A Comparative Assessment of Photovoltaics, Handpumps and Diesels for Rural Water Supply

By: A. Cabreal, A. Seiss, L. Slominski, M. Buresch,
& J. Kenna

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ABSTRACT

This report is an economic and technical assessment of photovoltaics (PV), handpumps and diesels for water supplies in rural areas of developing countries. The requirements and problems associated with rural water supply (RWS) systems are examined within the context of regional resource conditions, water needs, and cost and performance of the technology. This study found that PV RWS systems can supply water more economically than handpumps or diesels for villages of moderate size where the water table depths are 20 to 40 m. On the average, the cost-effective village size ranges from about 300 to 2000 persons per village for PV RWS systems. Contrary to popular belief, in many cases, on a per capita basis even the initial cost of PV systems is equal to and even less than that of comparable handpump RWS systems. Numerous sensitivity analyses were conducted and are provided to aid water supply planners decide whether PV systems would be appropriate for their specific needs. Preliminary specifications and market estimates were also compiled to aid PV manufacturers develop technology appropriate for the rural water supply market.

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LIST OF EXHIBITS (Continued)

A COMPARATIVE ASSESSMENT OF PHOTOVOLTAICS, HANDPUMPS, AND DIESELS FOR RURAL WATER SUPPLY

EXECUTIVE SUMMARY

Introduction

Safe, reliable, and accessible water supplies are critical to rural development and economic progress in developing countries. The United Nations, in cooperation with the World Bank and other international development institutions, established the International Drinking Water Supply and Sanitation Decade (1981-1990) in 1980, based on the goal of providing safe drinking water and sanitation to all persons in developing countries. Although the Decade has already made gains in expanding water supply access, nearly 1 billion people in the developing world still lack access to safe water supplies. The institutions involved in the Decade have reviewed the progress achieved to date and have concluded that the remaining problems are many and varied. They span the technical performance and reliability of rural water supply (RWS) systems, inadequate infrastructure and support systems, and ultimately system costs.

In an effort to promote the development of reliable, low-maintenance, and low-cost water supply technologies, the United Nations, World Bank, other multi- and bilateral-donor organizations and U.S. Government agencies have investigated handpumps, photovoltaics, and diesel water pumping technologies. Prior studies either evaluated each technology independently or conducted comparative assessments of two technologies.

This investigation examines the role for photovoltaics (PV) with respect to handpumps and diesels for supplying water to rural communities. The study explicitly considers all components of the water supply system; namely, water supply/demand relationships and other village characteristics, and the cost and performance of the well, the pumping system, the storage, and the water distribution network. The focus of this study is addressed at communities without access to grid electricity or safe surface water sources.

The study provides information useful to rural water supply planners who select water supply technologies to suit the needs of rural communities. The study results will also be useful to equipment manufacturers who develop products to meet the requirements of rural communities around the world.

Study Objectives

The purpose of this study is to determine under what circumstances PV pumping systems can compete technically and economically with handpumps and diesel pumps for supplying water to rural communities. The specific objectives are as follows:

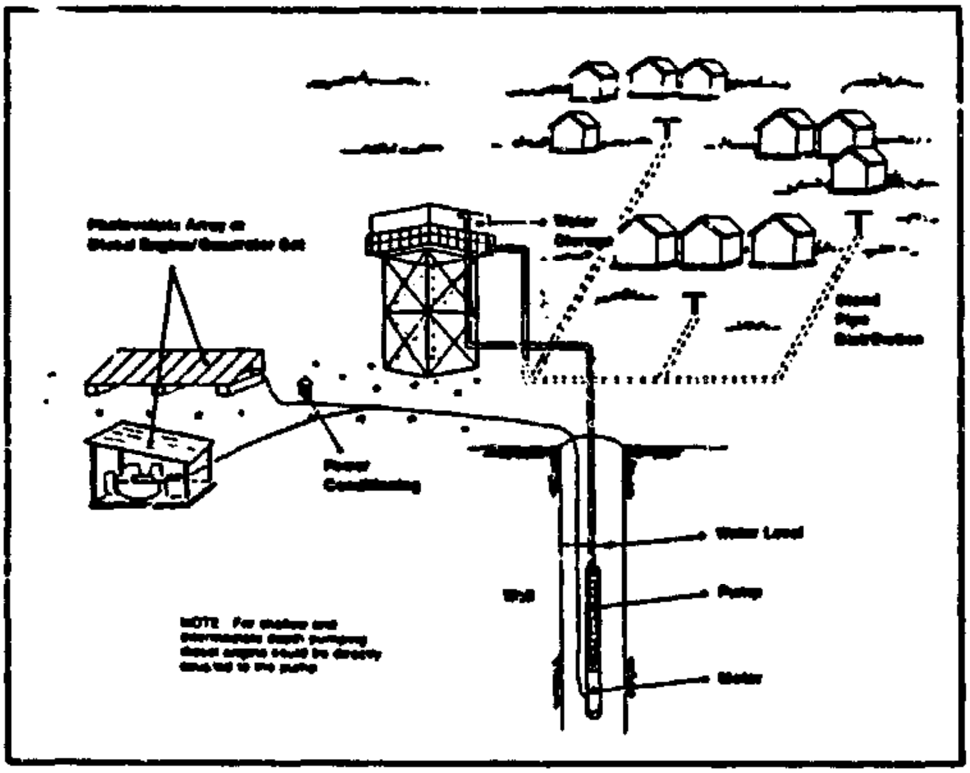
1. Determine economically competitive ranges for PV relative to handpumps and diesels for supplying water to rural communities as a function of water source depth, village size, level and quality of service, solar resource, and cost and performance characteristics.

2. Determine how the initial cost of a PV water supply system compares with that of a rural water supply (RWS) system using low-cost technology such as handpumps.

Exhibit I

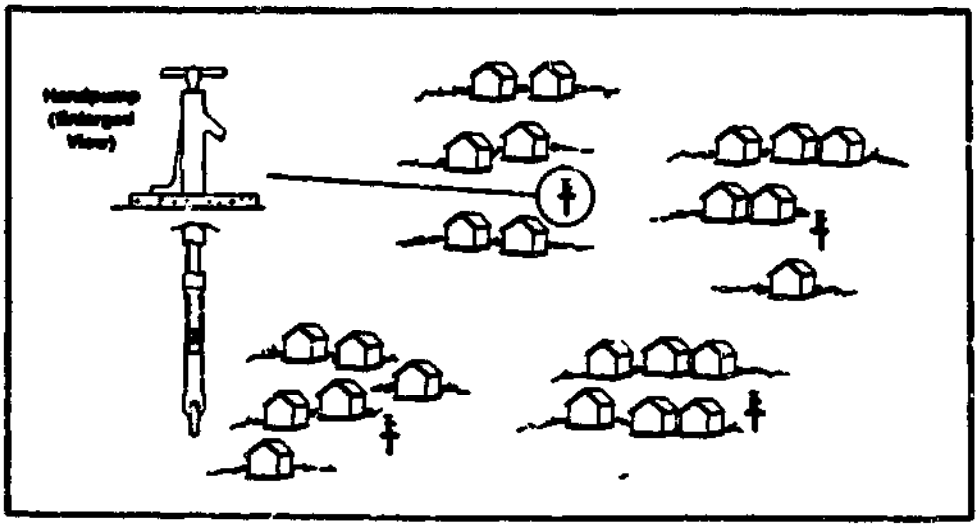
PUMPING SYSTEM CONFIGURATIONS

PV- or Diesel-Based Rural Water Supply System with Storage and Standpipe Distribution



HANDPUMP-BASED RURAL WATER SUPPLY SYSTEM

One Handpump Per Group Of Households



3. Estimate the potential market for PV-powered RWS systems.

4. Identify the functional specifications of PV-powered RWS systems so that PV systems manufacturers can design products to better meet user needs.

Technology Configurations Evaluated

The three water supply technologies considered in the comparative analysis, handpumps, PV pumps, and diesel pumps, are configured as follows:

1. Handpumps. Each handpump installed on a well serves a number of persons. The number of persons served depends on the quantity of water demanded per person, the number of hours a pump is used daily, and the amount of time a person is willing to spend gathering water. Handpumps are typically used when water demand is up to about 40 liters/capita/day. If the village has more people than can be supported by one handpump, then two or more handpumps are used. The principal handpump system components are the handpump and the well.

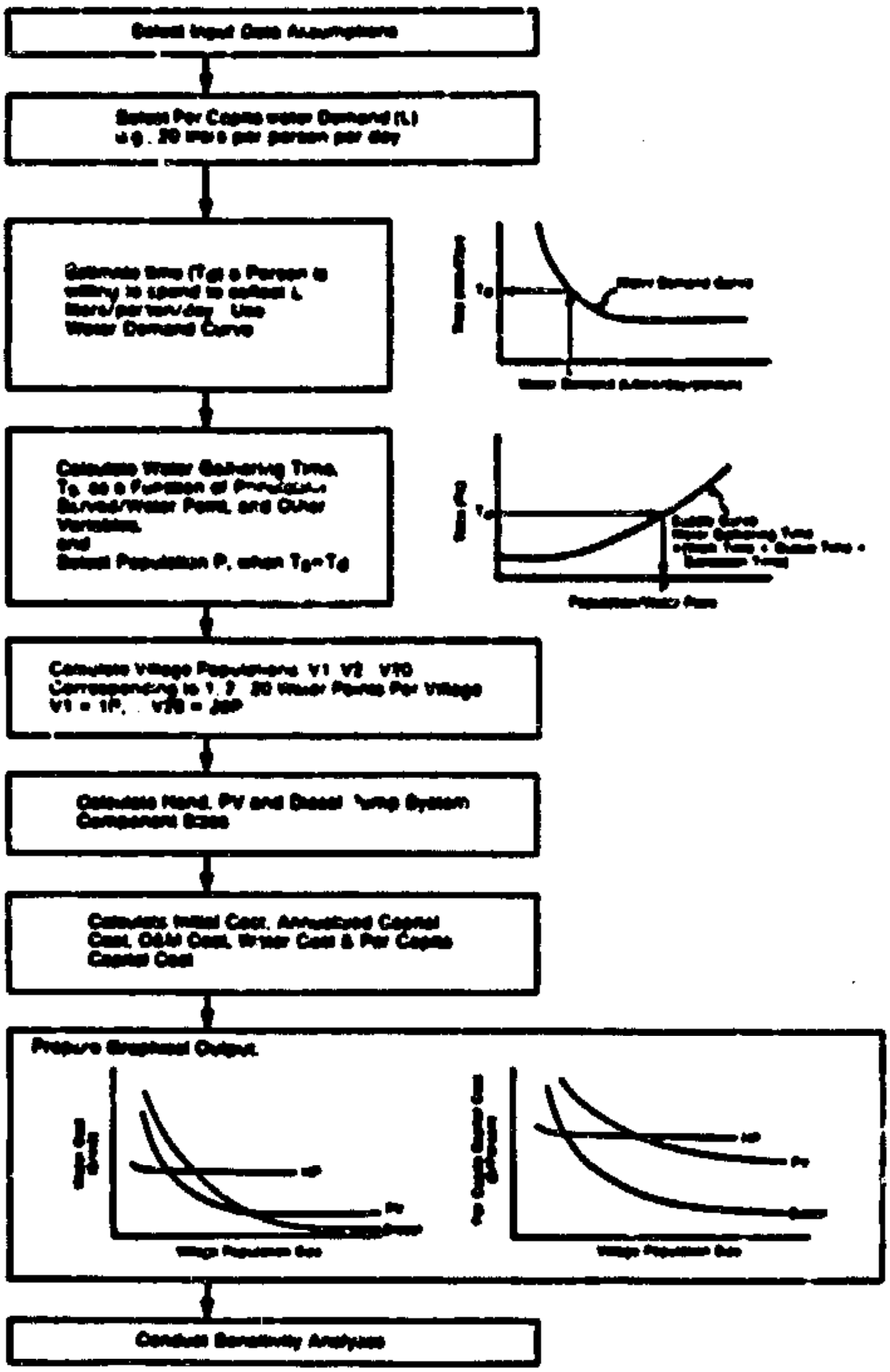
2. PV Pumping Systems. Each PV pumping system provides water to one or more standpipes (public faucets) through a piped distribution network. The number of persons served at a faucet is determined as in the handpump case. If the village has more people than can be supported by one standpipe, then two or more standpipes are used. One well with a PV pump usually supplies water to all standpipes. If well yield is limited, two or more wells are used and water is pumped at a lower rate. Alternately, batteries are employed to allow the pump to operate at a lower pumping rate over a longer time period. The principal PV pumping system components are the PV array, which directly converts sunlight into electricity; the motor and water pump; optional controls, battery, and power conditioning equipment; the well; water storage tank; distribution piping; and standpipes. Representative water pumping technologies used in the analysis are as follows: shallow well (less than 10 m deep water table) - surface-mounted centrifugal pump; intermediate-to-deep water table (20 m to 40 m) - jack pumps with surface-mounted motors for low flows (less than 30 m^3/day); and submerged motor/multi-stage centrifugal pump when flow rates are higher.

3. Diesel Pumping Systems. The diesel pumping system is identical to the PV pumping system except that the diesel pump replaces the PV pump. The engine is directly coupled to the pump for shallow and intermediate water table depth applications. In the case of submerged motor/multi-stage centrifugal pumps, a diesel engine/generator set (gen-set) is used to generate electricity to operate the pump. The principal diesel pumping system components are the diesel engine or gen-set, fuel tank, pump, motor (if electrical), well, water storage tank, distribution piping, and standpipes.

The three systems are illustrated in Exhibit I. The principal purpose of this study is to determine the competitiveness of PV relative to handpumps and diesel pumps. Therefore, the analysis did not consider yard taps (house connections) as handpumps are not commonly used to provide water to individual houses in developing countries. The analysis also assumes that in the case of diesel engines, fuel is readily available throughout the year.

Exhibit II

METHODOLOGY OVERVIEW



Technology Comparison Basis and Approach

A key feature of the analysis is that technologies are compared when they are providing the same level and quality of service. Service level and quality is defined as follows:

1. The amount of water supplied per person per day is the same across all three water supply systems being evaluated. Therefore health and other benefits accruing to an individual due to the availability of water are the same across all technologies. For example, all three technologies supply 20 liters per capita per day (lpcd) to the village population.

2. The cost in terms of time spent by villagers gathering the water is made equal across all three water supply systems. In the analysis, time spent collecting water is made the same across all three technologies by adjusting the number of persons served per water delivery point per technology. Therefore, more people can be served at water points where the water delivery rate is higher.

3. The technologies provide water at the same level of reliability so that water availability throughout the year is the same across all three technologies. The same availability levels are attained by using operation and maintenance practices consistent with reliable equipment performance and using adequate water storage in the case of the PV and diesel systems.

Since the level and quality of service are the same across all three technologies, the benefits derived from the water will be equal across all three technologies. Therefore, only the relative costs need to be compared using cost-effectiveness analysis -- this is an important advantage of the procedure used in the evaluation. Since the amount of water consumed per person and the water gathering-time are made equal across all three technologies, the cost of water gathering-time is not considered in the analysis.

The principal analysis steps are outlined in Exhibit II. The analysis procedure has been programmed using Lotus 1-2-3 Release 2 software. The analyses are based on current costs of equipment. Numerous scenarios were evaluated during the analysis by varying insolation, water demand, and well characteristics (Exhibit III). The scenarios allowed assessing the impact on PV competitiveness of the diversity of conditions found in locations around the world. Sensitivity analyses were also conducted to assess the impact on PV competitiveness of data uncertainties. A total of 56 analyses were conducted for water demands of 20 and 40 lpcd.

Analysis Results

For 20 lpcd water consumption, PV is the preferred technology when village population is about 1,500 persons. Exhibit IV shows the life-cycle cost competitiveness ranges for the three technologies as a function of village population size, insolation, and well characteristics when water demand is 20 lpcd. When a well costs $2,500 and the water table is 20 m deep, PV is the competitive technology at an insolation level of 5 kWh/m^2/day for a village of 1,000-2,000 persons. When insolation is 4 kWh/m^2/day, the competitive range for PV narrows to 1,200-1,500 persons/village. At insolation levels of 6 kWh/m^2/day, the competitive village size range for PV increases to 800-2,200 persons.

As well costs and water table depths increase, PV becomes competitive at smaller village sizes. Also, the competitiveness of PV systems encompasses a larger range of village sizes as insolation increases. Therefore, in some West African countries, where wells cost

Exhibit III

SCENARIOS EVALUATED AND SENSITIVITY ANALYSES CONDUCTED

A. For 20 and 40 lpcd water demand, plane-of-array worst-month insolation levels of 4, 5, and 6 kWh/m^2/day and the following well characteristics:

- $500 cost and a 5 m depth (e.g., Bangladesh)
- $1,500 cost and a 20 m depth (e.g., parts of India and East Africa)
- $2,500 cost and a 20 m depth (average conditions)
- $5,000 cost and a 20 m depth (e.g., West Africa)
- $5,000 cost and a 40 m depth (e.g., West Africa)

This consists of a total of 30 scenarios.

B. Sensitivity analyses were conducted for water demands of 20 and 40 lpcd by varying the following parameters from the Base Case:*

1. Diesel fuel cost equals $1/liter. This reflects situations where fuel delivery is difficult and costly.

2. One day of water storage for the PV system instead of three days. Three days of water storage ensures that 99% of the time the designated water demand (e.g., 20 or 40 lpcd) is available. When one day of storage is used, availability is about 97% or demand may not be fully satisfied for about 11 days of the year.

3. PV array cost of 50% to 200% of the base-case assumptions was used to assess the impact of PV array cost variations.

4. Reduction in handpump life from 10 to 5 years was used to evaluate the impact on PV competitiveness of shorter handpump life.

5. A reduction in analysis lifetime from 20 to 10 years.

6. Use of at least two wells per village for PV and diesel systems to ensure very high water supply reliability.

7. A reduction in well yield to 2 m^3/hour to account for situations where pumping rate must be limited so that excessively high drawdown does not occur during continuous pumping.

8. A reduction in water delivery rates of handpumps and standpipes to reflect water collection inefficiencies.

9. Halving the number of persons served per standpipe to assess the impact of making the number of persons served at a standpipe approximately equal to the number served at a handpump.

