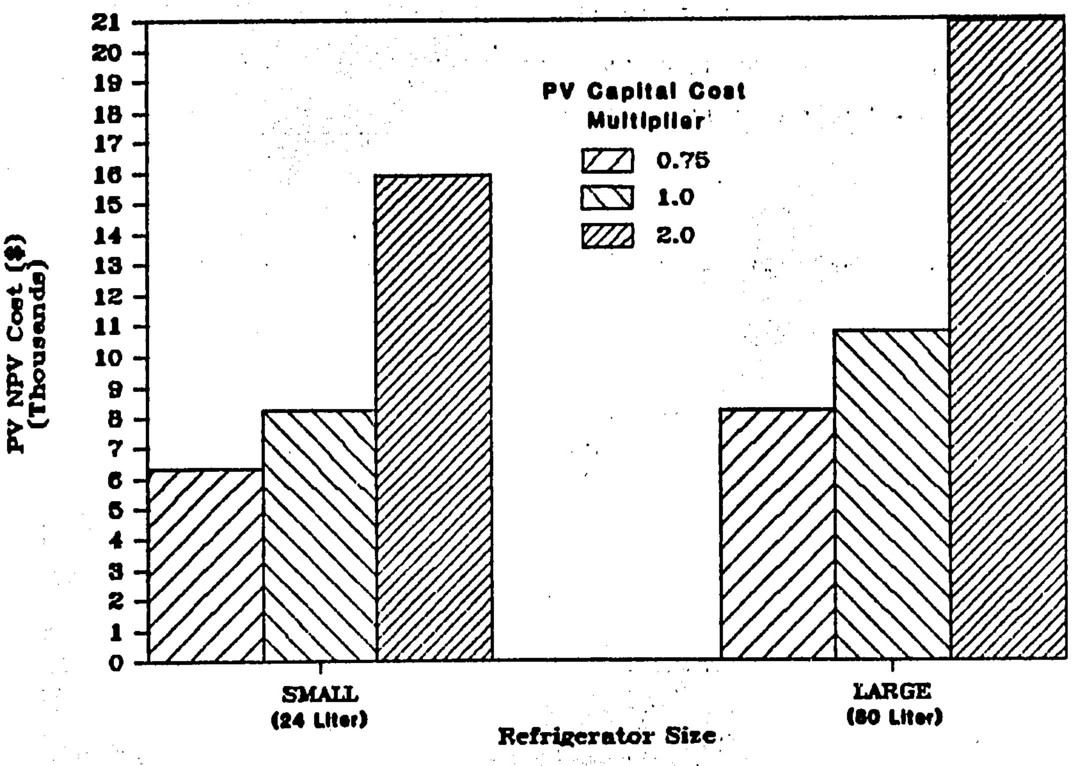
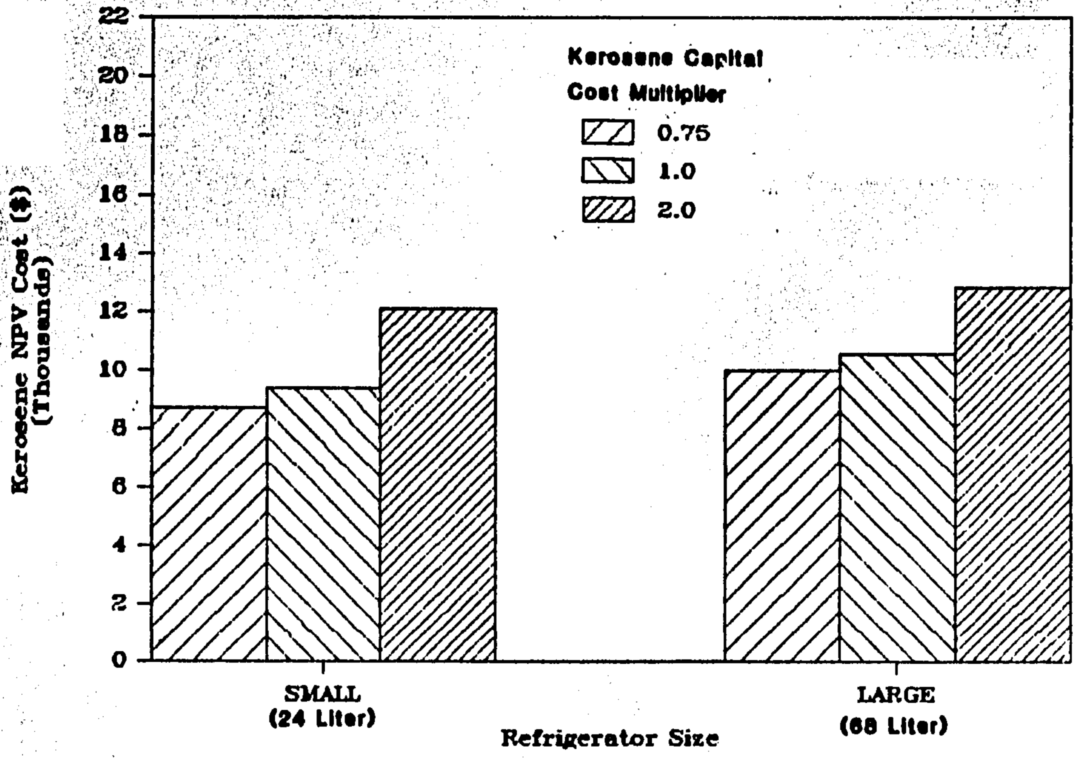


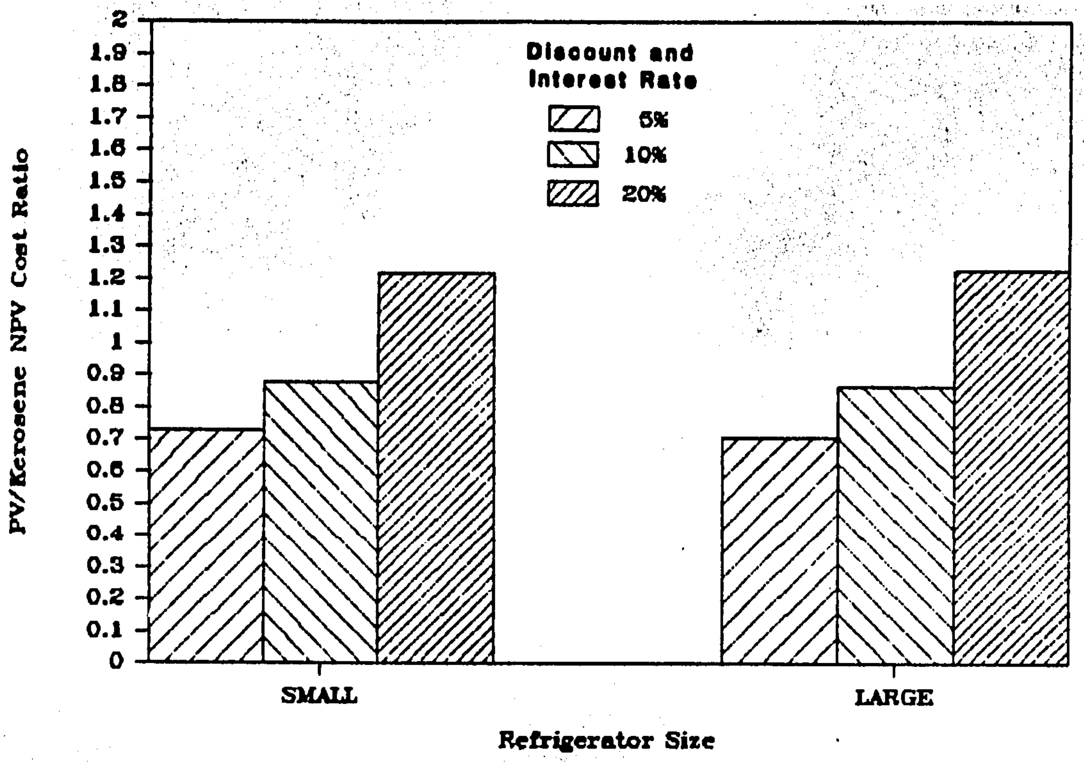
EXHIBIT 11-14. Sensitivity of Kerosene-Fueled Refrigeration Costs to Capital Cost



11.5.2 Sensitivity to Discount and Interest Rate

Exhibit 11-15 presents the sensitivity of refrigeration costs to discount and interest rate. As discount and interest rate decrease, PV-powered refrigeration systems become more cost effective than kerosene fueled systems beginning at rates between 10% and 20%.

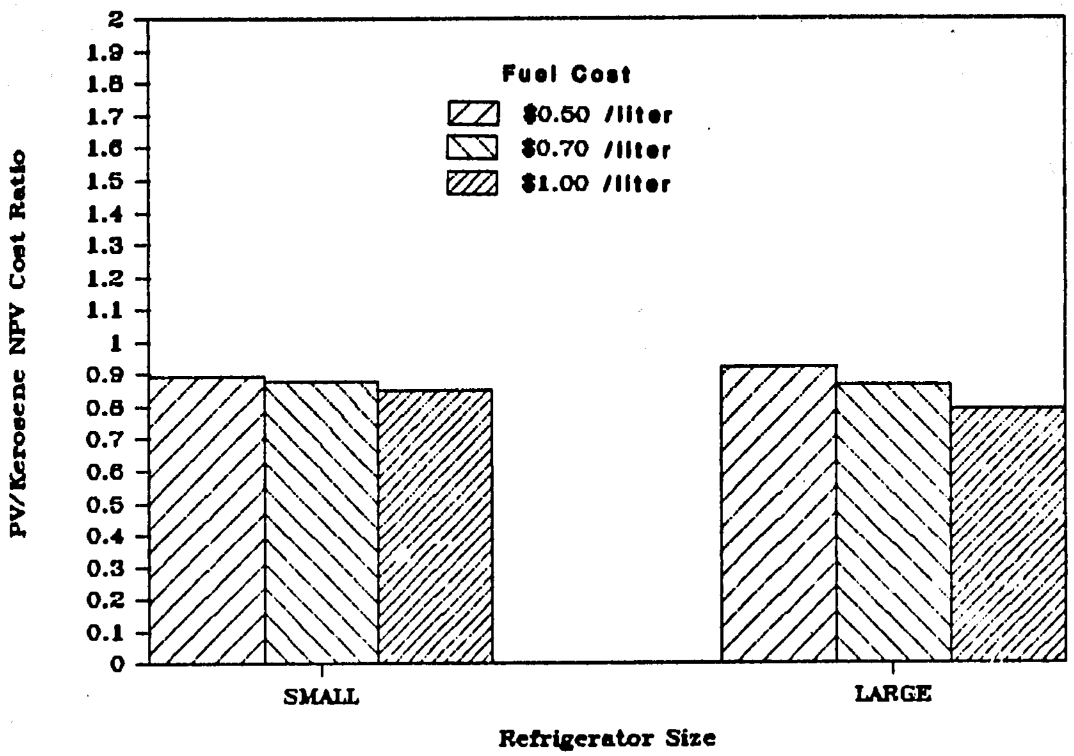
EXHIBIT 11-15. Sensitivity of Refrigeration Costs to Discount Rate



11.5.3 Sensitivity to Kerosene Fuel Cost

This section examines the effect that varying the cost of kerosene has on refrigeration costs. Exhibit 11-16 presents the ratio of the PV to kerosene NPV costs for kerosene fuel costs of $0.50, $0.70 (the base case) and $1.00 per liter. The graph shows that fuel cost does not play a significant role in the system NPV costs. In all cases, even at a fuel cost of $0.50/liter, PV-powered refrigeration systems are shown to be more cost-effective than kerosene-fueled systems.

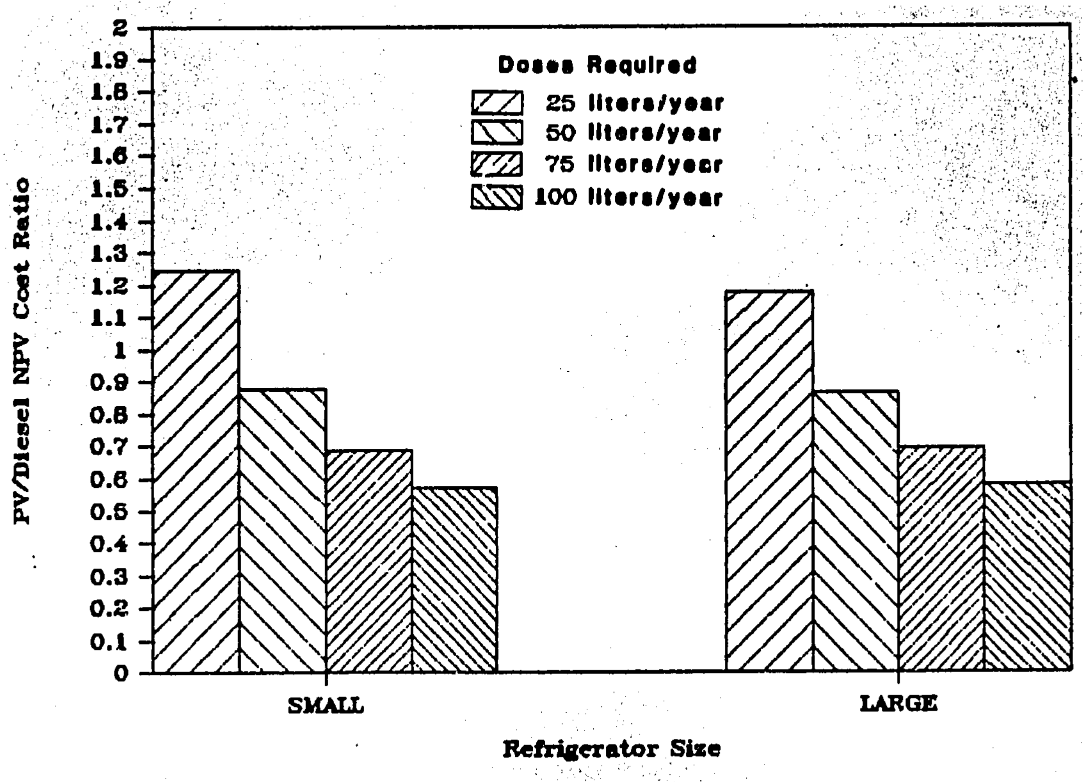
EXHIBIT 11-16. Sensitivity of Refrigeration Costs to Kerosene Fuel Cost



11.5.4 Sensitivity to Required Liters of Vaccines per Year

For the base-case analysis, it is assumed that 50 liters of vaccines are needed per year. Thus, vaccines lost due to the unavailability of the system need to be replaced through pure cash outlays. Exhibit 11-17 graphs the impact of varying the liters of vaccines required each year from 25 to 100 liters, by 25-liter intervals. This range corresponds to vaccinating the children and mothers of villages that have populations of 22,000 to 90,000 people (Reference 11-1). The graph indicates that between 25 and 50 liters per year, both PV-powered systems become financially more attractive. This result is due to the lower availability of kerosene-fueled refrigerators. Lower availability results in higher vaccine wastage and thus higher recurring costs to replace the lost vaccines. The unquantifiable cost of lost vaccines is not included in this analysis.

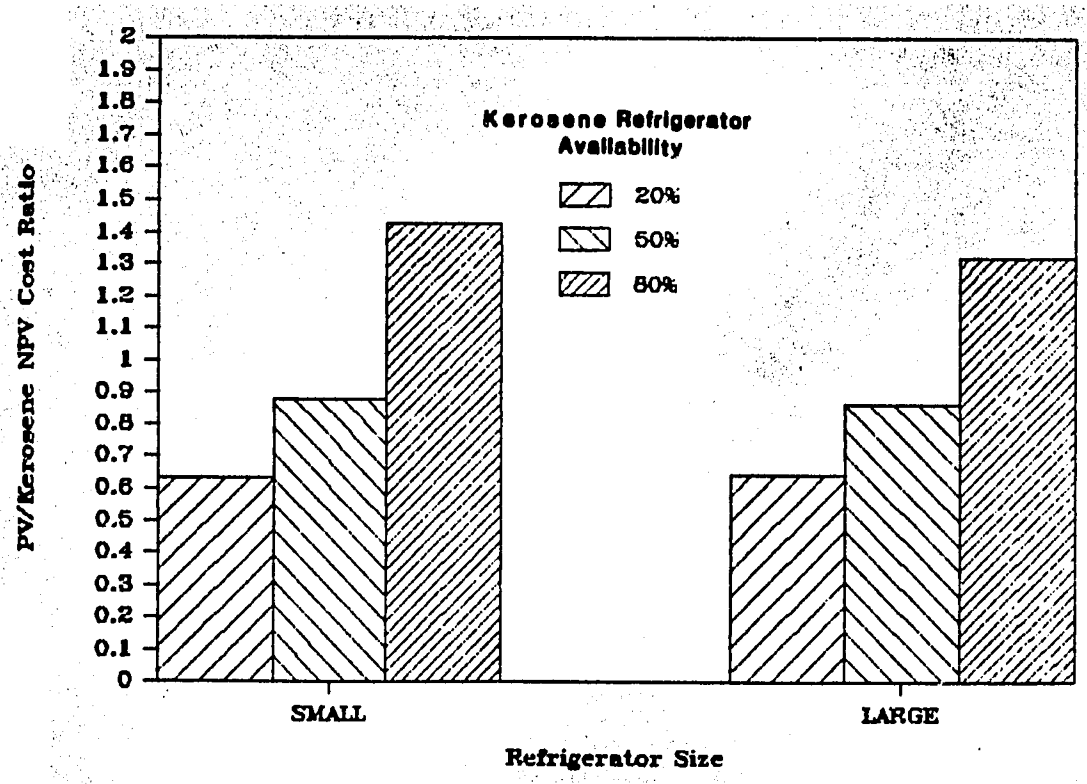
EXHIBIT 11-17. Sensitivity of Refrigeration Costs to Required Liters of Vaccines per Year



11.5.5 Sensitivity to Kerosene System Availability

This sensitivity is closely related to the sensitivity to required vaccines per year (Section 11.4.4), in that it has a strong impact on vaccine wastage. Exhibit 11-18 demonstrates the effect of varying kerosene system operating availability from 20% to 80% on refrigeration comparative costs (the base-case operating availability is 50%). Increasing kerosene system availability from 50% to 80% has a greater impact on the PV/kerosene NPV cost ratio than decreasing system availability from 50% to 20%. Obviously, as kerosene system availability decreases from the base case, the attractiveness of PV-powered refrigeration increases.

EXHIBIT 11-18. Sensitivity of Refrigeration Costs to Kerosene System Availability



CHAPTER 12

LIGHTING AND HOME POWER ANALYSIS

12.1 Overview

The financial analysis presented in this chapter compares PV and conventional (kerosene lamps and batteries) systems for home power, assuming development bank financing. The analysis shows that PV-powered systems are the least-cost option for small systems under all financial scenarios. Conventional home power systems of medium and large size are least cost only under the worst conditions for PV system viability: discount and interest rates between 10% and 20%, insolation of 4 kWh/m^2 and kerosene fuel cost of $.50 per liter (see Exhibit 12-1). The high degree of financial viability of the PV-powered systems suggests that shorter loan terms (applicable to individual, private users) would still show PV system attractiveness. For example, in French Polynesia, 5-year loans to finance these types of systems have resulted in a substantial expansion of the PV home power market.

The bar charts in Exhibit 12-1 depict the ratio of PV- to kerosene-powered home power system life-cycle costs for the best PV case and worst PV case scenarios. Both scenarios assume 20-year life-cycle costing and development agency financing. At an NPV cost ratio of 1.0, PV and diesel system life-cycle costs are equal. Under the best PV case scenario, the four parameters shown on the graph are adjusted to "reasonable extremes" that favor PV systems. An opposite adjustment is made under the worst PV case scenario.

As depicted in Exhibit 12-2, the life-cycle cost of PV home power systems is dominated by debt service, reflecting high installed system costs. Kerosene-powered system life-cycle costs are dominated by fuel expenses. Because PV systems are the least-cost option for all the base case systems evaluated, sensitivity analysis graphs are not included in this chapter.

The remainder of this chapter discusses the analyses and assumptions leading to Exhibits 12-1 and 12-2.

EXHIBIT 12-1. Sensitivity of Lighting and Home Power Costs to Best and Worst Conditions

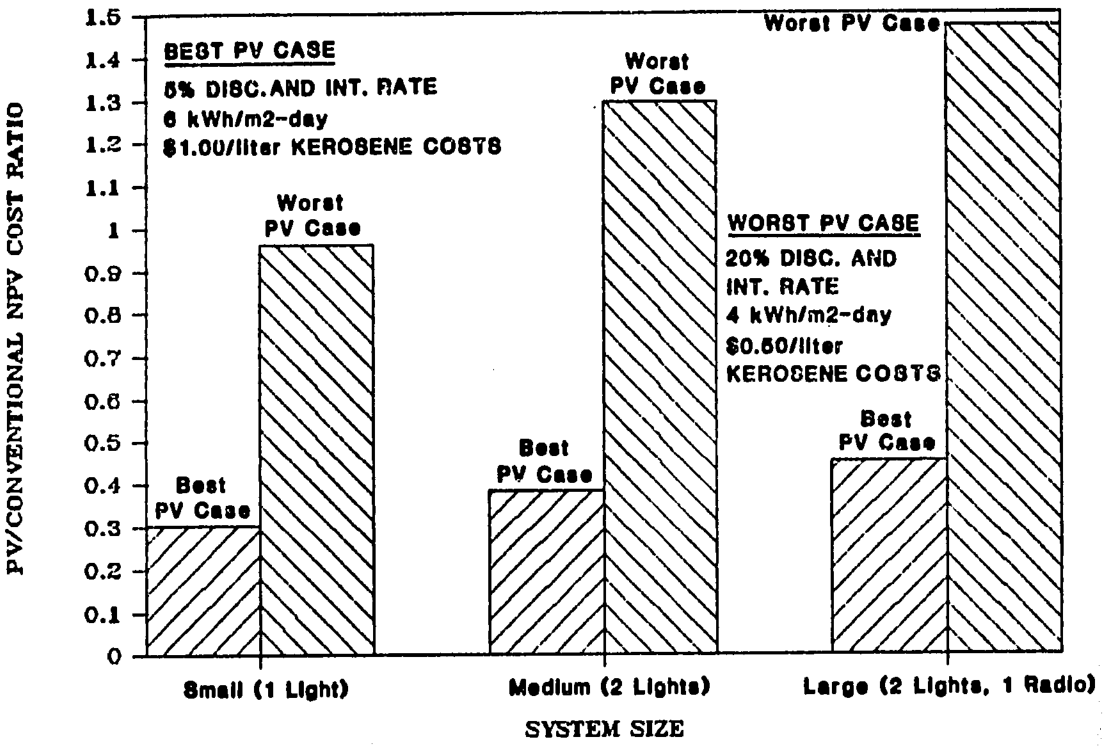
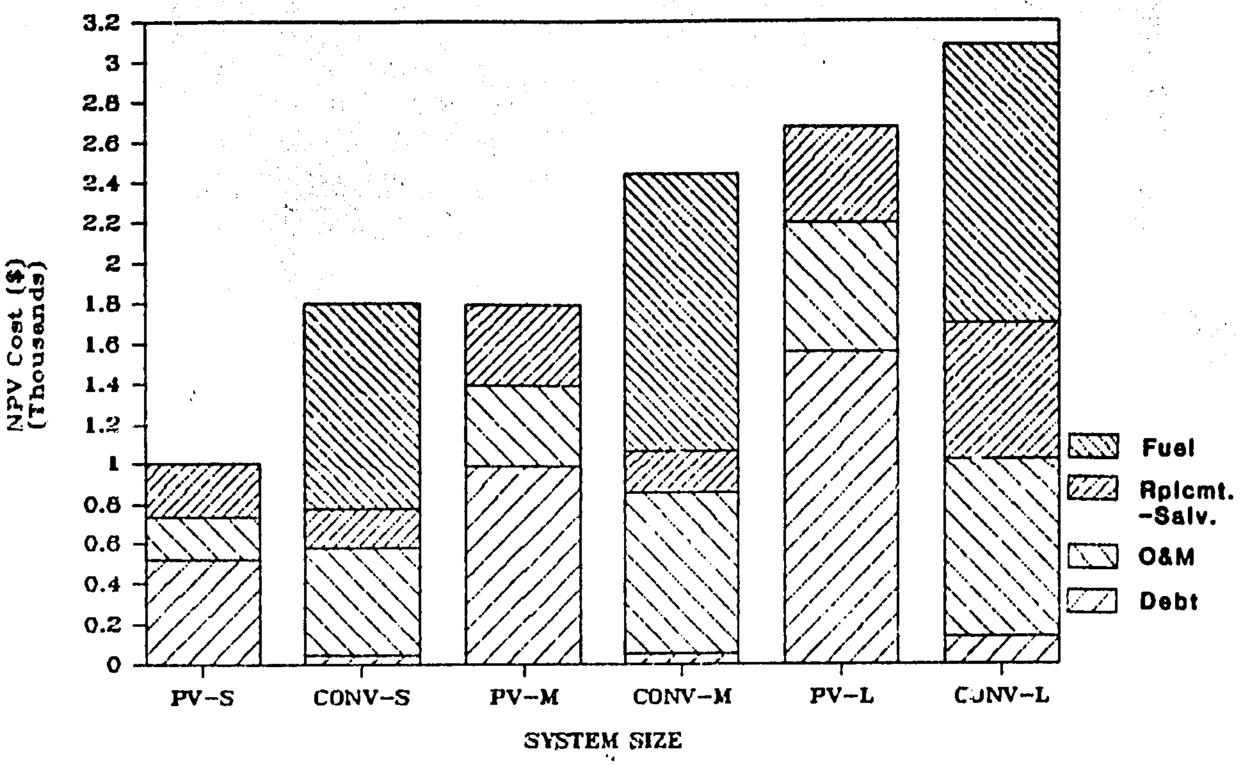


EXHIBIT 12-2. Base-Case Lighting and Home Power System Cost Components



12.2 Description of the Base Case

The base-case analysis concentrates on home power systems, the major components of which are lighting. While designing comparable PV- and conventional-powered lighting and home power systems, it is difficult to select a unit for financial comparison. A common unit for comparison, in terms of equivalent lighting power cost, is a net present value levelized annual cost in dollars per lumen, where the lumen corresponds to a source light intensity. Lux or lumens/square meter is the standard unit of illumination (i.e., 100-200 lux is a typical level required for reading or working). While lumens or lux may guide purchasing decisions in industrialized countries, it is believed that people in developing countries buy on a dollar-per-work-station basis.

Although users generally do not compare lighting systems on the basis of lumens, the improved lighting quality (a function of higher lumens) does have an impact on purchasing decisions. A 20-watt flourescent tube has been shown to provide approximately 100 lux, while a kerosene-fueled pressure lamp will provide about 12 lux on the same surface (Reference 6-1). In developing countries, this fact is an important qualitative benefit that is not easily quantifiable in terms of purchasing decisions.

Entire home power systems often involve a mixture of conventional power sources. For example, a typical household may use kerosene for lighting and a car battery to power a radio. This combination of power sources further complicates the selection of a comparison unit. To accommodate these issues, conventional home power systems are examined and their associated costs are compared with the costs of three PV-powered systems (small, medium and large) that could be used to replace the conventional systems. Lights are replaced on a unit basis (i.e., one kerosene-fueled lamp is replaced by one PV-powered fluorescent light). Thus, the increased quality of light produced by using fluoresent lights is not quantified. For each of the three typical system designs, the financial analysis compares the life-cycle costs of conventional and PV systems on the basis of net present value (NPV) cost. The conceptual system designs are described in the following sections.

.2.1 PV-Powered Home Power System Descriptions

Conceptual designs for three PV-powered systems were developed based on meeting the demand for typical small, medium and large conventional home power systems. (Conventional home power systems are described in Section 12.2.2.) The PV-powered system components and operating assumptions are as follows:

- Small - one 10-watt fluorescent light operating for 12 hours per day.
- Medium - one 20-watt and one 10-watt fluorescent light, operating for 6 and 12 hours per day, respectively.
- Large - one 20-watt fluorescent light operating for 9 hours per day, one 10-watt fluorescent light operating for 12 hours per day, and a 12-watt continuous electrical load (e.g., radio) operating for 9 hours per day.

Each of the PV-powered systems comprise the following components:

- PV array
- Battery storage
- Loads (When calculating the cost of load devices, only the cost of lighting components is used because other devices, i.e., the radio, cost the same as those used in the conventional-powered system).

