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Evaluation of International Photovoltaic Projects

Volume I: Executive Summary

D. Eskenazi, D. Kerner, L. Slominski
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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.

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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)

EXECUTIVE SUMMARY

1.0 OVERVIEW

1.1 Background

During the last decade, governments, donor agencies, and nonprofit organizations nave sponsored PV projects in developing countries to test, evaluate, and demonstrate the performance of PV as an energy technology for remote areas of the developing world. These PV-powered systems have provided electricity for water pumping, communications, refrigeration, lighting, and other basic necessities to people and areas that have never before had power.

Despite this increased use of PV-powered systems in developing countries, no attempt has been made to systematically analyze the cost and performance experiences of PV systems in this environment. Hence, there existed a need for a comprehensive and objective evaluation of the viability of PV systems for various applications in developing countries. It is toward this end that this evaluation is conducted.

This report is directed towards development agency officials, suppliers, and users of PV systems. Since quantitative performance data are not available, the report is based primarily on subjective information. It provides development agency officials with the information required to assess PV projects and with "lessons learned" recommendations for project implementation. The report also provides an assessment of potential applications as well as an evaluation of product performance and suggested areas for improvement. Users will learn from past experiences and will be provided with a methodology for making a rough comparison between PV and other technologies.

This work was performed by Meridian Corporation under contract to Sandia National Laboratories-Albuquerque (SNLA) and was supported by the U.S. Agency for International Development (USAID) and the U.S. Department of Energy (USDOE).

1.2 Purpose

The purpose of this report is twofold:

- To review the qualitative experience associated with the use of PV-powered systems in developing country applications.

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

To meet this dual purpose, the full report provides the following:

- A summary of field experience of PV-powered systems in developing countries. The experience associated with more than 2700 systems in 45 countries was reviewed across 5 applications (see Exhibit E-1).

- A discussion of current designs and costs for both PV- and conventional-powered systems. 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 an up-to-date comparison of PV to other systems, recent system improvements and current costs were obtained from system suppliers and recent tenders.

- Financial analyses for comparing PV-powered systems to conventional alternatives. The cost of PV systems was compared to the most likely alternative system using a net present value (NPV) life-cycle costing methodology that is consistent with World Bank standards. Exhibits E-2 and E-3 identify the technologies and base-case systems that were compared for each application. Sensitivity analyses were conducted to demonstrate the impact of key parameters on system life-cycle cost.

Exhibit E-1
SYSTEMS EXPERIENCE REVIEWED

APPLICATION	NUMBER OF SYSTEMS	NUMBER OF COUNTRIES
Water Pumping	> 194	22
Communications	>1100	14
Vaccine Refrigeration	> 105	43
Lighting and Home Power	>1260	14
Multi-Use	42	22
Total:	>2700*	>45*

* Total reflects overlap in subtotals.

Exhibit E-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 E-3
LOAD SPECIFICATIONS FOR BASE-CASE ANALYSES

APPLICATION	SPECIFICATION
Water Pumping	• Village drinking water system • 50 m3/day average water demand • 25-meter head
Communications	• Microwave repeater application • 7.2 kWh/day continuous load
Vaccine Refrigeration	• Vaccine Refrigeration • Two cases: - Small (24 liters) - Large (68-80 liters)
Lighting and Home Power	Three cases: • Small - one light • Medium - two lights • Large - two lights and a radio
Multi-Use	• 10 kWh/day average demand over a period of 12 to 15 hours

2.0 METHODOLOGY

The experience associated with more than 2,700 PV systems was incorporated into this evaluation. From these 2,700 systems, 29 specific projects were selected for detailed review. Performance information was collected from three principal sources: project reports and articles; questionnaires sent to end-users and/or participating in-country personnel; and interviews with 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; 20 percent of those receiving questionnaires responded.) The evaluation was conducted with the understanding that quantitative field performance data are limited, and what little data exist are of questionable accuracy.

Once all data were collected and analyzed, NPV life-cycle cost comparisons of photovoltaic-powered systems and the most likely conventional alternative system were performed for each of the five application areas (water pumping, communications, vaccine refrigeration, lighting and home power, and multi-use). NPV life-cycle cost analyses are presented as 20-year cash flows comparing the conventional alternative to PV using specific base-case assumptions. The common base-case financial and technical assumptions are presented in Exhibits E-4 and E-5. Sensitivity analyses were performed to estimate the comparative viability of PV and conventional alternatives based on particular country-specific parameters. All applications include a PV array cost (FOB) of $8.00 per peak watt. Parameters analyzed include equipment capital cost, discount rate, conventional fuel cost, diesel lifetime, insolation, kerosene refrigerator operating availability, and annual vaccine dose requirements.

Viability ranges for each of the five applications were developed by simultaneously varying the sensitivity parameters. The parameters were adjusted to reasonable extremes (lowest discount and interest rate, highest fuel cost, shortest conventional system lifetime, and highest insolation) in the best PV case scenario and to their opposite extremes in the worst PV case scenario. These viability ranges were included to provide a general picture of the circumstances under which PV systems are financially attractive.

Exhibit E-4
COMMON BASE-CASE FINANCIAL ASSUMPTIONS

PARAMETER	ASSUMPTION
Debt Service	• 100% financing of system initial capital 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% per year

Exhibit E-5
COMMON BASE-CASE TECHNICAL ASSUMPTIONS

SPECIFICATION	SYSTEM TYPE		
	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

3.0 EVALUATION FINDINGS

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. Although early systems experienced some technical problems, advancements in current equipment are resulting in more reliable systems. The major limitations to implementing PV systems for developing countries are institutional support and the lack of long-term financing. The evaluation findings are summarized in Exhibit E-6.

Exhibit E-7 graphically represents the financial viability of PV systems across all five of the selected applications (water pumping, communications, vaccine refrigeration, lighting and home power, and multi-use). "PV Least Cost" indicates the load range at which PV is the least-cost option even under unfavorable financial assumptions. Similarly, "Diesel Least Cost" indicates when diesel is the least-cost option even under assumptions favorable to PV. The "Break-Even Range" depicts the load range in which either PV or the alternative could be the least-cost option, depending on the parameter values selected.

EXHIBIT E-6. EVALUATION FINDINGS

TECHNICAL PERFORMANCE

Stand-alone PV-powered systems have been well accepted by users based on their reliability, independence from fuel, and minimal maintenance requirements.

- PV arrays are nearly 100 percent reliable.
- The performance of power conditioning and end-use equipment has varied, but the careful selection of field-proven components should ensure successful system operation. Diesel, gasoline, and kerosene systems face the same problem.