[*] The Base-Case assumptions: Insolation - 5 kWh/m^2/day; well cost - $2,500; water table depth - 20 m; diesel fuel cost - $0.50/liter; 3 days water storage for PV system; 6 hours per day use of water point; 20-year analysis time frame; one well per village for PV and diesel systems; and adequate well yield.

Exhibit IV

Life-Cycle Cost Competitiveness

VARIATION WITH VILLAGE POPULATION SIZE AND WELL CHARACTERISTICS (20LPCD)

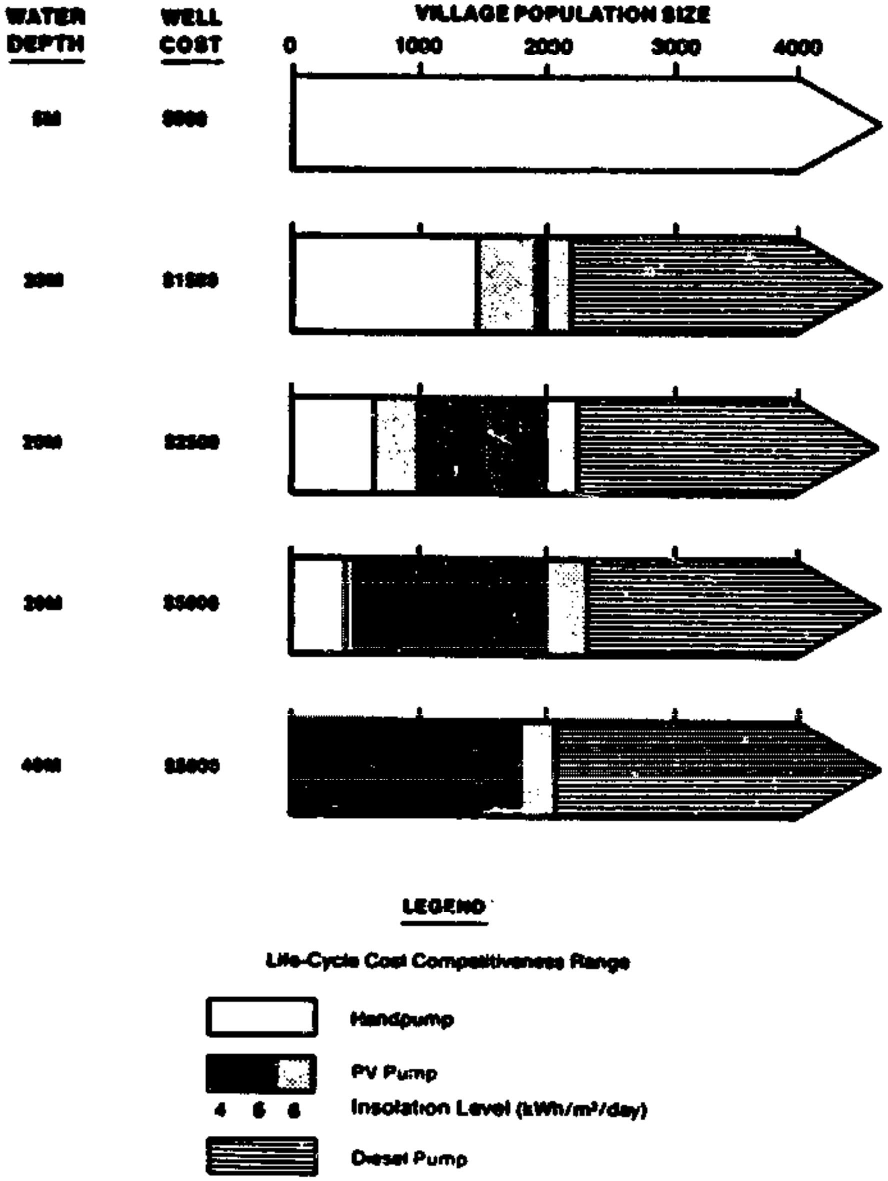
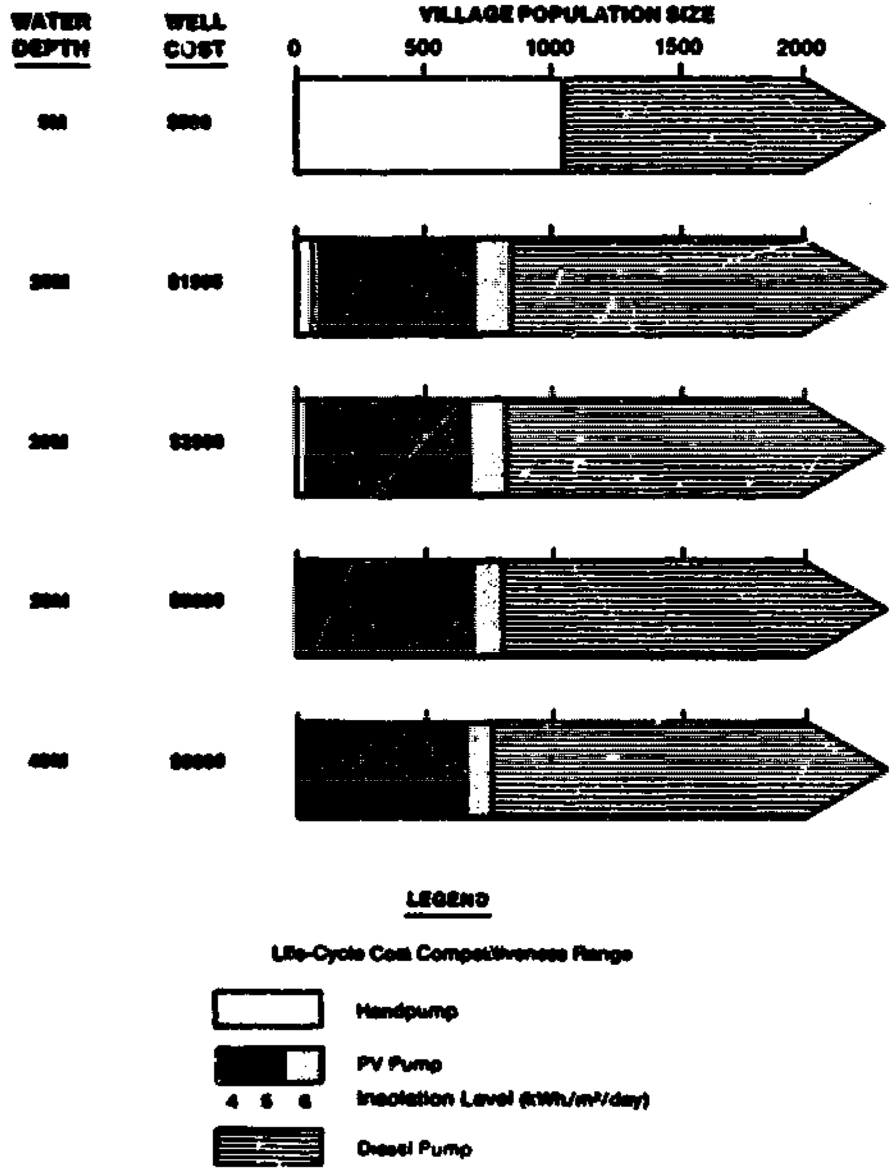


Exhibit V

Life-Cycle Cost Competitiveness

VARIATION WITH VILLAGE POPULATION SIZE AND WELL CHARACTERISTICS (40 LPCD)



$5,000 to $10,000 each, and insolation is 6-7 kWh/m^2/day, PV would be the preferred technology for villages with populations as small as 200 persons.

At a 40-lpcd consumption level, PV is the least cost technology for even smaller villages. Village sizes where PV is competitive range from 0 to 800, depending on insolation and well characteristics (see Exhibit V). The average village size where PV is competitive is about 400 persons. As in the previous case, PV competitiveness occurs at increasingly smaller village sizes as well cost and water table depth increase.

Exhibit VI shows competitive water costs, per capita initial capital costs, and corresponding village sizes under average (Base Case) conditions. When water consumption is 20 lpcd, average cost of water from a PV pumping system is about $0.44/m^3, or about $3.20/person per year. At a 40 lpcd consumption rate, average water cost is about $0.93/m^3, or about $13.60/person per year.

Exhibit VI
Least Water Cost Technologies for Various Village Sizes Under Average Well Conditions*

Insolation: 5 kWh/m^2/day

Least Water Cost Technology	Village Size Range (no./village)	Water Cost ($/cubic meter)	Per Capita Capital Cost ($/person)
<-------------------- 20 liters/person/day water consumption -------------------->			
Handpump	0 - 1,000	0.50	20
Photovoltaics	1,000 - 2,000	0.38 - 0.50	19 - 24
Diesel	> 2,000	0.20 - 0.38	6 - 10
<-------------------- 40 liters/person/day water consumption -------------------->			
Handpump	0 - 80	1.35	105
Photovoltaics	80 - 800	0.50 - 1.35	50 - 125
Diesel	> 800	0.35 - 0.50	20 - 25

* Average well conditions: 20m water table depth and $2,500 well cost.

Exhibits VII and VIII show the sensitivity of PV competitiveness to a number of variables when water demand is 20 and 40 lpcd, respectively. Analyses are conducted under average conditions (i.e., insolation at 5 kWh/m^2/day and 20-m water depth and a well cost of $2,500). The principal observation is that the village size at which water from PV becomes cheaper than that of handpumps does not vary significantly, even with major changes to important variables. The two exceptions for the cases occur when well yield is limiting and when a minimum of two wells is used. Another important inference is that for many cases, even on a per capita initial capital cost basis, PV is competitive with handpumps.

Exhibit VII

SENSITIVITY ANALYSIS,

Life-Cycle and Per Capita Initial Cost Competitiveness

SCENARIO

Water Consumption Level - 20 LPCD
Insolation Level - 5kWh/M^2/Day
Well Cost - $2500
Water Depth - 20 M

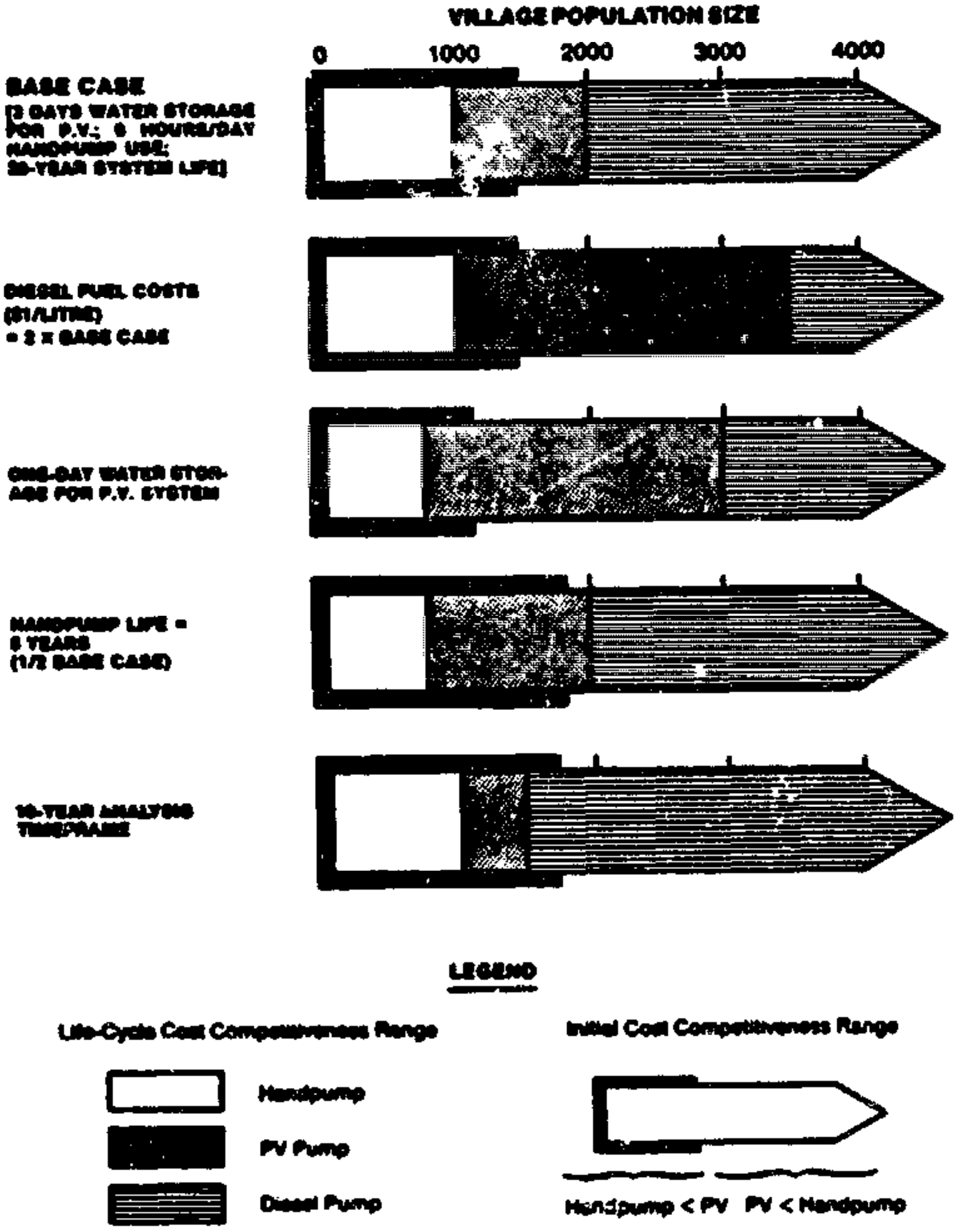


Exhibit VII (Cont'd)

SENSITIVITY ANALYSIS

Life-Cycle and Per Capita Initial Cost Competitiveness

SCENARIO

Water Consumption Level - 20 LPCD
Insolation Level - 5kWh/M²/Day
Well Cost - $2500
Water Depth - 20 M

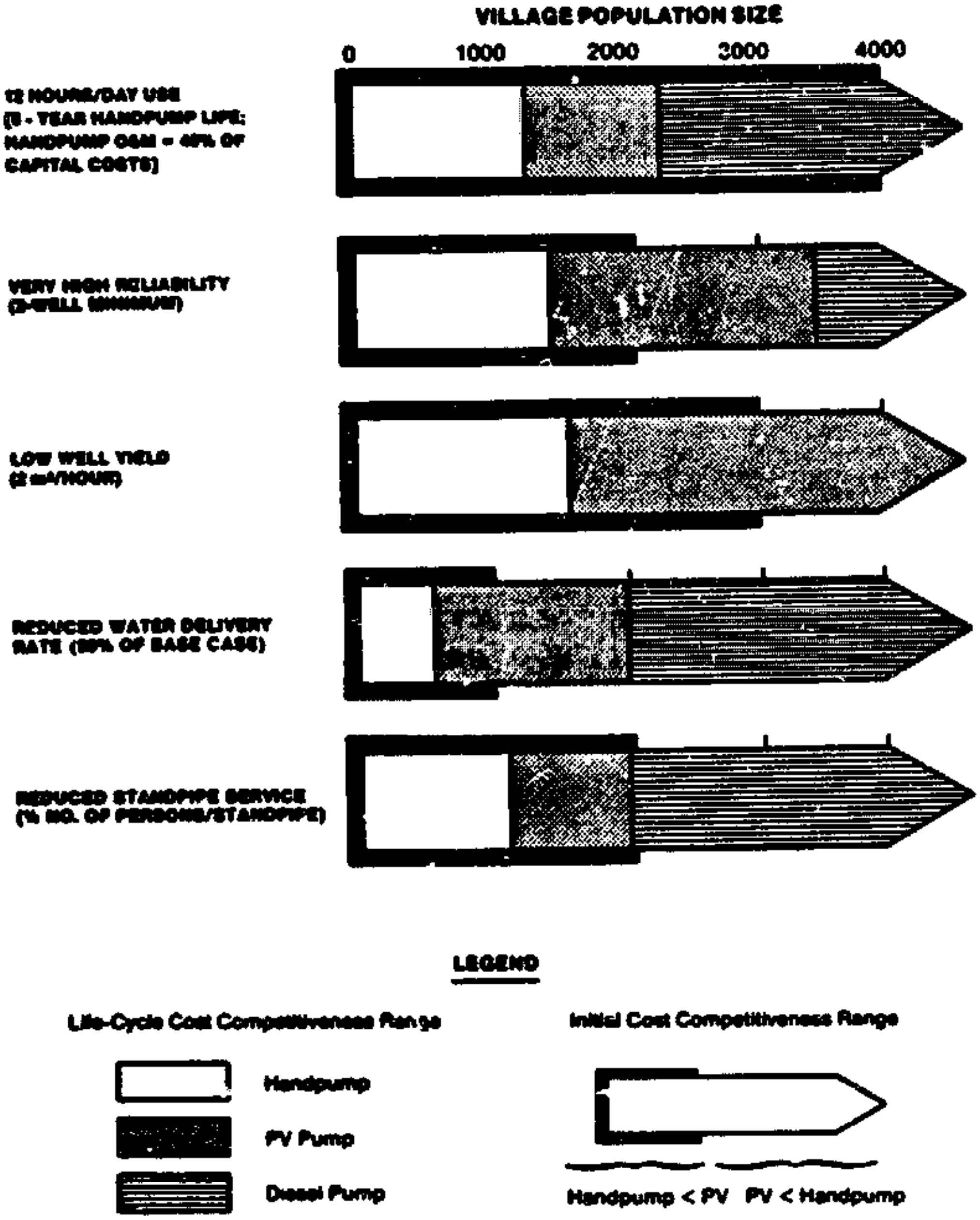


Exhibit VIII

SENSITIVITY ANALYSIS

Life-Cycle and Per Capita Initial Cost Competitiveness

SCENARIO

Water Consumption Level - 40 LPCD
Insolation Level - 5 kWh/M²/Day
Well Cost - $2500
Water Depth - 20 M