The batteries are assumed to be a deep-discharge type that are replaced every 5 years. Battery storage is sized for 2 days. The lowest-month daily insolation incident on the array is 4 kWh/m^2-day.

12.2.2 Conventional Home Power System Descriptions

Three representative levels of lifestyle/power requirements are established for the conventional-powered systems. These levels are outlined in Exhibit 12-3.

EXHIBIT 12-3. Typical Conventional Home Power Systems

COMPONENTS	SMALL	MEDIUM	LARGE
Kerosene Hurricane Lamps	-	1	1
Pressurized Kerosene Lamps	1	1	1
12-Volt Car Battery (e.g., for a radio)	-	-	1

Usage patterns are based on the results of a study performed in Papua New Guinea (Reference 12-1). This study determined that owners typically keep one pressurized lamp lit from early evening until the morning. Those who own a second lamp (assumed to be a hurricane lamp for the base case) keep it lit from early evening until midnight.

12.3 System Costs

12.3.1 PV-Powered Home Power System Costs

The small, medium and large PV-powered systems are assumed to be one-, two- and three-module systems. (The method for determining the sizes of the PV array and battery bank is presented in Section 6.2.1.)

Costs for the three base-case PV home power systems are outlined in Exhibit 12-4. PV array costs are assumed to be \$8/Wp. A simple charge controller, typical of home power applications, costs \$50. Fluorescent lights cost approximately \$40 each. The batteries are small deep-discharge batteries, such as those used in golf carts, and cost \$66 per kWh of capacity (Reference 12-2). The maintenance and repair costs include the replacement of bulbs and ballasts. Battery, controller and light replacement is assumed to occur every 5 years.

EXHIBIT 12-4. Base-Case PV-Powered Home Power System Costs (Reference 12-2)

Small System

SPECIFICATION	COSTS
Initial Capital Costs (FOB Manufacturer)	
- PV Array (39 Wp)	$310
- Battery Storage (0.3 kWh)	20
- Charge Controller	50
- Fluorescent Light (1 @ 10 W)	40
Total Capital Cost	$420
Recurring Capital Costs (FOB Manufacturer)	
- Battery/Controller/Light Replacement	$110 every 5 years*
Other Recurring Costs (% Initial Capital Costs)	
- Maintenance & Repair	4%/year*

Medium System

SPECIFICATION	COSTS
Initial Capital Costs (FOB Manufacturer)	
- PV Array (78 Wp)	$620
- Battery Storage (0.6 kWh)	40
- Charge Controller	50
- Fluorescent Lights (1 @ 20W; 1 @ 10W)	80
Total Capital Cost	$790
Recurring Capital Costs (FOB Manufacturer)	
- Battery/Controller/Light Replacement	$170 every 5 years*
Other Recurring Costs (% Initial Capital Costs)	
- Maintenance & Repair	4%/year*

Large System

SPECIFICATION	COSTS
Initial Capital Costs (FOB Manufacturer)	
- PV Array (132 Wp)	$1054
- Battery Storage (1.02 kWh)	67
- Charge Controller	50
- Fluorescent Lights (1 @ 20W; 1 @ 10W)	80
Total Capital Cost	$1,252
Recurring Capital Costs (FOB Manufacturer)	
- Battery/Controller/Light Replacement	$197 every 5 years*
Other Recurring Costs (% Initial Capital Costs)	
- Maintenance & Repair	4%/year*

* Plus appropriate escalation due to general inflation.

12.3.2 Conventional-Powered Home Power System Costs

The costs of conventional-powered systems are based on a study performed in Papua New Guinea (Reference 12-1). In this study, the initial cost of hurricane and pressurized lamps is cited as $5 and $40 apiece, respectively. Average spare parts costs are $20 per year for hurricane lamps and $40 per year for pressurized lamps. Fuel consumption (based on the usage patterns described earlier) is 40 liters per year for a hurricane lamp and 115 liters per year for a pressurized lamp. The lifetime of these lamps is 3 years.

The large system includes one automobile-type battery, with an initial cost of $65 (Reference 12-2). Annual recharging costs are equivalent to 10% of the initial cost, or $6.5 per year. A summary of the conventional-powered system costs used for the base-case analysis is presented in Exhibit 12-5.

EXHIBIT 12-5. Base-Case Conventional Home Power System Costs

Small System

SPECIFICATION	COSTS
Initial Capital Costs (FOB Manufacturer)	
- Pressurized Kerosene Lamp	$40
Recurring Capital Costs (FOB Manufacturer)	
- Lamp Replacement	$40 every 3 years*
Other Recurring Costs	
- Maintenance & Repair	$40/year*
- Kerosene Fuel (115 liters @ $0.70/liter)	$81/year*

Medium System

SPECIFICATION	COSTS
Initial Capital Costs (FOB Manufacturer)	
- Pressurized Kerosene Lamp	$40
- Kerosene Hurricane Lamp	5
Total Capital Cost	$45
Recurring Capital Costs (FOB Manufacturer)	
- Lamp Replacement	$45 every 3 years*
Other Recurring Costs	
- Maintenance & Repair	$60/year*
- Kerosene Fuel (155 liters @ $0.70/liter)	$109/year*

Large System

SPECIFICATION	COSTS
Initial Capital Cost (FOB Manufacturer)	
- Pressurized Kerosene Lamp	$40
- Kerosene Hurricane Lamp	5
- Battery	65
Total Capital Cost	$110
Recurring Capital Costs (FOB Manufacturer)	
- Lamp Replacement	$45 every 3 years*
- Battery Replacement	$65 every 2 years*
Other Recurring Costs	
- Maintenance & Repair	
o Lamps	$60/year*
o Battery	$7/year*
- Kerosene Fuel (155 liters @ $0.70/liter)	$109/year*

* Plus appropriate escalation due to general inflation.

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12.4 Twenty-Year Life-Cycle Costs

Using the base-case assumptions that have been outlined, 20-year cash flows were developed for the small, medium and large PV- and conventional-powered systems. The results of these cash flows are expressed as the annualized net present value (NPV) life-cycle cost in dollars per year, as summarized in Exhibit 12-6. The actual cash flows are presented in Exhibits 12-7 through 12-12.

EXHIBIT 12-6. Summary of Base-Case Life-Cycle Cost Analysis

SYSTEM	Twenty-Year NPV COST ($)		
	SMALL	MEDIUM	LARGE
PV	1,002	1,796	2,674
Conventional	1,797	2,447	3,087

EXHIBIT 12-7. Small PV-Powered Home Power System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$62	$525
Operating & Maintenance Expenses:																					
Annual Maintenance	$18	$19	$19	$20	$21	$23	$24	$25	$26	$27	$29	$30	$32	$33	$35	$37	$38	$40	$42	$45	$214
Recurring Capital Costs:																					
Batt/Ctrl Replace Cost	$0	$0	$0	$0	$111	$0	$0	$0	$0	$142	$0	$0	$0	$0	$181	$0	$0	$0	$0	$0	$167
Light Replacement	$0	$0	$0	$0	$64	$0	$0	$0	$0	$81	$0	$0	$0	$0	$104	$0	$0	$0	$0	$0	$96
Total Cash Outflow:	$79	$80	$81	$82	$258	$84	$85	$86	$88	$313	$90	$92	$93	$95	$382	$98	$100	$102	$104	$106	
Discount Factor (DF) DF = 1/(1+DR)^Y	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1485	
NPV Stream	$72	$66	$61	$56	$160	$48	$44	$40	$37	$121	$32	$29	$27	$25	$91	$21	$20	$18	$17	$16	

TOTAL NPV OF CASH OUTFLOW $1,002

EXHIBIT 12-8. Small Conventional Home Power System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$6	$50
Operating & Maintenance Expenses:																					
Annual Maintenance	$42	$46	$49	$51	$54	$56	$59	$62	$65	$68	$72	$75	$79	$83	$87	$92	$96	$101	$106	$111	$532
Fuel	$85	$89	$93	$98	$103	$108	$113	$119	$125	$131	$138	$145	$152	$159	$167	$176	$185	$194	$203	$214	$1,024
Recurring Capital Replace Cost:																					
Lamp Replacement Costs	$0	$0	$58	$0	$0	$67	$0	$0	$78	$0	$0	$90	$0	$0	$104	$0	$0	$121	$0	$0	$0 $190
Total Cash Outflow:	$132	$141	$206	$155	$162	$237	$178	$187	$274	$205	$215	$316	$237	$248	$365	$273	$287	$422	$315	$331	
Discount Factor (DF) DF = 1/(1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$120	$116	$155	$106	$101	$134	$91	$87	$116	$79	$76	$101	$69	$65	$87	$59	$57	$76	$52	$49	
TOTAL NPV OF CASH OUTFLOW	$1,797																				

EXHIBIT 12-9. Medium PV-Powered Home Power System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$116	$987
Operating & Maintenance Expenses:																					
Annual Maintenance	$33	$35	$37	$38	$40	$42	$44	$47	$49	$51	$54	$57	$60	$63	$66	$69	$72	$76	$80	$84	$402
Recurring Capital Costs:																					
Batt/Ctrl Replace Cost	$0	$0	$0	$0	$143	$0	$0	$0	$0	$182	$0	$0	$0	$0	$233	$0	$0	$0	$0	$0	$215
Light Replacement	$0	$0	$0	$0	$128	$0	$0	$0	$0	$163	$0	$0	$0	$0	$208	$0	$0	$0	$0	$0	$192
Total Cash Outflow:	$149	$151	$153	$154	$427	$158	$160	$163	$165	$513	$170	$173	$176	$179	$622	$185	$188	$192	$196	$200	
Discount Factor (DF) DF = 1/(1+DR)^Y	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$136	$125	$115	$105	$265	$89	$82	$76	$70	$198	$60	$55	$51	$47	$149	$40	$37	$35	$32	$30	
TOTAL NPV OF CASH OUTFLOW	$1,796																				

EXHIBIT 12-10. Medium Conventional Home Power System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$7	$56
Operating & Maintenance Expenses:																					
Annual Maintenance	$63	$69	$73	$77	$80	$84	$89	$93	$98	$103	$108	$113	$119	$125	$131	$138	$144	$152	$159	$167	$793
Fuel	$114	$120	$126	$132	$138	$145	$153	$160	$168	$177	$186	$195	$205	$215	$226	$237	$249	$261	$274	$288	$1,380
Recurring Capital Replace Cost:																					
Lamp Replacement Costs	$0	$0	$65	$0	$0	$75	$0	$0	$87	$0	$0	$101	$0	$0	$117	$0	$0	$135	$0	$0	$0 $213
Total Cash Outflow:	$184	$196	$270	$215	$225	$312	$248	$260	$360	$286	$300	$415	$330	$346	$480	$381	$400	$554	$440	$462	
Discount Factor (DF) DF = 1/(1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2997	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$167	$162	$203	$147	$140	$176	$127	$121	$153	$110	$105	$132	$96	$91	$115	$83	$79	$100	$72	$69	
TOTAL NPV OF CASH OUTFLOW	$2,447																				

EXHIBIT 12-11. Large PV-Powered Home Power System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$184	$1,564
Operating & Maintenance Expenses:																					
Annual Maintenance	$53	$55	$58	$61	$64	$67	$70	$74	$78	$82	$86	$90	$94	$99	$104	$109	$115	$120	$127	$133	$637
Recurring Capital Costs:																					
Batt/Ctrl Repl Cost	$0	$0	$0	$0	$187	$0	$0	$0	$0	$239	$0	$0	$0	$0	$385	$0	$0	$0	$0	$0	$281
Light Replacement	$0	$0	$0	$0	$128	$0	$0	$0	$0	$163	$0	$0	$0	$0	$208	$0	$0	$0	$0	$0	$192
Total Cash Outflow:	$236	$239	$242	$245	$562	$251	$254	$258	$261	$667	$269	$274	$278	$283	$801	$293	$299	$304	$310	$317	
Discount Factor (DF) DF = 1/(1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$215	$197	$182	$167	$349	$142	$130	$120	$111	$257	$94	$87	$81	$74	$192	$64	$59	$55	$51	$47	
TOTAL NPV OF CASH OUTFLOW	$2,674																				

EXHIBIT 12-12. Large Conventional Home Power System Twenty-Year Cash Flow (Base Case)

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$16	$137
Operating & Maintenance Expenses:																					
Annual Maintenance	$70	$77	$81	$85	$89	$94	$98	$103	$108	$114	$119	$125	$132	$138	$145	$152	$160	$166	$176	$185	$885
Fuel	$114	$120	$126	$132	$138	$145	$153	$160	$168	$177	$186	$195	$205	$215	$226	$237	$249	$261	$274	$288	$1,380
Recurring Capital Replace Cost:																					
Battery Replace Cost	$0	$90	$0	$99	$0	$109	$0	$120	$0	$132	$0	$146	$0	$161	$0	$177	$0	$196	$0	$0	$473
Lamp Replacement Costs	$0	$0	$65	$0	$0	$75	$0	$0	$87	$0	$0	$101	$0	$0	$117	$0	$0	$135	$0	$0	$213
Total Cash Outflow:	$200	$302	$288	$332	$244	$439	$267	$400	$380	$439	$321	$583	$352	$530	$504	$583	$425	$776	$467	$489	
Discount Factor (DF)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
DF = 1/(1+DR)^Y																					
NPV Stream	$182	$250	$216	$227	$151	$248	$137	$186	$161	$169	$113	$186	$102	$140	$121	$127	$84	$140	$76	$73	

TOTAL NPV OF CASH OUTFLOW $3,087

12.5 Sensitivity Analyses

Sensitivity analyses are provided to determine the impact of varying capital cost, discount and interest rate, kerosene fuel cost and insolation. In the ranges of parameters selected, the PV-powered systems are always more cost-effective for small systems. Medium size conventional systems would be least costly at discount and internal rates of 17.7% and higher or at insolation levels of 2.5 kWh/m^2-day and lower. Large PV systems were found to be more cost-effective up to discount and interest rates of 13.5% at fuel costs of more than $0.48/liter and for insolation levels above 3.3 kWh/m^2-day. Thus, the approach taken was to show the extreme conditions under which conventional systems will have a cost advantage. Exhibit 12-13 identifies those extremes.

EXHIBIT 12-13. Assumptions Necessary for Conventional Home Power System Cost-Effectiveness*

PARAMETER	SMALL	MEDIUM	LARGE
Discount and Interest Rate (%)	27	17.7	13.5
Kerosene Cost ($/liter)	0.15	**	0.48
Insolation (kWh/m^2-day)	1.6	2.5	3.3

*Any single assumption will result in conventional system cost-effectiveness

**NPV cost ratio leveled out before conventional systems showed financial attractiveness.

Exhibits 12-14 and 12-15 show the sensitivity of home power costs to the capital costs of PV- and conventional-powered systems, respectively.

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EXHIBIT 12-14. Sensitivity of PV-Powered Home Power Costs to Capital Cost

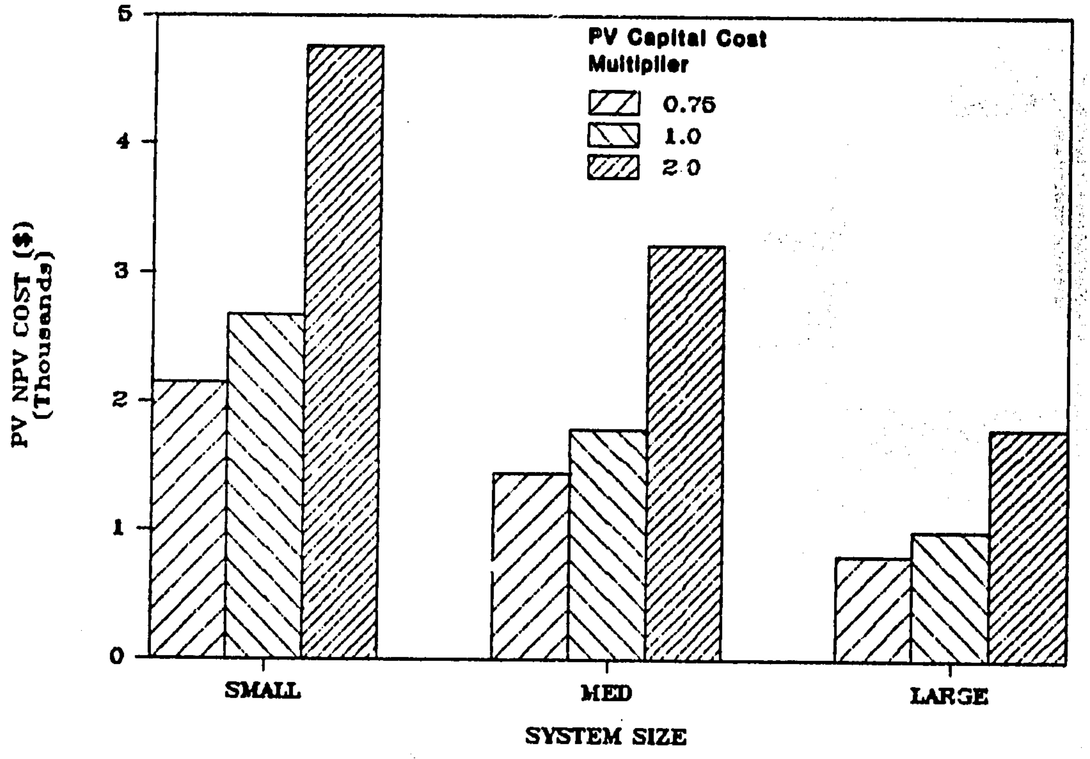
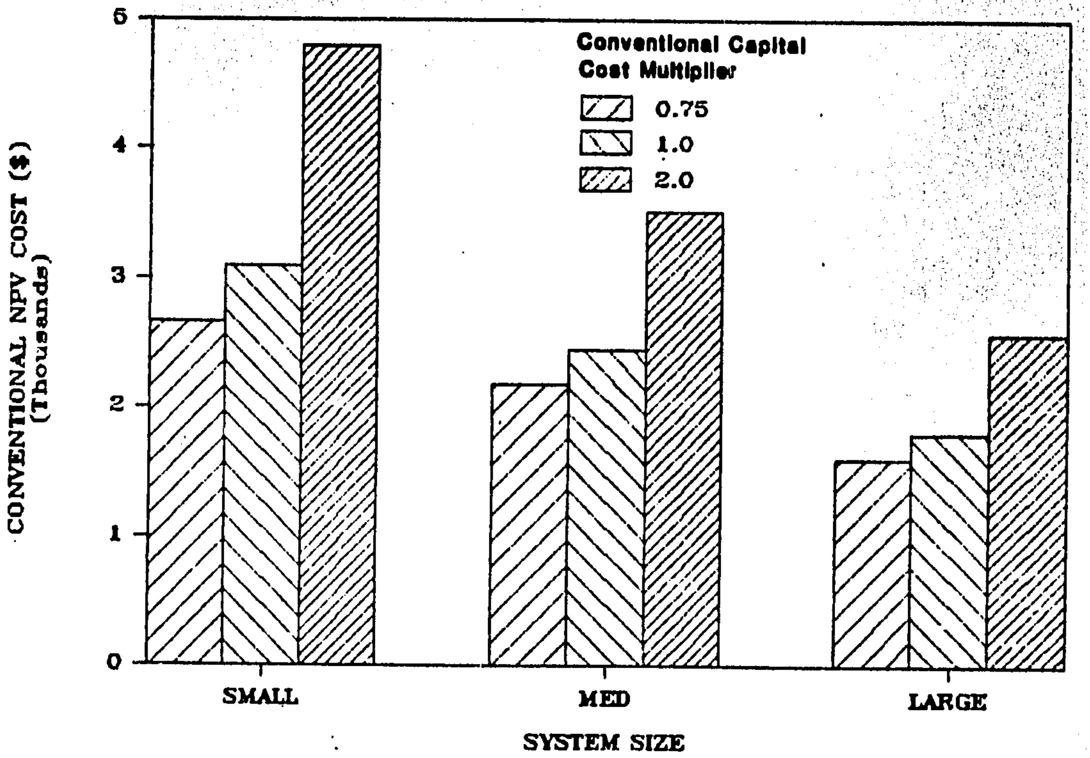


EXHIBIT 12-15. Sensitivity of Conventional Home Power Costs to Capital Cost



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CHAPTER 13

MULTI-USE ANALYSIS

13.1 Overview

The financial analysis presented in this chapter compares PV- and diesel-powered multi-use systems, assuming development agency financing. The analysis shows that PV-powered systems are the least-cost option at daily energy demands of up to 2 kWh, even under unfavorable financial assumptions (see Exhibit 13-1). When the financial parameters are more favorable, PV-powered systems are competitive up to 16 kWh per day.

The graph in Exhibit 13-1 depicts the ratio of PV- to diesel-powered multi-use system life-cycle costs for the best PV case and worst PV case scenarios. Both scenarios assume 20-year life-cycle costing and development agency financing. At an NPV cost ratio of 1.0, PV and diesel system life-cycle costs are equal. Under the best PV case scenario, the five parameters shown on the graph are adjusted to "reasonable extremes" that favor PV systems. An opposite adjustment is made under the worst PV case scenario. The area between the two curves represents a reasonable range of financial assumptions.

Exhibit 13-2 depicts the various cost elements of PV- and diesel-powered multi-use systems. As expected, PV life-cycle costs consist primarily of debt service. The diesel life-cycle cost is dominated by fuel cost. The sensitivity analyses in this chapter indicate that discount and interest rate and fuel cost are the most sensitive parameters when comparing PV-powered multi-use systems to diesel-powered systems.

The remainder of this chapter discusses the analyses and assumptions leading to Exhibits 13-1 and 13-2.

EXHIBIT 13-1. Sensitivity of Multi-Use Systems Costs to Best and Worst Conditions

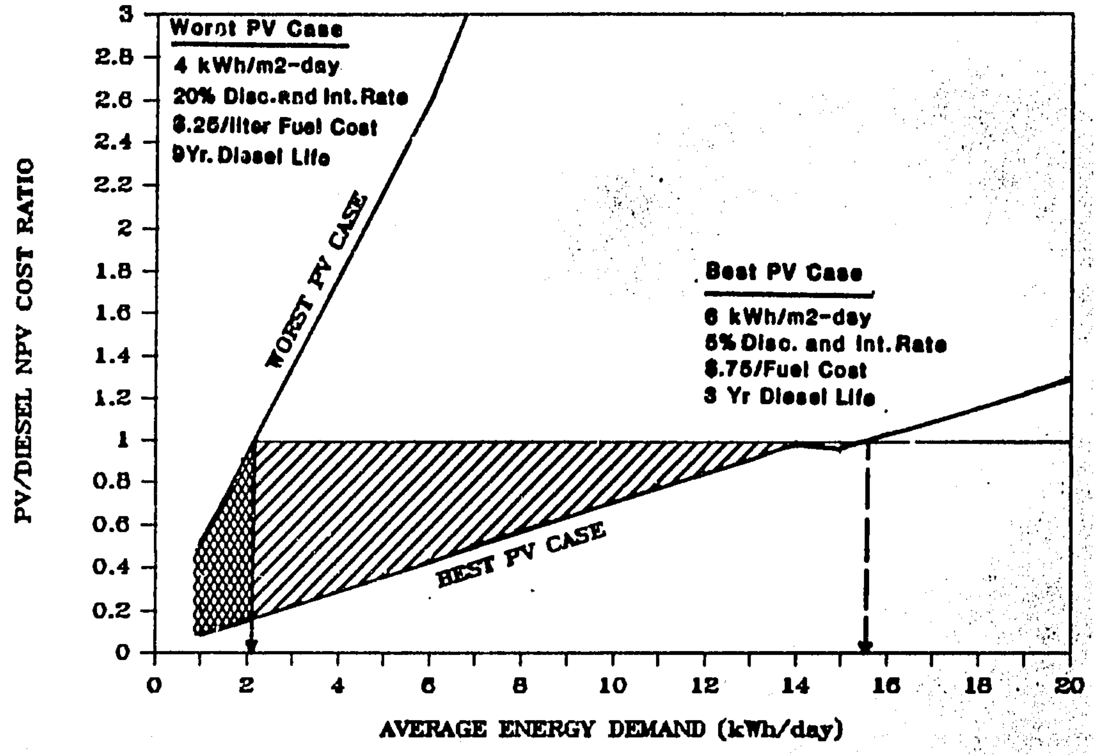
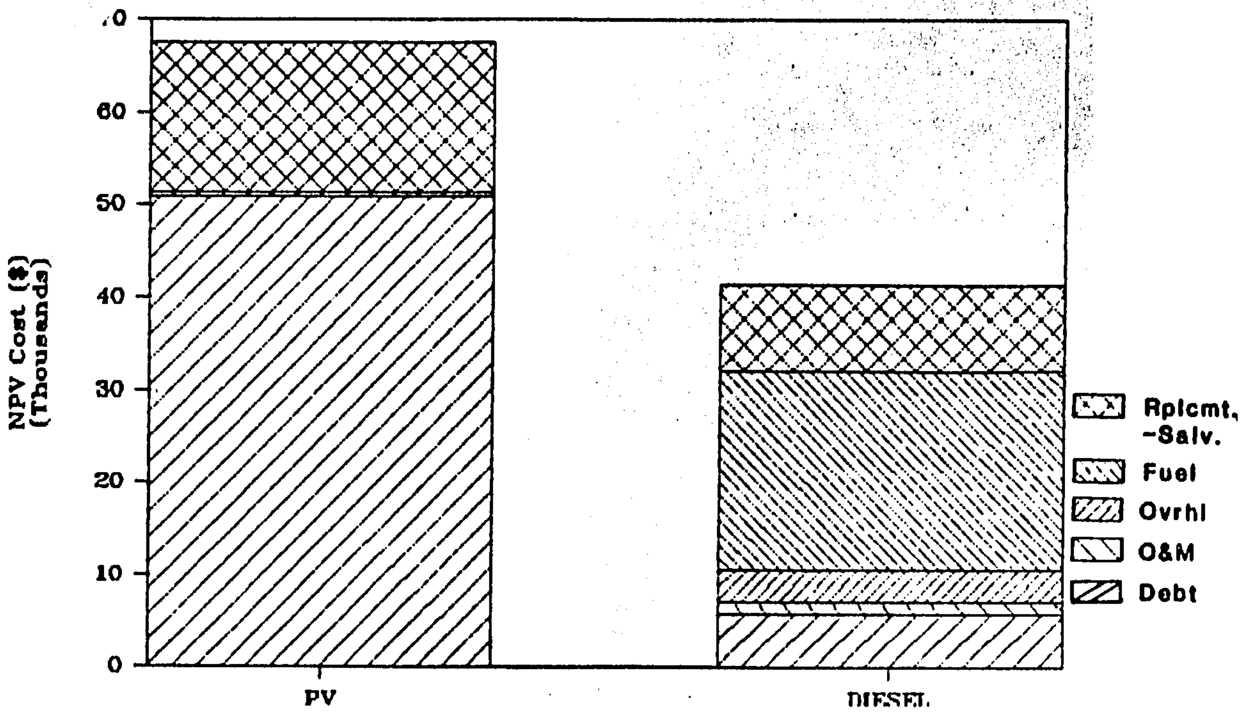


EXHIBIT 13-2. Base-Case Multi-Use System Cost Components



13.2 Description of the Base Case

The base-case multi-use load is predominantly a daytime and evening load typical of commercial, academic or administrative schedules. Load devices include AC lights and small AC appliances such as radios, televisions, micro-computers and small refrigerators. The loads are identical for the PV- and conventional-powered systems. The annual average energy demand is 10 kWh/day. The maximum energy demand is 50 percent higher than the average demand, or 15 kWh/day.

The financial comparison presented in this chapter is performed between PV and diesel power systems. It is assumed that the supply of diesel fuel and PV/diesel spare parts is never interrupted.

13.2.1 PV Power System Description

An AC PV power system is used for the base case. The system includes the following components:

- PV array (3.94 kWp)
- Charge controller
- Battery storage (37.5 kWh)
- Inverter (2 kW).

Battery storage is sized for 2 days. The insolation incident on the array is 5 kWh/m^2-day. The system is sized according to the graphs outlined in Chapter 7. PV power system availability is 97.5% (Reference 13-1).

13.2.2 Diesel Power System Description

The base-case multi-use conventional power system consists of a 3-kW diesel engine. The diesel is used for an average of 12 hours per day and a maximum of 15 hours per day. No back-up is provided. Diesel gen-set availability is 97.5%, assuming uninterrupted fuel and spare parts supply.