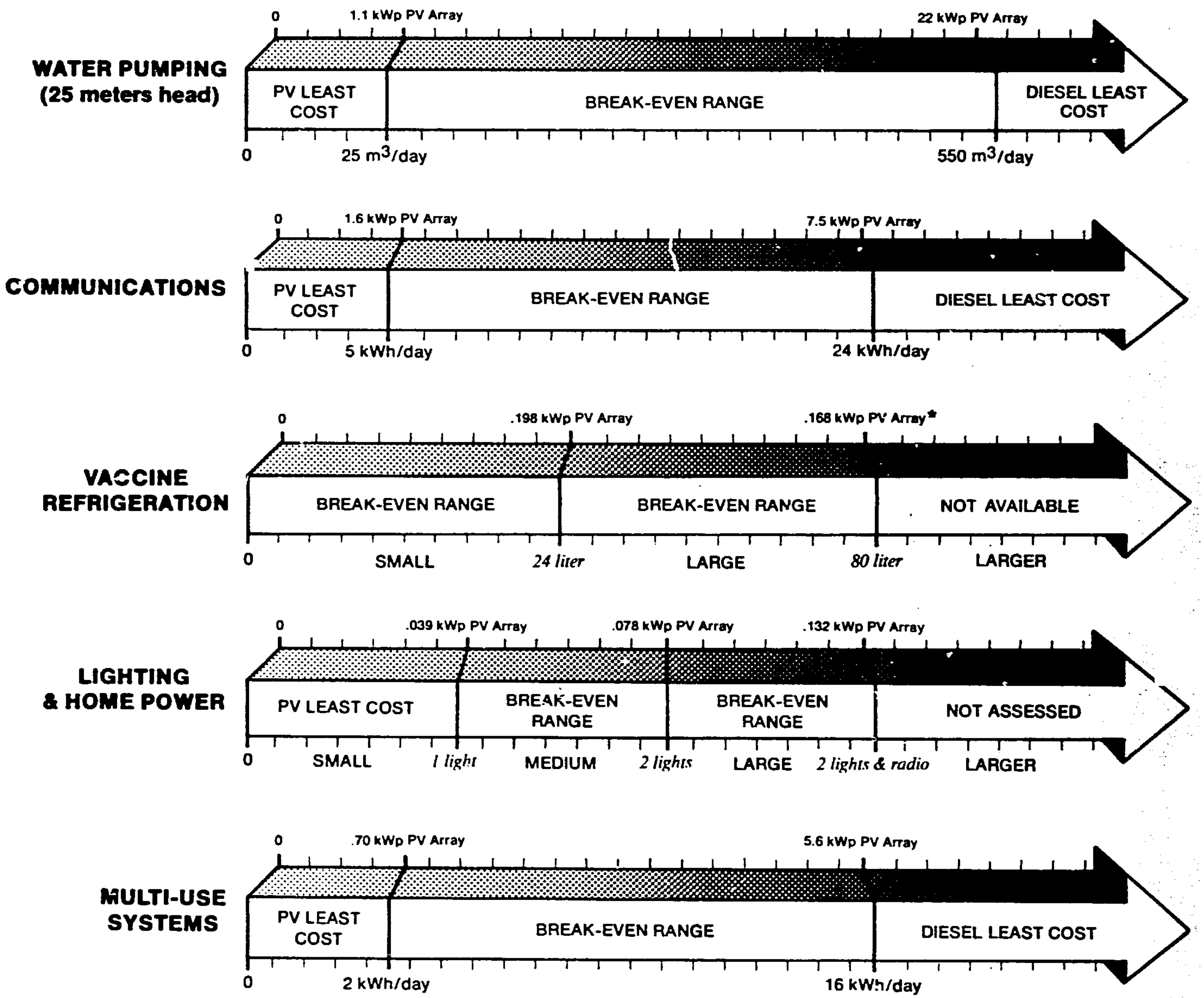
INSTITUTIONAL SUPPORT

Institutional support for PV-powered systems has been the overall weak link in implementing these systems in developing countries. Because PV is a relatively new technology, there is no established infrastructure to support training, maintenance, and repair. However, in cases where institutional support is lacking for both PV and conventional systems, PV-powered systems are more successful due to their lower operation, maintenance, and repair requirements.

FINANCIAL VIABILITY

- For loads smaller than 1 kilowatt, PV-powered systems are the least-cost option, on a life-cycle cost basis, for stand-alone water pumping, communications, vaccine refrigeration, lighting and home power, and multi-use systems when compared to diesel-, gasoline-, and kerosene-powered systems. This is largely because diesel engines are not available at sizes below 3 kilowatts for developing country applications.
- For loads between 1 and 20 kilowatts, a case-specific financial analysis is necessary to determine the least-cost option.
- For loads greater than 20 kilowatts, PV-powered systems are not generally the least-cost option. However, certain PV-powered system benefits often mentioned by users (such as reliability and independence from fuel) cannot be quantified. PV systems have been justified based on these subjective criteria.
- These financial viability findings are supported by the financial analyses performed as part of this evaluation and by case studies of programs that have stimulated the widespread implementation of PV-powered systems through financing.

Exhibit E-7 PV FINANCIAL VIABILITY LIMITS (Average Energy Demand and Relative PV Array Sizes)



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

3.1 Water Pumping

For this evaluation, the cost of PV-powered water pumping systems is compared to diesel-powered systems for rural water supply, assuming development agency financing. Exhibit E-8 provides the base-case parameters used in this comparison. PV-powered water pumping systems are conservatively determined to be financially competitive to diesel-powered systems up to demands of 25 m^3/day at a 25-meter head, even under unfavorable financial assumptions. 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. Systems with demands ranging from 25 to 550 m^3/day at a head of 25 meters are in the break-even range, with PV system viability dependent on case-specific parameters. Above this range, PV-powered water pumping systems are not financially viable at the present time.

Exhibit E-8
PUMPING: BASE CASE

SPECIFICATIONS:
- **Village Drinking Water System**
- **50 m3/day Average Daily Demand (supplies 2500 people)**
- **25 Meter Head**

	PV SYSTEM	DIESEL SYSTEM
TECHNICAL		
• SYSTEM CONFIGURATION	2.3 kWp PV array DC motor/pump	6.4 kW diesel gen-set AC motor/pump
FINANCIAL		
• INITIAL CAPITAL COST (FOB)	$19,784	$8,318
• RECURRING CAPITAL COSTS	$1,635 every 5 years	$6,754 every 6 years $1,564 every 5 years 15% every 3 years
• MAINTENANCE & REPAIR	1% per year	2% per year
• FUEL COSTS	NA	$552 per year
RESULTS		
• NPV OF 20-YEAR CASH FLOW	$31,166	$38,021
• ANNUAL WATER PUMPED	17,338 m3	17,338 m3

The graph in Exhibit E-9 depicts the ratio of PV- to diesel-powered pumping system NPV 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 more than twice as great as those shown in a 1983 UNDP/World Bank pumping study for rural water supply. (The UNDP/World Bank study has been accepted by applications experts as being very conservative.) 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 E-10 depicts the various cost elements of PV- and diesel-powered pumping systems. The sensitivity analyses indicate that diesel gen-set lifetime, fuel cost, discount and interest rate, insolation, and pumping head all have a strong impact on the cost analysis, with diesel gen-set lifetime and discount and interest rate being the most sensitive parameters. While PV-powered system costs have been dominated by debt service, diesel-powered system costs are primarily dependent on replacement and fuel costs.

The overall viability of PV-powered water pumping 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 resources and well yield characteristics has helped to avoid significantly oversized and undersized systems. Previous studies have shown that effective training corrects misconceived user expectations and reduces system downtime.