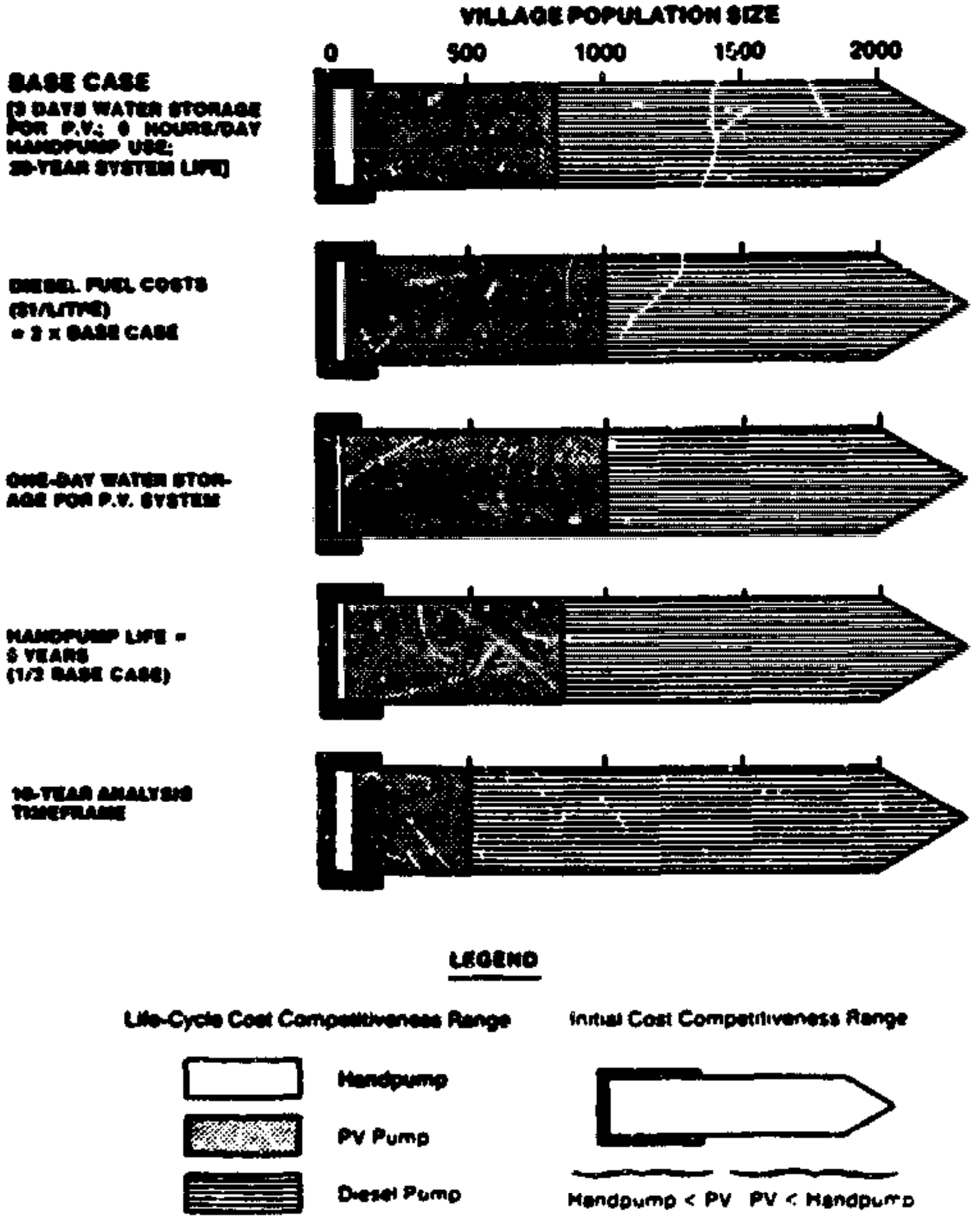


Exhibit VIII (Cont'd)

SENSITIVITY ANALYSIS

Life-Cycle and Per Capita Initial Cost Competitiveness

SCENARIO

Water Consumption Level - 40 LPCD
Insolation Level - 5 kWh/M²/Day
Well Cost - $2500
Water Depth - 20 M

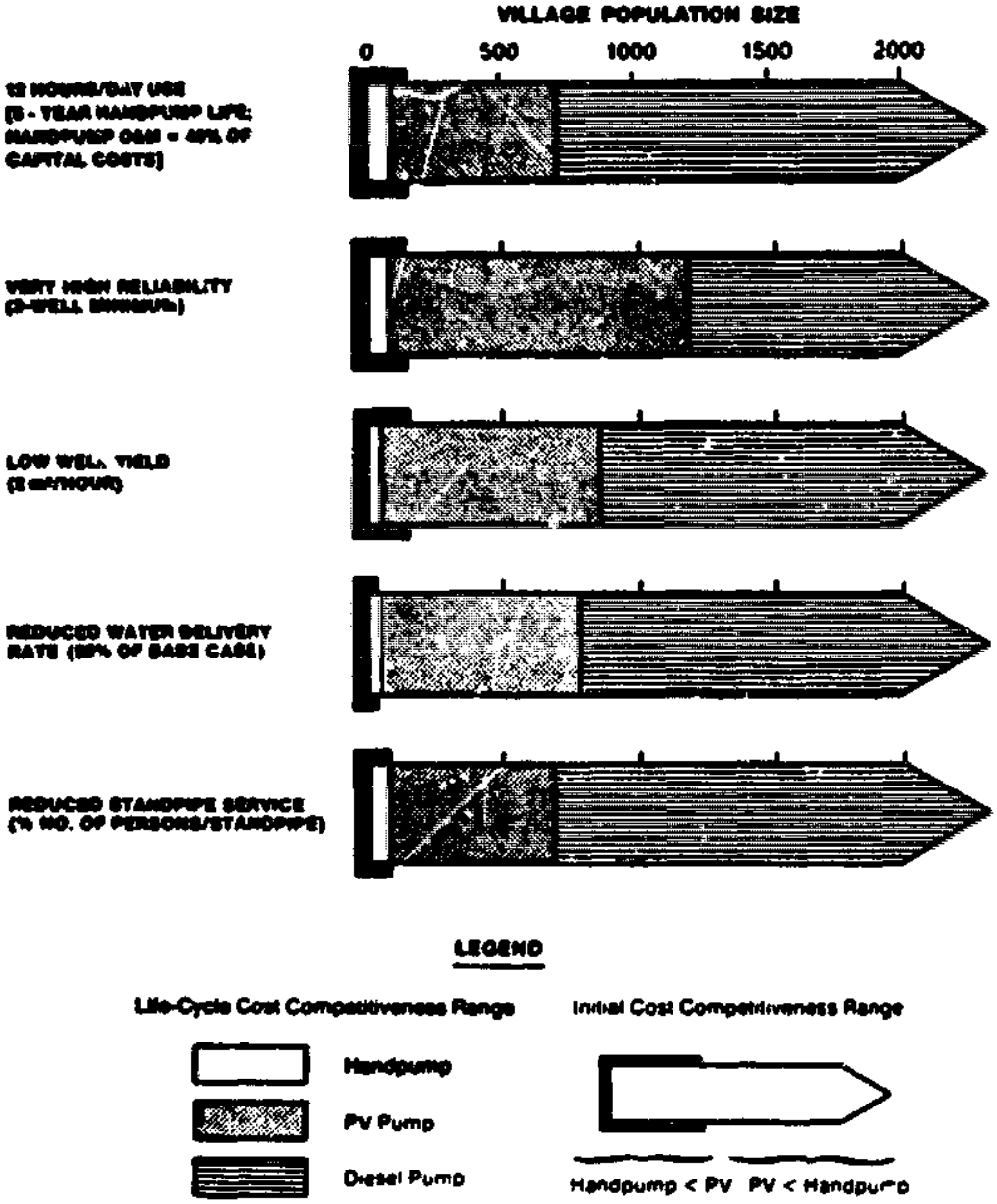


Exhibit IX

REGIONAL PUMPING SYSTEMS POTENTIAL DEMAND DISTRIBUTION
Total Potential Demand - 264 MWp

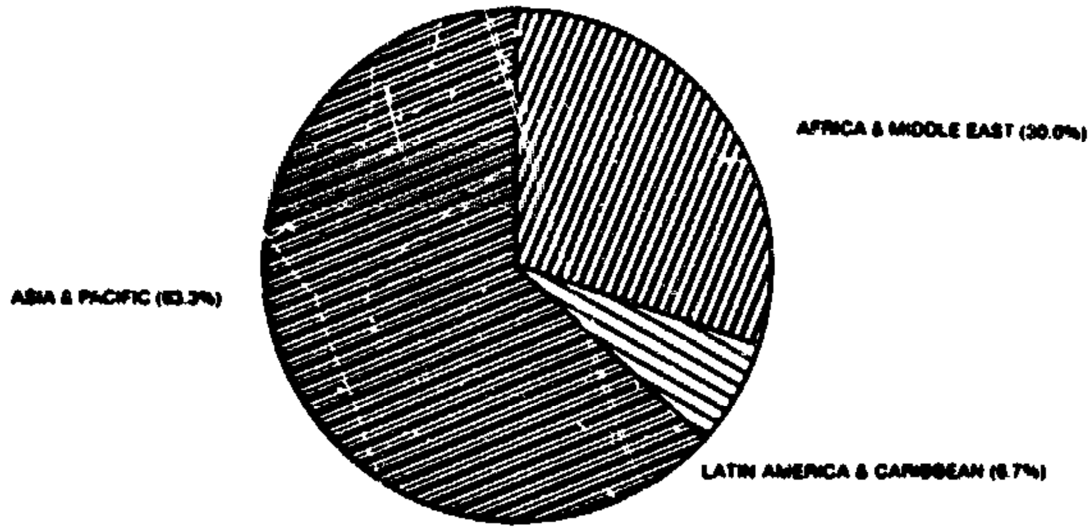
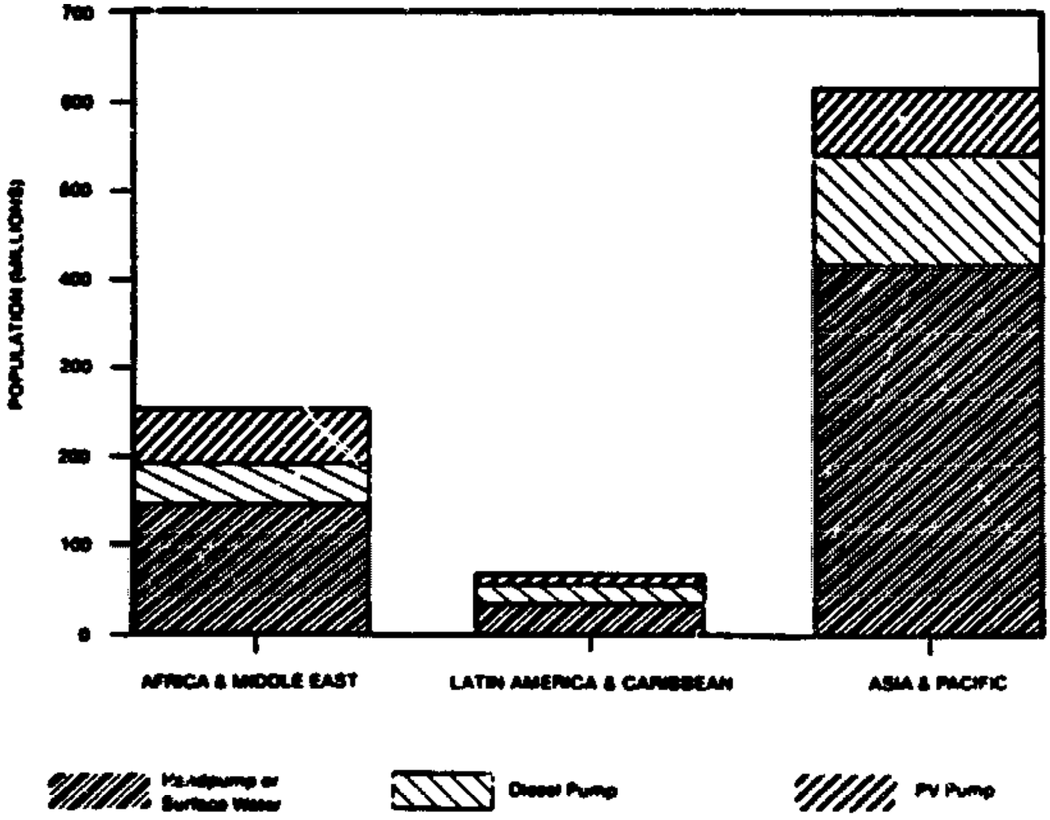


Exhibit X

POTENTIAL POPULATION SERVED BY HANDPUMPS, PV & DIESEL
Total Rural Population Without Access to Safe Water - 928 Mill. (1983 Est.)



A very large population can be served cost effectively by PV water supply systems. Exhibit IX presents a preliminary estimate of regional markets for PV water pumping systems. The market is of the order of 250 MWp, which is several times current worldwide PV production capacity. Additionally, rural populations are continuing to grow at a rate of 30 to 35 million persons per year. If PV retains its market share, the annual demand for PV for this new population is nearly 10 MWp per year. These assessments are based on current costs of PV.

Exhibit X shows the number of individuals in rural areas expected to be served by handpumps, PV, and diesel water supply systems. Handpumps will continue to serve the largest group. The handpumps will serve mainly the shallow well market.[1] It should be noted that the market estimate for diesels is based on the reliability of fuel supplies and maintenance services in rural areas. In many parts of the world, particularly in Africa, diesels have a poor operating record. If diesels are infeasible, then PV pumping systems could likely replace them.[2]

Exhibits XI and XII show the sensitivity of water costs to changes in installed PV array cost for 20- and 40-lpcd demand, respectively, under base case assumptions. The impact of PV array costs on the market for PV is shown in Exhibit XIII. As the exhibit shows, if array costs decrease to $4/Wp installed, the market for PV increases by about 42% to 376 MWp. Conversely if installed array cost is $12/Wp, the market declines by 57% to 113 MWp.

Conclusions

Three important conclusions emerge from the analyses:

1. Under average insolation and well conditions, at a 20-lpcd water use, PV supplies the lowest cost water for villages ranging in size from 1,000 to 2,000 persons. If the water demand is 40 lpcd, PV is the least cost option for villages ranging in size from 80 to 800 persons. As well costs increase, PV becomes competitive at even smaller village sizes. The potential market for PV RWS systems that can serve villages in the cost-competitive size range is immense, many times the current worldwide PV manufacturing capacity.

2. Contrary to conventional wisdom that claims PV is a capital-intensive technology, the analysis shows the per capita initial capital cost of PV systems to be similar to, and even less than that of handpump systems, which are traditionally considered a low-cost technology.

3. PV water supply systems can provide water at a cost acceptable to rural families. In the competitive range when water demand is 20 lpcd, cost of water from PV systems is equivalent to less than 2% of the annual income for a person in a poor developing

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[1] The handpump market segment includes populations to be served by surface water sources. Data were not available for disaggregating this market segment any further. It is conceivable that PV or diesels could be the power source for pumping water from non-gravity-fed surface water sources.

[2] Note that the present analysis did not consider other pumping power sources such as wind power which, in suitable areas, might pump water more economically than PV or diesels. A wind technology competitiveness analysis was beyond the scope of this study.