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13.3 System Costs

13.3.1 PV Power System

System costs for the PV-powered multi-use base case are outlined in Exhibit 13-3. The PV power system cost in multi-use applications consists of the PV array, battery storage, control electronics and inverter costs. Base-case array costs are specified as $8 per Wp. Batteries are assumed to be deep-discharge type, costing $150 per kWh of storage capacity. The controller cost is $0.40/Wp, and the inverter cost is $1,000 per kW of power demand (Reference 13-2).

EXHIBIT 13-3. Base-Case PV-Powered Multi-Use System Costs

SPECIFICATION	COST
Initial Capital Costs (FOB Manufacturer)	
- PV Array (3.94 kW)	$31,521
- Battery (37.5 kWh)	5,625
- Controller	1,576
- Inverter (2 kW)	2,000
Total Capital Cost	$40,722
Recurring Capital Costs (FOB Manufacturer)	
- Battery Replacement	$5,625 every 5 years*
- Controller Replacement	$1,576 every 10 years*
- Inverter Replacement	$2,000 every 10 years*
Other Recurring Costs (% Initial Capital Cost)	
- Maintenance & Repair	0.1%/year*

* Plus appropriate escalation due to general inflation.

13.3.2 Diesel Power System

Costs associated with the base-case diesel power system are outlined in Exhibit 13-4. The capital cost breakdown for the diesel gen-set is based on Exhibit 9-5 from Chapter 9. Once again, a 6-year life is assumed. Annual maintenance and repair costs are projected to be equivalent to 2% of the capital cost per year. Overhauls are performed every 3 years and cost an equivalent of 15% of the initial gen-set cost (Reference 13-3).

EXHIBIT 13-4. Base-Case Diesel-Powered Multi-Use System Costs

SPECIFICATION	COST
Initial Capital Costs (FOB Manufacturer)	
- Diesel Gen-Set (3 kW)	$4,771
Recurring Capital Costs (FOB Manufacturer)	
- Diesel Gen-Set Replacement	$4,771 every 6 years*
Other Recurring Costs	
- Maintenance & Repair	2% of gen-set cost per year
- Overhaul	15% of gen-set cost every 3 years*+
- Fuel (3,408 liters at $0.50/liter)	$1,704/year*

* Plus appropriate escalation due to general inflation.
\+ No overhaul during diesel replacement year.

Fuel requirements are taken from Exhibit 9-7 (of Chapter 9) and are based on a 3-kW diesel operating at 28% average load factor. It can be seen from the exhibit that fuel consumption for a gen-set of this size under such conditions is 0.78 liters per hour or 3,408 liters per year.

13.4 Twenty-Year Life-Cycle Costs

The base-case 20-year life-cycle cost analyses project net present value (NPV) costs of $67,715 and $41,486 for PV and diesel power systems, respectively. The cash flows used to determine these costs are presented in Exhibits 13-5 and 13-6. The crossover between PV and diesel power system costs, for the base-case conditions, occurs at 6.2 kWh/day average energy demand.

EXHIBIT 13-5. Base-Case PV-Powered Multi-Use System Cash Flow

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$5,979	$50,902
Operating & Maintenance Expenses:																					
Annual Maintenance	$43	$45	$47	$49	$52	$55	$57	$60	$63	$66	$70	$73	$77	$81	$85	$89	$93	$98	$103	$108	$518
Recurring Capital Costs:																					
Controller Replace Cost	$0	$0	$0	$0	$0	$0	$0	$0	$0	$3,209	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,237
Battery Replace Cost	$0	$0	$0	$0	$8,974	$0	$0	$0	$0	$11,453	$0	$0	$0	$0	$14,617	$0	$0	$0	$0	$0	$13,487
Inverter Replace Cost	$0	$0	$0	$0	$0	$0	$0	$0	$0	$4,072	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,570
Salvage Value	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Cash Outflow:	$6,022	$6,024	$6,026	$6,028	$15,005	$6,034	$6,035	$6,039	$6,042	$24,780	$6,049	$6,052	$6,056	$6,060	$20,681	$6,068	$6,072	$6,077	$6,082	$6,087	
Discount Factor (DF) DF = 1/((1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$5,474	$4,978	$4,528	$4,118	$9,317	$3,406	$3,098	$2,817	$2,562	$9,554	$2,120	$1,928	$1,754	$1,596	$4,951	$1,321	$1,201	$1,093	$994	$905	
TOTAL NPV OF CASH OUTFLOW	$67,715																				
PV System Generation(kWh/yr)	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	

EXHIBIT 13-6. Base-Case Diesel-Powered Multi-Use System Cash Flow

Year (Y)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	NPV COMPS
Debt Service	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$700	$5,963
Operating & Maintenance Expenses:																					
Annual Maintenance	$100	$105	$110	$116	$122	$128	$134	$141	$148	$155	$163	$171	$180	$189	$198	$208	$219	$230	$241	$253	$1,213
Diesel Engine Overhaul	$0	$0	$1,036	$0	$0	$1,199	$0	$0	$1,388	$0	$0	$1,606	$0	$0	$1,860	$0	$0	$2,153	$0	$0	$3,387
Fuel	$1,789	$1,879	$1,973	$2,071	$2,175	$2,284	$2,398	$2,518	$2,643	$2,776	$2,914	$3,060	$3,213	$3,374	$3,543	$3,723	$3,906	$4,101	$4,306	$4,521	$21,671
Recurring Capital Replace Cost:																					
Diesel Gen Replace Cos	$0	$0	$0	$0	$0	$7,992	$0	$0	$0	$0	$0	$10,709	$0	$0	$0	$0	$0	$14,352	$0	$0	$10,505
Salvage	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$8,439	$1,254
Total Cash Outflow:	$2,590	$2,684	$3,819	$2,888	$2,997	$12,302	$3,232	$3,359	$4,880	$3,632	$3,778	$16,248	$4,094	$4,263	$6,301	$4,628	$4,825	$21,535	$5,248	($2,964)	
Discount Factor (DF) DF = 1/((1+DR)^Y)	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	
NPV Stream	$2,354	$2,218	$2,869	$1,972	$1,861	$6,944	$1,659	$1,567	$2,069	$1,400	$1,324	$5,177	$1,186	$1,123	$1,508	$1,007	$955	$3,873	$858	($441)	
TOTAL NPV OF CASH OUTFLOW $41,486																					
Diesel Sys Gen (kWh/yr)	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	3,559	

13.5 Sensitivity Analyses

The sensitivity of multi-use system costs to several variables, including capital cost, discount and interest rate, diesel fuel cost, diesel lifetime and insolation is analyzed. The sensitivity graphs are expressed as the ratios of the net present value life-cycle costs for PV and diesel power systems over a range of electricity load demands.

13.5.1 Sensitivity to Capital Costs

To demonstrate the sensitivity of multi-use system life-cycle costs to capital costs, capital cost multipliers are applied to the PV and diesel power systems. The multipliers vary from 0.75 to 2.0. The 1.0 multiplier corresponds to the base-case system. Variations in capital costs can result from different equipment, customs, insurance, freight or installation costs. Installation costs are not included in the base case. Exhibits 13-7 and 13-8 present the net present value life-cycle costs for the PV and diesel multi-use power systems, respectively.

EXHIBIT 13-7. Sensitivity of PV Multi-Use System Costs to Power System Capital Costs

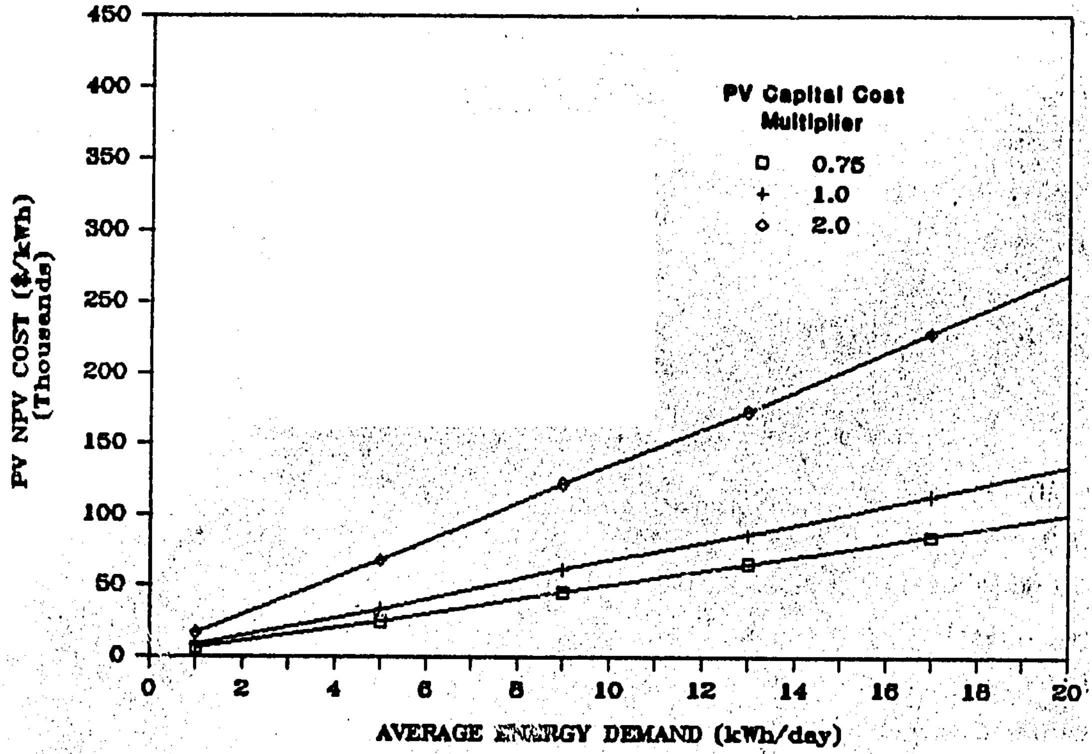
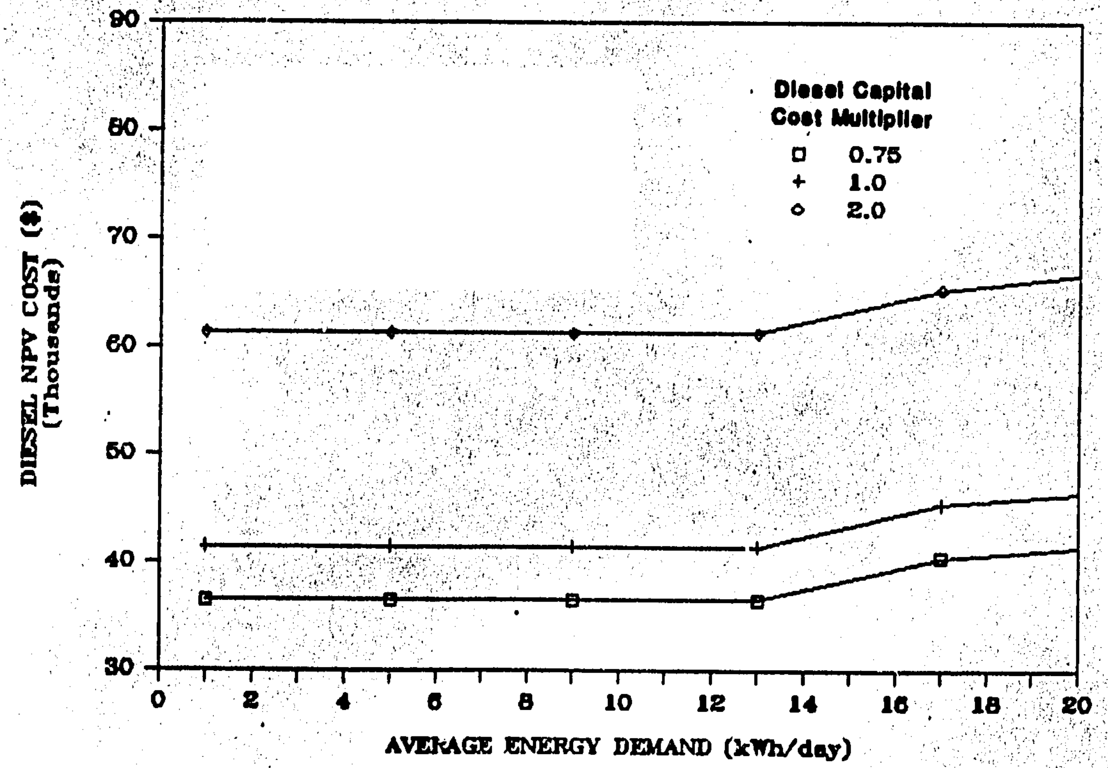


EXHIBIT 13-8. Sensitivity of Diesel Multi-Use System Costs to Power System Capital Costs



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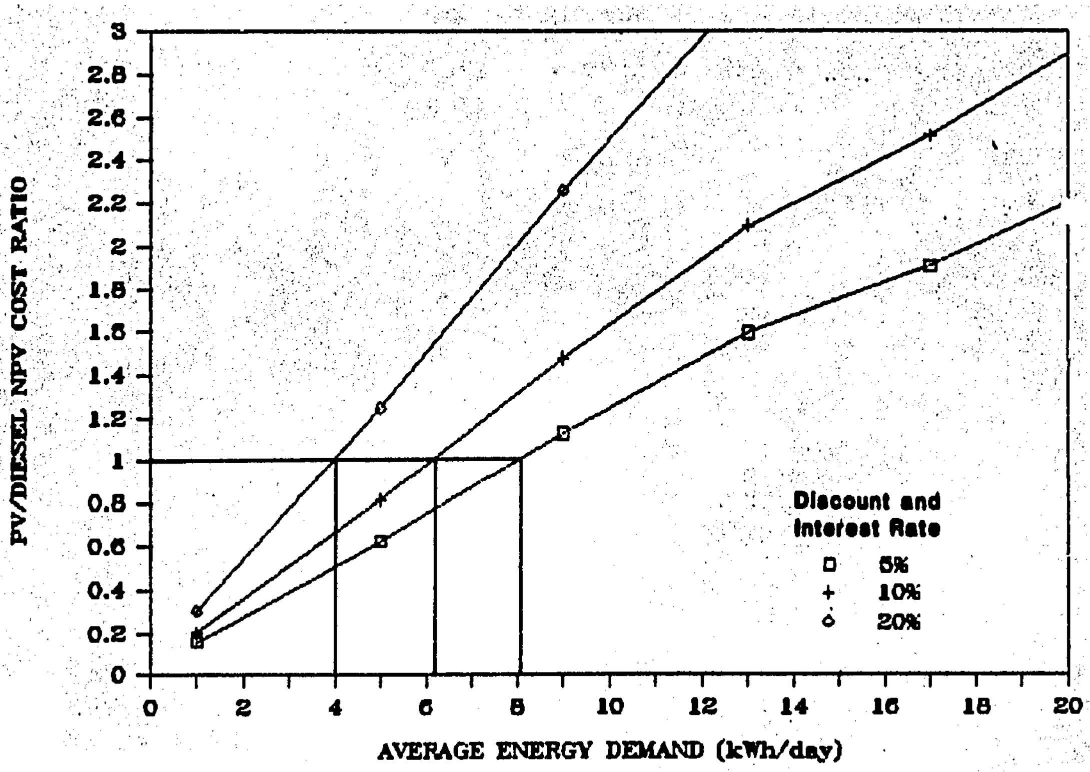
13.5.2 Sensitivity to Discount and Interest Rate

Exhibit 13-9 demonstrates the effect various discount and interest rates have on the cost of multi-use systems. If a 5% discount and interest rate is used, PV power systems are financially advantageous up to demands of approximately 8.0 kWh/day. At a 20% discount rate, PV power systems are financially advantageous up to demands of only 4.0 kWh/day.

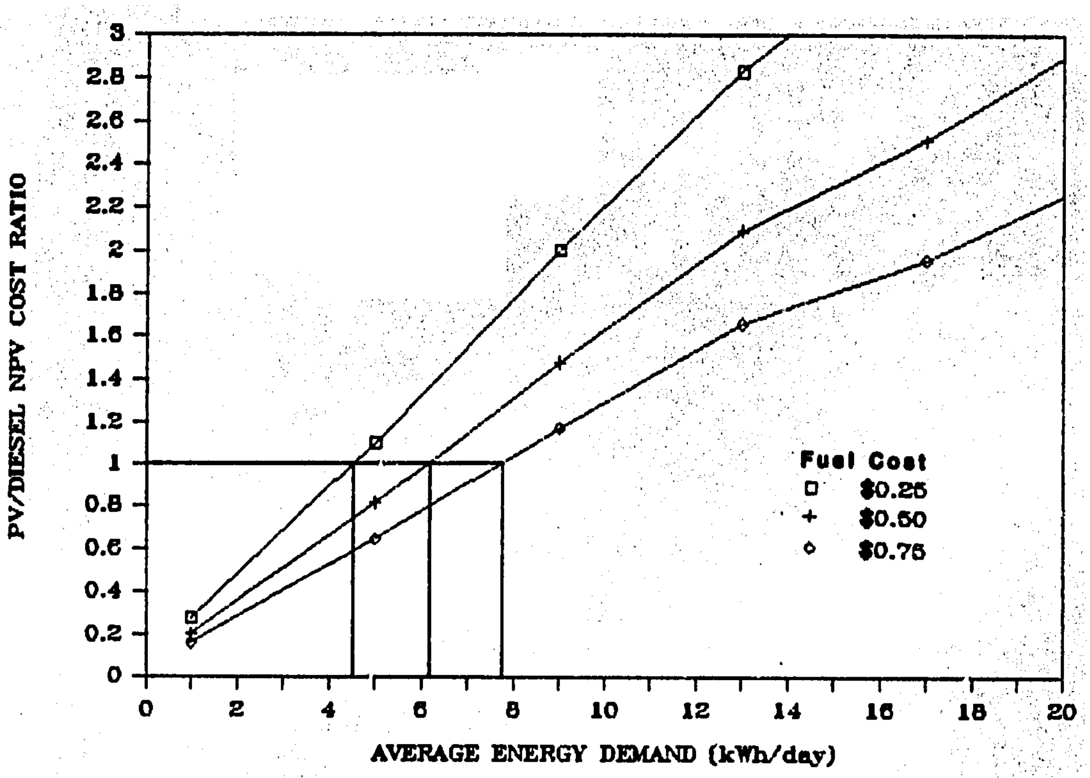
EXHIBIT 13-9. Sensitivity of Multi-Use System Costs to Discount and Interest Rate



13.5.3 Sensitivity to Diesel Fuel Costs

Exhibit 13-10 demonstrates the impact of diesel fuel price changes on the attractiveness of PV-powered multi-use systems. Varying the diesel fuel price of $0.50 per liter (the base case) to $0.75 per liter causes the value below which PV systems appear more favorable to move from approximately 6.2 kWh/day to 7.8 kWh/day. Moving to 50% lower than the base case (i.e., $0.25 per liter) drops the crossover to 4.6 kWh/day.

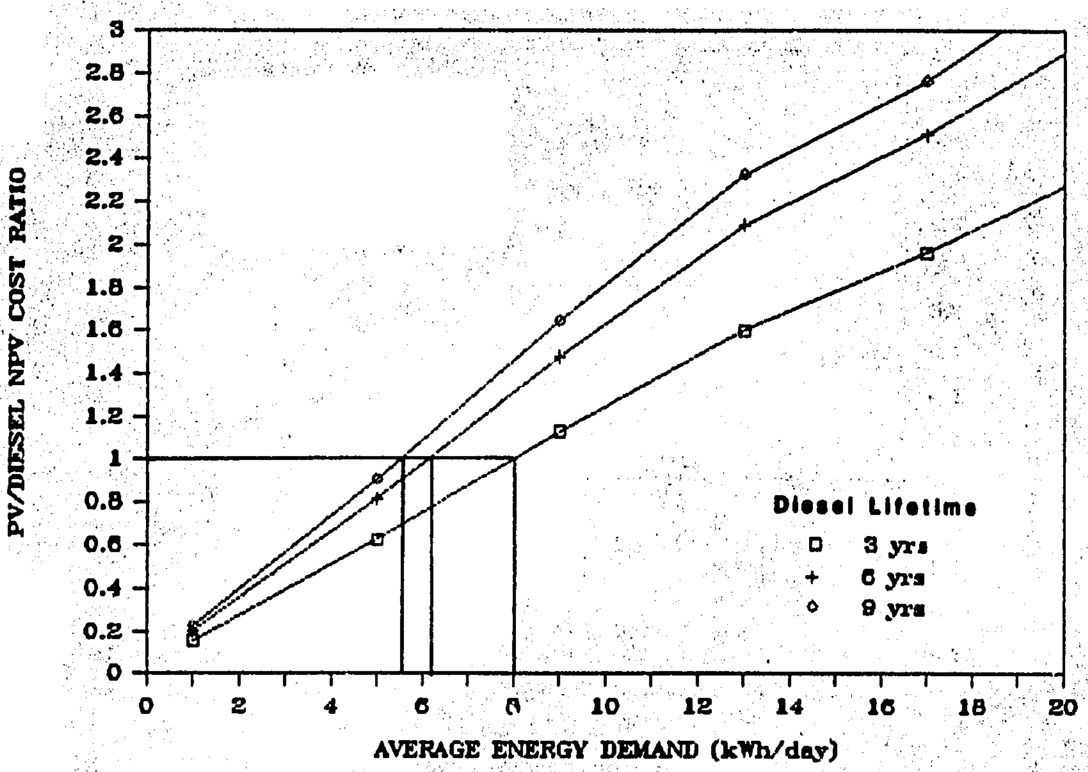
EXHIBIT 13-10. Sensitivity of Multi-Use System Costs to Diesel Fuel Costs



13.5.4 Sensitivity to Diesel Lifetime

Exhibit 13-11 shows the impact variations in the diesel gen-set lifetime have on multi-use system costs. While the 6-year base-case lifetime results in PV systems having a cost advantage at energy demands less than 6.2 kWh/day, the crossovers for 3- and 9-year lifetimes occur at 8.0 and 5.5 kWh/day, respectively.

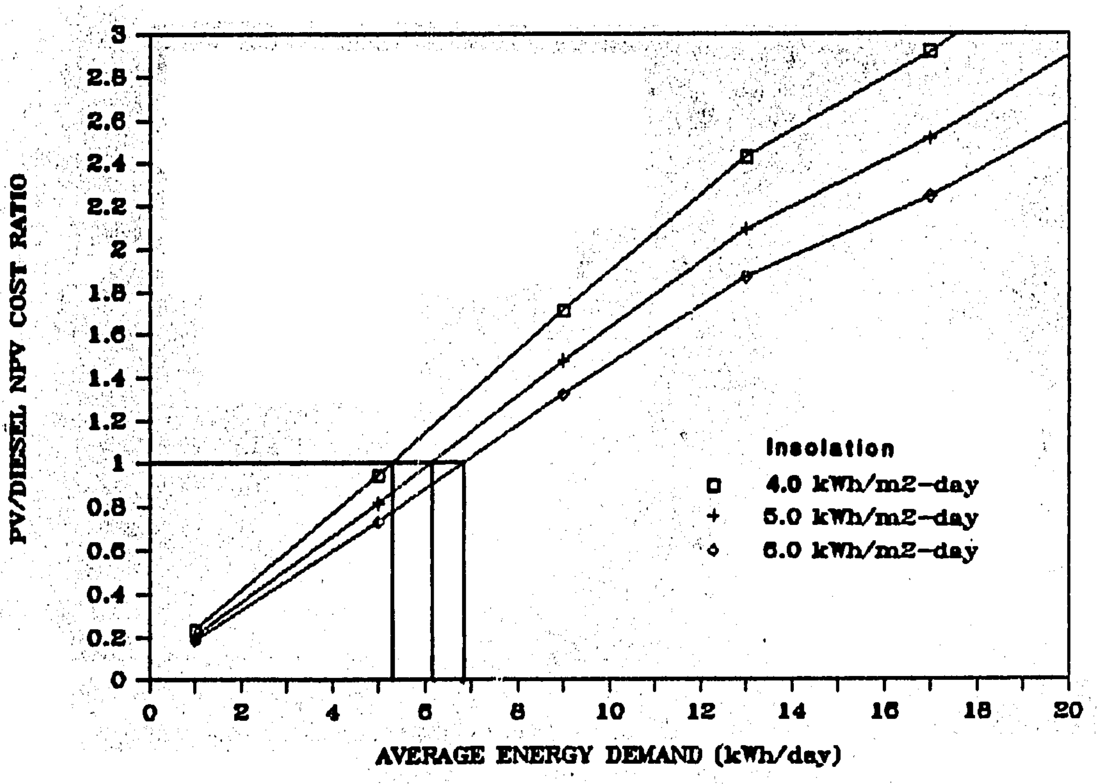
EXHIBIT 13-11. Sensitivity of Multi-Use System Costs to Diesel Gen-Set Lifetime



13.5.5 Sensitivity to Insolation

Exhibit 13-12 shows the effect varying insolation has on the comparative cost of PV and diesel multi-use systems. At 4 kWh/m^2-day, PV retains a cost advantage up to daily energy demands of approximately 5.4 kWh. At an insolation of 6 kWh/m^2-day, PV is competitive up to 6.8 kWh/day.

EXHIBIT 13-12. Sensitivity of Multi-Use System Costs to Insolation



CHAPTER 14

INSTITUTIONAL FACTORS

14.1 Introduction

In addition to the technical and financial factors discussed in previous chapters, there are a number of broader institutional issues that may impact the performance of PV-powered systems. Although these issues may not be readily quantifiable, they play a major role in the successful installation, operation, maintenance, and reliability of systems in remote locations, across the range of end-use applications. Thus, they will need to be considered by USAID and other donor agencies in the design and development of future PV projects.

This chapter discusses the major institutional issues that have been identified in past and ongoing PV projects sponsored worldwide. It was not within the scope of this evaluation to quantify or resolve these issues. Although the issues have surfaced in regards to PV-powered systems, it is important to recognize that they apply to conventional- and other renewable-powered systems as well. Data sources used to identify these issues included:

- Responses to questionnaires distributed to over 300 individuals involved in PV projects worldwide (see Appendix A)
- Review of available reports and articles on significant PV projects
- Results from the Round Table Meeting held on November 20, 1985, which addressed broader socio-economic and planning issues associated with PV projects in developing countries.

14.2 Key Institutional Issues

The major institutional issues relating to the implementation and operation of PV-powered systems, as determined in this study, are presented below.

14.2.1 Need for Targeted Decision-Maker/User Training

User training is one of the most critical components in the success of PV-powered systems. In particular, training is required in four areas: (1) operation and maintenance; (2) repair; (3) system specification and application; and (4) system management.

Operation and Maintenance

According to evaluation results, there is only a minimal requirement for training in general system operation and maintenance (O&M). In most countries, there appears to be a suitable technical skills base to manage the day-to-day O&M requirements of the systems. The exception has been vaccine refrigeration systems, where training in the capabilities and proper use of the systems has generally been shown to be ineffective. Users have often placed food and beverages into the refrigerators, causing the internal temperatures to rise above the acceptable limit for vaccines. Although design modifications of the refrigerator compartments may be made in order to restrict their use to vaccine storage only, appropriate user training is the preferable solution, from an institution-building perspective, for dealing with misuse.

Repair

A major problem with system performance has been the inability of local manpower to repair installed systems. In some instances, trained manpower was unavailable in the area; in others, adequate provision for in-depth training of local individuals was never made. Increased attention to training in the repair of electronic equipment (e.g., controllers and inverters) and end-use equipment (e.g., pumps, refrigerators, lights, etc.) is critical to the success of PV-powered systems.

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System Specification and Application

Technical expertise in the specification and application of PV-powered systems to particular end-user needs is probably the most important training factor in terms of the use and long-term viability of PV in developing countries. In order for PV-powered systems to have widespread application in these countries, it will be necessary for local personnel to become skilled in performing resource and load assessments, developing system designs, writing system specifications, and installing systems. Additionally, training will be required in the types and performance of available equipment.

System Management

The last major area in which user assistance is required is in the training of managerial-level personnel involved in planning and implementing PV systems. These individuals are responsible for the broader issues associated with system implementation, such as evaluating and determining the role for PV in national and local energy programs; assigning and supervising technical project personnel involved in the design, development, installation, operation and maintanence of PV-powered systems; arranging for the supply of spare parts; coordinating and administering the delivery of systems, components, and spare parts to designated remote sites; and evaluating user acceptance of these systems.

14.2.2 Availability of Spare Parts

Another element crucial to successful long-term operation of PV systems is the availability of spare parts. Although PV-powered systems require less support than conventionally powered remote systems, responsive technical assistance with the required replacement parts is vital to any significant application of PV in developing countries. In many cases, adequate funds for parts replacement have not been budgeted in the project, resulting in system failures and substantial downtime.