Exhibit E-9
SENSITIVITY OF PUMPING COSTS TO BEST AND WORST CONDITIONS

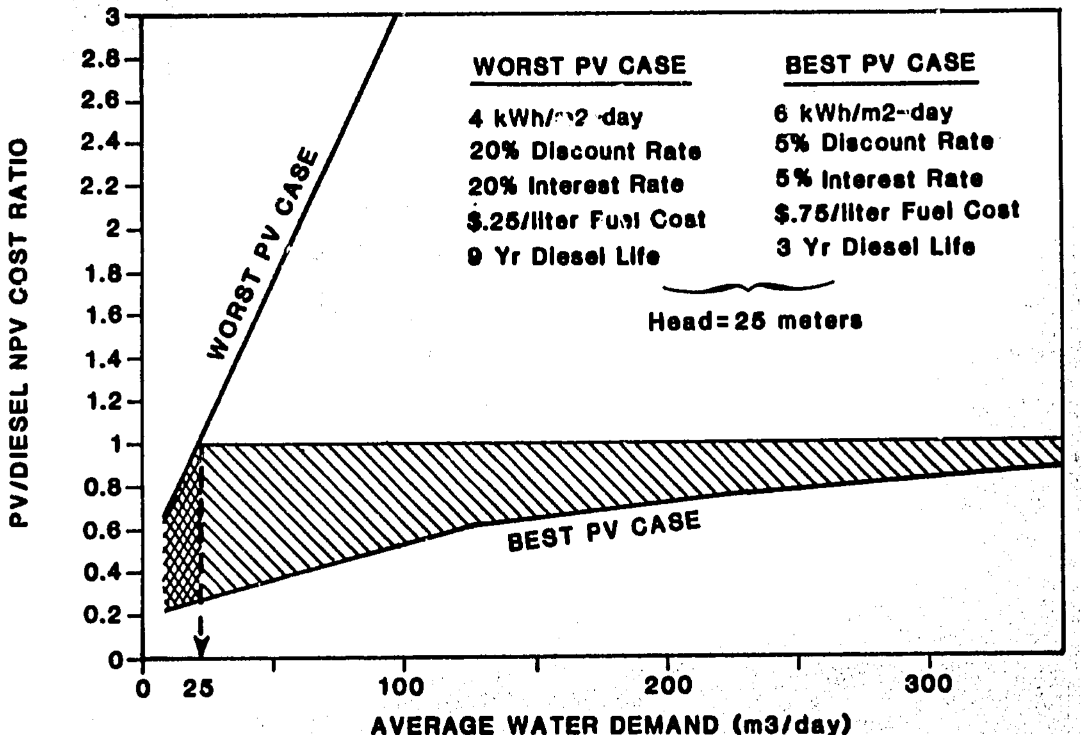
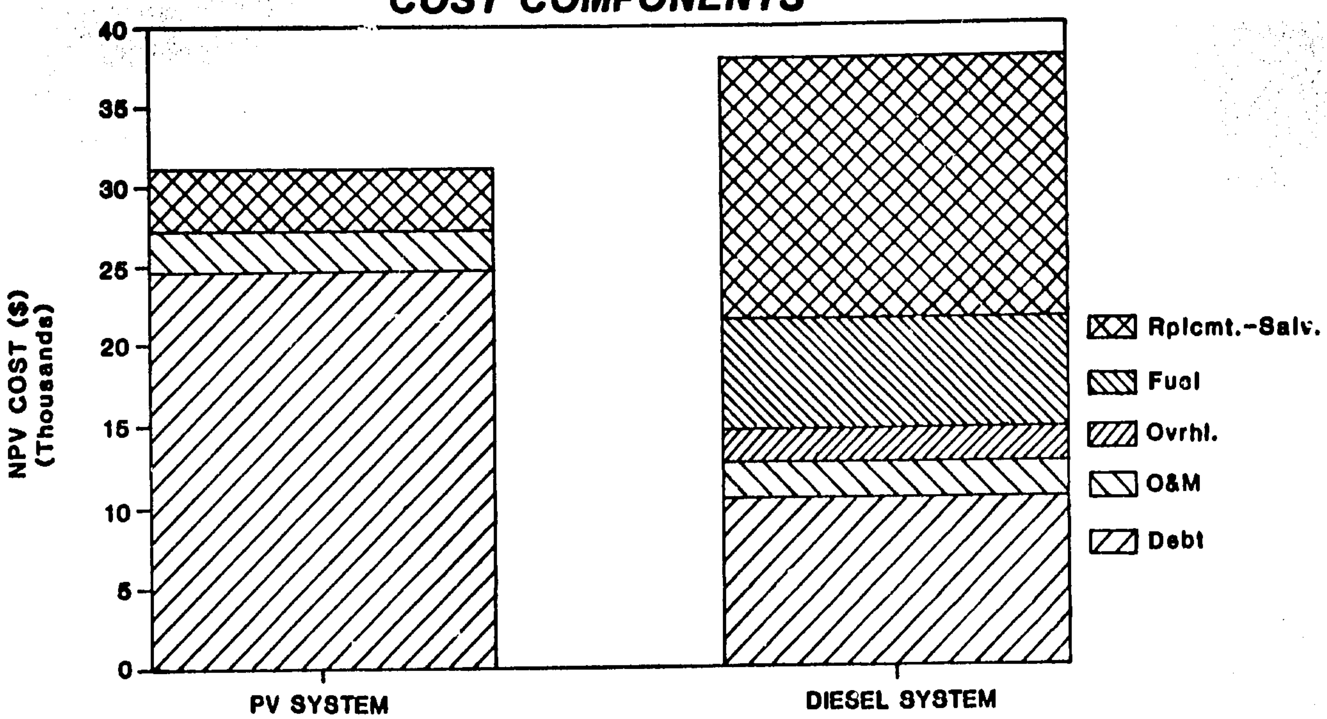


Exhibit E-10
BASE-CASE WATER PUMPING SYSTEM COST COMPONENTS



3.2 Communications

PV-powered communications systems have been proven reliable and financially viable, as evidenced by the recent substantial growth in the number of commercial PV systems. For this evaluation, the cost of PV- and diesel-powered microwave repeater systems were compared assuming development agency financing. Exhibit E-11 provides the base-case parameters used in this comparison. PV-powered systems are the least-cost option up to 5 kWh/day continuous load, even under unfavorable financial assumptions. Loads of 5 kWh/day to 24 kWh/day are in the break-even range, or dependent on case-specific parameters.

Exhibit E-11
COMMUNICATIONS: BASE CASE

SPECIFICATIONS:
- Microwave Repeater Station
- 7.2kWh/day Constant, Continuous Load

	PV SYSTEM	DIESEL SYSTEM
TECHNICAL		
• SYSTEM CONFIGURATION	2.3 kWp PV array 63 kWh battery storage charge controller	two 3 kW diesel gen-set 9 kWh battery storage battery charger
FINANCIAL		
• INITIAL CAPITAL COST (FOB)	$28,541	$10,891
• RECURRING CAPITAL COSTS	$9,450 every 5 years $909 every 10 years	$9,541 every 6 years $1,350 every 5 years 15% every 3 years
• MAINTENANCE & REPAIR	0.05% per year	2% per year
• FUEL COSTS	NA	$3,408 per year
RESULTS		
• NPV OF 20-YEAR CASH FLOW	$59,230	$86,529
• ANNUAL ENERGY GENERATION	2,625 kWh	2,625 kWh

The graph in Exhibit E-12 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 E-13 depicts the various cost elements of PV- and diesel-powered microwave repeater systems. The parameters with the largest impact on the viability of PV-powered systems are discount and interest rate, diesel fuel cost and diesel lifetime. The least sensitive parameter for this application is insolation, since PV-powered system costs are dominated by battery costs, not PV array costs. Life-cycle costs for PV-powered systems are split evenly between debt service (initial system cost) and replacement costs. Although a sensitivity analysis was not performed on battery life, the high percentage of replacement costs suggests that battery life is an important parameter. Diesel-powered system life-cycle costs are dominated by fuel cost, followed by replacement costs.