Exhibit XI

WATER COST VARIATION WITH PV ARRAY COST

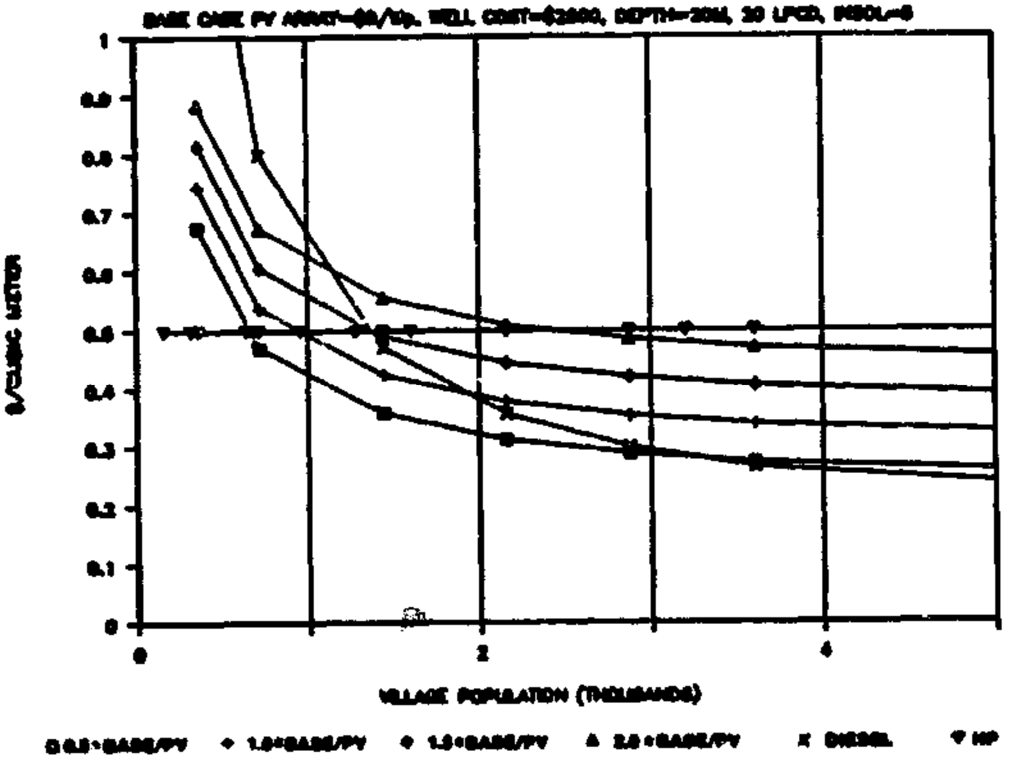


Exhibit XII

WATER COST VARIATION WITH PV ARRAY COST

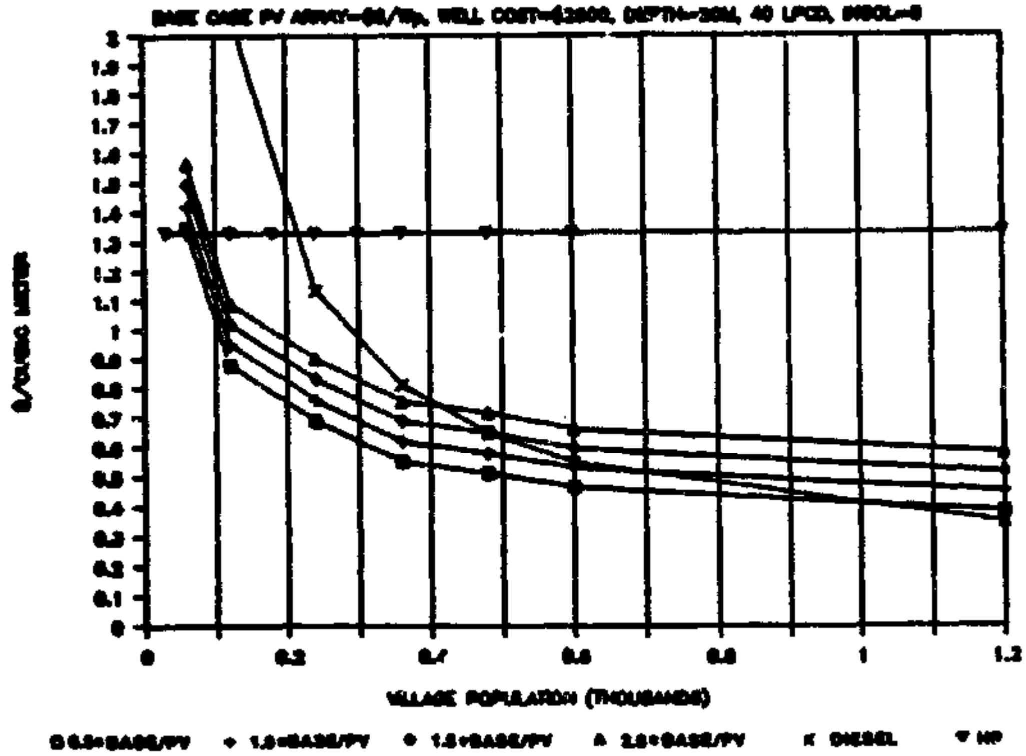
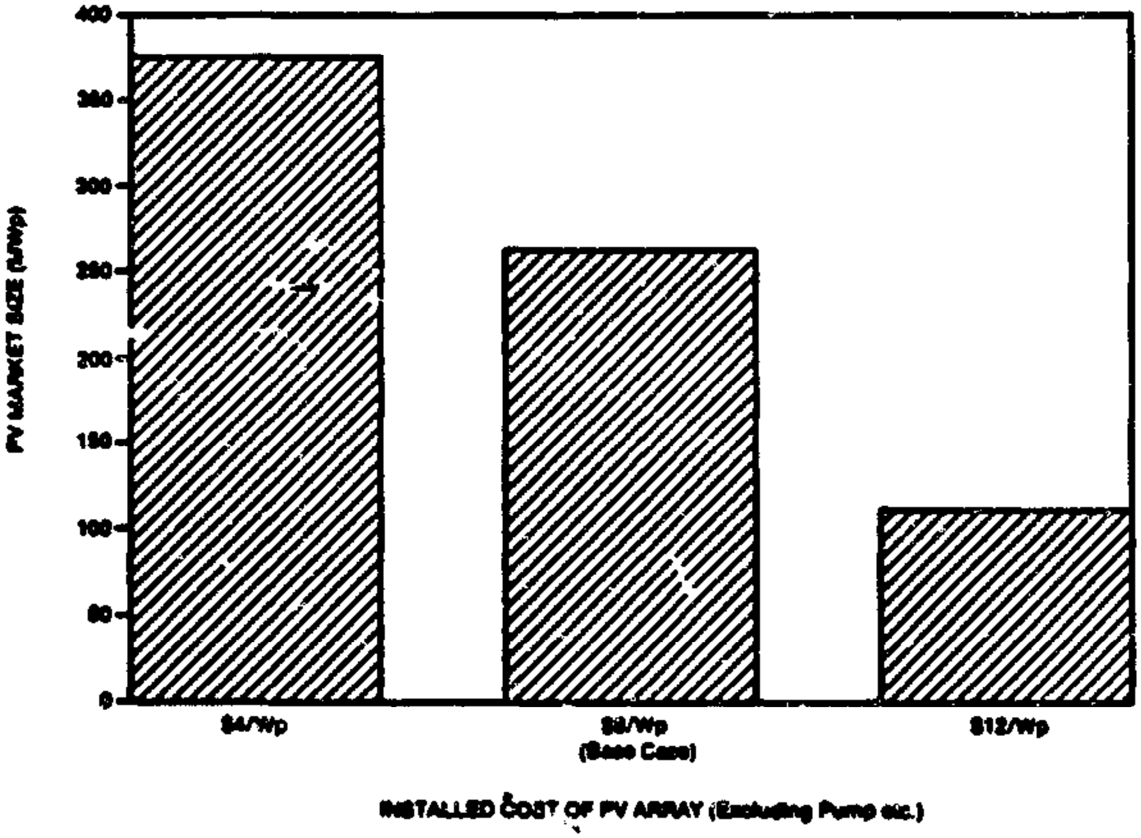


Exhibit XIII

IMPACT OF PV ARRAY COST ON POTENTIAL PV DEMAND



country.[3] Saunders and Warford of the World Bank note that "a frequently used rule-of-thumb" is that a rural, near-subsistence family "should never have to pay more than about 5% of their income for water."[4]

These inferences have two far-reaching implications for both rural water supply systems planners and for PV pumping system manufacturers:

1. <u>PV water supply projects are cost effective and affordable. They can be implemented at a cost comparable to a handpump-based system for moderate-sized villages</u>. In addition to providing water at lower cost than handpumps, the water supply project will also produce other benefits such as a more convenient water source that can be expanded incrementally as the village grows, without drilling additional wells.

2. <u>The potential market for PV pumping systems in the economically competitive range is very large</u>. Therefore, investing in the development of PV pumping products specifically tailored to suit the application requirements will have a high payoff. The potential market is of the order of 250 MWp for typical PV pumping systems of about 1-3 kWp each, for supplying 12-40 m^3/day of water from intermediate and deep water tables. These systems would serve villages with 300 to 2,000 persons.

PV provides a technically feasible and economic means for supplying water to moderate-sized villages. Previously, the only alternatives were diesels or handpumps where grid-electric-powered or gravity feed water supply systems were infeasible. The PV pumping systems, with their low recurrent costs, now provide the rural water supply planner a cost-effective alternative technology to handpumps and diesels. Planners should investigate the suitability of PV for their specific needs. Where necessary, assistance could be sought from international and bilateral donor organizations for assessing the feasibility of PV systems for specific applications and for procuring the systems.

A number of important institutional and organizational concerns must be addressed and resolved in the project design to ensure that a PV-based RWS system can be operated successfully in a rural setting. These concerns are also pertinent for handpump- and diesel-based RWS systems. These issues include the following:

- The demand for water must be accurately determined.

- Users must be educated on responsible water use.

- Extent and type of community involvement in specifying requirements, installation, operation, and maintenance of the system must be established.

- A responsive and reliable maintenance system must be established. In particular, the relative roles of the community and the public sector authority must be delineated. Appropriate training must be provided to community personnel on operation and maintenance of the system.

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[3] Water cost when well costs are \$2,500 and insolation is 5 kWh/m^2/day is \$0.40/m^3 lpcd. Assuming a per capita annual income of \$200, annual water expenses are 1.5% of per capita income (excludes water hauling cost).

[4] Saunders, R.J. and J.J. Warford, "Village Water Supply: Economics and Policy in the Developing World." The Johns Hopkins University Press, 1976, pp. 187-188.

1.0 INTRODUCTION

1.1 Background

Water supply is regarded by the international community as a "basic human right" and an integral component of any primary health care program aimed at eliminating waterborne diseases and morbidity. In 1980, the United Nations launched the International Drinking Water Supply and Sanitation Decade (1981 - 1990) with the goal of providing safe drinking water and sanitation to all rural and urban populations. While the Decade has succeeded thus far in expanding water coverage, nearly <u>one billion</u> people living in the rural areas of developing countries remain without access to a safe and reliable supply of water.[1] Involved development agencies have re-examined the progress achieved to date and concluded that the problems are many and varied. They encompass the technical performance and reliability of rural water supply pumping systems, the lack of adequate infrastructure to support systems, and the shortage of funds to pay for these systems.

A safe, reliable, and convenient water supply is critical to rural development and economic progress in developing countries. Groundwater sources, rather than limited, traditional surface sources, are preferred for rural water supply for sanitary reasons. Groundwater resources require the use of a pumping technology. In an effort to promote the development of reliable, low-maintenance, and low-cost pumping technologies, the United Nations, World Bank, and associated international agencies have investigated water supply systems based on handpumps, photovoltaics, and diesel pumping technologies.

The handpump is presently the most commonly used technology for rural water supply despite problems associated with the handpump including high failure rates, limited water withdrawal rates, and uneconomical use of expensive wells. The United Nations Development Programme (UNDP) and World Bank are attempting to solve some of the problems associated with handpumps by designing pumps which can be operated and maintained at the village level.[2] While diesel-based systems tend to have a low initial cost, they also tend to have a very high recurrent cost. Diesel systems also require skilled maintenance and operating staff as well as a reliable supply of fuel. Recent improvements in the cost and performance of PV pump systems have greatly improved their potential for rural water supply (RWS) application.

Previous studies carried out by the UN, World Bank, and government agencies have sought to define the technical, infrastructural, and economic factors of handpump, PV, and diesel technologies. "Small-Scale Solar-Powered Pumping Systems: The Technology, Its Economics and Advancement" by Sir William Halcrow and Partners, examined PV water pumping technology through a laboratory test program. The "Evaluation of International PV Projects" conducted by Meridian Corporation in 1986 was a systematic cost and performance analysis of PV-powered systems as an energy technology for use in remote areas of the developing world. While the Meridian study concluded that PV is cost competitive with

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[1] United Nations General Assembly, Economic and Social Council, "Progress in the Attainment of the Goals of the International Drinking Water Supply and Sanitation Decade," March 6, 1985.

[2] Arlosoroff, S.; G. Tschannerl; D. Grey; W. Journey; A. Karp; O. Langeneffer; and R. Roche, "Community Water Supply: The Handpump Option," A joint contribution by the United Nations Development Programme and the World Bank to the International Drinking Water Supply and Sanitation Decade, Washington and New York, May 1987.

diesel for selected ranges of water supply application, the focus was on pumping technology rather than on comparative performance within the total rural water supply system.

This investigation examines the conditions under which PV can compete with handpumps and diesels for supplying water to rural communities based on a consistent set of assumptions. The analysis takes into consideration all components of a RWS system, including the water supply/demand function and other characteristics of the village, and the cost and performance of the well, the pumping technology, the storage, and distribution network. This study was undertaken to ascertain conditions under which handpumps, PV, and diesels would be the cost-effective technology for RWS systems.

1.2 Study Objectives

The purpose of this study is to determine under what circumstances PV pumping systems can compete technically and economically with handpumps and diesel pumps for supplying water to rural communities. The specific objectives are as follows:

1. Determine economically competitive ranges for PV relative to handpumps and diesels for supplying water to rural communities, as a function of water source depth, village size, water demand, solar resource, and cost and performance characteristics.
2. Determine how the initial cost of a PV water supply system compares with that of a rural water supply (RWS) system using low-cost technology such as handpumps.
3. Estimate the potential market for PV-powered RWS systems.
4. Identify the functional specifications of PV-powered RWS systems so that PV systems manufacturers can design products to better meet user needs.

The focus of this investigation is on rural communities with no access to grid electricity or safe surface water sources.

1.3 Audience for the Study

This study provides information useful to rural water supply planners who select water supply technologies to suit the needs of rural communities. It will also aid planners in determining a niche for PV, diesel, and handpump water supply systems based on water depth, village size, level of demand, insolation levels, and cost and performance of the respective technologies.

The study results will also be useful to equipment manufacturers who develop products to meet the requirements of rural communities around the world. A preliminary estimate of the market for PV and preliminary PV system specifications have been developed to guide PV manufacturers in development of appropriate technology for the rural water supply market.

1.4 Organization of the Report

Chapter 2 of this study examines the water supply needs in rural communities in developing nations. It characterizes the extent of the need, discusses the water resource conditions found in many regions of the world and examines the major problems in meeting the rural water supply needs in developing countries.

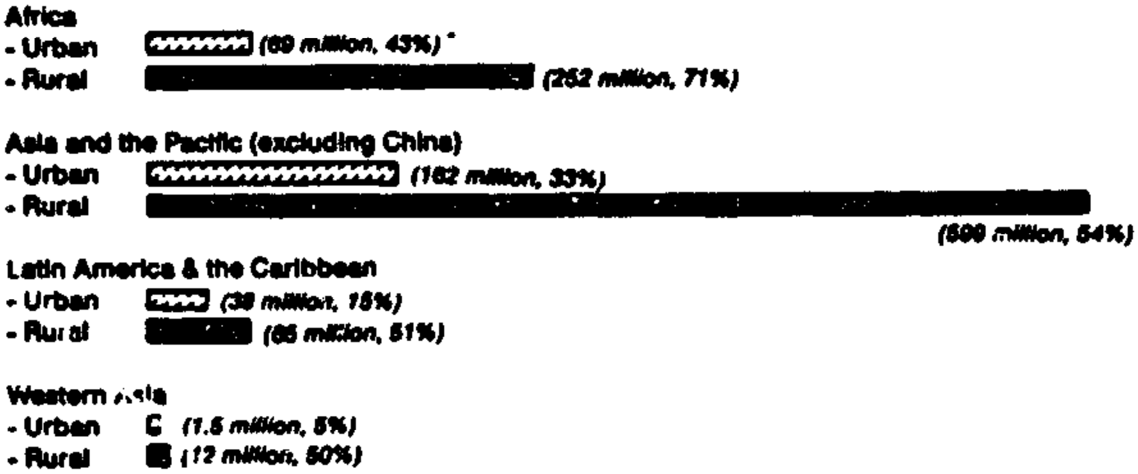
Chapter 3 presents representative handpump, PV, and diesel RWS system configurations used in the analysis. These characterizations are not meant to preclude other pumping technologies which may be equally, or even more suitable for specific water supply conditions. Detailed performance and cost data on the representative technologies are reported in Appendix A.

The analysis procedure is described in Chapter 4. Detailed descriptions of the model including all the mathematical relationships are given in Appendix B. A sample analysis is shown in Appendix C.

The detailed analysis results and its implications are presented in Chapter 5. Graphical output for the various scenarios investigated are provided in Appendix D. Finally, in Chapter 6, the study conclusions are discussed.

Exhibit 2-1

NUMBER OF PERSONS WITHOUT ACCESS TO SAFE WATER (1983)



** In parentheses: 1) the total number of people by sector without access to safe water supplies; and 2) the percent of that sector's total population without safe water supplies.*

Source: United Nations General Assembly, Economic and Social Council, "Progress in the Attainment of the Goals of the International Drinking Water Supply and Sanitation Decade," March 6, 1985.

2.0 RURAL WATER SUPPLY REQUIREMENTS

The United Nations estimates that over one billion people in the world currently lack access to an adequate supply of clean water (see Exhibit 2-1). Over 75% of these people live in rural areas of developing countries where populations are growing fastest and where basic services are the poorest. Contaminated water is a major source of disease and death in these parts of the world. Consequently, providing clean water to these areas has become a major health priority for both multilateral development institutions and individual governments.

Southeast Asia, Eastern South America, Eastern Mediterranean, and Africa are the regions with the largest unserved populations. Rural populations are growing at a rapid pace, and development organizations and governments have not been able to install safe water supply systems at a rate fast enough to even maintain historic levels of coverage. As a result, the problem has been worsening with time.

The safest supply of water is natural springs or wells that tap groundwater. Accessing safe groundwater supplies involves installing wells and various pumping equipment. In the absence of a safe water supply, most rural people have to rely on surface water from rivers, streams, ponds, or lakes to meet their needs. These surface water supplies are generally contaminated with various pollutants, commonly containing traces of human and animal wastes.

A high correlation exists between communities that have to rely on surface water and various crippling and fatal diseases that are borne by human and animal waste. Consequently, the World Health Organization (WHO) has determined that the "provision of a safe and convenient water supply is the single most important activity that could be undertaken to improve the health of people living in rural areas."[3]

In response to the growing health crisis, the United Nations Development Programme (UNDP) launched the 10-year program, "The International Drinking Water Supply and Sanitation Decade" (IDWSSD) in 1980. The goals of this program are to bring safe water to all rural people by the year 2000. An integral part of this program involves installing rural water pumping systems in villages. The United Nations Development Programme resident representatives have been designated to coordinate the United Nations Programme with external support for this initiative in each country.

2.1 Water Demand

The demand for water varies by region and depends on the climate, convenience, usage patterns, customs, and the degree of management to minimize waste. The regional variation in per capita water consumption is illustrated in Exhibit 2-2.

The major factor in determining water demand is convenience. The World Bank has determined that "if there is a supply in the house or courtyard, consumption may be five or more times greater than if water has to be fetched from a public water point."[4] Converse-

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[3] United Nations General Assembly, Economic and Social Council, "Progress in the Attainment of the Goals of the International Drinking Water Supply and Sanitation Decade," March 6, 1985.

[4] The World Bank, "Village Water Supply," 1984, p. 32.

EXHIBIT 2-2
Range of Water Consumption by Region

	LITERS PER CAPITA PER DAY (lpcd.)	
REGION	Minimum	Maximum
Africa	15	35
Southeast Asia	30	70
Western Pacific	30	95
Eastern Mediterranean	40	85
Europe (including Algeria, Morocco, and Turkey)	20	65
Latin America and the Caribbean	70	190
World Average	35	90

Source: World Bank, "Village Water Supply" 1984, p. 32.