14.2.3 Availability of Financing

A major impediment to the widespread use of PV in lesser developed countries (LDCs) is the availability of suitable financing for these systems (most LDCs lack the foreign exchange necessary to purchase these systems on their own). Although, in a number of cases, rural PV-powered systems are more reliable and less costly than conventional alternatives on a life-cycle basis, the budgeting procedures of host-country government agencies, private firms, and donor agencies are not geared towards the long-term (e.g., 20-year) capitalization of investments. Despite the fact that PV-powered systems have low O&M costs, their high initial capital costs put them at a disadvantage to less capital-intensive conventional alternatives. This occurs even though conventional systems have substantial operation, maintenance, repair and replacement costs--costs that are frequently not factored into procurement budgets.

14.2.4 Involvement of Local Manufacturers

On an increasing basis, developing countries are requiring that local firms become involved in the manufacture of system components. This local production contributes to increased growth in employment and income in these countries and, in cases where these products are exported, leads to reductions in trade deficits. Depending upon the skill levels in the country and the existing manufacturing infrastructure, local production of PV-powered system components can range from the development of batteries, support structures, and load devices in less sophisticated countries to the manufacture of PV cells in the more technologically advanced countries.

14.2.5 Involvement of Key Organizations

There are a number of organizations that should be involved in implementing successful PV projects in the developing world. These organizations include:

- USAID - Within USAID, the Science and Technology Energy Division should be responsible for informing other agency components and host-country governments of the general merits of PV and for performing pre-investment studies for potential projects under consideration. Regional bureau staff and missions should be responsible for educating host-country personnel on specific PV project applications in their countries and for conducting demonstration projects, as appropriate.

- Other Donor Organizations - These organizations, which include the World Bank, United Nations, and regional development banks, should play a role in the financing of PV projects. Like USAID, they maintain centralized energy offices that should be responsible for informing other agency staff and host-country governments of relevant PV applications.

- Host-Country Officials - Both public and private sector individuals within the host country need to be involved in planning and implementing PV systems to ensure long-term, widespread use of the technology.

To date, these groups have not worked in a coordinated and effective manner. Energy sector personnel at USAID and other donor agencies have not given sufficient attention to educating other staff members and host-country ministries on the merits of PV for supplying remote power needs. Education must be focused on decision-makers in the end-use sectors where PV is a technically reliable and cost-effective solution. These sectors include health, agriculture, communications, and water supply.

14.2.6 Existence of Market Imperfections

A number of LDCs have intervened in the market process in their countries by imposing trade barriers and energy subsidies that distort the true economic value of photovoltaics. Among the barriers imposed are tariffs, excise taxes, licensing controls, foreign exchange controls, import restrictions, and performance standards. Pricing subsidies are frequently provided for conventional fuels (e.g., petroleum and petroleum products) to make these sources artificially more affordable to host-country consumers. The result of these trade barriers and subsidies is a distortion of market prices, at both the national and consumer level, that perpetuates inefficient use of energy in the proponent countries.

14.2.7 Insufficient Resource Data

Credible data on solar insolation levels are key to identifying PV project opportunities in LDCs. This data does not currently exist in any detailed or reliable form. Efforts by the U.S Government (particularly USDOE or its national laboratories) to collect these data would assist U.S. firms, donor agencies, federal export assistance agencies, and host-country ministries and private firms in targeting PV markets and projects.

14.3 Recommendations

Institutional factors play an important role in the successful performance of PV-powered systems. However, to date, PV activities have focused on understanding and resolving technical and financial issues associated with PV systems, giving little attention to the broader institutional issues. Significant advances made over the last decade in mitigating PV technical problems and identifying competitive applications for this technology have enabled attention to now focus on critical institutional issues--the last major area related to successful PV system performance.

This chapter has identified the major institutional issues affecting PV systems in the developing world. Listed below are recommended activities that should be undertaken by USAID and other key organizations to further comprehend and address these issues.

14.3.1 Conduct Case Studies

Over the past few years, a number of countries, both developed and developing, have established successful PV programs and projects that are expected to significantly contribute to national development objectives. The first recommended item in the institutional area is to conduct case studies of these countries to identify critical institutional elements that influenced PV program/project success. Data collected from the selected countries should be cross-analyzed to determine a set of common institutional factors, which can then be applied to other developing countries to aid them in the design, development, and implementation of PV systems.

Institutional data should be collected on: availability/performance of government renewable energy institutions; availability/performance of national energy plans incorporating renewables; existing policy measures that impact PV technology investment and utilization (e.g., subsidies, tax credits, pricing policies, investment allowances, and import restrictions); and existence of local PV technicians, engineers, and equipment manufacturers. Among the countries to be considered for study are Mali, Fiji, French Polynesia and Spain.

14.3.2 Educate PV Decision-Makers and End-Users

Another important initiative required in the institutional area is the widespread education of decision-makers and end-users concerning PV. Specifically, decision-makers from national planning agencies (energy and end-use sectors), donor organizations, and financial institutions need to be informed about PV technical performance, economics, and applications; the true economic cost to the country of using conventional energy systems rather than PV in small-scale, remote applications; procedures for incorporating life-cycle cost methodologies and broader socio-economic considerations into investment analyses; and the impact various policy measures have on the use of PV in the country. This information is necessary to ensure that decision-makers make informed choices regarding the use of PV in their country. Data generated from the case studies above should be used in preparing decision-maker educational programs and materials.

Project managers, both mid- and senior-level, require training in system selection, siting, monitoring, distribution, and spare parts management. Local engineers and technicians need training in system design, installation, operation, and maintenance. In-country manufacturers require assistance in identifying PV system components that can be produced locally, as well as in component production and processing.

Among the tools that could be used in this education process are:

- In-country training workshops for project managers, engineers, technicians, and manufacturers (both formal classroom training and on-the-job field training)
- U.S. site training for technical personnel and manufacturers at U.S. national laboratories and U.S. photovoltaic manufacturing firms
- Decision-maker seminars (both in the U.S. and at regional sites overseas)

- PV end-use application brochures (e.g., brochures on water pumping, medical refrigeration, telecommunications, and lighting/home power systems)

- PV product catalogue(s) of available U.S. equipment and services.

14.3.3 Provide Financial Analysis Support

In addition to providing decision-makers in host-country, U.S. Government, and donor agencies with key information for their investment analyses (Section 14.3.2 above), there are a number of other activities that could be conducted by USAID to assist in PV project financing. These activities include:

- Identifying project opportunities in specific countries and working with multilateral and financial institutions in conducting investment analyses

- Arranging for financing for technically and economically viable projects

- Arranging joint ventures between U.S. and host-country PV firms.

14.3.4 Collect Solar Resource Data

The last institutional recommendation involves collecting site-specific resource data for developing countries. These data could be used by U.S. Government agencies, U.S. photovoltaic firms, donor agencies, and host-country public and private sector organizations in identifying project opportunities.

Since original data collection is extremely expensive and time consuming, resource data could be collected from secondary sources worldwide. Secondary sources should include U.S. and foreign government agencies and private firms, multilateral organizations (e.g., International Energy Agency, World Bank, United Nations, and regional development banks), and meteorological agencies. Data should be collected for as many country locations as possible because solar insolation readings are site-specific, varying significantly across a given country or region.

In conducting this task, USAID should work in cooperation with the U.S. Department of Energy and its national laboratories.

Exhibit 14-1 identifies the institutional factors addressed by each of the above recommended activities.

EXHIBIT 14-1. Recommended Activities For Institutional Follow-Up

RECOMMENDATION / INSTITUTIONAL ISSUE	CASE STUDIES	EDUCATION					FINANCING SUPPORT			SOLAR RESOURCE DATA
		IN-COUNTRY WORKSHOPS	U.S. SITE TRAINING	DECISION-MAKER SEMINARS	APPLICATION BROCHURES	PRODUCT CATALOGUE	INVESTMENT ANALYSES	PROJECT FINANCING	JOINT VENTURES	
DECISION-MAKER/ USER TRAINING	X	X	X	X	X	X	X	X	X	X
SPARE PARTS MANAGEMENT	X	X								
FINANCING	X			X	X		X	X	X	
LOCAL MANUFACTURING	X	X	X		X	X			X	
KEY ORGANIZATIONS	X	X	X	X	X	X	X	X	X	
MARKET IMPERFECTIONS	X			X						
RESOURCE DATA										

14.4 Conclusions

Institutional factors play a major role in the selection, application, and performance of PV-powered systems in developing countries. Issues such as training of system planners and users, availability of spare parts, access to suitable financing, involvement of local firms in the manufacturing of PV components, participation of key organizations, mitigation of trade barriers, and access to solar insolation data will determine the ultimate success or failure of PV systems in developing countries. Therefore, it is imperative that each of these issues be examined and addressed by USAID and other government donor agencies through the proposed recommendations.

CHAPTER 15

CONCLUSIONS

15.1 Summary

Across the five applications examined in this evaluation, the majority of PV-powered systems have been well accepted by users based on their reliability, independence from fuel, and minimal maintenance requirements. Most of the earlier technical problems associated with PV-powered systems have been resolved. The major limitations to implementing PV systems in developing countries are institutional support and the lack of long-term financing.

The conclusions reached as a result of this evaluation can be summarized as follows:

- Technical: PV arrays are extremely reliable under all conditions. The performance of power conditioning equipment and load devices has varied, but the careful selection of field-proven components should ensure successful system operation.
- Institutional: The institutional support for PV-powered systems has been the overall weak link in system implementation in developing countries. Because PV is a new technology, there is no established infrastructure to support training, maintenance, and repair. However, when institutional support is lacking for both PV and conventional systems, the PV-powered systems are more successful due to their lower operation, maintenance, and repair requirements.
- Financial: When 20-year life-cycle costing is used, all five PV applications are financially attractive at low power loads or in cases when conventional systems operate inefficiently. This conclusion is supported by the financial analyses presented in this report as well as by case studies of programs that have stimulated the widespread implementation of PV-powered systems through financing.

This report provides development agency officials with the information required to assess PV projects. Based on "lessons learned" from past projects, recommendations are provided for project implementation. The report also provides industry with an unbiased assessment of potential applications for their PV products as well as an assessment of product performance and suggested areas for improvement.

15.2 Financial Viability

Each financial assessment in this report includes a "best-case/worst-case" analysis in an attempt to identify the limits of financial viability for PV-powered systems. These limits are summarized in Exhibit 15-1. These analyses provide a general picture of when PV systems are financially attractive for developing country applications, using development agency financing. They are, however, based on the cost of today's systems; thus, changes in system cost could substantially alter the viability ranges.

These viability ranges were developed by simultaneously varying the following parameters:

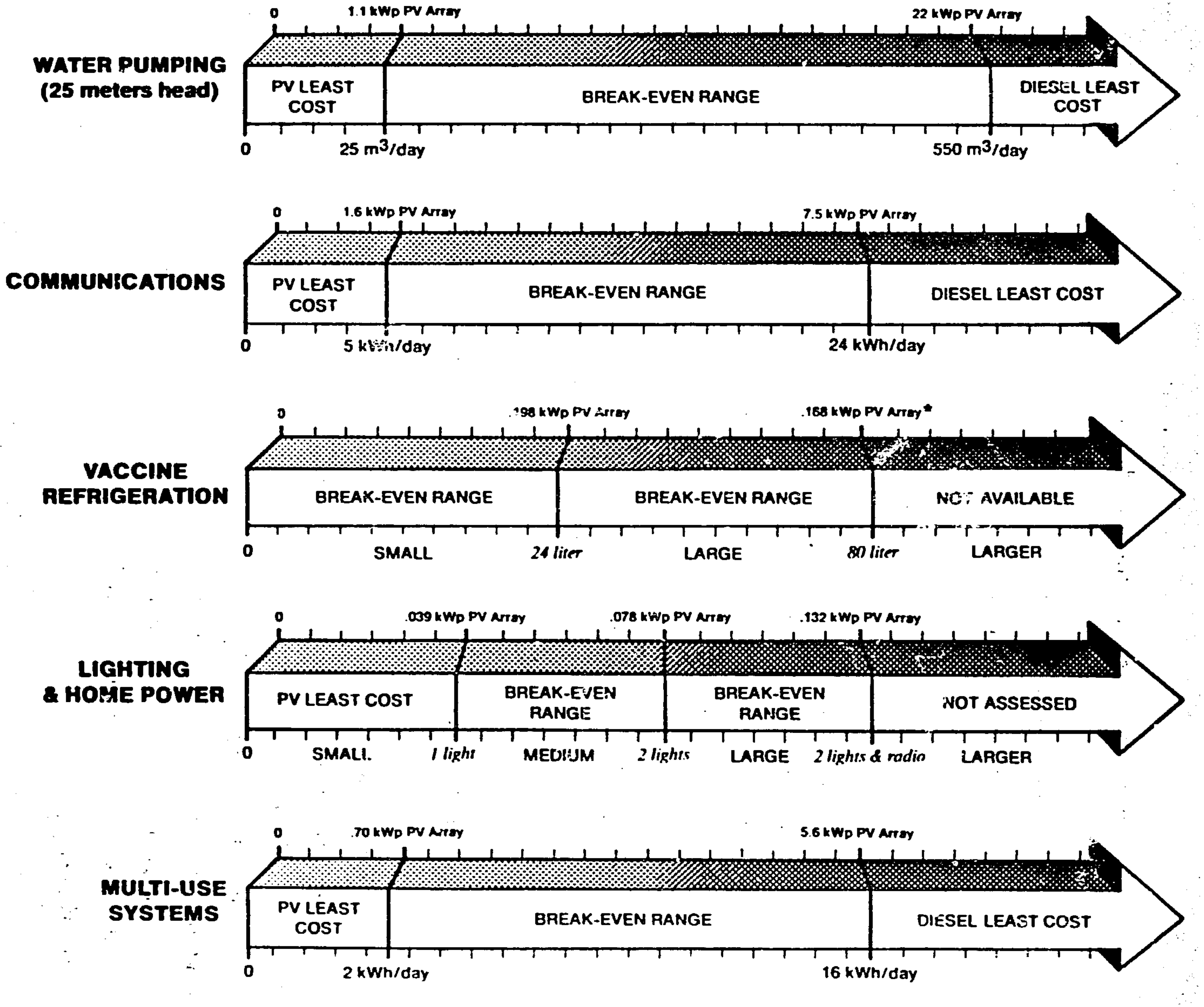
- Discount and interest rate (from 5% to 20%)
- Fuel cost (from \$0.25/liter to \$0.75/liter for diesel fuel and from \$0.50/liter to \$1.0/liter for kerosene fuel)
- Diesel lifetime (from 3 to 9 years)
- Insolation (from 4 to 6 kWh/m^2-day)
- Kerosene refrigerator operating availability (from 20% to 80%)
- Vaccine requirements (from 25 to 100 liters/year).

These parameters were adjusted to their extremes in the PV best-case scenario and to their opposite extremes in the PV worst-case scenario. In Exhibit 15-1, "PV Least Cost" indicates the load range at which PV is the least-cost option even under the PV worst-case scenario. Similarly, "Diesel Least Cost" indicates when diesel is the least-cost option even under the PV best-case scenario. The "Break-Even Range" depicts the load range in which either PV or the alternative system could be the least-cost option, depending on the parameters listed above.

The viability ranges in Exhibit 15-1 show that PV systems can be the least-cost option at loads larger than those indicated by previous studies. There are three major reasons for this change:

- Recent improvements in the cost and performance of PV systems
- The assumption of development agency financing

EXHIBIT 15-1. PV Financial Viability Limits



*PV Array is smaller for large refrigerator due to peculiarities in the World Health Organization specifications.

- Careful consideration of the performance of diesel and kerosene systems.

The following observations can also be made for each application:

- **Pumping:** Even under the PV worst-case scenario, PV is the least-cost option at loads more than two times greater than that claimed by a previous landmark study sponsored by the UNDP (Reference 15-1).

- **Communications:** PV-powered systems are competitive for many typical applications--a fact that is not surprising since PV systems are currently being used for commercial applications without favorable financing.

- **Refrigeration:** The comparison of PV- to kerosene-powered system is always in the break-even range, largely due to the varied performance of kerosene refrigerators. This suggests that site-specific parameters must be carefully considered.

- **Lighting and Home Power:** PV systems are the least-cost option for very small systems and are in the break-even range for all other scenarios considered in this evaluation.

- **Multi-Use Systems:** Small-size systems can be financially viable.

One reason that PV systems compare well with conventional systems in this analysis is that the inefficiencies of diesel gen-sets are considered. While diesel gen-sets are not available below 3 kW in size, they are often used for much smaller loads. This inefficient operation of the gen-set results in higher fuel consumption, shorter lifetime, and higher maintenance requirements. Although gasoline gen-sets are available at lower loads than diesel gen-sets, the discussion in Chapter 8 indicates that these systems are probably more costly than diesel systems.

15.3 Application-Specific Findings

15.3.1 Water Pumping

PV-powered water pumping systems (with centrifugal pumps) were conservatively determined to be competitive to diesel-powered water pumping systems for demands of less than 25 m^3/day at a 25-meter head. This is equivalent to demands of up to 625 m^4/day, where m^4/day refers to the volume of water pumped multiplied by the head. The cutoff of 625 m^4/day represents more than two times the viability range determined in the UNDP/ World Bank pumping study (Reference 15-1) for rural water supply. The UNDP/World Bank study, completed in 1983, has been accepted by applications experts as being very conservative. For water demands between 25 m^3/day and 550 m^3/day at a head of 25 meters (i.e., for 625 m^4/day to 13,750 m^4/day), PV system viability is dependent on case-specific parameters, the most sensitive of which are the discount and interest rate and diesel gen-set lifetime. Above this range, PV-powered water pumping systems are not financially viable at the present time. While PV-powered system costs have been dominated by debt service, diesel-powered system costs are mostly dependent on replacement and fuel costs.

The overall viability of PV-powered systems is also a function of technical and institutional performance. Successful systems have incorporated careful selection of pumps, motors and controls. The availability and proper use of credible data on solar resource and well yield characteristics has avoided significant over- and under-sized systems. It has been shown that effective training corrects misconceived user expectations and reduces system downtimes.

15.3.2 Communications

Photovoltaic-powered communications systems have been proven reliable and financially viable, as evidenced by the recent substantial growth in the number of commercial systems. When compared to diesel-powered systems, PV-powered systems are the least-cost option up to 5 kWh/day continuous load. Loads of 5 to 24 kWh/day are identified as being in the break-even range, or dependent on case-specific parameters. In this range, PV-powered system viability is most dependent on diesel fuel cost and diesel gen-set lifetime. Viability is less sensitive to insolation since PV-powered system costs are heavily influenced by battery capacity. Life-cycle costs for PV-powered systems are split fairly evenly between debt service and replacement costs. Although a sensitivity analysis was not performed on battery life, the high percentage of replacement costs suggests battery life is an important parameter. Diesel-powered system life-cycle costs are dominated by fuel cost, followed by replacement cost.

Reliability of PV-powered communications systems depends on the careful selection of charge controllers and load equipment that have been field-proven under the environmental conditions of interest. Careful load equipment selection is not unique to PV systems, but applies to conventional systems as well.

15.3.3 Vaccine Refrigeration

The financial analyses performed in this evaluation do not indicate a clear-cut range for PV-powered system viability at this time. PV-powered system viability, for both small and large systems, is always in the break-even range (or dependent on case-specific parameters). The most critical assumptions are related to vaccine wastage, which is a function of the annual vaccine dose requirement and system operating availability (the percentage of time the system operates within the proper temperature range). It is assumed that because vaccines are a critical item, any vaccines lost due to system unavailability must be replaced through pure cash outlays. In the PV-powered systems, the most dominant costs are the recurring capital costs (indicating that refrigerator and battery life are important parameters) and debt service. For the kerosene-powered refrigerators, the overwhelming cost is vaccine wastage (due to the low availability of kerosene units). Assuming the vaccination program can support the use of a large unit (i.e., have enough vaccines to keep the unit filled), the larger units show lower net present value life-cycle costs. The relative viability of PV to kerosene units in the small and large cases is approximately the same.

PV-powered vaccine refrigeration systems have demonstrated reliable performance in many developing countries. Operating availability of the PV systems has been significantly higher than that experienced with kerosene-fueled units. Credible solar resource data and load power consumption data under field conditions are fundamental to system sizing.

Institutional support is critical to the success of PV-powered vaccine refrigeration systems. Effective user training must be conducted so users understand the operating principles of the system, the consequences of overloading the system, and the required maintenance procedures. Also, complete coordination with end-user organizations results in an understanding of the particular vaccination program, which leads to more efficient and appropriate system designs.

15.3.4 Lighting and Home Power

For the typical small systems examined in this evaluation, PV-powered systems are financially more attractive, even under worst-case conditions. For medium and large configurations, PV-powered systems may be financially more attractive, depending on specific technical and financial project parameters. The conventional power system costs are dominated by fuel costs, followed by maintenance expenses. The PV-powered systems are dominated by debt service.

The strong financial viability of PV-powered systems suggests that shorter loan terms (applicable to individual, private users) would still show PV system attractiveness. For example, in French Polynesia, 5-year loans to finance PV systems have resulted in a substantial expansion of the PV home power market.

The most important technical factor in the successful use of PV-powered systems is the selection of field-proven, reliable charge controllers. The availability and distribution of spare parts for the loads and power conditioning equipment is a basic infrastructural need for widespread system implementation.

15.3.5 Multi-Use Systems

Multi-use systems have been shown to be the least-cost option for average energy demands of less than 2 kWh/day. Between 2 kWh/day and 16 kWh/day, PV system financial viability is in the break-even range (dependent on case-specific parameters). Above 16 kWh/day, PV multi-use systems are not viable. In the break-even range, the discount rate and diesel fuel cost are the most sensitive variables. In general, PV system life-cycle costs are dominated by debt service, and diesel system life-cycle costs are dominated by fuel cost.

Technically, photovoltaic multi-use systems have been successfully fielded. However, the reliability and complexity of power conditioning equipment must be carefully considered in the design of these types of systems. Small stand-alone inverters have had a relatively poor field performance record. As a result, applications experts have chosen to design DC systems whenever possible. However, DC is not an option for mini-utilities. For load centers, the decision between AC and DC is based on the commercial availability of DC loads.

A local infrastructure for managing power is required for successful application of multi-use systems. The power management structure for PV-powered systems is similar to that for conventional systems. The decision to design one large (mini-utility) system or many decentralized systems (load centers) is a major rural electrification policy issue.

15.4 Recommendations

Based on the review of past projects, the assessment of current technology status, and the financial analyses, certain recommendations can be made for implementing PV-powered systems in developing countries. These recommendations, which are summarized in Exhibit 15-2, cut across all five selected applications. They are based on an assessment of those factors that were most prevalent in successful systems and notably absent in unsuccessful systems. These recommendations are oriented toward suppliers, users, and financial institutions.

15.4.1 Technical Recommendations

Although most PV systems have performed reliably, there have been some "lessons learned." Factors that contributed to system failure included (1) components that were not field-tested under similar conditions; (2) systems not properly designed to meet the required load; or (3) improper system operation. The following recommendations address these concerns.

Select Field-Proven Components

Major components include PV modules, balance-of-system equipment (power conditioning and batteries), and load devices. Users have acknowledged that flat-plate PV modules made from crystalline silicon have proven their reliability and durability in the field. (Concentrators and amorphous silicon modules were not examined in this evaluation due to minimal field experience with these technologies in developing countries.) Successful PV-powered systems have used simple, field-proven power conditioning devices that have been designed to withstand specific environmental conditions. The type and capacity of batteries were properly selected and loads were chosen based on their field-proven durability.

Balance-of-system equipment and load devices have not been as reliable as PV modules. Therefore, these components should be selected based on their demonstrated field experience and the availability of replacement parts. Many of the problems associated with end-use devices have been related to poor quality control and/or misuse, rather than to serious design flaws. The failures have

EXHIBIT 15-2. Recommendations

TECHNICAL

- Select field-proven components
  - Tested under similar conditions
- Obtain and properly use design data
  - Load, solar, weather data
- Provide user-oriented product engineering
  - Design components for simple user interface
  - Anticipate operating errors

FINANCIAL

- Evaluate viability using life-cycle costing
- Utilize financing mechanisms for developing countries
  - Development agencies and banks

INSTITUTIONAL

- Establish field service capability
  - Management of technical support and spare parts
- Provide training at all levels
  - Operation and maintenance
  - Fault detection
  - Repair
- Coordinate activities with end-users
  - Local ownership and responsibility
  - Early involvement of users

rarely been related to PV as a power source, but rather reflect generic operating experience under developing country conditions. Over the past 3 years, new products with better performance and durability have emerged, allowing quality systems to be obtained in all application areas.

Obtain and Properly Use Design Data

Successful systems depend on the availability and proper use of credible load, resource, and meteorological data. Load data are related to either user demand (m^3/day, kWh/day, etc.) or equipment demand (power consumption). Resource data refers to the solar insolation and, in the case of pumping, the water characteristics at the site. Meteorological data include insolation, temperature, humidity, and other weather conditions. The meteorological factors can impact equipment power demand.

All of these data are critical to selecting the most appropriate system configuration. Successful system users frequently monitor test installations to compile load performance and resource characteristics to guide subsequent system designs. Specific operating design experience with a number of systems in a given environment has provided valuable design information to aid in avoiding costly systems resulting from overdesign and poor performance due to underdesign.

Provide User-Oriented Product Engineering

User-oriented product engineering refers to designing components for an uncomplicated user interface. It involves using minimal instrumentation and simple controls and anticipating potential operating errors. Any instruments and controls provided should be clearly labeled in the appropriate local language. While vast improvements have been made, these product engineering concepts must ultimately be extended to total system design across all the applications.

15.4.2 Institutional Recommendations

The lack of strong institutional support for operation, maintenance, repair, and training has been the weak link to successful PV system implementation. In part, PV systems suffer from the growing pains of a new technology. PV systems

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actually require less institutional support than most conventional power systems. However, because it is a new technology, the minimal support required often is not available. This results in the inability to use an otherwise reliable system and in the false perception that PV, as a technology, is not reliable. The following recommendations are intended to help mitigate these concerns.

Establish Field Service Capability

The efficient management of technical support and the procurement of spare parts are essential to the long-term reliable operation of PV-powered systems. While field experience has shown that PV-powered systems require less support than other remote technologies, responsive technical assistance with the correct replacement parts is vital to any significant application of PV technology in developing countries. The infrastructure necessary to support the management of PV parts and expertise is the same as that needed to support any other technology. In fact, under equally poor infrastructures, PV-powered systems have been shown to be more reliable than conventional alternatives due to lower requirements for operation, maintenance, and repair.

Provide Training at All Levels

Suppliers of successful systems have provided effective training to users and repair personnel. Suppliers of these systems have ensured user understanding of system operation and of the consequences of system misuse. Field reports have indicated that improved user training in basic maintenance and trouble-shooting, coupled with adequate documentation (in the local language) and spare parts, can reduce downtime. Technical personnel must be effectively trained to perform more complicated maintenance and system repairs.

Coordinate Activities with End-Users

The importance of working with the appropriate host-country agencies and local implementation organizations should be recognized. This factor is relevant not only to the application of PV-powered systems, but also to that of other technologies. Frequently, these in-country organizations are in a position to install sample systems, to assist in user training and to help provide data needed for successful design and equipment selection.

Another factor essential to successful system implementation is a feeling of local ownership and responsibility among end-users. Successful systems have also taken user expectations and cultural preferences into account throughout the design, construction, and operation phases. Early involvement of the end-user in the decision-making process has allowed communities sufficient time to plan for successful PV system implementation and management. While this factor is critical to the implementation of any technology, user expectations are more likely to be unrealistic when dealing with new technologies.

15.4.3 Financial Recommendations

The financial analysis presented in this report demonstrates that PV systems can be the least-cost option on a life-cycle basis, even though initial capital costs are 50% to 100% higher for PV systems. Although this is not new information, it is now being presented in conjunction with a substantial body of information on the cost and performance of PV and conventional systems. For PV systems to gain wide acceptance in developing country applications, two actions must occur. First, those responsible for selecting developing projects must use life-cycle costing in their financial assessment. Second, those responsible for developing PV projects must utilize the many financing mechanisms that are available for developing countries.