Overall reliability of PV-powered communications systems is dependent on selecting charge controllers and load equipment that have been field-proven under the appropriate environmental conditions. The importance of carefully selecting load equipment is not unique to PV, but applies to conventional systems as well.

Exhibit E-12
SENSITIVITY OF COMMUNICATIONS COSTS TO BEST AND WORST CONDITIONS

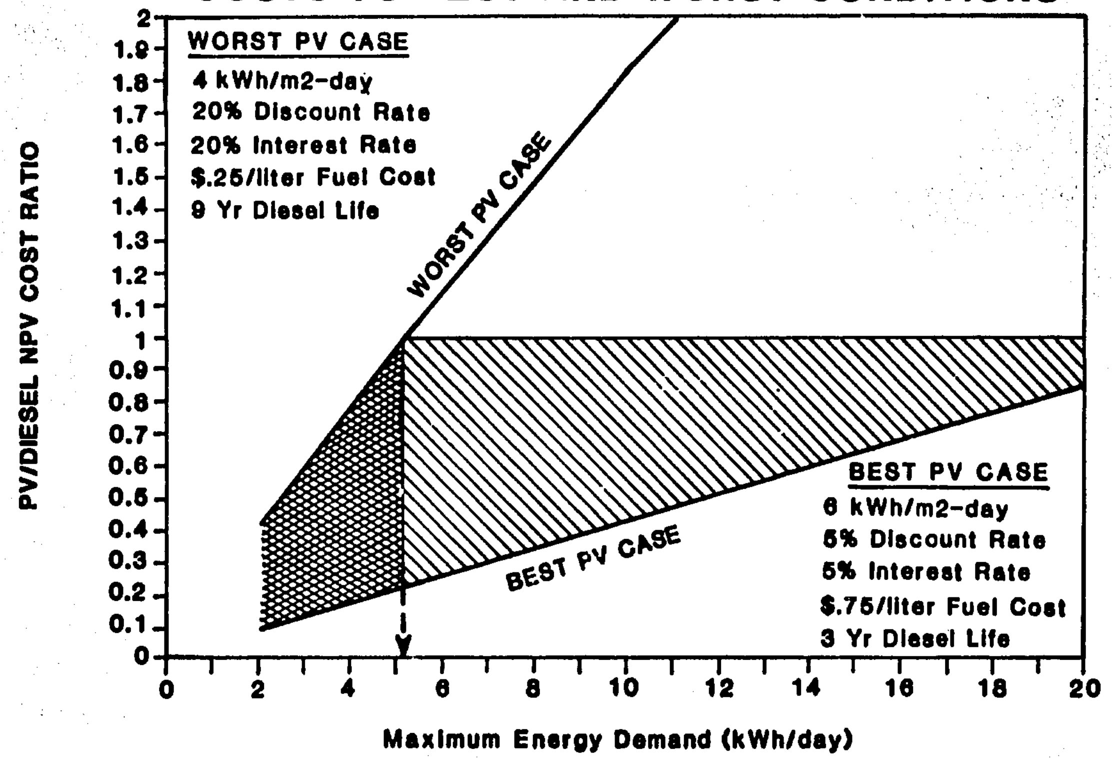
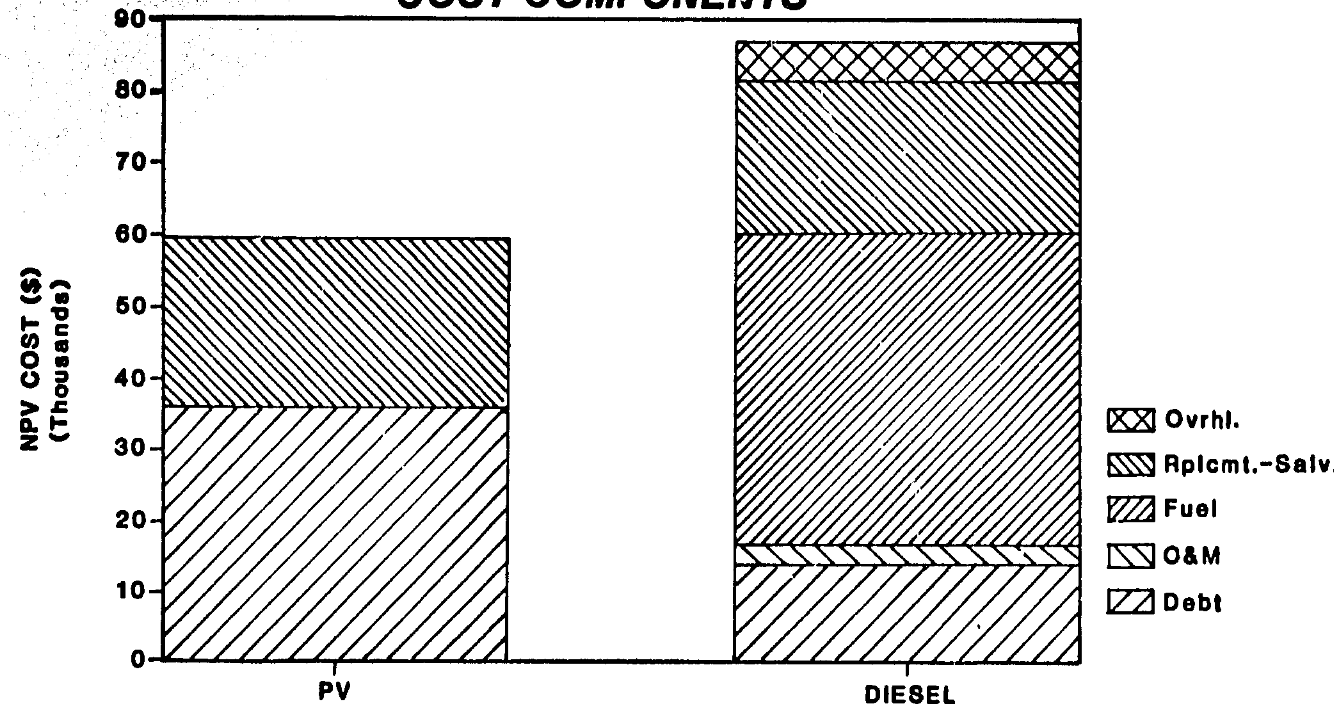


Exhibit E-13
BASE-CASE COMMUNICATIONS SYSTEMS COST COMPONENTS



3.3 Vaccine Refrigeration

For this evaluation, the cost of PV-powered vaccine refrigeration systems was compared to kerosene-fueled refrigerators, assuming development agency financing. Exhibit E-14 provides the base-case parameters used in this comparison. The financial analyses do not indicate a clear-cut preference between PV-powered and kerosene-powered vaccine refrigeration systems. PV-powered system viability, for both small and large systems, is always in the break-even range, dependent on case-specific parameters.