EXHIBIT 2-3
Average Regional Water Table Depths

LOCATION	AVERAGE DEPTH OF WATER TABLE (meters)
South America	10 - 20
Central America	10 - 20
North Africa & Middle East	20 - 50
West Africa	15 - 30
East Africa	15 - 30
Southeast Asia & Pacific	5 - 20

Source: Discussions with Dr. Robert Roche, World Bank, March 1987 and IT Power, Inc. water supply databases.

ly, if water has to be carried more than a mile, consumption may be as low as 5 liters/capita/day, which is close to the minimum needed to sustain life.

Convenience is also a critical factor in determining whether people will use a clean water source. If a newly installed well is not sufficiently convenient to use because of its location and the time spent waiting at the faucet, people often revert to using their old, often polluted surface water sources.

2.2. Water Resources

The availability of surface water in rivers, streams, lakes, and ponds has been sufficient to maintain rural communities, but at a major cost to their health and investment in time. The major source of clean safe water is groundwater. The critical factor that has a major impact on the cost and ease with which clean water can be provided to rural communities is the depth of the water table, the cost of drilling wells, and the cost of sustaining the pumping technology.

The depth of the water table can vary considerably by area. As a result of various meteorological and geological factors, some generalizations can be made about the depth of the water table on different continents. As shown in Exhibit 2-3, the average depth of the water table is greater in Africa (ranging between 15 to 25 meters) than in Southeast Asia (ranging between 5 and 15 meters). It is estimated that globally about 45% of the wells in rural areas have pumping lifts less than 10 meters. About 75% of the wells have lifts less than 20 meters, and 85% have lifts 25 meters and less.[8]

The cost of drilling wells also varies fairly dramatically from one region to the next, even though basic well-drilling techniques and equipment may be similar. For instance, in East Africa the cost of drilling a 15- to 20-meter well may be about $2,500; while the cost of drilling the same well in West Africa may be as high as $5,000 to $10,000. These large variations in well drilling costs are generally attributed to the lack of business competition in a region and the price structure for equipment and labor.

2.3 Major Problems in Meeting Water Supply Needs in Rural Areas of Developing Countries

The major challenges in developing safe water supplies in the rural areas of developing countries are financing, technical training, suitable technology development, and institution building to manage installation and ensure the reliability of rural water pumping systems. These rural water supply problems need to be addressed in a coordinated way in order to achieve any lasting success.

The International Drinking Water Supply and Sanitation Decade has helped alleviate the shortage of financing for water supply development, even though the need for funds exceeds what this program can provide. Despite the new input of funds, providing for rural water supply has sometimes been hampered. The major problem, after financing, has been maintaining system reliability in the field. In certain parts of the world, installation of new pumping systems has led to disappointing results -- the number of pumping systems that is breaking down are outpacing the number of new systems being installed. The solution to this problem lies in three basic strategies.

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[8] Arlosoroff, op. cit., p. 27.

First, the pumping technology must be appropriate for village-level operation and maintenance. Overly sophisticated technologies that require specialized parts and expertise to maintain have most often led to failure. In response, the World Bank has established criteria for handpump design that require village-level operation and maintenance (VLOM). The technology must be simple and reliable enough that it can be entirely maintained by a village technician, and spare parts should be simple, cheap, and stockpiled at the village level.

Second, local institutions should be encouraged and developed to ensure the necessary management to install and maintain pumping systems. As the World Bank has concluded, "The highest potential for sustainability is achieved when the community is involved in all phases of the project, starting from the planning stage. If the scheme is to continue to operate satisfactorily, people in the villages have to recognize the need for improved service, be able and willing to pay for the maintenance cost (and eventually the construction cost), and be willing to manage its maintenance."[6]

Third, financing for rural water supply systems generally requires some level of development organization and/or government funding, especially at the beginning. There is a continuing debate about the extent to which rural communities can be expected to pay for water pumping systems. There are two major factors that generally lead to the conclusion that some form of outside assistance is needed for financing capital equipment and installation: (1) the political coordination needed to collect payments from community members for a major capital investment is usually burdensome to the point that nothing proceeds; and (2) there is a strong tendency for rural people to return to their old contaminated water sources as soon as major delays, distances, or costs are encountered at a clean water source. Conversely, the cost of maintaining a pumping system can be and generally is assumed by the rural community.

2.4 Current Status of Rural Water Supply Technologies

In rural, nonelectrified areas, the most common means for drawing water from wells are human- and animal-powered pumps and diesels. Handpumps are by far the most common mechanical water pumping technology despite the problems relating to reliability and maintainability of the pumps. Recognizing these difficulties, the World Bank and UNDP with support from a number of multilateral and bilateral aid agencies embarked on a program to develop workable handpumps and sanitation technologies for the developing world. The program has spent over $30 million to date. The program has resulted in the development of the "Afridev"[7] handpump which meets the reliability and maintainability criteria.

Diesel-powered pumps are a familiar technology in many developing countries. If the infrastructure is in place for supplying fuel and for maintaining the engines, diesels are a cost-effective power source particularly for supplying water to larger rural communities.

Relative to handpumps and diesels, PV-powered pumps are a pumping technology of more recent origin. Over 2,000 PV pumps have been installed worldwide. A number of companies in the U.S. and in other countries manufacture PV pumps. Research and development activities aimed at improving PV pump performance and reducing costs are ongoing.

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[6] Arlosoroff, op. cit., p.3.

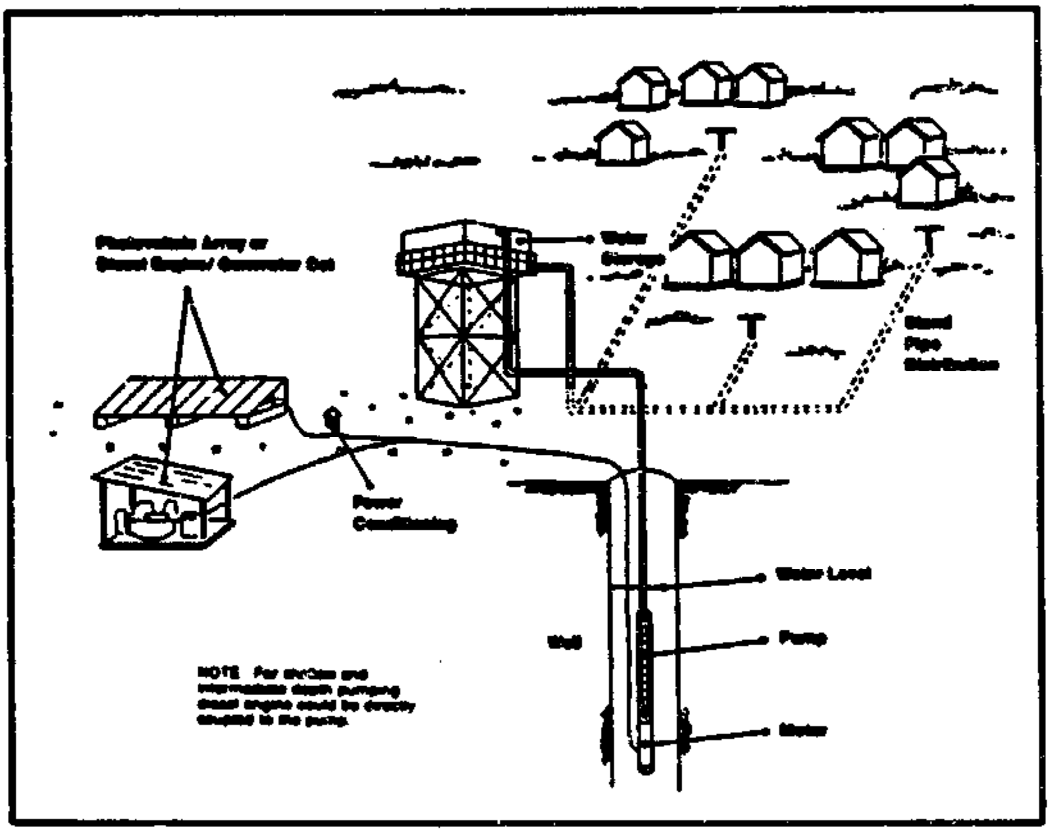
[7] East African Team of the UNDP/World Bank Handpump Project, "The Afridev Pump: Designed for Community Management," Executive Printing Works, Nairobi, Kenya, February 1987.

More details on these pumping technologies can be found in Appendix A.

Exhibit 3-1

PUMPING SYSTEM CONFIGURATIONS

PV- or Diesel-Based Rural Water Supply System with Storage and Standpipe Distribution

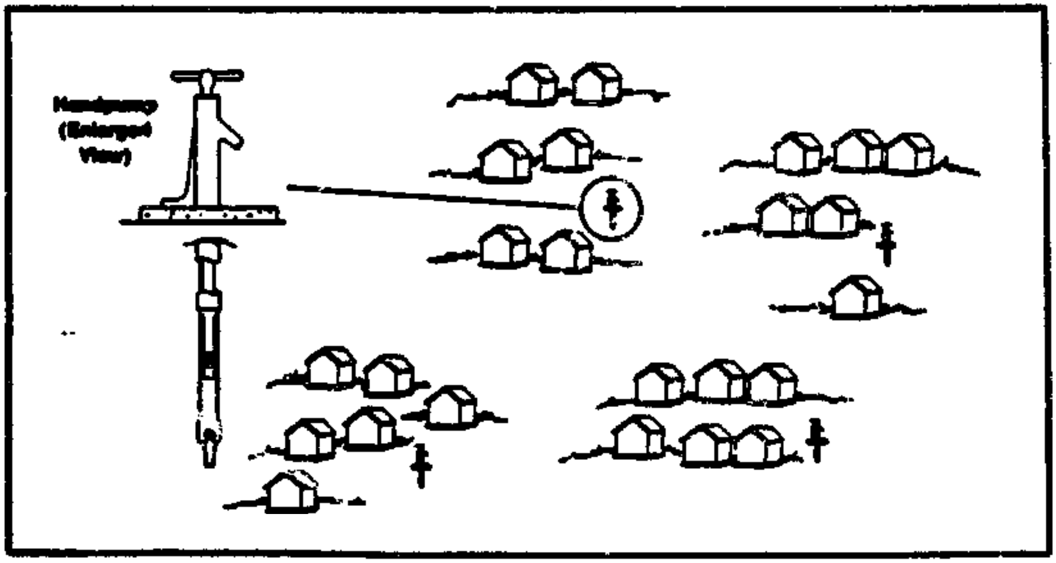


NOTE: For shallow and intermediate depth pumping diesel engine could be directly coupled to the pump.

Exhibit 3-2

HANDPUMP-BASED RURAL WATER SUPPLY SYSTEM

One Handpump Per Group Of Households



3.0 SELECTED RWS CONFIGURATIONS AND PERFORMANCE DATA

3.1 Technology Configurations Evaluated

The choice of technology will depend on a number of parameters including village size, per capita water demand, well characteristics, and cost and technical performance of the equipment. The following three systems are being compared:

1. Handpumps. Each handpump installed on a well serves a certain number of persons. The number of persons served depends on the per capita water demand, the number of hours a pump is used daily, and the amount of time a person is willing to spend gathering water. Handpumps are typically used for water demands up to about 40 liters/capita/day (lpcd). If the village has more people than can be supported by one handpump, then two or more handpumps are used. The principal handpump system components are the handpump and the well.

2. PV pumping systems. Each PV pumping system provides water to one or more standpipes (public faucets). The number of persons served at a faucet is determined as in the handpump case. If the village has more people than can be supported by one standpipe, then two or more standpipes are used. One well with a PV pump is used to supply water to all standpipes, unless well-yield limitations prevent an adequate amount of water to be withdrawn from the well. In such cases, two or more wells are needed, or batteries are used to operate the pump over a longer period at a lower pumping rate. The principal PV pumping system components are the PV array which directly converts sunlight into electricity; motor and pump; optional controls, battery, and power conditioning equipment; well; water storage tank; distribution network; and standpipes.

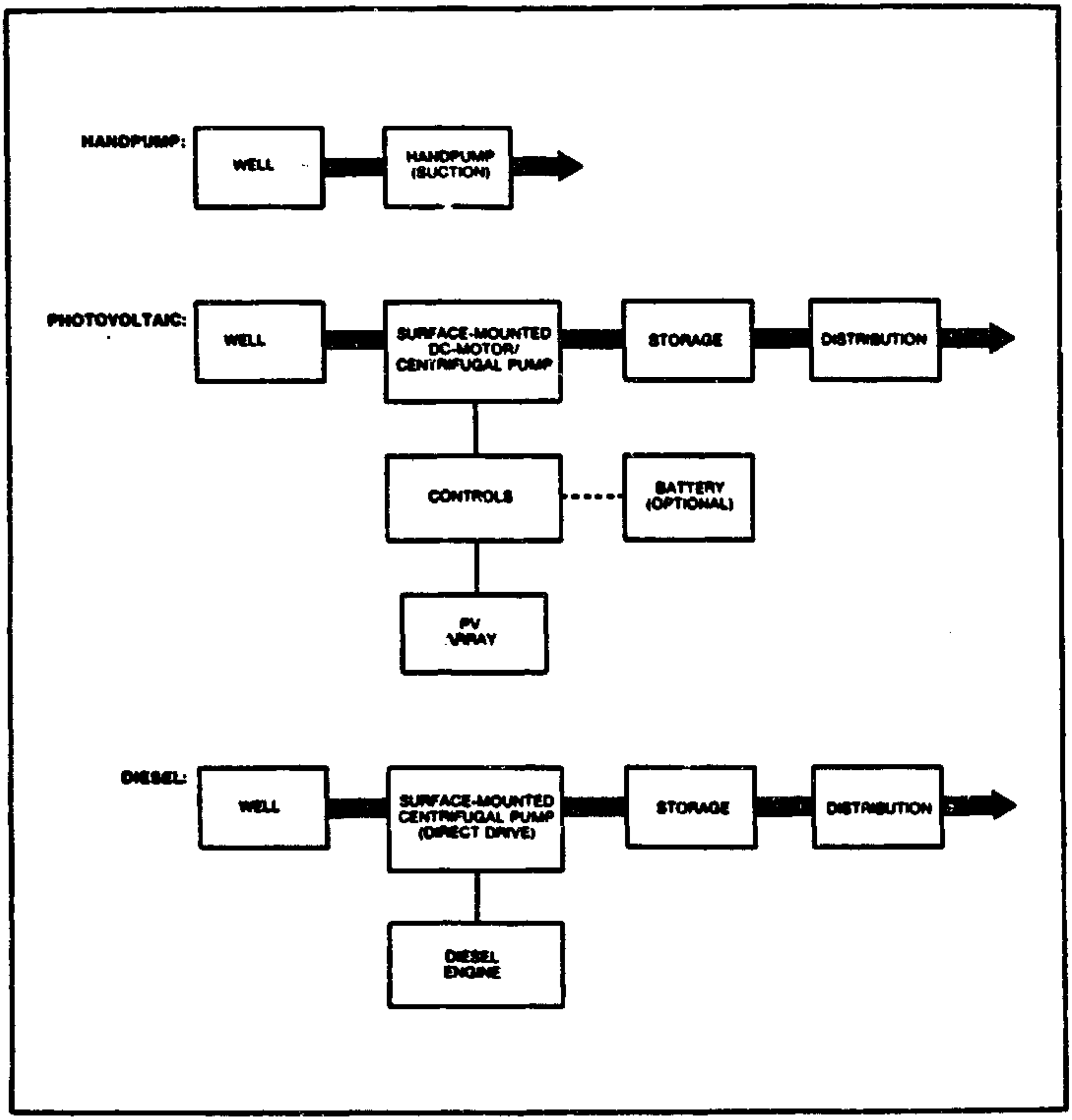
3. Diesel pumping systems. The diesel pumping system is identical to the PV pumping system except that the diesel pump replaces the PV pump. The principal diesel pumping system components are the diesel engine or generator set, fuel tank, pump, motor (if electrical), water storage tank, water distribution network, well and standpipes.

The analysis will not consider yard taps (house connections) as the principal purpose of this analysis is to determine the niche between handpumps and diesel pumps where PV pumping is competitive, and handpumps are not commonly used to provide water to individual households in developing countries. The same analysis method, with minor modifications to account for the increased water distribution costs associated with yardtaps, can be used to assess the competitiveness of PV with diesels for yardtaps. The analysis also assumes that in the case of diesel engines, fuel is readily available throughout the year.

Exhibits 3-1 and 3-2 show typical configurations of PV, diesel and handpump RWS systems. As Exhibit 3-1 shows, the difference between a PV and a diesel system is the power source. In the case of handpumps (Exhibit 3-2), one pump is used by a group of households in a village. For example, if the village has 100 households, five handpumps may be provided.

Water pumping systems have been configured for three general application ranges: (1) shallow water table; (2) low-flow, intermediate and deep water table applications; and (3) high-flow intermediate- and deep-water table applications. For each configuration the equipment capital costs, system life, performance, and operation and maintenance (O&M) costs were estimated for handpump, PV, and diesel-based water supply systems. These data serve as input for the competitive assessment of the pumping technologies. This section

Exhibit 3-3
SHALLOW WATER TABLE CONFIGURATIONS



presents a block diagram of the configured systems and provides key input data for each system. More detailed information is provided in Appendix A.

The selected equipment configurations are based on the recommended application ranges of commercially available motor/pump sets. These limits are a function of water table depth and daily water demand. For example, surface-mounted centrifugal pumps are limited to applications where the water table depth does not exceed 7 meters at sea level. Beyond 7 meters, a centrifugal pump will lose suction (i.e., the ability to draw water from the well). For intermediate and deep-well applications, the choice is a jackpump or submersible motor/pump set. The determinant in these cases is required daily flow. At a water depth of 20 meters, jackpumps are a good choice for water if demand is below 30 cubic meters per day. For demand more than 30 cubic meters per day, a submersible motor/pump set is preferred.[8] The representative pumping configurations should be viewed as examples only. Depending on specific circumstances, other pumping technologies may be better suited.

3.2 Shallow Water Table Depth Applications (< 7 Meters Water Table Depth)

The major components of handpump, PV, and diesel RWS systems are shown in Exhibit 3-3.

The handpump system consists of a well and suction handpump. A Tara suction handpump has been used as a representative technology. The Tara is a "new generation handpump," typical of current shallow-well pump technology, and considered suitable for water supply at depths of up to 15 meters. The Tara is a simple direct-acting handpump which is regarded as relatively easy to manufacture, maintain, and repair.