Evaluate Viability Using Life-Cycle Costing

As compared to remote conventional technologies, PV power systems generally have a high initial capital cost; however, assuming financing can be obtained, PV-powered systems have been shown to be more cost-effective on a life-cycle basis for significant load ranges in each application. For all applications except communications and lighting and home power systems, institutional loans, as opposed to commercial loans, are required. Government policies for subsidized loans for lighting and home power systems have allowed individuals to become purchasers. The intensive nature of PV system initial capital cost is exemplified through the sensitivity of the net present value life-cycle cost to the discount rate. At high discount rates, PV systems are less attractive because their costs are dominated by a large proportion of levelized debt service. Conventional systems, on the other hand, are dominated by recurring costs, which are reduced at higher discount rates.

Utilize Financing Mechanisms for Developing Countries

Most significant development projects in developing countries are funded by long-term loans under favorable terms. These loans are generally provided by development agencies established to promote progress in certain areas of the world.

Photovoltaic-powered systems have been shown to be a valuable tool for promoting progress in the underdeveloped areas of the world. The financial analyses presented in this report show that small PV systems are generally the least-cost option from the viewpoint of development banks, even though their initial capital costs are much higher than those of conventional systems. While there has been uncertainty and disagreement over the status of PV systems in the past, a substantial body of information now exists to address most of these earlier uncertainties. This information, which is summarized in this report, should stimulate the use of PV systems in situations where their application is the best choice, technically, financially, and institutionally.

APPENDIX A: SUMMARY OF QUESTIONNAIRE RESPONSES

This appendix includes statistical information on the questionnaires (Exhibit A-1); copies of the two questionnaires that were distributed; a Questionnaire Summary Response Table (Exhibit A-2); a listing of all projects referred to in the questionnaires; and a reference list of the persons or organizations who responded to the questionnaires.

Questionnaires were sent to over 300 individuals, organizations, and government agencies for the purpose of collecting PV project field performance experience. Two similar questionnaires, labeled "Project Field Questionnaire" and "Project Questionnaire," were sent to two basic participant groups: end-users and manufacturers. The end-user group included USAID Missions. Missions were requested to distribute the "field" questionnaire to pertinent host-country individuals, organizations, and government agencies that may have direct field experience with photovoltaic applications.

The "project" questionnaire was directed at manufacturers in both developed and less developed countries in order to solicit field experience and current cost information on PV systems.

Exhibit A-1 details response statistics as of September 30, 1985. The USAID Mission response, if considered separately, was 40%.

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Exhibit A-1 Questionnaire Statistics

	Field Questionnaire	Project Questionnaire
# Sent	162	141
# Undeliverable	0	6
Effective # Sent	162	135
# Answered Through Interview	1	2
# Returned	36	22
Effective # Returned (% of eff. # sent)	37 (23)	24 (18)

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PV PROJECT FIELD QUESTIONNAIRE

To the person filling out this questionnaire: please provide the following information.

Your Name ______________________________

Mailing Address ______________________________
____
____

Telephone No. (if available) ______________________________

Telex No. (if available) ______________________________

Position ______________________________

Role with Respect to PV System or Project ______________________________
____

Please fill in the following questionnaire to the best of your ability, or pass it to the appropriate individual. If you feel you cannot answer a question please write in "Do Not Know" or "DNK"

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I. PROJECT DESCRIPTIONS

Please provide a simple description of photovoltaic projects in your country. Describe PV systems which represent the general design and observed performance of systems in each of these application areas: water pumping, grain grinding, refrigeration (vaccines), communication, lighting, village electrification, and water desalinization and purification. Explain the purpose of the system (such as demonstration, R&D, training, commercially viable, etc.). Where possible, reference or provide reports on specific projects.

1. Project Title/Location ______

Application ______

Purpose ______

Sponsoring/Funding Agency ______

In-Country Participating Agency ______

Installation Date ______ Equipment Supplier ______
PV Array Size ______ Watts

Current Status of System: Working ______ Not Working ______

Explain: ______

______

2. Project Title/Location ______

Application ______

Purpose ______

Sponsoring/Funding Agency ______

In-Country Participating Agency ______

Installation Date ______ Equipment Supplier ______
PV Array Size ______ Watts

Current Status of System: Working ______ Not Working ______

Explain: ______

______

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3. **Project Title/Location** ______________________________

Application ______________________________

Purpose ______________________________

Sponsoring/Funding Agency ______________________________

In-Country Participating Agency ______________________________

Installation Date __________ **Equipment Supplier** ______________
PV Array Size __________ **Watts**

Current Status of System: Working __________ **Not Working** __________

Explain: ______________________________

____

4. **Project Title/Location** ______________________________

Application ______________________________

Purpose ______________________________

Sponsoring/Funding Agency ______________________________

In-Country Participating Agency ______________________________

Installation Date __________ **Equipment Supplier** ______________
PV Array Size __________ **Watts**

Current Status of System: Working __________ **Not Working** __________

Explain: ______________________________

____

5. **Project Title/Location** ______________________________

Application ______________________________

Purpose ______________________________

Sponsoring/Funding Agency ______________________________

In-Country Participating Agency ______________________________

Installation Date __________ **Equipment Supplier** ______________
PV Array Size __________ **Watts**

Current Status of System: Working __________ **Not Working** __________

Explain: ______________________________

____

II. PERFORMANCE OF SYSTEMS

A. Technical

What has been the observed technical performance of photovoltaic energy systems installed in your country? Consider and describe experiences in each major application area. Where possible, explain both problems and positive experiences with systems and individual components such as PV array, batteries, controls, instrumentation, and loads (pumps, refrigerator, lights, grain mills, radios, etc.). Use additional paper if necessary.

1. Reliability ____

2. Operating Performance (If possible provide specific performance data such as amount of water pumped and head, grain ground, number of vaccinations, etc. for example systems.) ________________________

3. Maintenance and Repair __________________________________

4. Have any problems emerged with user acceptance of PV systems? ________

5. Have any problems been experienced that relate to in-country institutional capability (technical and administrative) to operate and repair remote photovoltaic systems? __________________________

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B. Financial

To the extent possible, please provide the financial data specified below. Use any recognized currency and provide currency year (for example, 1980 dollars). Please be as detailed as possible and identify those numbers that are estimates. When data is not available in the units indicated, please provide any relevant information. For example, "Currently a Honda 400 Generator Model MD-4 is $900.00" or "10 liters of diesel fuel cost 12 Zimbabwe dollars in Harare in May 1984" or "40 Watt PV modules in Gaborone are $396.00 (U.S.)."

1. If available, what is the current commercial capital cost of PV power in your country? (Modules, packaged system costs, by application, etc.) Use recent projects (within the last year) as examples if necessary ________

____

____

2. What operating costs are associated with PV systems (number of persons, capability and pay, rate, hours/months in operation or support)? ________

____

____

3. What is the monetary value of the following products in rural areas of the country?

- Water (from what depth?) ________________
- Ground grain (what grain? grinding costs only.) ________
- Electricity (from what source? organization?) ________

4. Comparative energy costs in rural locations (circle correct units)

Electricity ________ per kilowatt-hour

Diesel Fuel ________ per liter or gallon

Kerosene Fuel ________ per liter or gallon

Gasoline Fuel ________ per liter or gallon

Wood ________ per pound or kilogram

Human Labor ________ per day or hour (indicate type of work)

Animal Labor ________ per day or hour (indicate type of work)

5. Capital costs and expected lifetime for other technologies:

Diesel Engines: Cost __________ Size __________ Expected Lifetime __________

Gasoline Engines: Cost __________ Size __________ Expected Lifetime __________

Portable Generator: Cost __________ Size __________ Expected Lifetime __________

Kerosene Lamps: Cost __________ Size __________ Expected Lifetime __________

Refrigeration (kerosene): Cost ______ Size ______ Expected Lifetime ______

Water Pumps: Cost __________ Size __________ Expected Lifetime __________

6. How does PV compare on a life-cycle cost basis to other remote energy technologies in use in your country? (Provide portions of recent energy/economic analyses. Where such data are not available, perception and justification are requested.) ______________________________

____

____

____

C. Institutional

1. How have local communities received the installation and use of PV systems?

____

____

____

2. To what extent have in-country personnel and local operating staff participated in the conceptual design, installation and start-up of PV systems?

____

____

____

3. Based on the observed or perceived technical, institutional, and cost performance of PV energy systems, what is the current viability of PV for remote energy supply in each area of application in your country?

D. **General Comments**

Your cooperation and assistance in filling out this questionnaire is greatly appreciated. Please indicate below if you wish to receive a summary of the resulting report and to whom it should be addressed.

Yes ____________ No ____________

Address ______________________________

PV PROJECT QUESTIONNAIRE

To the person filling out this questionnaire: please provide the following information.

Your Name ______________________________

Mailing Address ______________________________

____

____

Telephone No. (if available) ______________________________

Telex No. (if available) ______________________________

Title/Position ______________________________

Role with Respect to Specific PV Systems or Projects

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________
6. ______________________________

Please fill in the following questionnaire to the best of your ability, or pass it to the appropriate individual.

I. PROJECT DESCRIPTIONS

Please provide a description of significant photovoltaic projects with which you or your company have had direct field experience. Select and describe PV systems which represent the general design and field performance of systems in each of these application areas: water pumping, grain grinding, refrigeration (vaccines), communication, lighting, village electrification, and water desalinization and purification. Explain the purpose of the system or project (such as demonstration, R&D, training, commercially viable, etc.), and where possible, reference or provide reports and contacts for specific projects.

1. Project Title/Location ______________________________

Application ______________________________

Purpose ______________________________

Sponsoring/Funding Agency ______________________________

In-Country Participating Agency ______________________________

Installation Date __________ Equipment Supplier __________
PV Array Size __________ Watts

Current Status of System: Working __________ Not Working __________

Performance Details: ______________________________

____

____

2. Project Title/Location ______________________________

Application ______________________________

Purpose ______________________________

Sponsoring/Funding Agency ______________________________

In-Country Participating Agency ______________________________

Installation Date __________ Equipment Supplier __________
PV Array Size __________ Watts

Current Status of System: Working __________ Not Working __________

Performance Details: ______________________________

____

____

3. Project Title/Location ____________________

Application ____________________

Purpose ____________________

Sponsoring/Funding Agency ____________________

In-Country Participating Agency ____________________

Installation Date __________ Equipment Supplier __________
PV Array Size __________ Watts

Current Status of System: Working __________ Not Working __________

Performance Details: ____________________

____

____

____

4. Project Title/Location ____________________

Application ____________________

Purpose ____________________

Sponsoring/Funding Agency ____________________

In-Country Participating Agency ____________________

Installation Date __________ Equipment Supplier __________
PV Array Size __________ Watts

Current Status of System: Working __________ Not Working __________

Performance Details: ____________________

____

____

____

5. Project Title/Location ____________________

Application ____________________

Purpose ____________________

Sponsoring/Funding Agency ____________________

In-Country Participating Agency ____________________

Installation Date __________ Equipment Supplier __________
PV Array Size __________ Watts

Current Status of System: Working __________ Not Working __________

Performance Details: ____________________

____

____

____

6. Project Title/Location ____________________

Application ____________________

Purpose ____________________

Sponsoring/Funding Agency ____________________

In-Country Participating Agency ____________________

Installation Date __________ Equipment Supplier __________
PV Array Size __________ Watts

Current Status of System: Working __________ Not Working __________

Performance Details: ____________________

____

____

____

II. PERFORMANCE OF SYSTEMS

A. Technical

In general, what has been the technical performance of PV systems in developing countries? Consider and describe experiences in each of the major application areas as identified in Part I. Where possible, explain both problems and positive experiences with systems and individual components such as PV array, batteries, controls, inverters, instrumentation, and loads (pumps, refrigerators, lights, grain mills; radios, etc.) according to the technical criteria listed below. Use additional paper if necessary.

1. Reliability

2. Operating Performance (Provide specific performance data where possible, such as amount of water pumped and head, grain ground, number of vaccinations, referencing systems described in Section I).

3. Maintenance and Repair

B. Institutional

1. Have any problems emerged with user or community acceptance of PV systems?

____

____

2. Have any problems been experienced that relate to in-country institutional capability (technical and administrative) to operate and repair remote photovoltaic systems? ______________________________

____

____

3. To what extent have in-country personnel and local operating staff participated in the conceptual design, installation and start-up of PV systems?

____

____

____

4. Describe any other institutional or user related aspects which were significant to PV system overall performance.

____

____

____

C. Financial (Current System Costs and Performance)

The financial performance of PV systems is principally a function of the installed capital costs and the amount of product produced (life-cycle costing factors being held constant). The changing nature of the world wide PV industry precludes using past system performance as completely representative of current system performance. Therefore financial evaluations of PV systems will be considered using current system designs, equipment, and costs. Judgements on performance and reliability will be based on past system experience and the reasonable impact of any design changes proposed. With this background and based on your experience in the design, application, and/or operation of PV systems and their current costs, please answer the following questions as completely as possible. Please provide cost/performance information on PV systems for each major application area as provided in Section I. Where this is not possible, please provide current component costs.

1. For similar applications as those detailed in Section I, what design changes if any would you make to the systems? What equipment choices would be different?

2. Based on 1., what is the current capital cost (including spares) of such a "point" designed system? ("Point" design refers to a specific insolation and load character) Provide recent installed cost/performance quotes if possible for similar systems, representative of typical application environments in developing countries.

3. What is the expected output of the system in an average solar insolation of a 5 $KWh/m^2/day$, specified in KWhrs/day, gallons or cubic meters of water pumped per day (state average head), or kilograms of grain ground per day (state fineness)?

EXHIBIT A-2. Questionnaire Summary Response Table

		DID NOT RESPOND		NUMBER OF PROJECTS REFERENCED (SYSTEM)[a]												
									MULTI-USE LOAD CENTERS [1]							
	NO KNOWLEDGE OF PV PRODUCTS	UNABLE	WOULD NOT	COMMUNI-CATIONS	LIGHTING & HOME POWER	WATER PUMPING	REFRIG-ERATION	OTHER	COMMUNI-CATIONS	LIGHTING & HOME POWER	WATER PUMPING	REFRIGER-ATION	AGRO	OTHER	TOTAL SYSTEMS	MINI-UTILITIES
•USAID MISSIONS (Respondent)																
Antiqua (CARDI)						1										
Belize (Local PV rep.)				2(>5)	1(50)			Navigation (>1)								
Botswana (BRET)					3	5				3		3			3	
Burundi (health officer, AID)							1(10)									
Costa Rica	X															
Djibouti				1		2				2		1		School Equipment (1)	2	
Dominican Republic (gov. officials)				3			1									
Ecuador (gov. officials)							1			1		1			1	
Guatemala			X													
Guinea	X															
Haiti						4										
Indonesia (gov. officials)					6	2			1	1		1			1	
Kenya (AMREF)										1		1			1	
Lesotho				5	3(22)	1			1	1					1	
Liberia							1									
Malawi		X														
Mali (LESO)					1(>1)	1(>80)	1(>1)						1		1	
Nigeria					1											
Paraguay	X															
Portugal	X															
Senegal (Research Eng.)					1	2(>3)	1									1
Thailand (gov. official)				1(52)	2	2										
Uganda	X															
Yemen A.R. (AID/Peace Corps)					1(3)	3										
Zaire							2(10)		1	1		1			1	
Zimbabwe						2	1			2	1	1		Medical Sterilization (1)	2	
•ORGANIZATIONS																
Associates in Rural Develop.						5										
Danish Int'l Dev. Agency		X														
NASA LeRC				1	4	6	28		9	13	1	9	1	Sterilizers (5)	14	3
Research Triangle Institute						2										
United Nations				1(4)				Desalination (1)		3	3			Fans (3)	3	
•MANUFACTURERS																
A.Y. McDonald						4(22)										
ARCO Solar Inc.				2(7)	1			R&D Facility (2)	1	1	1			Lab Facility (1)	2	
Grundfos Int'l						3										
Kyocera Int'l						2				2	2				2	1
Motor Leroy Somer																1
Solar Electric Int'l					1	3				1		1			1	
Solar Voltaics						3(8)										
Solarex Pty. Ltd.				5(25)	1(>1)	1(>2)	2	Incubator (1)								1
Solec Int'l						1	1									
SunWatt								Battery Chargers (100) Filmstrip Projection Kits (240)								
TOTALS	5	2	1	21(>103)	27(>97)	55(>160)	40(>57)	6(345)	13	32	8	19	2	11	35	7

a. Projects may include reference to many systems, as in the case of Mali or Belize. Where the number of systems are not shown, it was either not provided or unclear as to the number more than two systems (ranges of system size were provided).

QUESTIONNAIRE PROJECT LISTING

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
1/1	Solar Photovoltaic Pumping System/ Diamonds Estate, Antigua, W.I.	Irrigation/Demonstration of Technology	1200 W ARCO	'82	USAID, Caribbean Development Bank	CARDI, Ministry of Agriculture
2/1	Navigational Aids/ Belize	Coastal Navigational Beacons/To assist in coastal navigation and channel marking	40 W ARCO	--	Originally British, currently none	Belize Ports Authority
2/2	Communications/Belize	Telecommunications in Rural Areas/To power telecommunication systems	40-80 W ARCO	--	--	Belize Telecommunications Authority
2/3	Communications/Belize	Radio Communication in Rural Areas/Powering radio communication systems for missionaries	40-80 W ARCO	DNK	Catholic, Baptist, and other religious groups	--
2/4	Residential Lighting/ Belize	Providing Low Level Electrical Power in Rural Areas/Single family electrification in rural areas	40-400 W ARCO	--	None	Individuals

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
3/1	Botswana Renewable Energy Technology (BRET)/Moduidi, Botswana	Water Pumping/R&D Training	1,376 W ARCO, Jacuzzi	Sep '84	USAID	Ministry of Mineral Resources and Water Affairs (MMRWA)
3/2	BRET/Mahalapye, Botswana	Water Pumping/R&D Training	516 W ARCO, Jacuzzi	Sep '84	USAID	MMRWA
3/3	BRET/Malapowalsajang, Botswana	Water Pumping/R&D Training	1,376 W ARCO, Jacuzzi	Jul '82	USAID	MMRWA
3/4	BRET/Otse, Botswana	Water Pumping/R&D Training	420 W ARCO, Honeywell, Mono	Jan '82	USAID	MMRWA
3/5	BRET/Mathuibudulewane, Botswana	Water Pumping/R&D Training	1,548 W ARCO, Mono Honeywell, Boss	Dec '82	USAID	MMWRA
3/6	BRET/Shoshong, Botswana	Refrigeration and Lighting/R&D, determine if viable	280 W ARCO, Marval, Comlite	Mid '84	USAID	MMRWA
3/7	BRET/Leutswaletau, Botswana	Refrigeration and Lighting/R&D, determine if viable	70 W ARCO, Polar Products, Comlite	Mid '84	USAID	MMWRA
3/8	BRET/Maloule, Botswana	Refrigeration and Lighting/R&D, determine if viable	420 W ARCO, Polar Products, Comlite	Mid '84	USAID	MMRWA

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
3/9	BRET/Oodi, Botswana	School Lighting, Village Development/ R&D, determine if worthwhile	86 W Comlile, ARCO	Mid '84	USAID	MMRWA
3/10	BRET/Princes Manna Hospital, Botswana	Outdoor Lighting/Test, Demonstration	43 W REC Specialties, ARCO	Jan '85	USAID	MMRWA
3/11	BRET/DEE Offices, Botswana	Outdoor Lighting/Test, Demonstration	43 W REC Specialties, ARCO	Jan '85	USAID	MMRWA
4/1	Expanded Program of Innoculation/Burundi	Solar Refrigeration/ Vaccine Storage	4 panels	before Jun '85	USAID	Ministry of Health

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
5/1	ISERST/VITA Building Project/Djibouti	Lighting, Refrigeration/To demonstrate the feasibility of PV power in Djibouti	5300 W ARCO	June'84	VITA	--
5/2	ISERST/VITA Solar Pumps, Djibouti	Water Pumping/ Agriculture	300 W Solar Electronic Int.	July'84	VITA	--
5/3	R.T.D. Project/ Ali-Sabieh, Djibouti	F.M. Radio Transmitter/Radio for the rural community	600 W AEG Telefunken	Jan.'83	G.T.Z.	G.T.Z. (German Aid)
5/4	High School/Djibouti	Measure power loads equipment and Lighting/Instructions and aid for students	420 W ARCO	April '84	--	Minister of Education
5/5	Agriculture/Atar, Djibouti	Water pumping/Pump water for drip irrigation	-- Solar Force	'82	F.A.C.	--
6/1	Solar Panel System/ Tierra Nueva, RPTR, Dominican Republic	Powering 71F2 Microwave Radio/To supply at a reasonable cost, continuous and reliable energy.	1,200 W ARCO	Oct 11, '83	CODETEL	--
6/2	700F1 Solar Repeater/ Loma Grande, Sanchez, Dominican Republic	Powering 700F1 Solar Repeater/To supply at a reasonable cost, continuous and reliable energy.	20 W GTE Lenkurt	Feb 5, '85	CODETEL	--

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
7/1	Rural Telecom Project DO-M/Dominican Republic	Communication/Provide service to villages where electrification is not available, commercially viable	35 W Sharp Through Fujitsu, Ltd.	'82	Japan and Dominican Republic Governments/OECF	Nissho Iwai Corporation
8/1	Refrigeration System -- Freezer activated with solar system/Dominican Republic	Refrigeration of Vaccines/R&D	265 W Solar Power	Aug 8 '82	AID	Secretary of Public Health - COENER
9/1	Demonstration in Rural Health (Pedro Vincent Maldonado Systems)/Ecuador	Refrigeration for Vaccines, Lighting and others/Demonstration	3000 W Solarex	March '83	The Ecuadorian State, AID/NASA	INE Eduadorian Institute of Sanitary Works (IEOSS)
9/2	Demonstration in Rural Health/ Cobos, Ecuador	Refrigeration for Vaccines/Demonstration	300 W Solar Power	Nov '81	The Ecuadorian State, AID/NASA	INE IEOSS

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
10/1	Mauge Water System/ Haiti	Water Pumping/Village drinking water supply	770 W A.Y. McDonald	Dec. '83	USAID, CARE	USAID, CARE
10/2	Bois Mauge Water System/Haiti	Water Pumping/Village drinking water supply	770 W A.Y. McDonald	Dec. '83	USAID, CARE	USAID, CARE
10/3	Baie de Henne Water System/Haiti	Water Pumping/Village drinking water supply	770 W A.Y. McDonald	Feb. '83	USAID, CARE	USAID, CARE
10/4	Bouhn-Jean Denis Water Systems (2 units)/Haiti	Water Pumping/Village drinking water supply	1120 W each A.Y. McDonald	May '83	USAID, CARE	USAID, CARE
11/1	Kibwezi Rural Health Centre/Kenya	Refrigeration and Lighting/Demonstration	2 KW NASA	Apr '83	USAID	Ministry of Energy
12/1	ATS Khubetsoana Workshop, Maseru, Lesotho	Communication/Demonstration of PV power uses	33 W DNK equipment supplier	DNK	USAID	Lesotho Government
12/2	ATS Malefiloane Workshop/Molchc tlong, Lesotho	Communication and Lighting/Demonstration of PV power uses	33 W DNK equipment supplier	DNK	USAID	Lesotho Government

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
13/1	Twelve Installations/ Lesotho	Household systems for lights, radio and some TV	8 @ 35 W 3 @ 70 W 1 @ 10 W	'84-'85	By Homeowners	--
13/2	Eight Installations/ Lesotho	Shops for cash registers, lighting, radio (Two-Way) or Hi-Fi sets.	6 @ 70 W 2 @ 35 W (Most are 24 V systems)	'84-'85	By Shop Keeper	--
13/3	Six Installations/ Lesotho	Two households with additional refrigeration	140 W	'84-'85	Self-Funded except 2-way Radio by Government	
		Two primary 2-way radio communications	35 and 70 W			
		One water pumping	60 W			
		One Repeater Station	20 W			
14/--	[No specific projects were referenced] Lesotho	- charging source for DC plant - repeater stations - telecommunications purposes	-	-	-	-
15/1	Prototype Clinics/ Liberia	Refrigerator/Vaccine Storage	DNK W NASA	Oct. 11, '85	USAID/NASA	Ministry of Health and Social Welfare

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
16/1	Renewable Energy Project/Mali	Water Pumping Systems/ Water Supplies to rural areas (human plus animal use)	1,300-2,600 W panes-Solarex pumps-Guinard	'81/'82	USAID	LESO
16/2	Renewable Energy Project/Mali	PV Lighting Systems/ Night-time illumination for Maternity Centres, Hospitals	40-160 W Solarex, ARCO	'82/'83	USAID	LESO
16/3	Renewable Energy Project/Mali	PV Refrigerators/ Storage of vaccines, medicines	160-200 W ARCO, Solar Products	'82/'84	USAID	LESO
16/4	PV Grain Mill/Mali	Grain Grinding, Milling/Easing task of milling by women in village context	2.44 kW PV Array-NASA Lewis, Mill-Jacobson	May '85	USAID	LESO
17/1	Personal Use/Niger State, Nigeria	Lighting, Refrigeration, and Ventilation/ Evaluation of PV Systems for national and expatriate use.	280 W ARCO	June'84	personal	--

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
18/1	Affinian/Senegal	Water Pumping for Irrigation/Commercially viable	600 W	Mar '80	F.E.D.	Centre d'Animateurs Ruvaux
18/2	N'Dioudioue/Senegal	Water Pumping/ Commercially viable	2,600 W	Feb '80	F.E.D.	Caritas
18/3	Mont Rolland/Senegal	Lighting/R&D	288 W	Apr '80	Ministir Francais de L'Industrie	Mission Catholique de Mont-Rolland
18/4	Mont Rolland/Senegal	Refrigeration (vaccines)/R&D	384 W	Apr '80	Ministere Francais de l'Industrie	Mission Catolique de Mont-Rolland
18/5	Niaga Wolof/Senegal	(Village) Rural Electrification/ R&D	5,280 W	Nov '82	PNUD-AFME	SENELEC
18/6	(various)/Senegal	Water Pumping				
19/1	House near hospital/ Kapanga, Zaire	Communication -- S/W radio/Intermission contact -- no telephones	48 W (6 panels each 24 cells)	Photo-watt (Now sold out)	Personal and Methodist Church	--
19/2	same system/Zaire	Refrigeration (vaccines)			Personal and Methodist Church	--
19/3	same system/Zaire	Lighting/Working lights in seven rooms			Personal and Methodist Church	--

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
20/1	Medical Refrigeration/ Chikwaka, Zimbabwe	Vaccine Refrigeration, Lighting, Medical Sterilization/ Demonstration	2,800 W Solarex	May '83	USAID	Government of Zimbabwe (Health & Energy Ministry)
20/2	Medical Refrigeration/ Chiota, Zimbabwe	Vaccine Refrigeration/ Demonstration	450 W Solar Power Corporation	Feb '83	USAID	Government of Zimbabwe (Health & Energy Minstry)
20/3	Cranborne Solar Water Pump/Harare, Zimbabwe	Water Pumping/ Demonstration	900 W Solar Force, Pompes Guinard	Nov '81	French Government	Government of Zimbabwe, Solamatics
20/4	Shutu Solar Pump/ Chiweshe, Zimbabwe	Water Pumping/ Demonstration	1,300 W Solar Force, Pompes Guinard	Jun '82	French Government	Government of Zimbabwe, Solamatics
20/5	Kat sande Village Solar Project/Mutoko, Zimbabwe	Water Pumping and Lighting/Demonstration	462 W ARCO	'83	Private Company William Smith & Gourock	--

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
21/1	Village Water Supplies/Haiti (5 sites)	PV Water Pumping for Potable Water/ Commercially viable demo.	5 x 800W A.Y. McDonald	early '83	CARE/AID	CARE/AID Port au Prince
21/2	Irrigation/Sudan	PV Water Pumping for Crops/Commericially viable irrigation demo.	1680 W A.Y. McDonald	mid '84	Private with UNDP overview	UNDP (United Nations Development Programmes)
21/3	PV Village & Livestock Pumping/ Mexico	PV Water Pumping for Potable Water/Commer. viable package systems.	630 W A.Y. McDonald	Nov '81	Private	Private
21/4	Various demos. in 15 countries	PV Water Pumping/ Potable water, small irrigation	0.5 - 3 kW A.Y. McDonald	since '81	Mostly Private	--