Exhibit E-14
REFRIGERATION : BASE CASE

SPECIFICATIONS:
- Vaccine Refrigeration (No Ice-Pack Freezing)
- Vaccine Cost $19/Liter
- 50 Liters Per Year Vaccine Application Level
- Insolation Level 5.8 - 7.0 kWh/m2-day

	PV SYSTEM	KEROSENE SYSTEM
TECHNICAL		
• SYSTEM CONFIGURATION	small [large] 24 [80] liters refrigerator 198 [168] Wp PV array* 5.5 [3.6] kWh battery storage	small [large] 24 [68] liters refrigerator fuel consumption = .2 [.7] liters/day
FINANCIAL		
• INITIAL CAPITAL COST (FOB)	$3,500 [$4,781]	$552 [$458]
• RECURRING CAPITAL COSTS	$821 [$540] every 5 years $1,096 [$2,897] every 10 years	$552 [$458] every 5 years
• MAINTENANCE & REPAIR	1% per year	10% per year
• FUEL COSTS	NA	$51 [$179] per year
• VACCINE WASTAGE	2.6 liters	26 liters
RESULTS		
• NPV OF 20-YEAR CASH FLOW	$8,252 [$10,757]	$9,406 [$10,569]
• VACCINE STORAGE CAPACITY	24 [80] liters	24 [68] liters

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

The bar chart in Exhibit E-15 depicts 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 and the life-cycle cost elements illustrated in Exhibit E-16 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 vaccine loss due to system unavailability must be replaced through pure cash outlays. The most dominant costs for PV-powered systems are debt service and replacement costs, indicating that refrigerator and battery life are important parameters. The overwhelming cost for kerosene refrigerators is related to vaccine wastage due to the typically low operating 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 NPV life-cycle costs. The relative viability of PV versus 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 of kerosene-fueled units. The availability of credible data on solar resource and load power consumption under field conditions is fundamental to successful 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, and the required maintenance procedures. Also, complete coordination with end-user organizations results in an understanding of the particular vaccination program and leads to more efficient and appropriate system designs.

Exhibit E-15
SENSITIVITY OF REFRIGERATION COSTS TO BEST AND WORST CONDITIONS

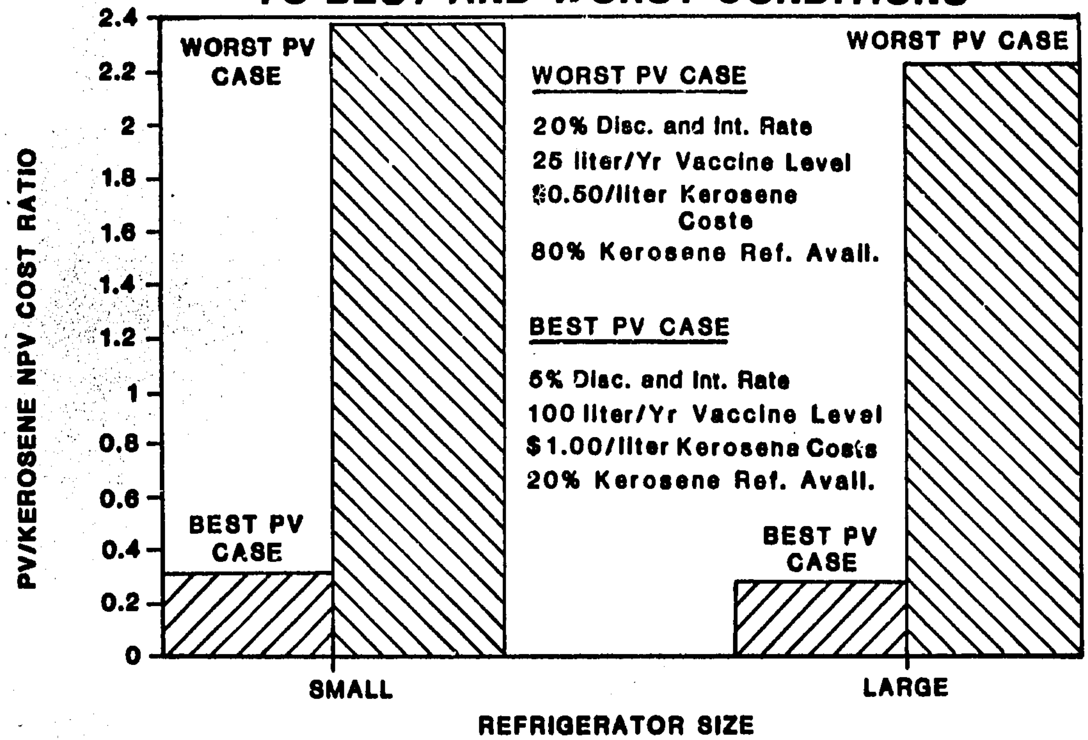
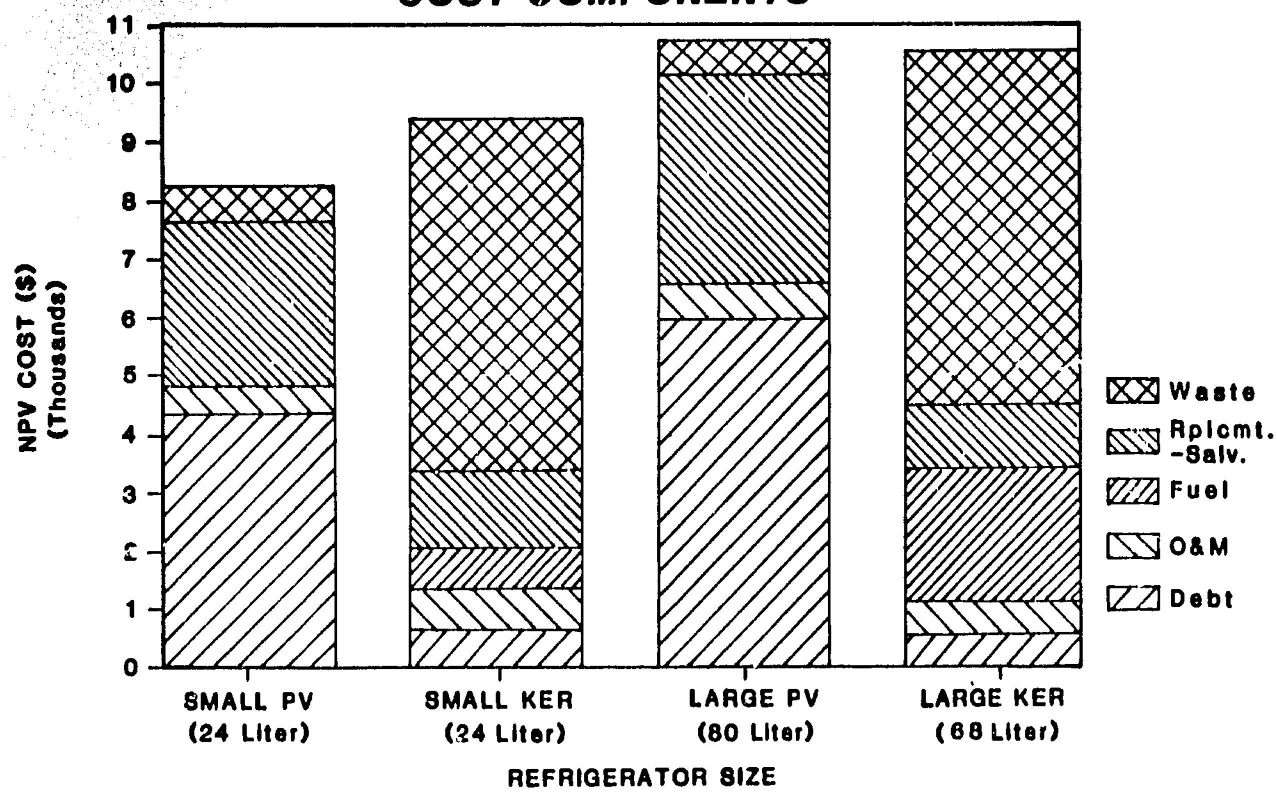