The photovoltaic pumping system consists of a well with a surface-mounted single-stage centrifugal pump powered by a DC motor. Power is supplied to the pump through a control system. Controls help improve the pump/motor efficiency by matching the current/voltage characteristics of the array to that of the motor/pump set.

The preferred diesel pump configuration for shallow pumping applications with a pumping head in the 3- to 10-meter range is a diesel engine directly coupled to a surface-mounted centrifugal pump. The diesel engine commonly used in these types of rural pumping applications in developing countries is a two-cycle engine with a large flywheel. The typical pump is a centrifugal pump that is mounted on, and operates entirely, from the surface.

3.3 Intermediate/Deep Water Table Depth Applications (20-40 Meters Water Table Depth)

3.3.1 Low Flow (< 30 m^3/day)

Block diagrams of the handpump, PV, and diesel systems configured for an intermediate/deep water table depth, low-flow application are shown in Figure 3-4.

Handpump system data such as capital costs, O&M requirements, and life for this application were based on data for two commercially available handpumps, the Mark II, the Volanta, and the newly developed Afridev which is highly regarded by the UNDP/World Bank Handpump Project.

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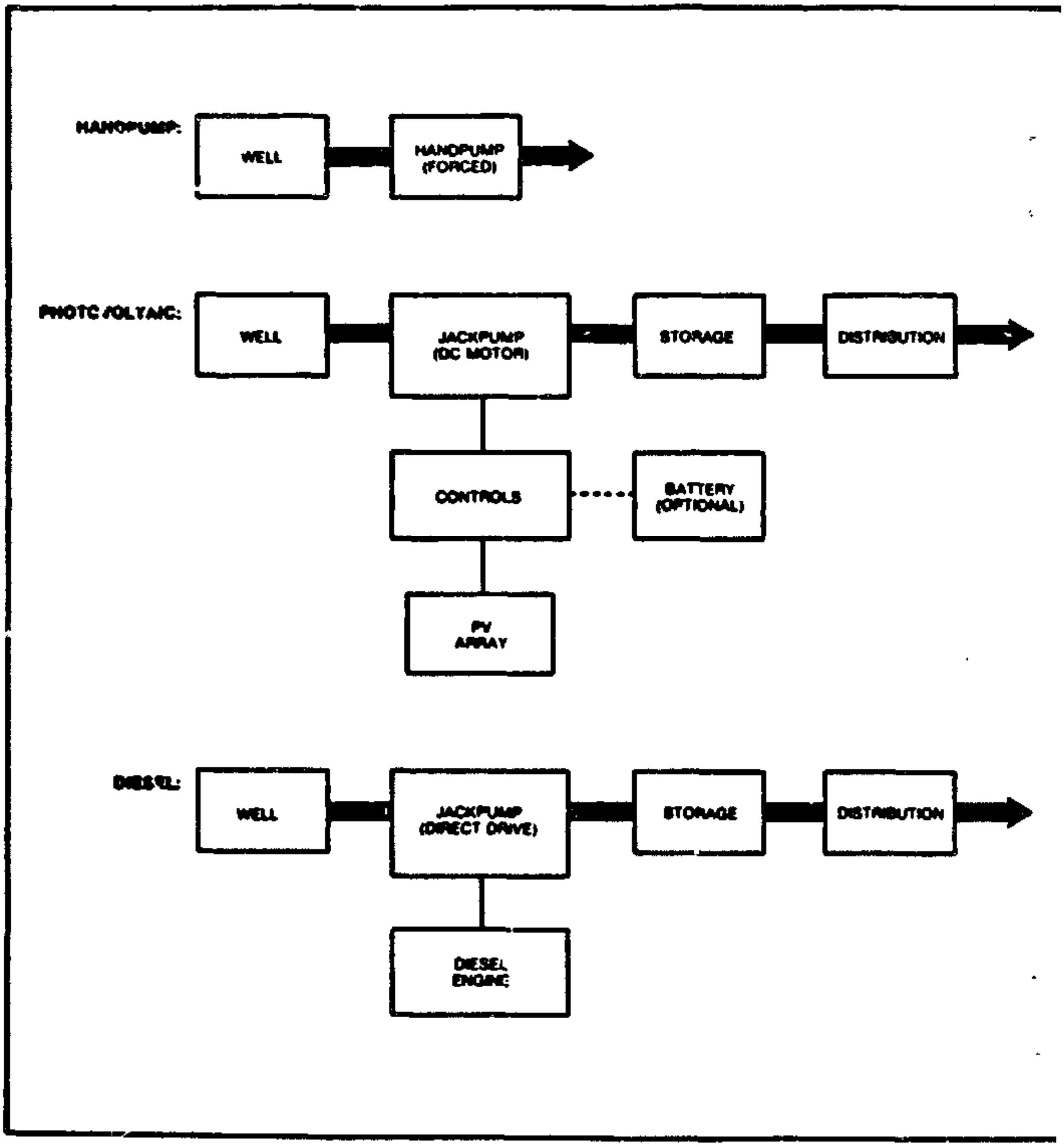
[8] Kenna, J. and B. Gillet., "Solar Water Pumping: A Handbook," Intermediate Technology Publications, London, U.K. 1985.

Exhibit 3-4
INTERMEDIATE/DEEP WATER TABLE SYSTEM CONFIGURATIONS (<$30M^3$/DAY)



The photovoltaic system selected is a PV array directly connected to a surface-mounted DC motor which drives a jackpump. The system includes power conditioning equipment to match the cyclic power demand characteristics of a jackpump to the more continuous PV power supply.

The preferred diesel pump configuration for intermediate well depths of about 20 to 40 meters is a diesel engine directly driving a jackpump. The diesel engine commonly used in this configuration is a four-cycle engine. The pump commonly used in this application is a positive displacement pump using a derrick arm design and a submerged pump cylinder.

3.3.2 High Flow (> 30 m^3/day)

Block diagrams of handpump, PV, and diesel systems configured for an intermediate/deep water table depth application are shown in Exhibit 3-5. The handpump system configuration is the same as in the low-flow case.

The photovoltaic system consists of a well, PV array, controls and inverter, and ac motor/pump set in the case of an ac system. A dc motor/pump set is used for motors less than a 1 kW rating. Controls are used with dc system. The system uses a multi-stage centrifugal pump with a submersible motor. For power demands greater than 1000 W, an ac system powering a submersible ac motor which operates a multi-stage centrifugal pump is assumed. The ac motor/pump set is similar to a number of systems powered by grid electricity that have been used for many years in developing countries. Controls and an inverter are needed for the ac system.

The diesel pump configuration is a diesel engine driving an electric generator which in turn drives an electric motor and pump. The diesel engine commonly used in this configuration is a four-cycle engine with an ac generator. The pump is a centrifugal submersible pump with an electric motor. Because the submerged pump requires electric conductors only between the diesel gen-set and the bottom of the well, installing the pump is easier than the jackpump design discussed earlier.

3.4 Use of Batteries in PV Water Pumping System

Batteries are sometimes used in PV water pumping systems and serve a number of purposes:

- If water storage costs are high, battery storage may be the preferred alternative.
- Because the batteries act as a constant voltage source they can be used to operate the pump under optimal conditions. The gain in pump efficiency results in a reduced PV array size and may compensate for both battery energy losses and the cost of the battery.
- If the well yield is limited, such as in areas of West Africa where well yield is 1-2 m^3/hour,[9] a battery is needed to allow the pump to operate over a longer period of time at a reduced pumping rate. If a battery was not used, the pumping rate would be proportional to sunlight intensity and at around noontime, the pumping rate could exceed well yield. There have been cases in which pumps have been damaged due to

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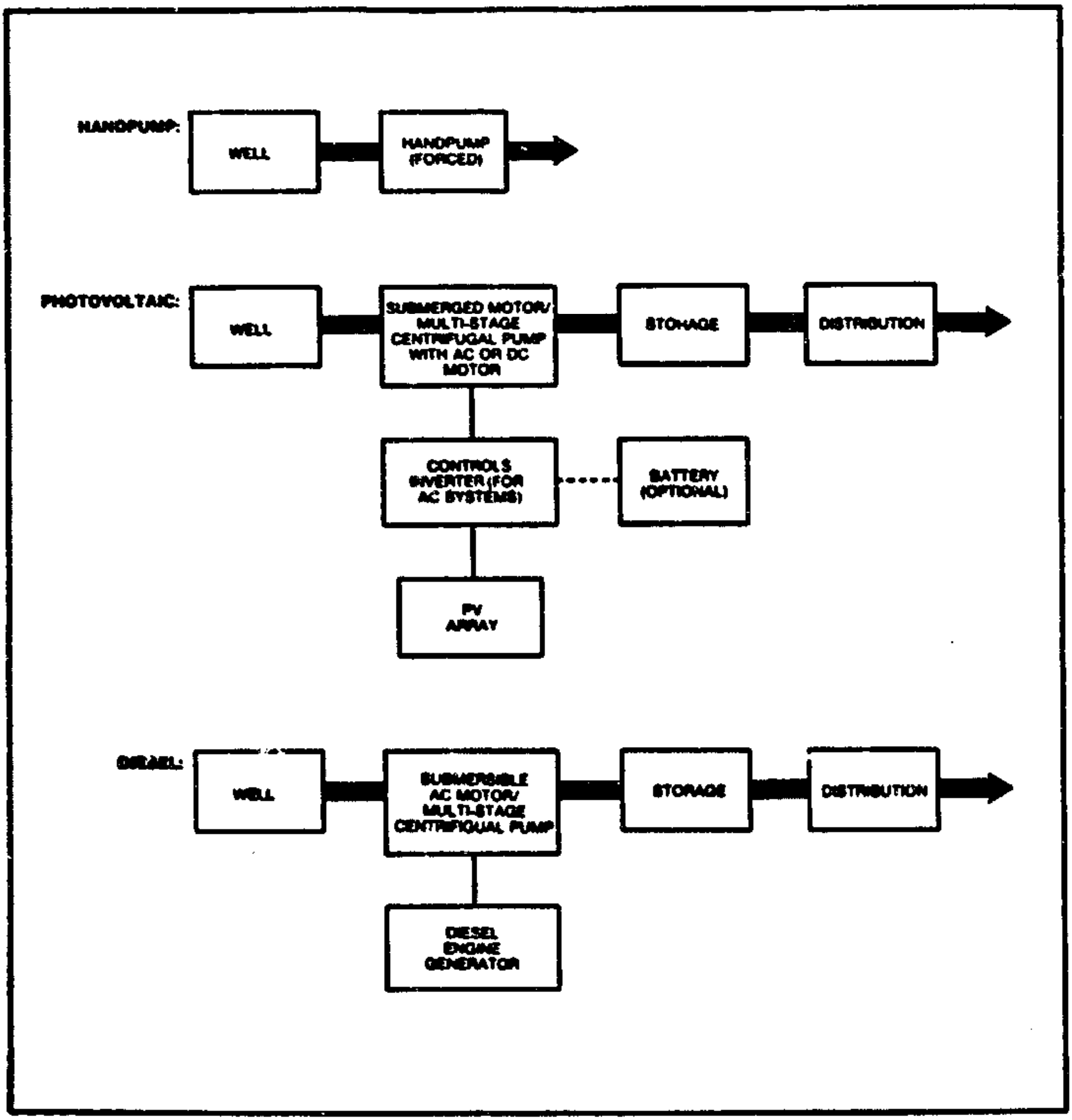
[9] Arlosoroff, op. cit., p. 53.

Exhibit 3-5
INTERMEDIATE/DEEP WATER TABLE SYSTEM CONFIGURATIONS (>30M³/DAY)



excessive drawdown caused by too high a pumping rate. The alternative to batteries would be to drill extra wells and reduce the amount of water withdrawn from each well.

The analysis will consider the effect of using batteries on PV system viability.

3.5 Key Input Data Assumptions

Exhibit 3-6 is a tabulation of data used in the analysis. Detailed data are shown in Appendix A. The analysis is conducted for three "worst month" plane-of-array insolation levels of 4, 5, and 6 kWh/m^2/day. As Exhibit 3-7 shows, these plane-of-array insolation ranges are representative of the values occurring in most of the developing world. These data are used to perform comparative analyses of handpump, PV, and diesel pumping technologies for various application scenarios.

Exhibit 3-6

INPUT DATA ASSUMPTIONS

PARAMETERS	**WATER TABLE DEPTH**		
	Shallow	**Intermediate**	**Deep**
1. Lift[a] (Meters, Suction/Discharge)	5/10	20/10	20/10
2. PV Motor/Pump Efficiency[b]	25%	35%	35%
PV Motor/Pump Efficiency (with battery)	45%	45%	45%
PV Array Efficiency	10%	10%	10%
PV Balance of System Efficiency	90%	90%	90%
Battery Efficiency	80%	80%	80%
3. Diesel Fuel/Water Efficiency[c]	5%	5%	5%
4. Water Storage (equivalent days of average daily consumption)			
- PV[d]	3	3	3
- Diesel[e]	1	1	1
5. Water Consumption (liters per capita per day-LPCD)[f]	20,40	20,40	20,40
6. Worst Month Insolation On Plane of Array (kWh/m²/day)[g]	4,5,6	4,5,6	4,5,6
7. Operation & Maintenance (% of Capital Cost/yr)			
- Non-Mechanical Equipment[h]	1%	1%	1%
- Handpump[i]	15%	10%	10%
- PV Array[j]	1%	1%	1%
- Motor/Pump Set[j]	10%	10% (< 30 m³/day) 5% (> 30 m³/day)	
- Diesel Engine Set[j]	15%	15%	15%
8. Equipment Life (years)			
- Handpump[k]	10	10	10
- PV Array[l]	20	20	20
- Motor Pump[m]	10	(20 - 40, Head, < 30 m³/d = 15 yrs) (20 - 40 , Head, > 30 m³/d = 7.5 yrs)	
- Diesel Engine[n]	10	10	10
- Battery	5	5	5
9. Handpump Capital Costs[p]	$ 240	$500 + 8 * Water Table Depth (m)	
10. Submerged Centrifugal Pump[p]	$ 275 + 25*Head + 75*(hourly flow rate (m³))		
11. Diesel Engine[q]	$ 3000 + 200*kW, for over 3 kW		
12. Diesel Gen-Set[r]	$ 5000 + 240*kW, for over 3 kW		
13. Water Storage Costs[p]	$ 1000* (Volume in cubic meters)$^{0.5}$		
14. Battery Storage	$ 200/kWh		

Exhibit 3-6

INPUT DATA ASSUMPTIONS
(Cont'd)

PARAMETERS	WATER TABLE DEPTH		
	Shallow	Intermediate	Deep
15. Labor[b]			
- Central Maintenance	NA	$ 4/day	$ 4/day
- Area Mechanic	$ 4/day	$ 4/day	$ 4/day
- Village Attendant	$ 4/day	$ 4/day	$ 4/day
16. Attendant			
- Handpump (hrs/day/pump)	0.5	0.5	0.5
- Standpipe (hrs/day/standpipe)	0.5	0.5	0.5
- PV pump (hrs/week/pump)	2	2	2
- Diesel (hrs/day)	8	8	8
17. Well Cost	$800	$1500, 2500, 5000	$5000
18. Piping Cost	$6/m	$6/m	$6/m
19. Standpipe Cost	$150	$150	$150
Number of taps/standpipe	2	2	2
20. Delivery Rate (l/min)[b]			
- Handpump	20	15	12
- Standpipe	15	15	15
21. Discount Rate %	10	10	10
22. System Analysis Lifetime (Years)	20	20	20
23. PV System Capital Costs ($/Wp)	Up to Array Size (Wp)	Array Cost	Motor/Pump Cost
	300	$ 8.00	$ 7.00
	500	7.75	4.25
	1000	7.50	2.50
	> 1000	7.25[c]	See Note[c]
24. Village Characteristics[b]			
- Number Households/Hectare		25	
- Percent Income Spent on Water		3%	
- Wage Earning Work Hours/family		20/day	
- Walking Speed		3 km/hour	
- Minimum Water Demand		10 lpcd	
- Household Size		6 persons	

NOTES FOR EXHIBIT 3-6:

a. Nominal depth to water table. A discharge head of 10 meters is added to PV and diesel systems for storage and distribution related head requirements.

b. Efficiency of PV-powered motor/pump set is daily average operating efficiency (Based on results of "Small-Scale Solar Powered Pumping Systems: The Technology, Its Economics and Advancement." Main Report UNDP Project GLO/80/003 executed by the World Bank).

c. Diesel system overall operating efficiency. J. Kenna, "Cost and Performance Data on Diesel Engine Generators and Pumps," SAND87-7100 (Albuquerque: Sandia National Laboratories, May 1987). Work performed by IT Power, Ltd.

d. Storage requirements for PV system cover insolation variance and peak demand. The level of storage for PV system corresponds to insolation variance protection representing 99% availability (Sandia National Labs, 1985).

e. Water storage for diesel system based on recommended practice (Associates in Rural Development (ARD) - Botswana, and Republic of the Philippines - National Water Resources Council, March 1980).

f. Water consumption sensitivity analysis values.

g. Insolation sensitivity analysis values.

h. Operation and maintenance costs for non-mechanical equipment based on UNDP/World Bank Handpump Project estimates.

i. Handpump, motor/pump set and diesel engine set are based on scheduled and unscheduled maintenance requirements.

j. O & M values for PV array are based on typical values used by industry.

k. Equipment life for handpumps based on UNDP/World Bank adopted values for handpumps used approximately 6 hours per day.

l. PV array life based on DOE accelerated testing programs and related field experience.

m. PV motor/pump set life for shallow wells based on approximate average of motor and centrifugal pump life. For intermediate and deep well applications, two motor/pump set lives are used: for required demands less than 30 m^3/day, a jackpump system is designated with a life of approximately 15 years (Chronar TriSolar Corporation estimates 20-year pump life with motor replacement at 10 years); for demands greater than 30 m^3/day a submersible motor/pump set is used with life of 7.5 years (Life estimates for submersibles ranged from 5 years by A.Y. McDonald and ARD to 7 - 12 years by Grundfos).

n. Diesel engine life (Kenna, *op. cit.*)

o. Cost function for conventional AC submersible accounting for efficiency differences. Also inverter cost of $ 0.75/Wp added to PV array cost.

p. Estimates from UNDP/World Bank Handpump Project.

q. Meridian Corporation, Egypt Renewable Energy Options Identification Reports, 1985.