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
22/1	Botswana Renewable Energy Project/Otse, Botswana	Water Pumping/Drinking and irrigation water supply	280 W Blue Sky	Oct., '82	USAID	MMRWA
22/2	Botswana Renewable Energy Project/ Mahalapye, Botswana	Water Pumping/Drinking and irrigation water supply	516 W ARCO, Jucuzzi	June, '84	USAID	MMRWA
22/3	Botswana Renewable Energy Project/ Molapowaba Long, Botswana	Water Pumping/Drinking and irrigation water supply	1376 W ARCO, Jucuzzi	July, '84	USAID	MMRWA
22/4	Botswana Renewable Energy Project/ Mochudi, Botswana	Water Pumping/Drinking and irrigation water supply	1376 W ARCO, Jucuzzi	July, '84	USAID	MMRWA
22/5	Botswana Renewable Energy Project/ Mathubudukwand, Botswana	Water Pumping/Drinking and irrigation water supply	1548 W Mono, Boss, Honeywell	Aug., '84	USAID	MMRWA
22/6	Botswana	Various	--	--	--	--
23/1	Izimbaya, Tanzania	Water Pumping/Supply to clinic	1400 W	Apr '85	--	N/W Diocese
23/2	Merti, Kenya	Water Pumping/Supply to Mission Station	1400 W	Oct '84	CIDA (Canada)	Merti Mission
23/3	Ilpartimaro, Kenya	Water Pumping/Cattle watering and supply to cattle dip	1400 W	Mar '85	DANIDA	Rural Development Fund

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
24/1	Shikoku Electric Power Company, Ltd. Japan	1 MW Grid System/ Utility Power PV System	300 kW	1982 on	Japanese Special Development Fund	NEDO
24/2	Kankoi Project/ Pakistan	Village Electrification/Lighting and Water Pumping	5.2 kW	'82	Kyocera Corporation Donation Program	--
24/3	Village Power System/ Sri-Lanka	Village Electrification/Lighting	4.4 kW	'84	Japanese AID Program	--
24/4	Well Pumping System/ Senegal	Water Pumping/Drinking water supply	6.0 kW	'84	Japanese AID Program	--
24/5	Well Pumping System/ Sudan	Water Pumping/Drining water supply	4 kW	'84	Brigeston Corp.	N.W.A.
24/6	Village Power/Pakistan	Village Electrification/Lighting and Water Pumping	120 kW	'83 on	Pakistan Government	--
25/1	Paomia, Ronducinui, Corsica, France	Paomia PV Plant/ Powering a village	44,064 W Solar Force, Leroy Somer	Jul '83	EEC, EDF, AFME	--

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
26/1	PV Pumping, CRAFA/ Taroundant, Morocco	Water pumping for irrigation for an Agricultural Training Center/Demonstration of PV pumping	7 kW Solar Engineering Services	Jun '85	USAID/Rabat, Morocco	CDER/CRAFA, Morocco
26/2	Ecole Des Mines/ Marrakech, Morocco	Water pumping for irrigation at a technical school/Research and testing of modules and pumps, and irrigation	4,320 W Solar Engineering Services	Nov '85	USAID/Rabat, Morocco	CDER/Ecole des Mines Marrakech
27/1	UNDP Project GLO/80/003/UK	Water Pumping/Testing for Phase II	351 W SEI	Oct '82	World Bank	Sir William Halcrow & Partners
27/2	SEI 43 LS/Egypt Basaisa Village, near Cairo	Water pumping (water is being sold to field owners to pay for system)/Irrigation	480 W SEI	Mar '84	--	American University in Cairo
27/3	Shirati Irrigation Scheme/Tanzania	Water Pumping/Plot Irrigation	280 SEI W S250 System	Sep '81	Mennonite Central Committee	--
27/4	Katilu Health Centre/ Kenya	Lighting and Refrigeration to replace diesel generator	930 W Arco, Polar Products, Fisher Karpark	Oct '84	NORAD	NORAD
27/5	Magumu Church/Tanzania	Lighting	640 W Arco, REC, FKI	May '85	Mary Knoll Fathers	Mary Knoll Fathers

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
28/1	Solarhouse "Lanser-Wiese"/Salzburg, Austria	Household Electrification Demo., R&D, Commercial viable	1728 W AEG-Telefunken VARTHA, Solar Voltaic (SV)	Jan '84	Government of Salzburg (Province)	Through Solar Voltaics
28/2	Sunwind Pump/ "University of Vienna"	Solar/Wind Water Pumping/R&D	264 W Helios Techn., SV, University Vienna	Nov '83	Solar Voltaics Company	Through Solar Voltaics
28/3	Sun pump/Argentina	Solar Water Pumping/ Demo.	520 W Siemens, Grundfos	Nov '83	Solar Voltaics Company	Agro Solar, Mr. Gold (agent)
28/4	Solar-Osmotic-Irrig.-System (Agronet; Old Version)/Mexico, Venezuela, Brazil, Argentina, USA (AZ), Peru, Chile	Irrigation/Demo., R&D	Each 9 or 18 W Solavolt, AGE, SV	Nov '83 Jun '84	Solar Voltaics Company	7 different agents
28/5	Solar-Osmotic-Irr.-Syst (New Version)/ Volders, Austria	Irrigation/R&D	163 W ARPE-PLAST, Sr., Helios Techn.	Mar '85	Solar Voltaics Company	ARPE-PLAST, Austria
28/6	Sunpump/Dominican Republic	Solar Water Pumping/ R&D, Demo., Training, Comm. viable	840 W Zontec, Grundfos	May '85	INDOTEC*, Santa Domingo	Sir William Halcrow & Partners, G.B.

*Dominican Institute of Industrial Technology

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
29/1	Central Communications Inc. Repeaters (5 systems)/Phillippines	Communications Repeater Stations Power Supply/To provide reliable power supply	5-330 W Solarex	Jun '82	United Planters Coconut Bank	Central Communications, Inc.
29/2	MHS Solar Powered Repeaters (5 systems)/ Phillippines	Communications/To provide reliable power supply in remote mountain tops	5-120 W Solarex	Jun '83	Ministry of Human Settlements	Ministry of Human Settlements
29/3	Northern Samar Rural Integrated Devt. Project/ Mt. Adga, Calbayog, Samar, Phillippines	Communications/To provide reliable power to a repeater station	560 W Solarex	Sep '81	Australian Devt. Assistance Bureau	Northern Samar Rural Integrated Devt. Project Office
29/4	National Irrigation Administration Microsiesmic and Flood Warning System (12 systems) Magat Dam. Isabela, Phillippines	Telemetry, Communications/To supply power to remote areas where equipment is located.	2 x 384 W Microsiesmic stations 10 x 84 W Siren flood warning systems Solarex	Mar '82	World Bank Loan	National Irrigation Administration
29/5	Eliseo Lizada's Lighting/TV System/ Pililia, Rizal, Phillippines	Lighting/Replacement of 600 W gasoline generator to avoid noise and air pollution.	42 W Solarex	Sep '82	Mr. Eliseo Lizada	Mr. Eliseo Lizada

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
29/6	WHO Solar Refrigera - tor	Refrigeration (Vaccines)/Testing Demo. solar refrigators	528 w Solarex	Jun '84	World Health Organization Manila Office	Bureau of Energy Devt. Ministry of Energy,PNOC
29/7	Pilot Solar Pump Plant and Photovoltaic Field Laboratory	Village Electrification and several small applications/R&D, Demostration, Testing	13 kW village electrification 7 KW small application AEG, Telefunken	Feb "83	Bureau of Energy Economic Cooperation	Bureau of Energy Development Ministry of Energy, PNOC-EROC (Phil. National Oil Co.-Energy Research & Development Center)
30/1	Gokal Pumping System/ Karachi, Pakistan	Water pumping/Farm Irrigation	400 W	Mar '83	None	None
30/2	Refrigeration Systen/	Refrigeration/	140 W	Aug '83	None	None
30/3	Lumisol Light/Various locations	Outdoor Lighting/High efficiency outdoor space lighting	66 W	Various	None	None

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
31/1	Medical Solar Chargers/Zimbabwe	Set of 100 small (Sun-Watt #F-2) PV battery chargers/To recharge 2V 5AHr lead-acid gel-cell batteries for remote medical clinic.	2 W [$11/W]	Oct '83	Prolea Medical Services	same
31/2	Filmstrip Projection kits/Shipped worldwide	PV modules to recharge 12V battery pack for slide projectors/ Educational tool for remote areas of 3rd world.	5 W [$20/W]	Dec '84 to present	World Neighbors	varies

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
32/1	Rural Energy Centres/ Mehrarahmat, Khan, NWFP, Pakistan	Village Lighting, Fans, Pumping/ Demonstration	20 kW Solarforce	Dec '84	UNDP/UNDTCD	Director General Energy Resources
32/2	Rural Energy Centres/ Malmara, Sind, Pakistan	Village Lighting, Fans, Pumping/ Demonstration	10 kW ARCO	For May '85	--	--
32/3	Rural Energy Centres/ Khurkera, Baluchistan Pakistan	Village Lighting, Fans, Pumping/ Demonstration	5 kW	For May '85	UNDP/UNDTCD	DGER
32/4	Prototypes in Renewable Energy/Abu Ghosun, Red Sea Governorate, Egypt	Vapour Compression Desalination of Seawater/Demonstration	8 kW AEG TELEFUNKEN	For Jun '85	UNDP/UNDTCD	Ministry Electricity and Energy
32/5	Prototypes in Renewable Energy/Egypt	Solar HF Telecommunication/Demonstration	1040 W BP Solar	Sep '83	UNDP/UNDTCD	Ministry Electricity and Energy
32/6	Plus solar projects in Maldives, Gambia, Mongolia, PDR Yemen, Seychelles.					

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
33/1	Photovoltaic Solar Cells/Manggala, North Lampung, Indonesia	Lighting and Television/ Demonstration, field test, social acceptance test	35 W Tideland-MG-600	May '82	Directorate General for Electric Power	Directorate General for Electric Power
33/2	Photovoltaic Solar Cells/Rongkop, Yogya Karta, Indonesia	Refrigeration, Lighting and Television for Remote Hospital/Demonstration, field test, social acceptance test	40 W ARCO M-51	September '83	Directorate General for Electric Power	Directorate General for Electric Power
33/3	Photovoltaic Solar Cells/Palas, Lampung Province, Sumatra, Indonesia	Lighting and Television/ Demonstration, field test, social acceptance test	37 W ARCO AS1 16-2000	April '82	Directorate General for Electric Power	Directorate General for Electric Power
33/4	Photovoltaic Solar Cells/Cibinong, Cianjur, West Java, Indonesia	Water Pumping for drinking water/Demonstration, field test, social acceptance test	31 W ARCO AS1 16-2000	April '82	Directorate General for Electric Power	Directorate General for Electric Power
33/5	Photovoltaic Solar Cells/ Pilangkenceng, Madiun, East Java, Indonesia	Lighting and Television/ Demonstration, field test, social acceptance test	40 W ARCO M51	January '84	Directorate General for Electric Power	Directorate General for Electric Power

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
33/6	Photovoltaic Solar Cells/Labanan, Kalimantan, Indonesia	Lighting and Television, Demonstration, field test, social acceptance test	37 W Philips BP X-47-C	June '81	Directorate General for Electric Power	Directorate General for Electric Power
33/7	Photovoltaic Solar Cells/Boyolali, Cetre of Java, Indonesia	Lighting and Television/ Demonstration, field test, social acceptance test	33.5 W Solarindo CXG-4331	February '85	Directorate General for Electric Power	Directorate General for Electric Power
33/8	Photovoltaic Solar Cells/Majalengka, West Java, Indonesia	Lighting and Television/ Demonstration, field test, social acceptance test	33.5 W Solarindo CXG-4331	February '85	Directorate General for Electric Power	Directorate General for Electric Power
33/9	Photovoltaic Solar Cells/Secang, Central Java, Indonesia	Water Pumping for Drinking Water/Demonstration, Field test, social acceptance test	33.5 W Solarindo CXG-4331	February '85	Directorate General for Electric Power	Directorate General for Electric Power

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
34/1	Center for Experimental Rural Energy/ Niaga Wolof, Senegal	Village Electrification/ Demonstration	5 kW Photowall Aerowatt, Oldham, Faiveley	November '82	PNUE (UNEP), French Agency for Energy Management (AFME)	Senelec
35/1	Water Lifting Project/Ban Tha Yiam, Sakon Nakom Province, Thailand	Water Pumping/Village water supply	720 W Solavolt Int'l	December '83	USAID	National Energy Administration (NEA)
35/2	Water Lifting Project/Thailand	Water Pumping/Irrigation	4480 W ARCO	Planned	USAID	NEA
35/3	NEA Solar Cell Project/Khao Kraw, Petchaburi Province, Thailand	Lighting, Audio Visual Aids/ Lighting, TV-Video	385 W Thai Solar Co. Ltd.	February '85	Thai Government	NEA
35/4	NEA Solar Cell Project/Thailand	Lighting/Domestic Lighting	80 @ 10 W	Planned	Thai Government	NEA
35/5	PV Telecommunication Project/52 stations, Thailand	Telecommunication/Power station for remote telecommunication stations	86,910 W (1.7kW/ installation, avg.)	'84 - '86	World Bank	Telephone Organization of Thailand

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
36/1	The Whomadia Water Pumping System/Yemen Arab Republic (Y.A.R.)	Water Pumping/Village potable water supply	1440 W Grundfos	June '83	USAID	Confederation of Yemeni Development Association (CYDA)
36/2	Mahshish Village Water System/ Y.A.R.	Water Pumping/Village potable water supply	560 W Grundfos	May '84	American Peace Corps	CYDA
36/3	Jebah Boovah PV Project/Juran Village, Y.A.R.	Lighting/Lighting for a school and a health clinic	3 @ 330 W Abdo Rahman Noeman Trading (ARCO Dist.)	February '85	American Peace Corps	CYDA
36/4	Mukha Water Pumping System/ Y.A.R.	Water Pumping/Tree Irrigation	560 W Grundfos	January '85	American Peace Corps	CYDA

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
37/1	Photovoltaic Project at Kionzo Mission/Kionzo, Bas Zaire	Refrigerator, freezer/To assess the effect of PV equipment on rural health care	350 W Solar Power Corp.	February '82	NASA	
37/2	Integrated Health Project (660-0093)/ 9 systems near Kasangulu, Zaire	Refrigerator, Freezer/ Rural health centers	9 @ 245 W Solar Power Corp.		Salvation Army	
38/1	UMM-SAID Tracker/Qatar	Two-Axis Flat-Plate PV Tracker to supply power to R&D facilities/Research and Development	10 kW ARCO	May '84		
38/2	King Saud University/Rujadh, Saudi Arabia	Two-Axis Mirror Enhanced PV Tracker/Research and Development	8 kW ARCO	To be installed	Saudi Arabia	None
39/1	King Aboulaziz International Airport/Jeddah, Saudi Arabia	Lighting/To have a stand-alone, autonomous lighting system for the parking lot	58 kW ARCO	June '82	K.A.I. Airport Authority	K.A.I. Airport Authority

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REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
40/1	IMSS/Mexico City, Mexico	Remote Clinic/DC lighting and communications	140 W ARCO	'82	IMSS (Mexican Social Security)	ARCO Solar, Inc.
40/2	AC Remote Electrification/ Sadat City, Egypt	Power to Lab Facility and Water Pumping/Sacredrip irrigation project. Move people out of populated areas between Cairo and Alexandria into desert	13.5 kW ARCO	'82	American University at Cairo	Egyptian Government
40/3	Microwave Repeater/Atachama Desert, Chile	PV Power to 6 Repeater Stations/Replace diesel generators and frequent maintenance	5.25 kW ARCO, Italtel	'84	Italtel	Antel-Uriguay, and ARCO Solar, Inc.
40/4	Radio Telephone/ Papua New Guinea	Telephone Communications/ Link outer villages to world	80 W ARCO	'79	Post telephone and telegraph	Papua New Guinea Government

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
41/1	PV-Powered Water Pump and Grain Grinding System/ Tangaye, Burkina Faso	Water Pumping (Potable Water) and Grain Grinding/ Support Study of "socio-economic effects of reducing time required by women to draw water and grind cereal grain	1.8 kW (increased to 3.6 kW in '81)	March '79	USAID	USAID
41/2	Tunisia Renewable Energy Project/ Tunisia	- Village Power - Water Pumping - Farm House Power	- 29 kW - 201.4 kW - 1.4 kW Solar Power Corp., and Tri-Solar Corp.	February '83	USAID/Tunisia	Societe Tunisienne de l' Electricite et du Gaz (STEG)
41/3	Medical Systems in Developing Countries/Guyana (1), Ecuador (1), Kenya (2), Zimbabwe (1) Gabon (4)	Rural Clinic Systems/ Demonstrate use of PV to meet electrical needs of rural health facilities	1.4 kW each except Ecuador which is 2.8 kW Solarex	February - June '83	USAID	Ministries of Health

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
41/4	PV-Powered Vaccine Storage Refrigerator-Freezers	Refrigerator, Freezer Vaccine Storage/Field test PV-powered refrigerator for vaccine storage				
	Pucara, Peru		248 W Solar Power Corp. (SPC), Adler-Barbour (AB)	October '82	CDC	
	Bocas Del Palo, Columbia		284 W SPC, AB	August '82	AID	
	Las Tablas, Dominican Republic		284 W SPC, AB	August '82	AID	
	Tierra Blanca, Guatemala		248 W SPC, AB	October '82	AID	
	Guaimaca, Honduras		200 W Solavolt Int'l., AB	January '84	AID	
	Anse-A-Veau, Haiti		284 W SPC, AB	September '82	AID	

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
41/4 (cont'd)	Schepmoed, Guyana		284 W SPC, AB	September '82	AID	
	Comuna Cobos, Ecuador		284 SPC, AB	September '82	AID	
	New Sandy Bay, St. Vincent & the Grenadines		200 W SVI, Marvel (M)	January '84	AID	
	Canouan, St. Vincent & the Grenadines		160 W SVI, Polar Products (PP)	January '84	AID	
	Waramuri, Guyana*		Solarex (SX), AB	February '83	AID	
	Pedro Vicente Maldonado/Ecuador*		SX, AB	February '83	AID	
	Kaur, Gambia Gunjar, Gambia		2 @ 320W SPC, AB	January '83	CDC	
	Niofouin and Zaranou, Ivory Coast		2 @ 355 W SPC, AB	February '83	CDC	

* R/F is part of larger clinic system

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
41/4 (cont'd)	Menee, Ivory Coast		280 W SVI, PP	February '84	CDC	
	Orodara, Burkina Faso		200 W SVI, PP	February '84	AID	
	Seuhn, Liberia		390 W SPC, AB	October '84	AID	
	Kionzo, Liberia		355 W SPC, AB	February '83	AID	
	Chiota, Zimbabwe		284 W SPC, AB	February '83	AID	
	Ouelessebougou, Mali		200 W SVI, PP	February '84	AID	
	Kibwezi and Ikutha, Kenya*		SX, AB	May '83	AID	
	Chikwakwa, Zimbabwe*		SX, AB	May '83	AID	
	Mowagar, Jordan		160 W SVI, M	June '84	AID	

* R/F is part of larger clinic system

REFERENCE NUMBER/ PROJECT NO.	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	INSTALLATION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
41/4 (cont'd)	Es-Smirat and Bir Amama, Tunisia		2 @ 240 W SVI, PP, M	February '84	AID	
	Bouaboute, Morocco		355 W SPC, AB	October '83	AID	
	Hammam Biadha, Tunisia*		SPC, AB	January '83	AID	
	Kuluduffushi, Maldives		284 W SPC, AB	May '82	AID	
	Bhoorbaral, India		355 W SPC, AB	October '81	AID	
	Cibung Bulangand Batujaya, Indonesia		2 @ 320 W SPC, AB	April '82	AID	
	Tambon Tha Thong, Thailand		200 W SVI, M	November '83	AID	

* R/F is part of larger clinic system

REFERENCE NUMBER/ PROJECT NUMBER	PROJECT TITLE/ LOCATION	APPLICATION/ PURPOSE	SYSTEM SPEC	IN-STALLA-TION DATE	FUNDING AGENCY	IN-COUNTRY PARTICIPATING AGENCY
41/5	Public Service PV Power Load Systems/ Gabon (4 sites)	Water Pumping, Lighting, Medical Clinics, TV and VCR/ Demostrate applicability of PV in village applications in Gabon	12 kW (total) Solavolt	Sept'84 to Jan.'85	DOE, Government of Gabon	Ministry of Electricity and Hydraulic Resources
41/6	PV Powered Satellite Earth Station and Classroom/Wawotobi, Indonesia	Send/Receive Earth Station, Telephone, Audio Convener, Graphics Facsimile Equipment/Demonstrate use of PV for remote satellite earth station applications	2.22 kW Hughes Aircraft Corp.	June'85	AID	Ministry of Education
41/7	Utirik Island Project/ Republic of the Marshal Islands	Village Power/Domestic and institutional lighting, institutional use fans, refrigerator (vaccines and food)	7.92 kW Huges Aircraft Corp.	June'84	DOE	Republic of the Marshal Islands

REFERENCE LIST PROJECTS:

1. ANTIQUA, Caribbean Agricultural Research and Development Institute (CARDI). Laxman Singh, Technical Coordinator.
2. BELIZE, Robert Nicolait & Associates Ltd. Robert Nicolait, President.
3. BOTSWANA, Botswana Renewable Energy Technology (BRET). Jonathan Hodgkin, Engineer.
4. BURUNDI/USAID. Health/Pop Officer, Project Manager.
5. DJIBOUTI, Republic of, ISERST/VITA. Abdoulkarim Moussa, Technician.
6. DOMINICAN REPUBLIC, CODETEL. Rafael L. Zorilla, Gerente Mant. Sist. Transmision.
7. DOMINICAN REPUBLIC, Direccion General de Telecomns. Bartolome Rosario, Rural Telecommunication Project Chief.
8. DOMINICAN REPUBLIC, Oficina Regional de Salud 1. Ing. Hanna Elias, Regional Engineer.
9. ECUADOR/USAID, Instituto Nacional de Energia (INE). Victor Castellanos, Consultant, Solar Energy Unit.
10. HAITI/USAID, Foundation CARE. A. Scott Faiia, Assistant Director.
11. KENYA, AMREF. Dr. Sam Kazibwe and Dr. Christopher Wood, Senior Medical Officer.
12. LESOTHO, Appropriate Technology Section (ATS), Ministry of Co-ops & Rural Development. B. Kanetsi, Acting Head of Section.
13. LESOTHO, Senakangoeli Solar Systems. Gary Klein, President.
14. LESOTHO, Swedish Telecomns. International. John Blaxland, Project Manager.
15. LIBERIA/USAID. Robert C. Braden, Liberia Civil Engineering Advisor.
16. MALI/USAID, LESO. Cheickna Traore, Director, LESO.
17. NIGERIA. Lary van Zee, Church and Community Developer.
18. SENEGAL, C.E.R.E.R. Ibrahima Lo, Engineer.
19. ZAIRE, Republic of. Pauline Chambers, M.D., Medical Director Samuleb Memorial Hospital.
20. ZIMBABWE, Ministry of Energy. C. Mzezewa, Research Officer.

REFERENCE LIST PROJECTS:

(CONTINUED)

21. A.Y. McDonald Mfg. Co., Iowa, USA. John Eckel, Manager of Energy Products.

22. Associates in Rural Development, Inc. (ARD), Vermont, USA. Richard McGowan, Senior Engineer.

23. GRUNDFOS International a/s, Denmark. Michael Arbon, Product Line Manager, Solar Pumping Systems.

24. Kyocera International, Inc., Japan. Koreyuki Taketani, General Manager, Sakura Plant.

25. Moteurs Leroy Somer, France. Dominique Mercier, Engineer.

26. Research Triangle Institute, North Carolina, USA. Alan Wyatt, Technology Specialist.

27. Solar Electric International Inc., Malta. John M. Williams, Managing Director.

28. Solar Voltaics, Austria. Lennart Muigg, Ing., Managing Director.

29. Solarex Pty. Ltd., Phillippines. Efren B. Katague, Manager.

30. Solec International, Inc., California, USA. Gregory S. Glenn, Design & Sales Engineer.

31. SunWatt Corporation, Indiana, USA. Richard J. Komp, Vice President, R&D.

32. United Nations, New York, USA. Derek Lovejoy, Interregional Advisor Renewable Energy.

33. INDONESIA, Directorate General for Electric Power and New Energy. Endro Utomo Notodisuryo, Head, Sub Directorate of Rural Energy Development.

34. SENEGAL. [Not indicated].

35. THAILAND, National Energy Administration. Sompongse Chantavorapap, Director, Energy Research and Development Division.

36. YEMEN ARAB REPUBLIC. Mark K. Leverson, Coordinator of Solar Energy Projects.

37. ZAIRE/USAID. Debra A. Rectenwald, Mission Evaluation Officer.

38. ARCO SOLAR Inc., California, USA. Michael Curley, Manager, Field Operations.

39. ARCO SOLAR Inc., California, USA. Gary J. Shushnar, Manager, System Design.

40. ARCO SOLAR Inc., California, USA. Gary Zahnstecher, Engineer

41. NASA Lewis Research Center, Ohio, USA. Anthony F. Ratajczak, Head, Solar Energy Project Office.

APPENDIX B: SIGNIFICANT PROJECT DESCRIPTIONS

The first phase of the evaluation involved the review of field experience with each of the applications: pumping, communications, refrigeration, lighting and home power, and multi-use. The experience associated with approximately 2700 PV power/load systems is incorporated into this study. From these, 29 specific projects are reviewed in detail based on their representative nature, the amount of available data, or their importance to understanding the key factors of PV system performance in particular applications. Project title and location, number and/or capacity of systems, and key comments provided by the references of these projects are tabulated by application in the body of this report. Performance summaries and lessons learned from these 29 significant projects are detailed in this appendix. In some cases, a "project" consists of many similar systems (e.g., the NASA-Lewis refrigerator field tests total 28 systems), but they are treated as one project.

B.1 Pumping

The review of the field performance of PV water pumping systems is based principally on project reports and interviews with key personnel on the performance of pumping systems in Mali, Botswana, India, Egypt and the significant pumping evaluation work performed for the United Nations Development Program (UNDP) and the U.S. Agency for International Development (USAID).

The following pumping projects have been reviewed in detail for this report:

- UNDP Pump Tests
- Mali Solar Energy Lab
- Sadat City, Egypt--Desert Development Project
- Botswana PV vs. Diesel Study
- Remote Village Pumping System in India
- Mali Aqua Viva Program

B.1.1 UNDP Pump Tests (References 3-1 and 3-5)

A major pumping evaluation was performed from 1980 to 1983 on PV pumping systems by Sir William Halcrow and Partners with Intermediate Technology Limited. The study, which was funded by the UNDP, also resulted in a 1984 publication Handbook on Solar Water Pumping, which describes the technology, its application, and its economic viability. The following quote, taken from this handbook, assumes installed system costs of $15 to $23 per Wp.

> As a general approximation it can be shown that solar pumping systems for irrigation are beginning to become cost competitive compared to diesel pumps in situations where the peak daily water requirements are less than about 150 m^4/day (for example 30 m^3/day through a head of 5 m) and where the minimum monthly average solar irradiation is greater than about 15 MJ/m^2 per day [4.2 kWh/m^2-day]. For windy locations where the minimum monthly average wind speed is greater than 3 m/s a windpump would be a cheaper option.
>
> Similarly for rural water supply applications solar pumping systems are becoming cost competitive compared to diesel pumps where the average daily water requirements are less than about 250 m^4/day (for example 25 m^3/day through a head of 10m) and where the monthly average solar irradiation is greater than 10 MJ/m^2 per day [2.8 kWh/m^2-day]. Windpumps are generally cost competitive at locations with minimum monthly average wind speeds greater than 2.5 m/s.

B.1.2 Mali Solar Energy Lab (References 3-8, 3-9 and 3-10)

During the past five years, a subtantial amount of field work has been performed by the Mali Solar Energy Lab and related organizations in Mali. Over 80 PV pumps have been installed in Mali. Unfortunately, few publicly disseminated reports have come out of the lab. An interview was conducted with N'To Diarra, the former head of the PV research group at the lab.

According to Mr. Diarra, Mali's experience has concentrated on centrifugal pumping systems, both low- and medium-head. No jackpumps have been evaluated. There have been very few problems with PV arrays. Most performance difficulties have come from the pumps and electronics. In multi-stage vertical turbine pumps, vibration in the connecting drive shaft (surface-mounted motor and submerged pump) has caused at least one broken shaft. For shallow well applications, centrifugal pumps are preferred since they provide the best electrical match to the array. Direct electrical coupling is desired in order to avoid sophisticated electronics. Data on the peak yield of the well and low-level water controls are two of the most important system design requirements.

Maintenance and technical support is most hampered by inadequate and unresponsive communications from the site to the manufacturer. Emphasis must be placed on training engineers in PV pumping system technology to perform trouble-shooting, repair, and maintenance management.