Exhibit E-16
BASE-CASE REFRIGERATION SYSTEM COST COMPONENTS



3.4 Lighting and Home Power

For this evaluation, the cost of PV and conventional (kerosene lamps and batteries) systems for home power are compared, assuming development agency financing. Exhibit E-17 provides the base-case parameters for this comparison. For the typical small systems examined in this evaluation, PV-powered systems are financially more attractive. For medium and large configurations, PV-powered systems may be financially more attractive, depending on specific technical and financial project parameters.

Exhibit E-17
LIGHTING AND HOME POWER: BASE CASE

SPECIFICATIONS:
- Medium Size System - Two Lights
- 20-Watt and 10-Watt Fluorescent Lamps, 6 and 12 hours/day
- Comparison to One Pressurized and One Hurricane Kerosene Fueled Lantern

	PV SYSTEM	KEROSENE SYSTEM
TECHNICAL		
• SYSTEM CONFIGURATION	78 Wp PV array 0.6 kWh battery storage DC fluorescent lights (20W, 10W)	pressurized kerosene lamp hurricane kerosene lamp
FINANCIAL		
• INITIAL CAPITAL COST (FOB)	$790	$45
• RECURRING CAPITAL COSTS	$170 every 5 years	$45 every 3 years
• MAINTENANCE & REPAIR	4% per year	$60 per year
• FUEL COSTS	NA	$109 per year
RESULTS		
• NPV OF 20-YEAR CASH FLOW	$1,796	$2,447

In some situations, PV-powered lighting and home power systems have shown viability under shorter loan periods. 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 E-18 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 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.

As illustrated in Exhibit E-19, the life-cycle cost of PV home power systems is dominated by debt service (i.e., initial capital cost), reflecting high installed system costs. Kerosene-powered system life-cycle costs are dominated by fuel expenses, followed by maintenance expenses.

The most important technical factor in the successful use of PV-powered lighting and home power systems is the selection of field-proven, reliable charge controllers. The availability and distribution of spare parts for the load and power conditioning equipment is a basic infrastructural need that must be met to ensure successful widespread system implementation.

Exhibit E-18
SENSITIVITY OF HOME POWER COSTS TO BEST AND WORST CONDITIONS

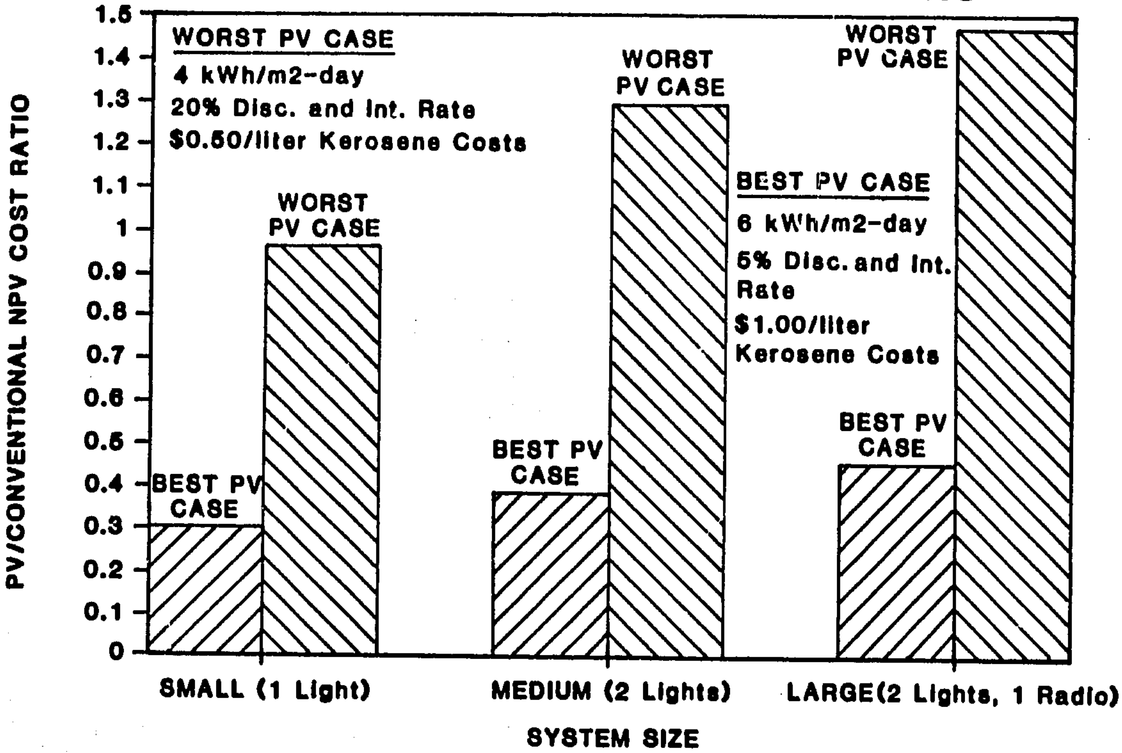
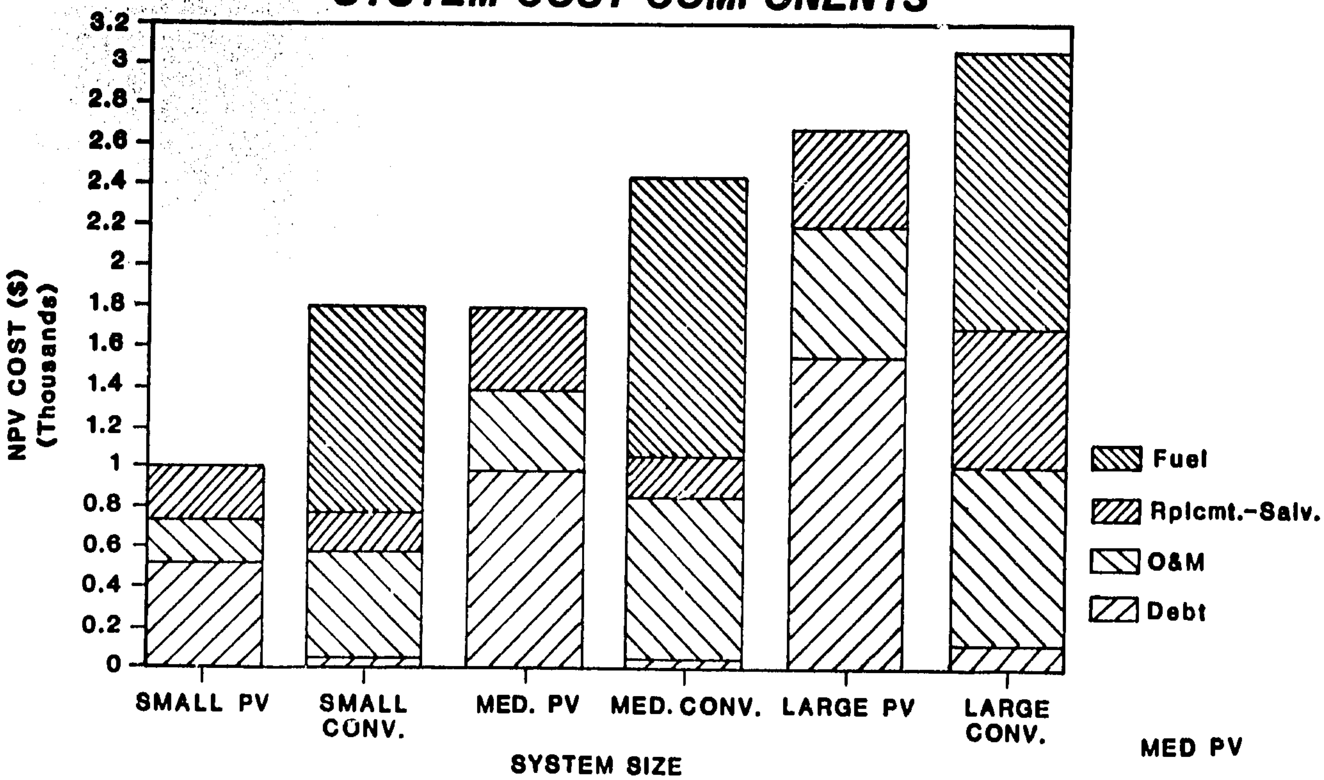