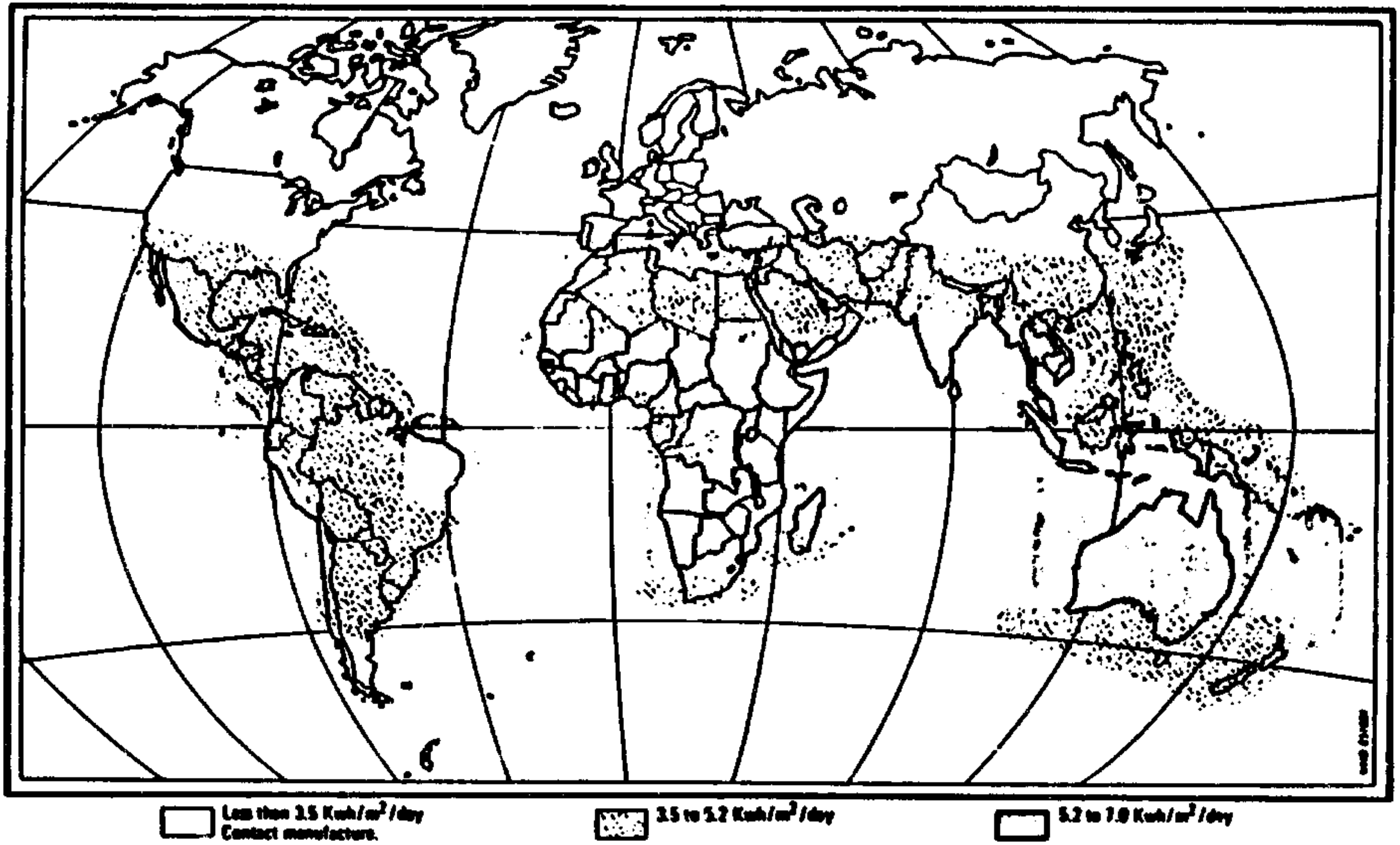
r. Meridian Corporation, *op. cit.*

s. Estimates for labor rate by UNDP/World Bank Handpump Project.

t. PV system cost on a $/Wp basis used. Based in part on IT Power data presented in "Solar Powered Pumping Systems: Their Performance, Cost and Economics," July 1986 and PV industry quotes. Costs include shipping and installation.

Exhibit 3-7

AREAS OF THE WORLD IN WHICH SOLAR RADIATION (IN THE WORST MONTH) FALLS BETWEEN 3.5 TO 5.2 KWH/M^2/DAY AND 5.2 TO 7.0 KWH/M^2/DAY



Source: EPI Technical Series, The Cold Chain Product Information Sheets, 1986/1987, No. 1. Expanded Program on Immunization. WHO/UNICEF EPI Technical Series.

4.0 METHODOLOGY

4.1 Technology Comparison Basis

A key feature of the analysis is that technologies are compared when they are providing the <u>same level and quality of service</u>. Service quality and level are defined as follows:

1. The amount of water supplied daily per person is the same across all three water supply systems being evaluated. Therefore, the benefit accruing to an individual, based on availability of water, is the same across all technologies. For example, all three technologies would supply 20 liters per capita per day to a given village population.

2. The time spent by villagers gathering water is the same across all three water supply systems. Therefore, the <u>cost</u> of collecting water is the same across all three technologies. Water collection time is composed of time spent walking to and from the water point, queuing time at the water point, and water collection time. Water collection time in the case of a handpump is the time spent pumping the water. In the case of PV or diesel pumping systems, water collection time is the amount of time spent by a villager at the standpipe waiting for the water container to fill.[10]

3. The technologies provide water at the same level of reliability so that water availability throughout the year is the same across all three technologies. The same availability levels are attained by using operation and maintenance practices consistent with reliable equipment performance and using adequate water storage in the case of the PV and diesel systems. For example, handpump usage has been limited to 6 hours a day, and pumps are assumed to be maintained regularly. Handpump maintenance is estimated based on the concept of "Village Level Operation and Maintenance (VLOM)" promoted by the UNDP/World Bank.[11] Diesel engines are maintained at manufacturer recommended intervals using appropriately skilled (and paid) labor. In the case of PV, adequate storage is provided to account for cloudy days when the solar energy output is below average. Also, in the case of PV, appropriately skilled and paid labor is used for maintenance.

Since the level and quality of service are the same across all three technologies, the benefits derived from the water provided will be equal across all three technologies. <u>Therefore, only the relative costs need to be compared using cost effectiveness analysis: this is an important advantage of the procedure used in the evaluation.</u>[12] Since the water gather-

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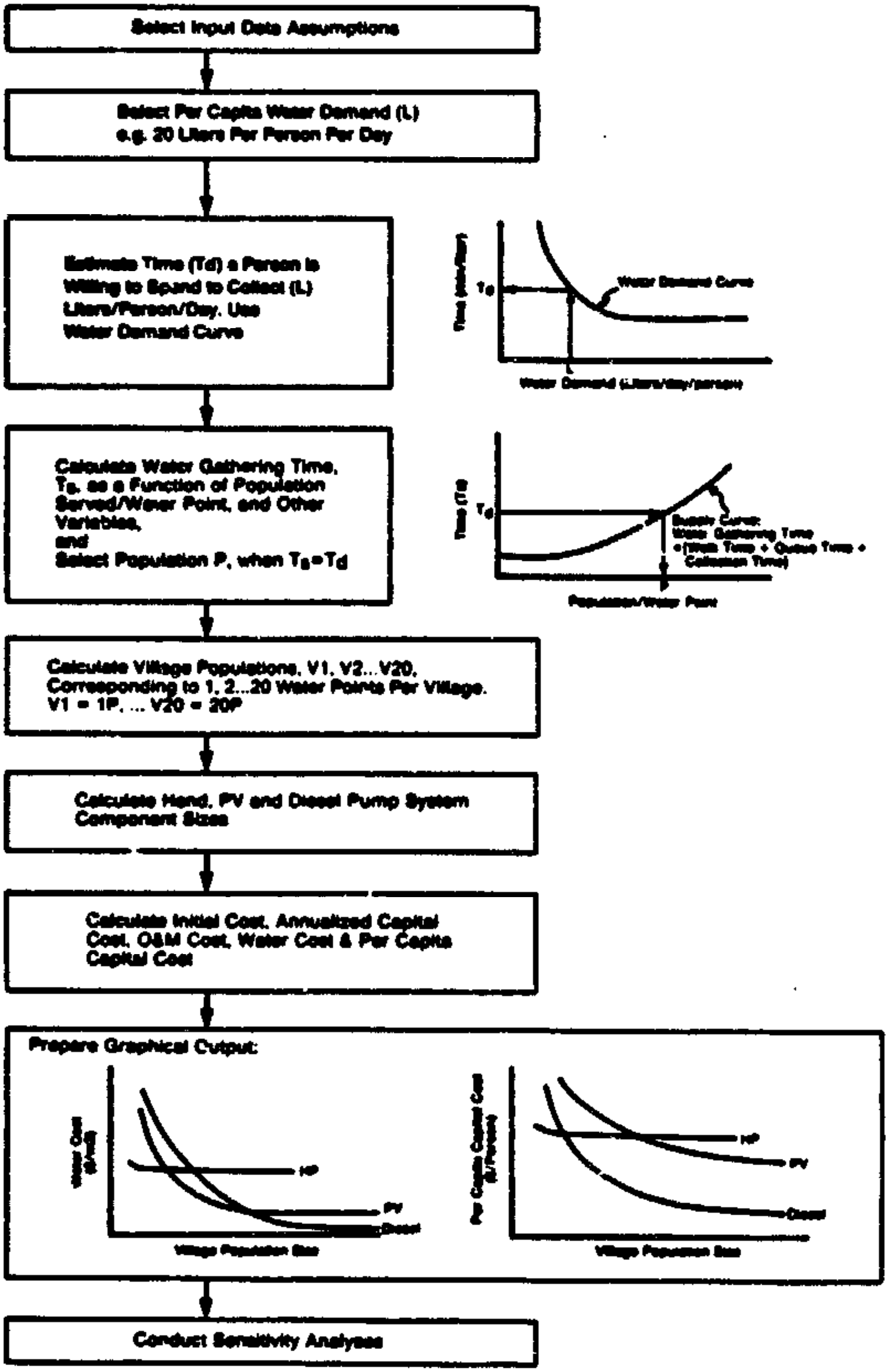
[10] The analysis does not take into account the greater effort needed to pump the water using the handpump.

[11] World Bank and United Nations Development Programme, "Global/Inter-regional Project for the Testing and Technology Development of Handpumps for Rural Water Supply and Urban Fringe Areas" (the "Handpump Project"). The handpump project has developed preliminary designs for VLOM pumps for lifts up to 25 meters. Development of VLOM pumps with greater lifts will be undertaken in the future.

[12] Cost effectiveness analysis based on the "constant effects" method was used in the analysis. This method selects the alternative with the lowest present worth cost that meets the stated level of benefits, including intangible benefits. See: Gittinger, J.P., "Compounding and Discounting Tables for Project Analysis," EDI Series in Economic Development, Second Edition, The Johns Hopkins University Press, Baltimore and London, 1984, p. 189.

Exhibit 4-1

METHODOLOGY OVERVIEW



ing cost ("haul cost") is the same across all three technologies for a specific village and water demand level, haul costs are not included in the cost analysis.

4.2 Analysis Procedure

This procedure draws on and extends some of the analytical concepts used by the World Bank in its water pumping technology evaluations.[19] The principal analysis steps are outlined in Exhibit 4-1 and briefly described below:

Select input data assumptions. Data needed for the analysis fall into three general categories:

1. Village Characteristics. These include population density, percent of income spent on water, minimum water requirements, household size, productive work hours per family, maximum water load carried, walking speed, and other factors needed to estimate the amount of time a villager is willing to spend gathering water. Some of the above information together with technology performance data is used to calculate the number of persons served at each water supply point.

2. Technology Performance Specifications. These include water delivery rates from handpumps and standpipes, pumping technology efficiencies, water storage requirements, solar insolation levels, well depth and yield, and equipment life. This information is needed to compute component sizes and system configurations.

3. Cost Data. These include unit installed costs of equipment (e.g., PV array cost in $/Wp), operation and maintenance costs, fuel costs, and labor costs. This information is needed to calculate the initial capital and life-cycle costs of the three water supply systems.

Select per capita water consumption level. Per capita water consumption is a key decision variable. The analysis is conducted at two water consumption levels, although other values could easily be used. The two levels are 20 and 40 liters per capita per day (lpcd). In African countries, 20 lpcd is the average quantity of water used for domestic consumption in rural areas. Twenty lpcd is used to represent the case of minimal water use. Forty lpcd is the World Health Organization-recommended level of water consumption. It also represents higher consumption levels observed in Asia and Latin America.

Estimate amount of time a person is willing to spend gathering water. A water demand curve developed by the UNDP/World Bank Handpump Project is used to calculate the time a person is willing to spend gathering water. The curve shows the relationship between per capita water demand (liters/capita/day) and water-gathering time (hours/m^3). Therefore, when per capita water demand is known, time spent gathering water can be calculated.

Calculate water-gathering time and population served per water point. Water collection time has three components: time spent walking to and from the water point, queuing time, and water collection time. Both walking and queuing time depend on the number of persons served per water point and other factors. For example, for a given household density (houses/hectare), as the number of persons served per water point increases, each person, on the average, will have to walk further to reach the water point. Also, as the number of

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[19] The World Bank, "Rural Water Supply and Sanitation: Time for Change," Unpublished typescript, June 1986.

persons per water point increases, each person will have to wait longer to gain access to the water point, i.e., the queuing time increases. Queuing time is modeled using commonly used waiting line models.[14] The water collection time is a function of the water delivery rate of the standpipe and handpump. Population served per water point is estimated by determining the population at which water-gathering time equals the time a person is willing to spend (from the demand curve calculation). This procedure is illustrated in Exhibit 4-1.

Select village population sizes for analysis. Village population sizes are set at multiples of the number of persons served per water point. For example, if one water point serves 200 persons, 2 water points will be required for a village of 400, and 10 water points are needed for a village of 2,000. In the case of a handpump system, each water point consists of one well and a handpump. For PV and diesel systems, a number of water points will require one or more wells,[15] distribution piping, and a storage tank. Each well has a pump and an associated power generator.

Calculate system component sizes. Standard engineering analyses are used to calculate system component sizes. In the case of the handpump system, sizing only involves selecting an appropriate pump that matches the water table depth. In a PV system, the number of wells, the PV array size, pumping rate, and battery capacity (if used), storage tank size, and piping length are computed. The components in a diesel system are similar to the PV system; the only variations are that the PV power source is replaced by a diesel, no battery is needed, and a different pump is used.

Calculate system costs. For each water supply system, corresponding to the previously defined village sizes, the following costs are computed:

- initial capital costs
- annualized capital costs
- annual operation and maintenance costs
- water costs ($/cubic meter)
- annual per capita costs ($/person/year)
- per capita initial costs ($/person).

Graphical output. The model generates graphical output showing the variation in water cost and per capita initial capital cost with village population size for each of the three technologies. These graphs are useful in answering questions such as: "What is the technology that can supply water at the least cost for a village of 1,000 persons if each person is to receive 20 lpcd?" or "Which technology has a lower initial cost per person served if the village has 400 people and each person needs 40 lpcd?" Sample output is shown in Exhibit 4-1 and other examples can be found throughout the following sections of this report.

Sensitivity analyses. The model can perform a large number of "what if" analyses. This capability is an important feature of the model. It enables the model to be used for site-specific analyses or to assess the sensitivity of the technology choice to key uncertain data.

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[14] Wagner, H. M., "Principles of Operations Research," Prentice Hall Second Edition, 1975, Chapter 20. The handpump is represented as a single-server model with Poisson input and exponential service. Since each standpipe has two taps, the standpipe is depicted as a two-server model with Poisson input and exponential service.

[15] More than one well is needed if the well yield is limited, or if very high reliability provided by the availability of two or more wells is required.

Uncertainties could include diesel fuel cost, PV array cost, solar insolation, pump efficiencies, life of handpump and other equipment, labor costs, etc.

The analysis procedure has been programmed using Lotus 1-2-3 Release 2.0 software.[16] The program includes several macros to help conduct the analyses, print reports, and generate the graphs. A detailed description of the model is given in Appendix B. Sample model output is shown in Appendix C.

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[16] Lotus Development Corporation, "Lotus 1-2-3," Release 2.0, Cambridge, Mass.

5.0 COMPETITIVE ASSESSMENT AND SENSITIVITY ANALYSES

5.1 Scenarios Analyzed

The objective of the analysis is to determine where PV water pumping systems would be economically viable for supplying water to rural communities when compared to handpumps and diesel pumps. The analyses were conducted for per capita water consumption levels of 20 and 40 liters/day. Numerous sensitivity analyses were also conducted to assess how the conclusions are affected by key data uncertainties. The scenarios described in Exhibit 5-1 are analyzed for the 20 and 40 liters per capita/day water consumption levels (lpcd). A total of 56 cases was analyzed.

Exhibit 5-1

SCENARIOS EVALUATED AND SENSITIVITY ANALYSES CONDUCTED

A. For 20 and 40 lpcd water demand, plane-of-array worst-month insolation levels of 4, 5, and 6 kWh/m²/day and the following well characteristics:*

- $500 cost and a 5 m depth (e.g., Bangladesh)
- $1,500 cost and a 20 m depth (e.g., parts of India and East Africa)
- $2,500 cost and a 20 m depth (average conditions)
- $3,000 cost and a 20 m depth (e.g., West Africa)
- $3,000 cost and a 40 m depth (e.g., West Africa)

This consists of a total of 30 scenarios.

B. Sensitivity analyses were conducted for water demands of 20 and 40 lpcd by varying the following parameters from the Base Case:*

1. Diesel fuel cost equals $1/liter. This reflects situations where fuel delivery is difficult and costly.

2. One day of water storage for the PV system instead of three days. Three days of water storage ensure that 99% of the time the designated water demand (e.g., 20 or 40 lpcd) is available. When one day of storage is used, availability is about 97% or demand may not be fully satisfied for about 11 days of the year.