Demand is usually more than supply and this fact tends to lead to user dissatisfaction. Furthermore, because of the common failure to perform a "full system design," which incorporates sanitation considerations, users perceive problems with storage tanks, distribution systems and runoff systems as being failures of the PV system.

On performance and costs, a 1983 tender attracted bids of US \$10 to \$12 per Wp CIF Bamako. This included array, pump, structure, and wiring for an installation to produce 30 meters head at flows of 20 to 30 m^3/day. This results in volume-head products of 600 m^4 to 900 m^4. This value is more than twice the upper limit of the "viable" range specified in documentation on the UNDP pump tests (B.1.1); however, Mr. Diarra indicated that the decision to install pumping systems was of a political nature to show "real development." The choice of PV was necessary because of the unavailability of fuels.

B.1.3 Sadat City, Egypt--Desert Development Project (References 3-11, 3-12, 3-13 and 3-14)

The Desert Development Demonstration and Training Program utilizes an 8 feddan area (10 acres) for renewable energy/agricultural development work. The site has been entirely powered by a 10-kWp and a 3-kWp PV array since 1981. The 10-kWp array supplies 220-volt, 50-Hz power through a NOVA inverter to the headquarters building and an AC submersible pump at 43 meters of head. It includes 88.8 kWh of Exide battery storage. The 3-kWp system provides power exclusively to a positive displacement deep-well pump with DC motor and a booster pump for irrigation.

The array has performed reliably with an average daily conversion efficiency of 7.2%. The deep-well AC submersible pump has also performed well. The positive displacement screw pump has run reliably without failure since mid-1984. Prior to that, excessive mechanical vibrations in the drive shaft of the pump prevented continuous operation and resulted in a number of pump failures. Additional drive shaft stabilizing bearings were added and the pump operates with an average of 60% efficiency. Significant experience was also obtained with the battery systems. Mr. Fadel Assabghy, who is responsible for the PV power systems at Sadat City, has indicated that battery maintenance must be tended with unfailing regularity.

B.1.4 Botswana (References 3-15 and 3-16)

A study was performed, based on actual field data, on the question of the economics of PV versus diesel for water supply in rural Botswana. It was based on more than 3 years of actual field experience in the maintenance and operation of diesel-powered water supply systems.

Fuel usage, the cost of regular maintenance, the initial costs of the system and the replacement of individual components were considered. The study compared a 6-kW single-cylinder diesel engine and rotary screw pump with a PV power system and permanent magnet DC motor powering the same pump. The study found that "there are no significant mechanical obstacles to the introduction of PV water pumping into the country.... The one question...is cost."

The study points out that a significant technical consideration for the application of PV is the borehole peak yield character. In a typical application, a maximum demand of 2 to 6 m^3/hr will occur at solar noon on clear days. Borehole yield tests often indicate that this rate is higher than the well recovery rate, and thus the well would dry out. Well peak yields may in fact be a significant limiting factor to the applications of PV systems.

Another pertinent design factor is the use of existing pumps and wells to capitalize on any equipment infrastructure. The design effort to do so, however, requires good communication between the equipment suppliers and the field.

A "continuous discounting" life-cycle cost analysis, based on a 2% real discount rate and a 20-year life, showed that PV is economically competitive with diesel engine systems at the present time. Diesel costs ranged from \$0.216/m^3 for 1368 m^4 hydraulic daily energy demand to \$0.581/m^3 for 3000 m^4 hydraulic daily energy demand. Comparative costs for PV were \$0.099/m^3 and \$0.372/m^3 respectively. The report also states that "all of the unit costs [PV] except for the desert village [3000 m^4] were below the current price charged for water and there are no associated labor costs." This covered an analysis of borehole volume-head products of 150 m^4 to 1368 m^4. PV initial capital costs for the system were \$13 to \$14 per Wp for 150 m^4 to \$11 to \$12 per Wp for 3000 m^4. (This range of economic competitiveness is significantly higher than any previously reported work and it may be due in part to the use of existing pumps and infrastructure to design, produce and install the systems.)

B.1.5 Remote Village in India (Reference 3-17)

The installation of a PV pumping system in a rural Indian village raised many important socio-economic issues. These involved bureaucratic and administrative problems, villager integral participation, and the ownership and management of facility and water.

The choice of the PV system was based on the past experience and technical limits of other water pumping technologies. Two villages in the area had diesels, but high incidence of breakdown and irregular fuel availability outweighed the value of the amount of pumped water. Bullocks could not be used because the water depth was 15 meters. Biogas would require cattle to be corralled to collect manure and the resulting questions of energy ownership and distribution were serious.

The PV system was installed following a long and difficult bureaucratic and administrative struggle. Transport of the equipment, customs, drilling of the well, testing of the yield, and well casing were a few of the tasks that progressed slowly. On one occasion, management problems and tribe rivalry resulted in violence. The following conclusions were reached:

> Such a project could never be successful without the close following and constant pressure of people alien to the village but fully accepted by it.... A solar water management committee came into being by consensus for the best and fairest distribution of solar water and has managed to satisfy contradictory needs.

At the time this article was published, the system had provided irrigation for one successful winter crop.

B.1.6 Mali Aqua Viva Program (Reference 3-18)

In May 1974, the Mali Aqua Viva program initiated an effort to provide forage for animals and water supply for the local minister. By 1984, over 900 manual pumps, 4 diesels, and 30 PV-powered pumps were installed and operating. The 30 PV-powered pumps deliver more than 800 m^3 per day from a depth of 20 meters. The peak installed capacity of PV power is over 48 kW. The following table gives the type and number of the installed systems:

30 Pumps	39.0 kW
Hospital Power	8.6
4 Refrigerators	0.6
Classroom Lighting	0.2
Religious Mission Lighting	0.1
Total	48.5 kW

Based on the operating experience with the pumping systems it has been calculated that the cost of water from the PV pumps for one year was 3.1 Ff/m^3 (0.34 \$/m^3) compared to the manual pumps (foot operated) of 1.42 Ff/m^3 (0.16 \$/m^3). The cost of the solar pump was six times that of the manual pump. However, the volume of water produced was not comparable. The PV system produced 30 m^3/day and the foot pump 6 to 8 m^3/day; therefore, more foot pump installations would be necessary. Also no cost was associated with the manual pumping labor.

The most important information to come out of this work thus far has been the cost of infrastructure, on a unit pump basis, for operation and maintenance. For the PV pumping systems, 4870 Ff/year/pump (536 \$/year/pump) was the cost of maintenance and operation for 30 pumps. The costs are likely to be reduced to 3000 Ff/year/pump (330 \$/year/pump), which is six times more than manual pumps, but also yields six times the volume of water. Therefore, the indication is that per equal volume of water, PV and manual pump systems require the same cost level of supporting infrastructure.

Comparisons to diesel were performed. For a 5.2-kW system, PV water pumped from 10 meters depth costs 0.65 Ff/m^3 (0.07 \$/m^3) at a rate of 350 m^3 per day, while diesel-pumped water costs 0.50 Ff/m^3 (0.06 \$/m^3) at a rate of 50 m^3/hr. The level of maintenance was not included in the comparison. In addition, no background was provided on how water costs were determined.

B.2 Communications

The following communication projects have been reviewed in detail for this report:

- Microwave Telecommunications in Papua New Guinea
- Telecommunications Systems in Australia
- Niger PV-Powered Televisions
- Gabon Telecommunications Relay
- NASA-Lewis PV Medical System Radios
- Health Care Communication Systems.

B.2.1 Microwave Telecommunications in Papua New Guinea (Reference 4-4)

In Papua New Guinea (PNG), telecommunication repeater stations are located primarily on mountain tops and are accessible only by helicopter. Traditionally, repeaters in PNG have been powered by primary batteries. Primary batteries must be replaced on a regular basis, disposed, and imported (i.e., supply is subject to political and economic policies of foreign countries).

On June 13, 1976, a PV-powered repeater system was commissioned on Mount Namsbamati. The PV system powers a microwave repeater that carries both domestic and international traffic and thus is a vital link in the Trans-PNG Telecommunication Network. The system consists of nine 26-W modules (Solar Power Corp.). Because of the required reliability, the system was oversized by 50 percent (i.e., only 6 modules were really needed). The batteries are nickel-cadmium with a total of 240 A-h capacity. To operate at the nominal voltage of 36 V, 28 cells were connected in series and float charged at 41 V. Performance as of October 1978 was as follows:

- System functions well except for one failure in the voltage regulator.
- Dust accumulation on the array is minimal.
- Water consumption by the batteries is negligible.
- Maintenance was non-existent.

There are no institutional difficulties, as the management of parts and technical personnel is performed by a skilled, established organization. Maintenance and repair frequency have been reduced considerably compared to conventional systems.

Cost analyses of PV systems (at a price of $26 per Wp) versus primary batteries showed a one and a half to two-year payback in 1978. High costs for maintenance in primary battery systems and for transport to the site makes the choice of PV inevitable.

Six more PV-powered telecommunication routes were to have been installed between the following cities by 1981:

(1) Boroko-Lae
(2) Lae-Goroka-Madang
(3) Goroka-Mt. Hagen-Wewak
(4) Lae-Raboul
(5) Boroko-Altoan
(6) Boroko-Mt. Hagern.

B.2.2 Telecommunications Systems in Australia (Reference 4-8)

Although Australia is not a developing country, its experience with PV-powered communications systems in remote sites are still applicable to this study.

Telecom Australia has been installing systems of up to 2000 Wp (300 W continuous) in rural and remote areas of Australia since the 1970s. On the order of 75 to 100 PV-powered repeaters are currently installed. Plans for 1100 more in the next few years are in progress. Of the major systems installed, there have been no system failures. Telecom Australia has been obtaining "gratifying results" for over 10 years.

PV has proven to be "extremely reliable and economical for telecommunications loads in the range of 1-300 watts continuous." For systems greater than 300 W, they plan to use hybrid systems of PV and wind or diesel (a demonstration project is underway).

B.2.3 Niger PV-Powered Televisions (Reference 4-5)

In Niger, more than 1000 PV-powered television sets have been installed. PV technology was chosen because it is compatible with rural village conditions--isolated villages and precarious roads. The televisions serve as a valuable educational tool. The systems have been successful and the program is continually expanding.

B.2.4 Gabon Telecommunications Relay (Reference 4-5)

A 650-Watt PV unit powers a relay station in Gabon. Installed in 1981, it has taken the place of a gasoline generator. In 1982, the French program SEMI concluded that this power level represents the upper limits of use in isolated villages. It is a pilot system still in the R&D stages. The costs of the system were two times that of a comparable gasoline generator. The system has run satisfactorily since its installation.

B.2.5 NASA-Lewis PV Medical System Radios (Reference 4-6)

Radios were installed as part of the loads in three of the five remote medical systems located in Guyana, Ecuador, Kenya, and Zimbabwe. The radios were STONER VHF radios, each with a dipole antenna. They were designed to be powered from a 12-volt source.

The radio in Guyana performed without difficulty and provided good communications across distances of more than 200 km. Although not related to the PV power system, a problem was experienced in Kenya where two radios were installed 50 km apart at two medical health centers--in Kibwezi and Ikutha, Kenya. The radio frequencies were found to be in error and not matched to each other. After the radios had been returned to Nairobi and the antenna positions had been changed, the quality of the transmission only improved a small amount. The conclusion was that interference from the terrain and other local transmissions were at fault.

B.2.6 Health Care Communication Systems (Reference 4-7)

The importance of two-way radio communications to medical programs can be described using examples from the Africa Medical Research Foundation and Guyana. Comments relative to the power system are as follows:

> Power supplies are a persistent technical problem. In locations with an existing power source (perhaps a town power supply or a generator for a hospital), voltage regulators may be needed to prevent damage from power surges. If voltage is much below specified output, it may not be possible to use local power to run the radio or recharge its batteries.
>
> A common self-contained power source for two-way radios is a standard 12-volt DC automobile storage battery, recharged by a small diesel generator that must be properly cleaned and maintained. The costs and logistics of transporting diesel oil to remote locations--often it must be flown in--can make this one of the highest costs of operating a radio system. In contrast, solar panels can serve as the recharging source and can eliminate the need for generators and fuel. Although at present [1980] their capital cost is higher, they are becoming less expensive, and they require little maintenance until replacement is necessary. Field tests do not indicate any major problems with solar panels, but none have been in use long enough for definitive evaluation.

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B.3 Refrigeration

Project reviews for this evaluation incorporate the experience associated with more than 105 systems in 43 countries. The most significant work to date has been that performed by NASA in cooperation with the World Health Organization, the U.S. Center for Disease Control and the U.S. Agency for International Development. The formal development and field demonstration programs conducted by these organizations have led to increased operating knowledge and subsequently improved system designs. Most recently, a significant cost analysis project was conducted in The Gambia on the competitiveness of PV with kerosene. That work is detailed in this section. Other work has been done by UNDP, UNICEF, AFME (France), GTZ (Germany), ODA (UK), Oxfam, ICRC and SWASO. However, the collection of detailed information on these projects is difficult as many are using a single or few refrigerators. Many of these projects are not being monitored, and there is little information available.

In the near future two additional projects should provide statistically significant operating data on PV refrigerators. Projects are currently underway to install 100 systems in Zaire and 20 in the South Pacific, both funded by the European Development Fund. Because these have not yet been documented, they have not been summarized in this report. The separately bound report by IT Power does contain details of these projects.

The following refrigeration and medical system projects have been reviewed in detail for this report:

- NASA-Lewis 28 R/F Systems
- World Health Organization (WHO) Field Trials
- Immunization Program in The Gambia.

B.3.1 NASA-Lewis 28 R/F Systems (References 5-3 and 5-5 through 5-12)

PV-powered refrigerators for vaccine storage were installed by NASA-Lewis at 28 sites around the world from 1981 to 1983. The packaged systems included a PV array (160 to 363 Wp), refrigerator/freezer (R/F), and battery bank. Each R/F was instrumented with a thermograph and alarm to indicate internal compartment temperatures.

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From October 1981 to July 1984, the R/Fs in the NASA trials accumulated almost 500 system months of operation. The R/Fs are reported to have operated correctly (i.e., maintaining internal temperatures within the required temperature range) for slightly more than 80 percent of the time. Although this is not an acceptable level of reliability for vaccine refrigeration, it is comparable with that of kerosene refrigerators. More significantly, all of the problems experienced are believed to be avoidable in future installations.

Systems in the Dominican Republic, The Gambia, Guyana, India, Mali and Thailand have experienced instances when the internal refrigerator temperature was outside the required limit. Reasons cited for inadequate performance include:

- defective components (e.g., temperature controllers, thermostatically controlled air doors, voltage regulators)
- incorrect setting of the thermostat
- excessive amounts of warm material (e.g., food and drinks) being put in the refrigerator
- array shadowing.

Exhibit B-1 details component reliability in the NASA field tests. Of the various component failures encountered, none occurred consistently across the systems, and most were not considered serious. From a NASA-Lewis report, "...there have been no known PV system problems.... The R/Fs have been relatively problem free with no compressor problems.... A few problems [have occurred] with compressor electronic control modules (ECM).... Instrumentation has been a major problem." In particular, instrumentation problems were encountered with the pyranometers and amp-hour meters--instruments that have been used successfully in many other projects.

The systems operate with little operator support. Misuse of R/Fs (e.g., for cold drinks, meat storage, etc.) has been observed in several systems. The thermograph incriminates the user. Some R/Fs have yet to be used for vaccines because the health programs or the vaccines themselves are not available.

The cost of current PV powered R/F systems ranges from $3500-6500 and is dependent on the location, system design and supply point of the R/F. ECM failures are not substantial enough to consider reliability a serious concern.

EXHIBIT B-1. NASA-Lewis Field Trials - Component Reliability

COMPONENTS	SPC/ADLER BARBER	SOLAVOLT/ MARVEL	SOLAVOLT/ POLAR PRODUCTS
Systems Installed	19	5	5
Systems Reporting	19	2	2
Photovoltaic Module	1 - Ivory Coast (refrigerator remained functional)		
Voltage Regulator	1 - Indonesia	1 - St. Vincent (before installation)	
Cable Connector	1 - Indonesia 1 - Guyana 1 - Ivory Coast		
Batteries	Minor corrosion experienced		
Electronic Control Unit	Fuse blown - Indonesia Fuse blown - Guyana ECU failure - Ivory Coast	1 - Jordan	
Compressor	NIL		
Refrigerant Loop	1 unit received low on freon in Maldives		
Fan	1 - Ivory Coast	1 - Honduras (before installation)	
Air Door	NIL	1 - Thailand	
Thermostat/Alarm	1 - Alarm incorrectly wired by SPC delivered to Ecuador	1 - Honduras (before installation)	

B.3.2 World Health Organization (WHO) Field Trails (References 5-1, 5-3, 5-4 and 5-14)

The WHO Expanded Program on Immunization has sponsored laboratory tests (1980-1983) and field trials (installed in 1983 and 1984) of PV-powered refrigerators for vaccines. A total of twenty field trials were initiated in Ghana, Kenya, Tanzania, Columbia, Yemen Arab Republic, India, the Philippines and the South Pacific Islands. These field tests were conducted either solely by WHO/Pan American Health Organization (PAHO) or jointly with other agencies, notably NASA. Other field tests were conducted directly by manufacturers or government agencies.

Based on laboratory tests and initial field trial results, four refrigerator models have been approved by WHO for vaccines (Polar Products RR2, LEC EV 570, Frigesol 40 and Marvel 4 RTD). Others tested by WHO were rejected based on characteristics such as high energy consumption, lack of ice-making capabilitv and unacceptable holdover time.

Technical problems encountered with the field trials include improper sizing of the array/battery and instrumentation failures. A number of systems in the Philippines have undersized arrays. There is also concern over the array/battery sizing of six systems in India and one in Yemen Arab Republic. WHO has found that energy consumption in the field does not match that anticipated based on laboratory tests. Discrepancies are most likely due to the fact that their strictly controlled laboratory tests did not account for misuse of equipment in the field.

B.3.3 The Gambia (Reference 5-14)

An analysis of an actual immunization program in the Republic of The Gambia was recently conducted. The analysis assumes that the solar vaccine refrigerator will be 90 to 100% reliable, compared with a reliability of 85% for kerosene refrigerators (i.e., 90 to 100% of the vaccines stored are usable from solar refrigerators but only 85% from kerosene units). This assumption is based on the field experience in The Gambia and the experience with other PV refrigeration systems around the world.

The methodology used for the financial analysis entails calculating life-cycle costs for each option by taking the summed present values of their respective cash flows. These are annualized to obtain relative annual running costs, discounted to the present using a 10% discount rate.

The total program overhead is $400,000 or approximately $14,000 per health center. For the purposes of analysis, both a low program overhead and a high overhead have been used for comparison. These are $8,000 and $16,000 respectively. Similarly, for the solar refrigerator a high-cost and low-cost case are considered as given in Exhibit B-2.

It was assumed in the analysis that (on the basis of 1983 figures) 14,208 doses per refrigerator per year would be administered using kerosene, while 15,044 to 16,716 would be administered from the same supply of vaccines if solar refrigerators were used. These figures reflect 85%, 90% and 100% refrigerator availability for kerosene, solar high, and solar low, respectively. Exhibit B-2 summarizes the assumptions and results of the analysis in The Gambia. The cheaper overhead cost per dose with the PV-powered R/Fs is not a cost-saving as such, but it does draw attention to the substantial overhead involved in giving a vaccination over and above the costs of the refrigerator and its operation and maintenance. A small increase in refrigeration costs could be acceptable if it allows significantly better use to be made of a relatively expensive infrastructure. Therefore, the benefit consists of improved cost-effectiveness rather than reduced costs.

EXHIBIT B-2. Summary of Comparative Costs for Kerosene and Solar Refrigerators (based on actual data in The Gambia)

	Low-Cost Case		High-Cost Case	
	Kerosene	Solar	Kerosene	Solar
1. <u>Assumptions</u>				
Installed Capital Cost ($)	400	3,424	400	8,856
Recurrent Costs ($ yr)	853	150	853	150
Availability (%)	85	100	85	90
Program overhead cost per refrigerator ($)	8,000	8,000	16,000	16,000
2. <u>Results</u>				
Useful doses per annum	14,208	16,716	14,208	15,044
Annualized cost for refrigerator ($)	913	664	913	1,478
Refrigerator cost/dose ($)	0.06	0.04	0.06	0.10
Overhead cost/dose ($)	0.56	0.48	1.13	1.06
Total cost/dose ($)	0.62	0.52	1.19	1.16

B.4 Lighting and Home Power

The following lighting and home power projects have been reviewed in detail for this report:

- Papua New Guinea Lighting Systems
- PV Versus Kerosene Lighting - Papua New Guinea
- Zimbabwe Lighting Systems
- Mali School Lighting
- Traffic Lighting - United Arab Emirates
- French Polynesia.

B.4.1 Papua New Guinea (References 6-2 and 6-3)

The field operating experience with PV systems in rural applications in Papua New Guinea has provided important insight into technical and financial aspects of PV lighting systems. Charge controllers were previously found to be complex in circuit design and operation and were unreliable. In 1980, as a result of Papua New Guinea field experience, fully "tropicalized" charge controllers were made available and have since been proven reliable. For safety and reliability reasons, a policy was adopted to use 12-volt DC PV lighting systems for village and government patrol post lighting. As to the quality of lighting, a 20-watt fluorescent bulb provides a light intensity of 100 lux at one meter below the lamp. A kerosene pressure lamp provides 12 lux, measured one meter below the lamp and outside the lamp's shadow. In addition to these obvious improvements in quality, the high cost of kerosene (about $1/liter) result in paybacks of from two-to-four years for simple PV lighting kits.

A number of PV systems have been installed in Papua New Guinea for communications, lighting, water pumping, and medical refrigeration. The total installed capacity in 1982 was approximately 50 kW. Over half of the amount was for telecommunications systems. The remaining systems were for mission radios and lights, mobile radios, village water pumping, and village house lighting. The potential for village house lighting systems over the next 10 years was estimated at 500,000 single module units (35 watts each), or 17.5 megawatts.

In related work, the Appropriate Technology Development Institute of the University of Technology in Lae, Papua New Guinea has started testing fluorescent tube "lanterns" powered by rechargable Ni-Cad batteries. The lanterns are designed to look like their kerosene counterparts but to be charged by PV. A photo is provided in Exhibit 6-3.

B.4.2 PV Versus Kerosene Lighting - Papua New Guinea (Reference 6-1)

A survey was conducted among 30 village houses to assess the cost components of kerosene-fueled lighting as experienced in rural villages. The cost and performance of a comparable PV lighting system were analyzed over a 5-year period.

A typical household was found to use two kerosene powered lights, a hurricane lamp and a pressurized lamp. The cost of operating these lamps was found to be 196 Kina (1 Kina=$1.34) for the first year. A 5-year expenditure of 817 Kina could be anticipated, using a 10% discount rate.

The comparative PV system was a single ARCO panel (ASI 16-2000), a Delco 2000 battery, a regulator and two 20-watt fluorescent lamps. It was capable of delivering 160 watt-hours/day. The array was guaranteed for five years and the batteries for three years. The installed cost of the PV system in 1981 was 655 Kina.

The following excerpts were taken directly from the reference:

> ...the PVC kit is less expensive to operate over a 5-year period. It would take under five years to recover its cost through savings on kerosene lighting. Undoubtedly this may be too long a period for a villager to pay for a commodity which does not in return derive an income for him, with unknown performance and reliability. However costs alone should not be used to determine the favourability of either of the lighting systems. Hence other comparative criteria are taken into account.
>
> Quality of Lighting
> ...with the PVC lighting quality at least five times better than the kerosene light there is reason to pay extra money....

> Initial Lighting and Convenience
> ...the PVC kit merely provides light at the flick of the switch. For the kerosene pressure lamp it takes at least five minutes to refuel the tank, clean the glass and then to actually light it....
>
> ...the costs and benefits are compared [and] it is clear that benefits out-weigh the costs. Thus from a national point of view, the replacement of kerosene lighting of the type described with a PVC kit and hurricane lighting is worthwhile, although the high capital requirement for the PVC kit makes it unlikely that many people will take up the PVC option.

The reference suggests that the government should finance and encourage lending institutions in Papua New Guinea to provide loan opportunities to customers willing to purchase PV kits.

B.4.3 Zimbabwe (Reference 6-4)

A 1983 report by PTA Consulting Services of Harare, Zimbabwe addressed the economic viability of PV for water pumping and lighting. A comparison is made between lighting by candles, gas, or kerosene and a single PV module, battery and two fluorescent lamps (40 watts each). The cost to a family for conventional lighting was between $24 and $144 per year depending on the affluence of the residents. The capital cost of the PV system was $660. Portability of the lamps was stressed as an important design parameter. Six-to-seven year payback periods were noted. Another comparison was made between a 500-watt petrol generator and PV system to supply equal amounts of lighting. The capital cost of $2000 for the PV system was compared to the $550 initial cost and $975 annual running cost of a petrol generator. Payback of less than two years was calculated.

The report does not provide sufficient detail for an analytical critique. However, it is probable that the operating assumptions used for the petrol generator relate more to actual conditions than to ideal.

B.4.4 Mali School Lighting (Reference 6-5)

In November 1980, a classroom received PV-powered fluorescent lighting for use during evening classes. The competing alternative is gas lamps. PV has performed well and with little maintenance; however, the reference stated that despite the risks of bottled gas, the use of PV could only be regarded as an interesting experience. The conclusion reached was that the use of PV cannot be developed further unless there is a substantial reduction in the cost of systems and/or a substantial increase in the budget devoted to rural education.

B.4.5 Traffic Lighting - United Arab Emirates (Reference 6-6)

Twenty-one PV-powered street lights and a high-mast, traffic-circle light were installed in June 1983 in Dubai, United Arab Emirates by Mobil Solar Energy Corporation. Each street light consists of a 20-watt fluorescent tube, two 35-watt modules and a 12-VDC ballast. The high mast light consists of eight 400-W, high-pressure sodium vapor (HPS) lamps powered by a 15-kW array.

During the design of the street lights, five commercially available tubes were tested. The test results showed large differences in efficiency (lumens per watt). The most efficient ballast was chosen. The customer has been pleasantly suprised at the illumination delivered by the 20-W fluorescent systems. The light level is sufficient to read a newspaper while standing on the roadway, 18 feet beneath the lamps. Through the first 10 months of operation, the street lighting performed reliably.

There were initial problems with the HPS light because of the inherent difficulty with operating HPS lamps with modified square-wave inverters. The solution was to use a ferroresonant inverter at 77% efficiency compared to a 90% efficient, modified square-wave inverter. Development of high-efficiency, high-power, DC ballasts for these lamps was mentioned as vital to optimizing these PV lighting systems.

B.4.6 French Polynesia (Reference 6-7)

The activity in PV applications in French Polynesia is significant. Over 1000 home power systems have been installed to provide lighting, television, and fans for individual houses. The efforts are supported by the French Atomic Energy Commission (CEA), the French Agency for Energy Management (AFME) and the Government of French Polynesia. The program in which systems are being provided is similar to that practiced worldwide for rural electrification--subsidization. Studies as long ago as 1980 showed that it would be more cost-effective to support the introduction of PV power systems than to extend the grid.

A typical system consists of three 13-watt lights, an 80-watt television, a fan, and a small refrigerator. The cost of the system is approximately 17,600 Ff ($2000), including taxes. The modules are 50 percent subsidized by the program. End-users can pay the balance up-front or over a 5-year period at 9 percent interest. The conclusions of the recent work are that PV is economically justified where the user is more than 200 meters from the grid. By 1982, 50 kW (representing 300 huts) had been installed under this program. Another 120 kW were expected in 1983, representing 25 percent of French PV production at that time. The South Pacific Commission was encouraged by this program and has proposed the development of such a rural electrification scheme throughout the South Pacific.

B.5 Multi-Use

Multi-use projects at the following locations have been reviewed in detail for this report:

- Tunisia
- Gabon and the Marshall Islands
- Basaisa Village - Egypt
- Charsarati, West Bengal, India
- Niaga Wolof Energy Centre - Senegal
- NASA-Lewis Medical Systems
- Senegal Medical Systems
- Bourkina Fasso.