Exhibit E-19
BASE-CASE LIGHTING AND HOME POWER SYSTEM COST COMPONENTS



3.5 Multi-Use Systems

For this evaluation, PV- and diesel-powered multi-use systems are compared, assuming development agency financing. Exhibit E-20 provides the base-case parameters used in this comparison. Multi-use systems are the least-cost option for average energy demands 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 currently financially viable.

Exhibit E-20
MULTI-USE: BASE CASE

SPECIFICATIONS:
- Load Center - 10 kWh/day Annual Average Demand
- AC System
- Peak Demand = 1.5 X Average Demand

	PV SYSTEM	DIESEL SYSTEM
TECHNICAL		
• SYSTEM CONFIGURATION	3.94 kWp PV array 37.5 kWh battery storage 2 kW inverter	3kW diesel gen-set
FINANCIAL		
• INITIAL CAPITAL COST (FOB)	$40,722	$4,771
• RECURRING CAPITAL COSTS	$5,625 every 5 years $3,576 every 10 years	$4,771 every 6 years 15% every 3 years
• MAINTENANCE & REPAIR	0.1% per year	2% per year
• FUEL COSTS	NA	$1,704 per year
RESULTS		
• NPV OF 20-YEAR CASH FLOW	$67,715	$41,486
• ANNUAL ENERGY GENERATION	3,559 kWh	3,559 kWh

The graph in Exhibit E-21 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 E-22 depicts the various cost elements of PV- and diesel-powered multi-use systems. In general, PV-powered multi-use system life-cycle costs are dominated by debt service, while diesel system life-cycle costs are dominated by fuel cost. The sensitivity analyses in this chapter indicate that discount rate and fuel cost are the most sensitive parameters when comparing PV-powered multi-use systems to diesel-powered systems.

PV-powered multi-use systems have been successfully fielded; however, the reliability and complexity of power conditioning equipment must be carefully considered when designing these types of systems. As a result of the field performance record of small stand-alone inverters, and a poorly developed infrastructure for maintaining the equipment, applications experts have chosen to design DC systems whenever possible. However, DC is not considered to be a realistic option for mini-utilities. For load centers, the decision between AC and DC is based on the commercial availability of DC appliances.

A local infrastructure for the management of power is required for the successful application of multi-use systems. The energy 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 (e.g., load centers) is a major rural electrification policy issue.

Exhibit E-21
SENSITIVITY OF MULTI-USE SYSTEM COSTS TO BEST AND WORST CONDITIONS

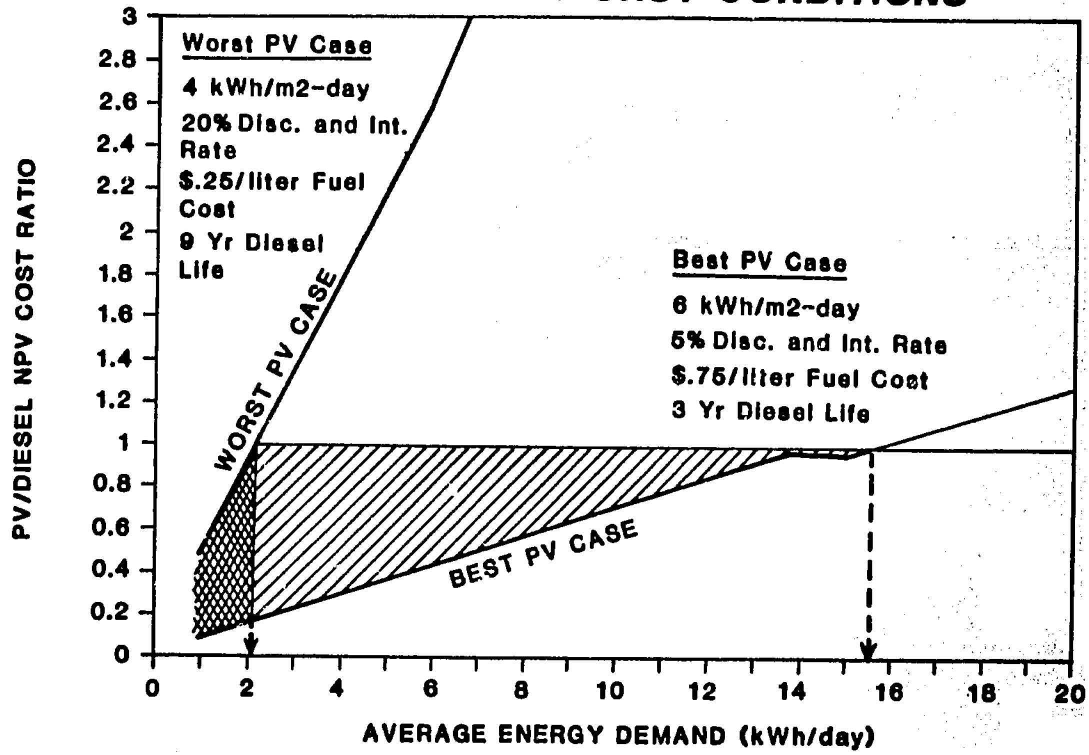
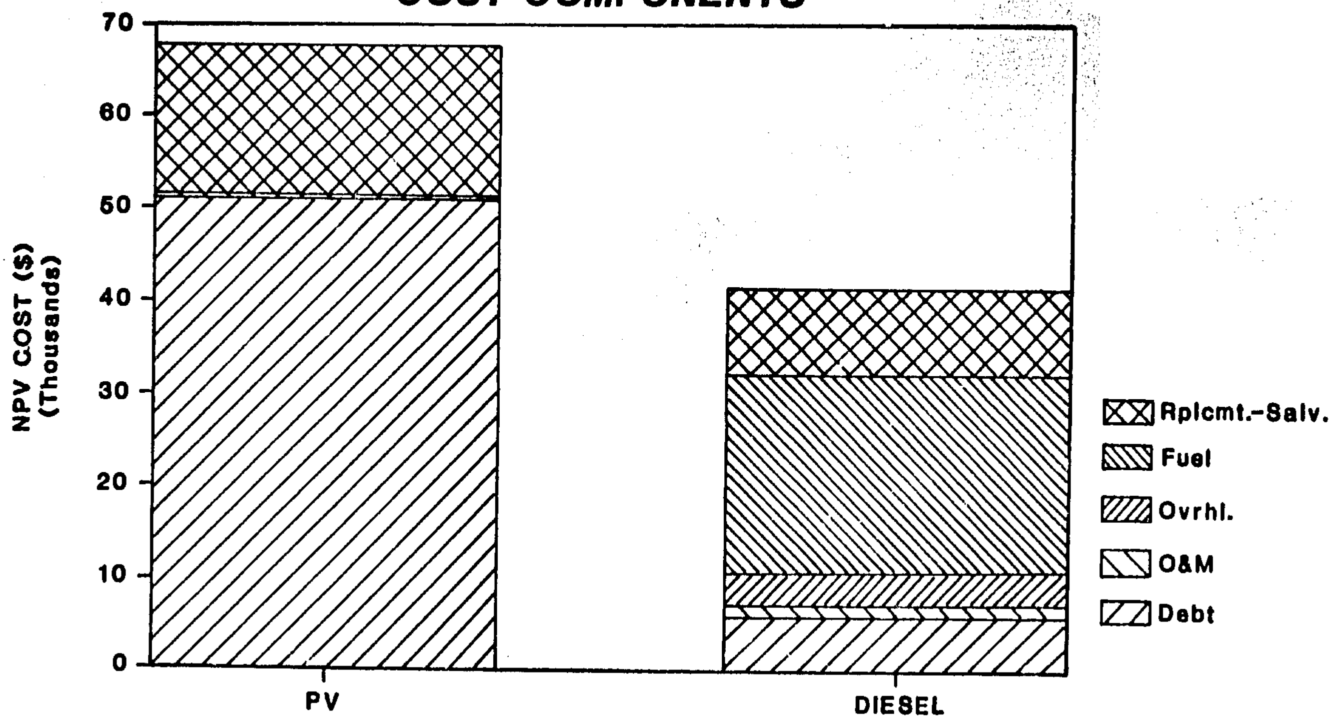