B.5.1 Tunisia (References 7-2, 7-3, 7-4 and 7-5)

Significant multi-use projects have been performed by NASA-Lewis Research Center over the last two years. Included in these is a 27-kWp system in Tunisia. This village electrification project of PV, wind, and solar heating has been operating since February 1983. The PV system consists of a 29-kW, 220-volt, 50-Hz system to serve public and commercial sectors of a village of 120 persons. Additionally, a 1.4-kW remote farm house system for lighting, R/F, TV and radio and two 1.4-kW drip irrigation systems were installed. Operation and evaluation is the responsibility of the Societe Tunisienne de L'Electricite et du Gas (STEG). There is very little instrumentation included, although there are kilowatt-hour meters on the system and for individual users. Users are billed for specific consumption. Project participants believe that STEG has been recording basic production data.

The 1-kW inverter in the farm house system has had numerous problems, and extensive time was required to effect repairs. The village system inverter experienced a failure brought on by what appeared to have been improper switch sequencing during manual start-up. Some array wiring has deteriorated due to abrasion and sunlight damage. It is believed that the wrong wire sheathing was specified or procured.

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B.5.2 Gabon and the Marshall Islands (References 7-6, 7-7 and 7-8)

NASA-Lewis Research Center also managed the 8-kWp, 120-VDC village electrification system in the Marshall Islands on Utirik Atoll and the series of 17 separate community service DC systems for 4 villages in Gabon. The Gabonese community service systems for each village include a water pump (0.7 - 3.2 kWp), a school system (560 Wp), community light (80 Wp), and a health dispensary (640 Wp). The Utirik Atoll system and the Gabon systems became operational in 1984 and 1985, respectively. So far, both PV systems have had 100 percent availability.

Minor problems have occurred with control systems and with street light inverter ballasts in Gabon. The fluorescent lights have an integral inverter for each lamp that has experienced a failure rate that is proportional to outdoor storage time in the moist tropic environment before installation. Inverters that were installed in fixtures directly, (i.e., not stored in unairconditioned areas) have not had any failures. All fixtures that were stored in Gabon prior to installation were replaced. Failed inverters are being analyzed. The Gabon systems are completely instrumented, and data collected over the next few years should provide a valuable indicator of that system's overall performance.

B.5.3 Basaisa Village - Egypt (References 7-9, 7-10 and 7-11)

A PV village electrification system was introduced in Basaisa in November 1977 under the sponsorship of the American University in Cairo and the National Science Foundation. The initial 33-Wp system powered a 12-inch screen black and white television, a 12-V radio cassette recorder and a 12-V manual slide projector. The storage system consisted of a 12-V car battery. In December 1978, another 33 Wp was added to power a 12-V loudspeaker and a 12-V, 60-W emergency light. In 1981, solar pumps were added for irrigation.

The village has established a community cooperative, community club, technical center and community clinic. A fee is charged for membership in the cooperative or club. Members of the cooperative may use the community audio-visual (AV) equipment, emergency light and irrigation pumps. Members of the club may use the TV, AV equipment and light. The technical center uses the AV equipment and pumps, and the clinic uses the light. Members of the cooperative and club must pay rent for the pumps and AV equipment during times of use.

As of September 1983, the system was operating satisfactorily. The initial pump that was used in the system was not designed well for the given application--low lift pumping. However, a new pump was developed and was in use as of September 1983. Operation and maintenance activities include cleaning the array every two weeks and monitoring battery state-of-charge with a multimeter and hydrometer.

Operation, maintenance and repair is performed by volunteers in the community. In the case of system breakdowns, the villagers first attempt to correct the situation themselves; the project team only intervenes if the villagers cannot fix the system. The energy cooperative not only provides for the basic energy needs of the community but also establishes an educational atmosphere and a type of community spirit. There has not been much conflict over the use (and scheduling of the use) of the various equipment. However, some farmers still prefer using their animals to pump water for irrigation rather than the PV-powered pumps.

B.5.4 Charsarati, West Bengal, India (Reference 7-12)

In December 1980, a 200-Wp PV system was installed to power a community center. One of the main functions of the center is to provide adult education. The loads for this system include a 65-W television, two 40-W fluorescent lamps and one 20-W fluorescent lamp. A DC-DC converter (24VDC-110VDC) is used for the television, and an inverter (24VDC-150VAC) is used for the lamps. Storage consists of two 12-V, 120-Ah lead-acid batteries. In October 1981, a 300-Wp water pumping system was installed for irrigation. The pump is a DC centrifugal model rated at 96 V and 400 W. A maximum power point tracker and five 42-V, 60-Ah leadacid batteries are included in the system. This project was originated and is administered by the University of Kalyani. All modules were supplied by CEL, an Indian manufacturer.

As of 1984, the system seemed to be operating smoothly. The principal investigator of PV projects at the University of Kalyani feels PV systems have been proven technically feasible in India. Futhermore, the community center was economically viable. BOS costs (per peak watt) are less in India than in the U.S., due to low labor costs. The cheaper BOS costs allow for the use of low efficiency (5%) solar cells.

There were some problems when modules failed after three years due to the cracking of cell interconnects. They could (as of 1984) only be replaced by physically taking them to CEL. Motor-pump set problems were also encountered mainly with the carbon seals and commutators. This project, nevertheless, has generated "tremendous enthusiasm," even attracting people from neighboring villages in the evenings. The villagers manage security, operation and maintenance on a cooperative basis.

B.5.5 Niaga Wolof Energy Centre - Senegal (Reference 7-13)

Niaga Wolof is a village of 1500 inhabitants. In February 1983, a PV-wind hybrid system (5 kW PV; 4.5 kW wind) began powering a public lighting system. In April 1983, a water pump (20 to 25 m^3/day) was connected to the system. The system was officially considered operational in January 1984, after 9 months of preliminary tests. By January 1984, the system also powered two refrigerators and two fluorescent tubes. The system is intended to also eventually supply residential lighting, a communal TV, carpentry and sewing equipment, a grain mill and an ice maker.

As of October 1984, no problems with the PV portion of the system had been reported. According to the reference, the system "confirmed the reliability of photovoltaic solar energy." The system also demonstrated that a full-time system operator is not necessary and that periodic inspections suffice. The cost-competitiveness of this system versus diesel has not been determined yet since the grid is still undergoing expansion and more accurate instrumentation is needed.

The system is located near Dakar and is thus close to technical support. Users of the system are billed according to an established tariff structure. Residences are billed at the cheapest rate, whereas a tourist center in the village is charged a higher rate.

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B.5.6 NASA-Lewis Medical Systems (References 7-20 and 7-21)

NASA-Lewis installed five stand-alone PV-powered medical systems in four countries--Guyana, Ecuador, Kenya (2), and Zimbabwe. The 1.5-kW PV systems were designed to supply power for an R/F, lights, sterilizer, and radio. All materials and load devices, excluding concrete and fencing, were supplied as a package. Ecuador's system was 3 kW and included a dental drill and inverter. Guyana's system included a water pump. Kenya systems included two-way radios. The systems were heavily instrumented to produce detailed data on load use, resource availability, and equipment performance.

All five systems have functioned reliably regarding array, battery, and control function. However, the systems have produced little useful data due to instrumentation failures. The automatic data acquisition systems were customized for the project and did not work. Some electronic "logic card" design problems were experienced with the controller. The sterilizers (electrochemical) failed to perform properly in all the systems. No health problems resulted, however. Subsequent analysis has shown that electrochemical sterilization, passing an electric current through a saline solution, does not meet health standards. (Since sterilization is as important as vaccine refrigeration for rural health care, other sterilizer technologies, such as electric steam heat, are being investigated.) Several fluorescent light ballasts and R/F fuses have blown. Spare light tubes were not available beyond those supplied with the system. One R/F had an electronic control module (ECM) failure. Radio performance in Kenya was poor because of terrain and other radio interference.

No problems have arisen with respect to the acceptance and use of the systems. However, vaccines were not regularly available at the Guyana site for at least the first 18 months of operation. Difficult battery access resulted in acid spillage in Guyana. In Ecuador, the electric grid has reached the village and the health center is no longer dependent on PV though they continue to use it to meet their energy demands. The system in Kibwezi, Kenya, was installed at a hospital which had an existing 20-kW diesel engine generator. Operation and maintenance difficulties with the diesel engine generator resulted in changing the initial passive interest in the PV system to active support as its reliability and low maintenance have been realized.

Design of these basic systems today would replace the electrochemical sterilizer with a steam/pressure sterilizer, omit the instrumentation, and minimize controller functions. With total loads of 1.5 to 2 kW, the current (1985) price for such a system, including end-use components, would be \$25,000-\$30,000 installed according to Solarex Corporation.

B.5.7 Senegal Medical Systems (Reference 7-22)

A 670-Wp medical power system was installed at Mt. Rolland in the Theis region of Senegal in 1982. The system provides for loads up to 56 watts. The PV system competes against the following alternatives to supply basic medical service power:

- The use of gas or butane for refrigerators and lighting (reliability of these refrigerators had been poor)
- The supply of distilled water with medical supplies obtained from administrative headquarters
- Ironing of laundry with charcoal-heated irons
- Microscope work during the daytime with sun reflection lights
- Human-powered water pumping
- Little or no ventilation.

The PV system provides lighting, improved ventilation with the use of fans, and high-quality power for use with laboratory instruments. Overall it made a decisive improvement in health service effectiveness. Each dispensary deals with 10,000 inhabitants, providing 100 to 150 consultations per day.

The system costs 200,000 Ff (US\$20,000--1985 conversion). The system is experimental and the price includes R&D work. The system was oversized; 430 Wp would have supplied the load. Oversizing was the result of a load over-estimate.

B.5.8 Bourkina Fasso (References 7-15 through 7-19)

As part of a program sponsored by USAID to improve the quality of life and productivity of small farmers in rural areas of developing countries, a PV system powering a grain mill and water pump was designed and installed in the remote African village of Tangaye, Bourkina Fasso (formerly Upper Volta) by the NASA-Lewis Research Center (NASA-LeRC). The Government of Bourkina Fasso helped sponsor the project. The original system, which became operational in March 1979, included a 1.8-kW array, 540 Ah of battery storage, instrumentation, automatic controls, and a data collection system. In addition to powering the mill for grinding grain and the water pump for provision of domestic and stock water, the PV system powers two 20-W fluorescent lights in the mill building. Since installation, NASA-LeRC has monitored the system closely and made several design and equipment changes.

A 3-part operations manual was provided to enable the villagers, Government of Bourkina Fasso personnel, and AID/OUAGA personnel to understand, use, maintain, and repair the system. NASA-LeRC personnel conducted a training program for local personnel. The help of a Peace Corps worker who is fluent in both French and the local African dialect enabled the training to proceed without difficulties.

With assistance from the Government of Bourkina Fasso, the villagers organized a cooperative to manage the operation of the mill. About 60 village families invested 500 Fr CFA (about $2.35) in the cooperative, which is responsible for selecting and hiring milling personnel, determining milling prices and operating hours, and managing the fund collected for the milling. Proceeds from membership and milling are used to pay two full-time millers, to generate capital for spare parts and repairs, and to support other village development projects. The water from the pumping system is available to all villagers free of charge.

Village support and assistance was enthusiastic since the installation of the system. Under NASA-LeRC supervision, men from the village assembled and installed the PV panel support structures, prepared the trenches, and helped with numerous other tasks. They also constructed the mill building. The local operators' performance in terms of recording and forwarding data on the milling operation to NASA-LeRC has been superb, emphasizing the competence and reliability of interested local people. Operators are able to manage the operation of the system, conserving energy when necessary (during the cloudy season) and increasing use when permissable (during periods of high insolation). Operators also self-regulate the load (current demand of the mill motor) to prevent overload and optimize mill throughput. This lessens the risk of excessive battery discharge. The result of this experience with manual energy management is that automatic load limiting controls are no longer considered necessary. The effectiveness of local management of the milling operation has contributed to the success of the system.

Significant problems experienced with the system involved the grain mill, module thermal stress failures, and the controller. Although the burr mill orginally selected operated satisfactorily, its wear rate was greater than anticipated. The villagers' desire for very fine flour resulted in extremely high wear rates on other parts of the mill as well. When the replacement burr mill began to also rapidly wear, NASA-LeRC personnel procured and installed a hammermill. The mill was changed to another hammermill to meet demands for fineness of grind, equipment durability, and efficiency of the milling process.

Another significant problem experienced with the system in its first two years of operation was the premature failing of 29% of the PV modules by April 1981 due to thermal stress (while this was a problem with some of the early modules, subsequent generations of the technology have resolved this issue). When replacement modules were installed in May 1981, the array size was also doubled to 3.6 kWp to meet additional milling energy requirements. The PV modules were replaced by local personnel. The expansion of the Tangaye system is significant in that it represents the first time that a PV system has been scaled-up by a factor of two in a field operational setting.

Since the system has been enlarged, the number of hours the mill can run has nearly tripled. Even so, the system is still pushed to its full capacity. According to the station manager, people are coming from 30 to 40 km away to use the mill at Tangaye, and there is always grain waiting overnight to be milled.

The controller that NASA-Lewis designed and built was changed to a commercial solid state "black box" version to improve perception of simplicity. The original controller had intimidated the local technicians due to its complexity.

Ordering spare parts has been a problem for local users. This difficulty emphasizes the need for an appropriate infrastructure to handle the supply of spare parts and technical expertise. A paradox of this sort of development project is that, whereas the responsibility for the Tangaye demonstration has been given to an in-country institution, the mill is of American manufacture and so its parts must come from the U.S. Placing an order for them is difficult from Tangaye or from the in-country institution without the assistance of AID staff.

The milling operation continues to be the arena of local-level politics and the social focus for Tangaye. PV-powered lighting in a nearby building which was used for living accommodations during site visits, has permitted a number of activities to be organized: infant care clinic, adult literature classes. The station manager has also set up a bar in the building in which cold beer and soda are sold. In addition, an entrepreneur has built a new store facing the station.

The development of the system has been continuous over the last five years. The system has achieved an average availability of over 93% for 4 years of measured operation. Efficiency improvements may yet be made by using a voltage regulator for the mill to control speed and thus operate the mill at its optimum grinding rate.

APPENDIX C: ROUND TABLE MEETING PARTICIPANT LIST

Exhibit C-1: EVALUATION OF INTERNATIONAL PHOTOVOLTAIC PROJECTS
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APPENDIX D: SIZING AND FINANCIAL MODELS

D.1 Overview

The technical and financial models used to develop the sizing curves located in Chapters 3 through 7 and the cash flows and sensitivity curves found in Chapter 9 through 13 are presented in this appendix. Technical sizing models were developed for both the PV- and conventional-powered systems for each application except refrigeration. In the case of vaccine refrigeration, PV- and kerosene-powered systems were already sized for the World Health Organization (Reference 11-1), so it was not necessary to develop a technical sizing model. The costing of the base-case systems was outlined in Chapters 9 through 13. Using the initial capital and recurring costs generated, net present value life-cycle costs were determined for the base-case systems using a financial model that was the same for each application.

D.2 Water Pumping Technical Model

PV and diesel power system sizing requires calculation of the maximum and average daily energy and power demands of a load. PV array sizing considers the maximum ratio of daily energy demand to insolation anticipated over the year. Diesel power system sizing relates primarily to the maximum daily power demand.

The average energy demand over the year is used to calculate the annual fuel consumption. The average water demand (m^3/day) is used to determine the total volume of water pumped in a year. The daily water demand throughout the year (in cubic meters per day, where a day is 24 hours) and the total static and dynamic head (the height water must be pumped, in meters) are needed as inputs to calculate these values. Energy demand (ED) is a direct function of the hydraulic energy demand (HED) and the motor-pump efficiency (MPE). The hydraulic energy demand in kWh/day can be calculated as follows:

$$\text{HED} = \frac{(9.8)(\text{VH})}{(3600)}$$

where VH = the volume of water to be pumped multiplied by the head, in m^4/day.

The maximum HED can be calculated using the maximum VH, where the maximum VH is the maximum water demand (MWD) multiplied by the head. Average HED is calculated similarly, but using the average water demand (AWD).

Because there is an inefficiency in the coupling between the motor and pump in converting electrical energy into mechanical energy, the energy required from the power system is greater than the HED. Assuming a motor-pump efficiency (MPE), the energy demand (ED) in kWh/day can be calculated as follows:

$$\text{Energy Demand} = \frac{\text{HED}}{\text{MPE}}$$

Once again, maximum and average energy demands can be calculated using the appropriate HED. The energy demands are used to perform PV array and gen-set sizing and to determine the water outputs of the respective systems.

D.2.1 PV Power System Sizing

The equation for calculating the required PV array size (in peak kilowatts) is as follows:

$$\text{PV Array Size} = (\text{PPR}/\text{SE}) * (\text{ED}/\text{IN})_{\max}$$

where PPR = photovoltaic power rating in kilowatts/m^2
SE = System operating efficiency (conversion efficiency of sunlight into electrical energy including temperature effects, wiring and control system losses)
[PPR/SE = System sizing factor (1.1 used in this analysis)]
(ED/IN)max = Maximum ratio of energy demand to insolation anticipated are the year. (Calculated as 1.5 times the ratio of average energy demand to average insolation for this analysis).

The annual PV-powered system output in cubic meters of water per day is determined as follows:

$$\text{Water Output} = \text{AWD} * 365 * \text{PVAV}$$

where AWD = Average water demand over the year in m^3/day
PVAV = PV power/load system availability (where availability refers to the percentage of time the system operates within specifications).

C.2.2 Gen-Set Power System Sizing

The required gen-set size in kilowatts is calculated as follows:

$$\text{Gen-Set Size} = \text{MED}/(\text{MOH} * \text{MLF})$$

where MED = maximum energy demand during the year in kWh/day
MOH = maximum operating hours of the gen-set in a day
MLF = maximum load factor at which the gen-set operates.

Maximum operating hours (MOH), which is needed to calculate the gen-set size as indicated in the equation above, is determined as follows:

$$MOH = MWD/PFR$$

where MWD = maximum water demand during the year in m^3/day

PFR = pump flow rate in m^3/hour.

It is specified that the gen-set must operate for at least one hour. Thus, if the maximum water demand is low, such that the calculated MOH is less than 1 hour, the gen-set runs for 1 hour at a lower-than-maximum load factor.

To determine the amount of fuel consumed by the diesel, it is necessary to calculate the annual average daily operating hours (AOH) and then the average load factor (ALF):

$$AOH = AWD/PFR$$

where AWD = average water demand during the year in m^3/day

PFR = pump flow rate in m^3/hour.

$$ALF = AED/(PR * AOH)$$

where AED = average energy demand during the year in kWh/day

PR = gen-set power rating in kW

AOH = average operating hours as calculated above.

The PR specified here is not necessarily the same as the gen-set size calculated above. The gen-set size calculation refers to the ideal gen-set size for the load. The PR refers to the size being used, which is dictated by the commercial availability of gen-sets. For example, diesel gen-sets are not commonly available in sizes less than 3 kW. Therefore, even if the diesel gen-set size comes out to less than 3 kW, a 3-kW diesel must be used, resulting in a PR equal to 3 kW. Using the AOH, the average annual fuel consumption (FC) in liters/year is calculated as follows:

FC = AOH * FCR * 365

where AOH = annual average daily diesel operating hours as calculated above
FCR = fuel consumption rate, in liters/hour, for the particular engine at the average load factor.

The annual water output in cubic meters of water per day is determined as follows:

Water Output = AWD * 365 * GSAV

where AWD = Average water demand over the year in m^3/day
GSAV = Gen-set power/load system availability (where availability refers to the percentage of time the system operates within specifications).

D.3 Communications Technical Model

Sizing of a PV- or conventional-powered communications system begins by calculating the maximum daily energy demand (MED) over the year. The MED is determined by summing the products of the wattage and duration (in hours) of each individual load. For many systems, such as repeater stations, the load can be assumed to be constant and continuous.

C.3.1 PV Power System Sizing

The required PV array size (in peak watts) is determined as follows:

PV Array Size = (PPR/SE) * (ED/IN)max/EBE

where PPR = Photovoltaic power rating in kilowatts/m^2
SE = System operating efficiency (conversion efficiency of sunlight to electrical energy including temperature effects, wiring and control system losses)
[PPR/SE = System sizing factor (1.1 used in this analysis)]
ED/IN)max = Maximum ratio of energy demand to insolation anticipated over the year. (Calculated as constant energy demand divided by the lowest-month daily plane-of-the-array insolation: 4 kWh/m^2-day used in this analysis)
EBE = Effective battery efficiency
= PDL + (1 - PDL) * BE
where PDL = fraction of PV array output that goes directly to the load
BE = round-trip battery efficiency
[1-PDL = Battery Use Factor].

The required battery capacity (BC) is obtained with the following equation:

$$\text{BC} = (\text{MED} * \text{SD})/\text{MDD}$$

where MED = Maximum energy demand during the year in kWh/day
SD = Number of storage days required
MDD = Maximum depth-of-discharge over total storage period.

The electrical output of the PV power system in kWh/year is as follows:

$$\text{Electrical Output} = \text{AED} * 365 * \text{PVAV}$$

where AED = Average energy demand in kWh/day
PVAV = PV power system availability.

D.3.2 Gen-Set Power System Sizing

The required gen-set size in kilowatts is calculated as follows:

$$\text{Gen-Set Size} = \text{MED}/(\text{MOH} * \text{MLF} * \text{BCE})$$

where MED = Maximum daily energy demand during the year in kWh/day
MOH = Maximum diesel operating hours per day
MLF = Maximum load factor
BCE = Battery Charger Efficiency.

The required battery capacity (BC) in kWh is calculated using the equation:

$$\text{BC} = (\text{MED} * \text{SD})/\text{MDD}$$

where MED = Maximum energy demand during the year in kWh/day
SD = Number of storage days required
MDD = Maximum depth-of-discharge over total storage period.

Fuel consumption (FC) in liters/year calculated as follows:

$$FC = AOH * FCR * 365$$

where AOH = Average gen-set operating hours over the year in hours/day

FCR = Fuel consumption rate in liters/hour, which is a function of engine size and load factor.

The electrical output of the gen-set system in kWh/year is as follows:

$$\text{Electrical Output} = AED * 365 * GSAV$$

where AED = Average energy demand in kWh/day

GSAV = Gen-set power system availability.

D.4 Lighting and Home Power Technical Model

D.4.1 PV Power System Sizing

The required PV array size (in peak watts) is determined as follows:

$$\text{PV Array Size} = (\text{PPR}/\text{SE}) * (\text{ED}/\text{IN})\text{max}/\text{EBE}$$

where PPR = Photovoltaic power rating in kilowatts/m^2

SE = System operating efficiency (conversion efficiency of sunlight to electrical energy including temperature effects, wiring and control system losses)

[PPR/SE = System sizing factor (1.1 used in this analysis)]

(ED/IN)max = Maximum ratio of energy demand to insolation anticipated over the year. (Calculated as the average daily energy demand divided by the lowest-month daily plane-of-the-array insolation; 4 kwh/m^2-day is used in this analysis)

EBE = Effective battery efficiency

= PDL = (1-PDL) * BE

where PDL = fraction of the array output that directly powers the load

BE = round-trip battery efficiencv

[1-PDL = Battery Use Factor].

The required battery capacity (BC) can be determined as follows:

$$\text{BC} = (\text{MED} * \text{SD})/\text{MDD}$$

where MED = Maximum energy demand during the year in kWh/day

SD = Number of storage days

MDD = Maximum depth-of-discharge over the total storage period.

In calculating the array size and battery capacity, it is necessary to know the energy demand, which is calculated by summing the products of the wattage and the duration (in hours) of each individual load. Exhibit D-1 provides an example of this calculation.

EXHIBIT D-1. Typical Loads for a Home Power System

LOAD	POWER RATING (W)	DURATION (hrs/day)	ENERGY DEMAND (Wh/day)
Fluorescent Light	20	9	180
Fluorescent Light	10	12	120
Radio	12	9	108
Peak Demand	42		408

D.4.2 Conventional Power System Sizing

For the conventional lighting and home power systems, no sizing model is required. Lighting requirements are specified as a number of each type of lamp. Fuel consumption for each lamp is determined from field experience. Electrical loads are assumed to be powered by a battery. Batteries used in these conventional systems are not sized to meet load requirements, as they are used to provide as much power as they can produce.

D.5 Multi-Use Technical Model

Sizing of a PV- or conventional-powered multi-use system begins by calculating the daily energy demand over the year. The energy demand is determined by summing the products of the wattage and duration (in hours) of each individual load on a daily basis. The maximum energy demand (MED) and average energy demand (AED) can then be determined. Maximum power demand (MPD) in kW is specified as 1.8 times the average power demand (APD) where APD equals AED divided by 12 hours.

D.5.1 PV Power System Sizing

$$\text{PV Array Size} = [(\text{PPR}/\text{SE}) * (\text{ED}/\text{IN})\text{max}]/(\text{EBE} * \text{IE})$$

where PPR = photovoltaic power rating in kilowatts/m^2

SE = System operating efficiency (conversion efficiency of sunlight to electrical energy including temperature effects, wiring and control system losses)

[PPR/SE = system sizing factor (1.1 used in this analysis)]

(ED/IN)max = Maximum ratio of energy demand to insolation anticipated over the year (calculated as 1.5 times the ratio of average energy demand to average insolation for this analysis)

EBE = Effective battery efficiency

= PDL + (1-PDL)*BE

where PDL = fraction of the array output that directly powers the loads

BE = round-trip battery efficiency

[1-PDL = Battery use factor]

IE = Inverter efficiency.

Battery capacity (BC) in kWh is determined as follows:

$$\text{BC} = (\text{MED} * \text{SD})/\text{MDD}$$

where MED = Maximum energy demand during the year in kWh/day

SD = Number of storage days required

MDD = Maximum depth-of-discharge over the total storage period.

The electrical output of the PV power system in kWh/year is as follows:

$$\text{Electrical Output} = AED * 365 * PVAV$$

where AED = Average energy demand in kWh/day
PVAV = PV power system availability.

D.5.2 Diesel Power System Sizing

The required gen-set size in kilowatts is calculated as follows:

$$\text{Gen-Set Size} = MED/(MOH * MLF)$$

where MED = Maximum energy demand during the year in kWh/day
MOH = Maximum operating hours per day
MLF = Maximum load factor.

The gen-set must also be capable of meeting the maximum power demand (MPD). Thus, the larger value of the two (the calculated gen-set size or the MPD) must be used.

Fuel consumption (FC) in liters/year is calculated as follows:

$$FC = AOH * FCR * 365$$

where AOH = Average gen-set operating hours over the year in hours/day
FCR = Fuel consumption rate in liters/hour, which is a function of engine size and load factor.

The electrical output of the gen-set power system in kWh/year is calculated as follows:

$$\text{Electrical Output} = AED * 365 * GSAV$$

where AED = Average energy demand in kWh/day
GSAV = Gen-set power system availability.

D.6 Financial Model

The financial model used in this analysis was designed to calculate the net present value (NPV) life-cycle cost of the systems being compared. In order to calculate the NPV costs, 20-year cash flows were developed for each of the systems, per the chart of accounts shown in Exhibit D-2.

EXHIBIT D-2. Chart of Accounts for Financial Analyses

Account	PV-Powered Systems	Conventional-Powered Systems
Initial Capital Cost	X	X
Equipment Replacement (Recurring Capital Cost)	X	X
Engine Overhaul[1]	NA	X
Maintenance and Repair	X	X
Fuel	NA	X
Debt Service	X	X
Vaccine Waste[2]	X	X

1. Only used for generator applications (viz., pumping, communications, and multi-use)
2. Only used for medical refrigeration.

The present value of costs for each year is determined by multiplying the future value of those costs by the discount factor (DF).

$$DF = \frac{1}{(1 + r)^j}$$

where r = discount rate
j = year.

Thus, the present value of costs is calculated as follows:

$$\text{Present Cost} = \text{Future Cost}_{\text{year } j} * DF_{\text{year } j}$$

The present value of all costs over the period of financial analysis is determined by summing the products of the future costs and discount factors for each year.

$$\text{Total Present Costs} = \sum_{j=1}^{n} (\text{Future Cost}_{\text{year } j} * \text{DF}_{\text{year } j})$$

where n = period of financial analysis.

Since each application produces an end-use such as electricity, water, refrigerated volume or household expense, the total present costs can be expressed as a function of the total system output over the period of analysis. The net present value costs for each application can thus be expressed in terms of end-use product, as shown in Exhibit D-3.

EXHIBIT D-3. Application NPV Cost

Application	Net Present Value Life-Cycle Cost Unit
Water Pumping	\$/m^3 of water
Communications	\$/kWh of electricity
Vaccine Refrigeration	\$/liter of refrigerated volume
Lighting and Home Power	\$/year of household expense
Multi-Use	\$/kWh of electricity

APPENDIX E: REFERENCES AND BIBLIOGRAPHIC SOURCES

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