Exhibit E-22
BASE-CASE MULTI-USE SYSTEM COST COMPONENTS



4.0 RECOMMENDATIONS

Based on the review of past projects, current PV technology status, and financial analyses, certain recommendations are made for implementing PV-powered systems in developing countries. These recommendations, outlined in Exhibit E-23, are based on an assessment of those factors that were most prevalent in successful systems and notably absent in unsuccessful systems. Recommendations are oriented towards suppliers, users, and financial institutions.

4.1 Technical

Although most PV systems have performed reliably, there have been some "lessons learned" about system design and operation. Systems that failed usually included: (1) components that were not field tested under similar environmental conditions; (2) systems not properly designed to meet the specified load; or (3) improper system operation. The following recommendations address these three areas of concern:

- Select Field-Proven Components. Successful PV-powered systems have been installed using field-proven components. Failures of these field-proven components have rarely been related to PV as a power source, but rather reflect generic operating experience under developing country conditions.

- Obtain and Properly Use Design Data. Successful PV-powered systems depend on the availability and proper use of credible load, resource, and meteorological data. Specific operating design experience with a number of systems has been used to avoid excessive costs resulting from system overdesign and poor performance due to system underdesign.

- Provide User-Oriented Product Engineering. Minimal instrumentation and simple controls should be used, potential operating errors should be anticipated, and all instruments and controls should be clearly labeled in the appropriate local language. User-oriented product engineering concepts must ultimately be extended to total system design across all PV applications.

Exhibit E-23
RECOMMENDATIONS

TECHNICAL

- **Select Field-Proven Components.** Use PV components and systems that are capable of operating in similar environments.
- **Obtain and Properly Use Design Data.** Use site-specific weather data, where possible.
- **Provide User-Oriented Product Engineering.** Use minimal instrumentation and simple controls.

INSTITUTIONAL

- **Establish Field Service Capability.** Repair capability should be equal to or better than that available for conventional systems.
- **Provide Training At All Levels.** Planners, operators, users, and repair personnel must understand the PV system.
- **Coordinate Activities With End Users.** Local involvement will ensure that local needs are met.

FINANCIAL

- **Evaluate Viability Using Life-Cycle Costing.** PV systems that are cost-effective on a life-cycle basis usually have high initial costs.
- **Utilize Financing Mechanisms for Developing Countries.** Many financing programs are available which could be utilized to minimize the high initial costs of PV systems.

4.2 Institutional

The lack of strong institutional support for operation, maintenance, repair, and training has been the weak link in the successful implementation of PV systems in developing countries. PV systems actually require less institutional support than most conventional systems; however, since PV is a new technology, the minimal support required is often unavailable. This lack of institutional support 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. Efficiently managing technical support and procuring spare parts is important to the long-term reliable operation of PV-powered systems. Under equally poor infrastructures, PV-powered systems have been shown to be more reliable than conventional alternatives due to their lower requirements for operation, maintenance, and repair.

- Provide Training at All Levels. Suppliers of successful systems have effectively trained users and repair personnel in system operation and the consequences of system misuse. Field reports have indicated that improved user training in basic maintenance and troubleshooting, coupled with adequate documentation (in the local language) and spare parts, can reduce system downtime.

- Coordinate Activities with End-Users. Working with the appropriate host-country agencies to promote feelings among end-users of local ownership and responsibility is vital to successful PV system operation. Taking user expectations and relevant cultural aspects into account throughout the system's design, construction, and operation phases is also important.

4.3 Financial

The financial analyses demonstrate that PV-powered systems can be the least-cost option on a life-cycle basis, even though their initial capital costs are 50 to 100 percent higher than those of conventional systems. However, for PV systems to gain wide acceptance in developing countries, two actions must occur:

- Evaluate Viability Using Life-Cycle Costing. At high discount and interest 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. In light of PV's high initial capital cost, decision-makers responsible for selecting development projects should use life-cycle costing in their financial analysis to ensure that accurate system costs are assessed.

- Utilize Financing Mechanisms for Developing Countries. Most significant development projects in developing countries are funded by long-term loans with favorable terms. These loans are generally provided by development agencies established to promote progress in certain areas of the world. To aid in the continued financing of PV systems, decision-makers must use the many financing mechanisms currently available for developing countries.

Photovoltaic-powered systems have been shown to be a valuable tool to promote progress in the underdeveloped areas of the world. The financial analyses conducted for this evaluation show that small PV systems are generally the least-cost option, even though their initial capital costs are much higher than those of conventional systems. Although in the past there has been some uncertainty and disagreement over the status of PV systems, substantial information now exists that can successfully answer most of these past uncertainties. This information, which is summarized in this report, should help to stimulate the use of PV systems in situations where their application is the most cost-effective and represents the best choice, technically and institutionally.

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