3. PV array cost of 50% to 200% of the base-case assumptions was used to assess the impact of PV array cost variations.

4. Reduction in handpump life from 10 to 5 years was used to evaluate the impact on PV competitiveness of shorter handpump life.

5. A reduction in analysis lifetime from 20 to 10 years.

6. Use of at least two wells per village for PV and diesel systems to ensure very high water supply reliability.

7. A reduction in well yield to 2 m³/hour to account for situations where pumping rate must be limited so that excessively high drawdown does not occur during continuous pumping.

8. A reduction in water delivery rates of handpumps and standpipes to reflect water collection inefficiencies.

9. Halving the number of persons served per standpipe to assess the impact of making the number of persons served at a standpipe approximately equal to the number served at a handpump.

*The Base-Case assumptions: insolation - 5 kWh/m²/day; well cost - $2,500; water table depth - 20 m; diesel fuel cost - $0.30/liter; 3 days water storage for PV systems; 6 hours per day use of water point; 20-year analysis time frame; one well per village for PV and diesel systems; and adequate well yield.

WELL COST: $2,500
DEPTH: 20 m
DEMAND: 20 lpcd

Exhibit 5-2

COST OF WATER

WELL TYPE = 3, LPCD = 20

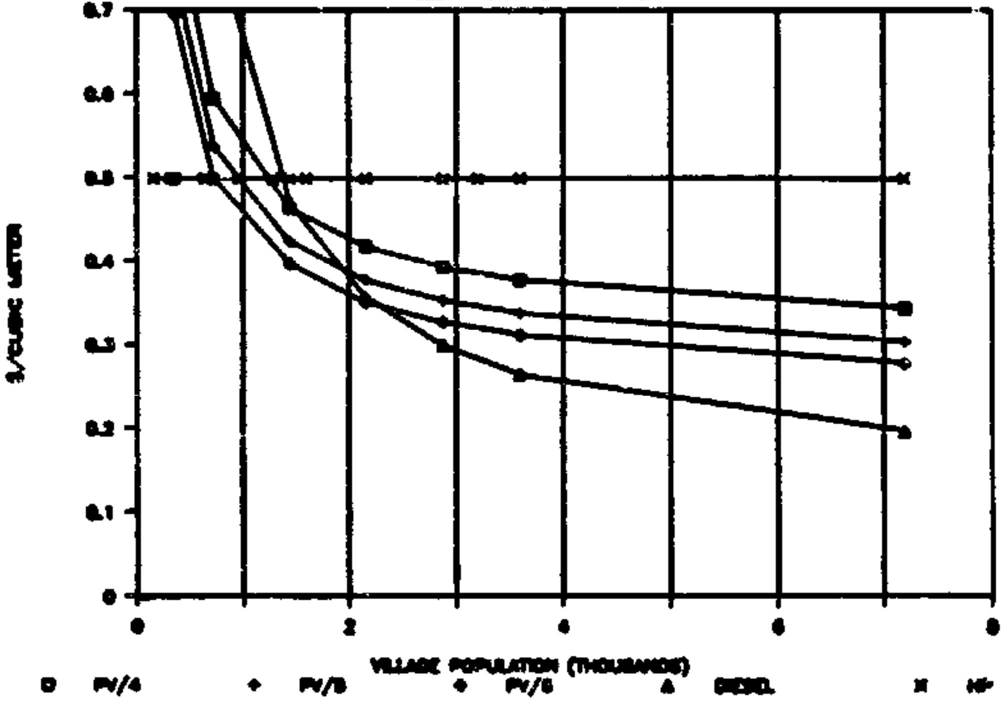
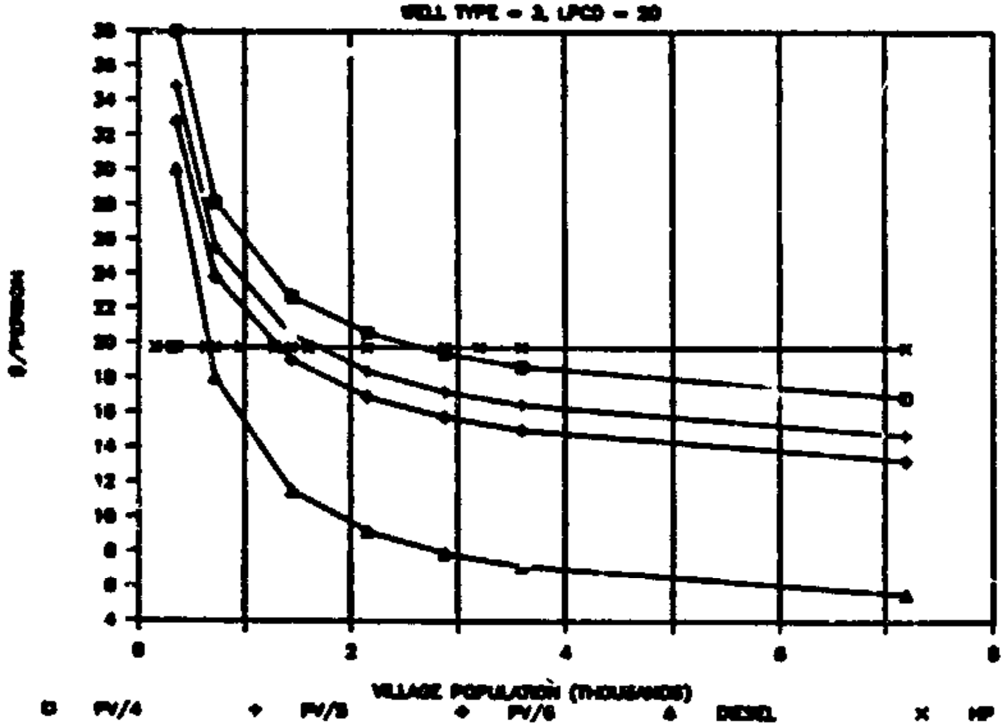


Exhibit 5-3

PER CAPITA CAPITAL COST

WELL TYPE = 3, LPCD = 20



Exhibits 5-2 and 5-3 show sample graphical output from the analysis for the base case. Exhibit 5-2 shows the variation in water costs as a function of village population size for handpump, PV, and diesel pumping systems. Water costs for the PV systems are shown for insolation levels of 4, 5, and 6 kWh/m^2/day. The graph shows that at an insolation of 5 kWh/m^2/day, water from a PV system becomes cheaper than water from handpumps at a village size of about 1,000 persons. At village sizes greater than 2,000, least cost water is obtained from a diesel system. As insolation increases from 5 to 6 kWh/m^2/day, the range of village sizes for which PV is competitive increases to between 800 and 1,200 persons.

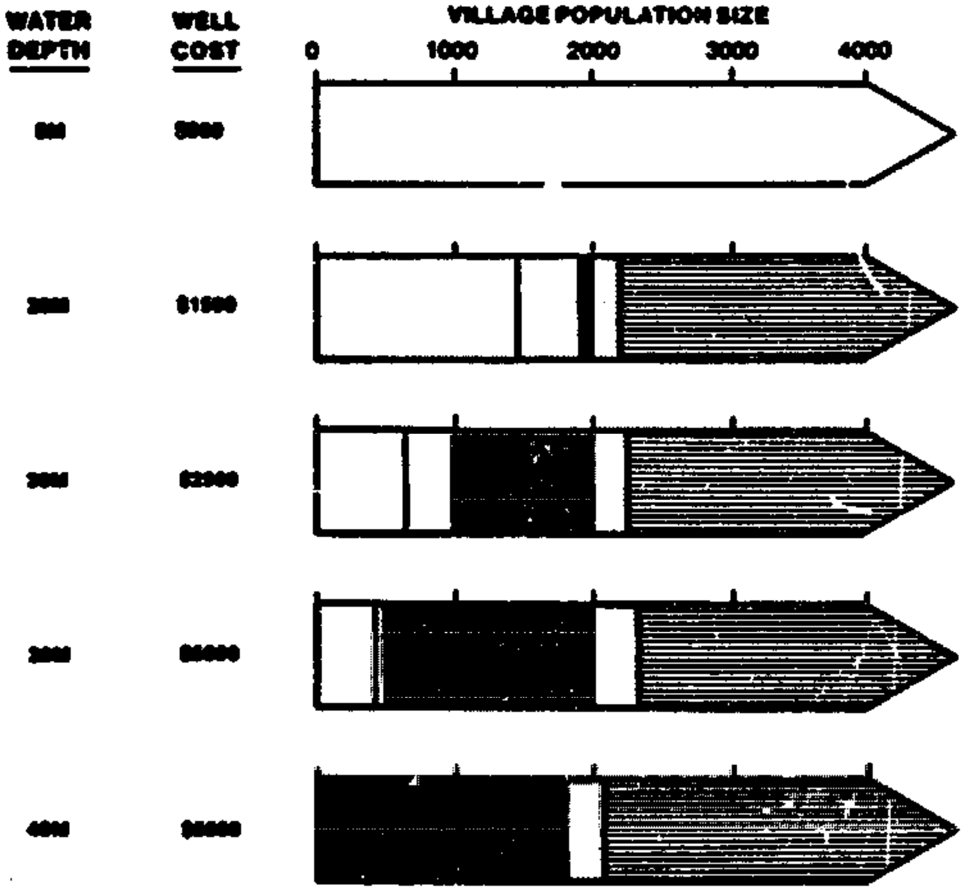
Exhibit 5-3 shows how the per capita initial capital cost changes with increasing village population size. Diesel systems have the lowest per capita capital costs after a village size of about 800 persons. However, the very high recurrent costs of diesels must be noted as well. Per capita capital costs of PV become cheaper than those of handpumps at 1,200, 1,800, and 2,600 persons per village at insolation levels of 6, 5, and 4 kWh/m^2/day, respectively.

Similar graphs for the other cases mentioned in Exhibit 5-1 are shown in Appendix D. The graphical results are summarized and analyzed in the following sections.

Exhibit 5-4

Life-Cycle Cost Competitiveness

VARIATION WITH VILLAGE POPULATION SIZE AND WELL CHARACTERISTICS (20 LPCD)



LEGEND

Life-Cycle Cost Competitiveness Range

☐ Handpump

■ PV Pump
4 5 6 Insolation Level (kWh/m²/day)

▤ Diesel Pump

5.2 PV Life-Cycle Cost Competitiveness at 20 LPCD Consumption

Exhibit 5-4 shows the life-cycle cost competitiveness ranges for the three technologies as a function of village population size, insolation, and well characteristics.

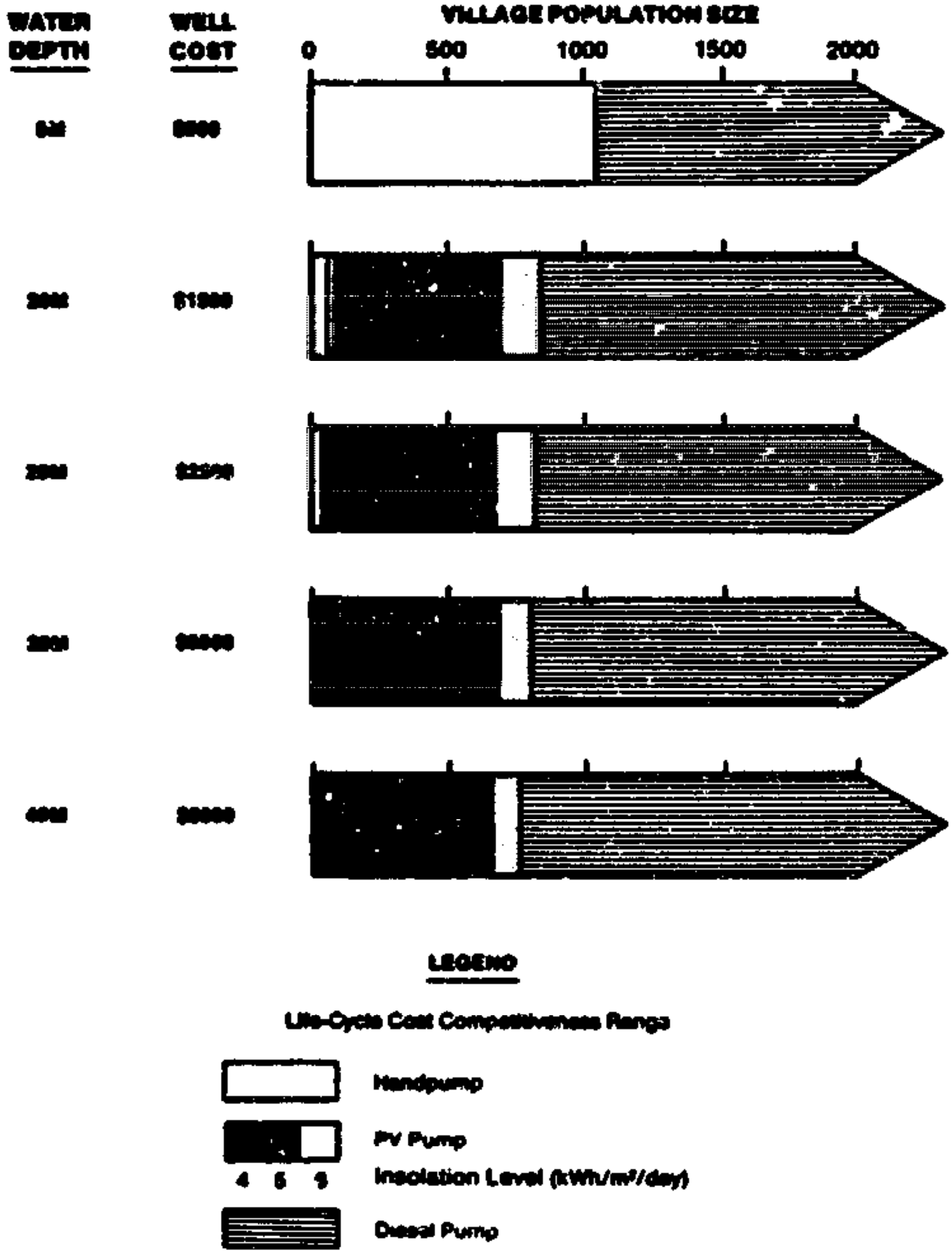
For 20 lpcd water consumption, PV is the preferred technology for a village of about 1,500 persons. When a well costs $2,500 and the water table is 20m deep, PV is the competitive technology at an insolation level of 5 kWh/m^2/day for a village of 1,000-2,000 persons. When insolation is 4 kWh/m^2/day, the competitive range narrows to 1,200-1,900 persons/village. Correspondingly, as insolation increases, PV is the competitive technology for a large range of village sizes (800 to 2,200 persons per village at 6 kWh/m^2/day insolation). As well cost and water table depth increases, PV becomes competitive at smaller village sizes.

In some West African countries, where wells cost between $5,000 and $10,000 each and insolation is 6-7 kWh/m^2/day, PV would be the preferred technology for villages with populations as few as 200 persons, if water table depths are around 20 meters. At higher water table depths, for example, 40 meters, PV would provide lower-cost water even for villages with very small populations in West Africa.

Exhibit 5-6

Life-Cycle Cost Competitiveness

VARIATION WITH VILLAGE POPULATION SIZE AND WELL CHARACTERISTICS (40 LPCD)



5.3 PV Life-Cycle Cost Competitiveness at 40 LPCD Consumption

Exhibit 5-5 provides the same type of information as Exhibit 5-4 for a higher water consumption levels.

At 40 lpcd of water consumption, PV can provide lowest cost water than the alternatives for even smaller villages when compared to consumption levels of 20 lpcd. Village size where PV is competitive ranges from 0 to about 900, depending on insolation and well characteristics. The average village size for which PV is competitive is about 500 persons. As in the previous case, PV competitiveness occurs in smaller villages as well costs increase.

EXHIBIT 5-6
Least Water Cost Technologies for Various Village Sizes Under Average Well Conditions*

Insolation: 4 kWh/m^2/day

Least Water Cost Technology	Village Size Range (no./village)	Water Cost ($/cubic meter)	Per Capita Capital Cost ($/person)
<------------------- 20 liters/person/day water consumption ------------------->			
Handpump	0 - 1,200	0.50	20
Photovoltaics	1,200 - 1,500	0.46 - 0.50	22 - 24
Diesel	> 1,500	0.20 - 0.46	6 - 11
<------------------- 40 liters/person/day water consumption ------------------->			
Handpump	0 - 90	1.35	105
Photovoltaics	90 - 560	0.60 - 1.35	50 - 105
Diesel	> 560	0.35 - 0.60	20 - 28

* Average well conditions: 20m water table depth and $2,500 well cost.

Least Water Cost Technologies for Various Village Sizes Under Average Well Conditions*

Insolation: 5 kWh/m^2/day

Least Water Cost Technology	Village Size Range (no./village)	Water Cost ($/cubic meter)	Per Capita Capital Cost ($/person)
<------------------- 20 liters/person/day water consumption ------------------->			
Handpump	0 - 1,000	0.50	20
Photovoltaics	1,000 - 2,000	0.38 - 0.50	19 - 24
Diesel	> 2,000	0.20 - 0.38	6 - 10
<------------------- 40 liters/person/day water consumption ------------------->			
Handpump	0 - 80	1.35	105
Photovoltaics	80 - 800	0.50 - 1.35	50 - 125
Diesel	> 800	0.35 - 0.50	20 - 25

* Average well conditions: 20m water table depth and $2,500 well cost.

5.4 Water and Capital Cost of Cost-Competitive Water Supply Technologies

Exhibit 5-6 shows the competitive water costs, per capita initial capital costs, and corresponding village sizes for the least cost water supply technologies. Results at insolation levels of 4, 5, and 6 kWh/m^2/day are shown in the exhibit.

Under average conditions (insolation equal to 5 kWh/m^2/day) when water consumption is 20 lpcd, the average cost of water from a PV system is about $0.44/m^3 or about $3.20/person/year. At a 40 lpcd consumption level, average water cost is $0.93/m^3, or about $13.60/person/year.

The exhibits also show that the initial capital cost of PV on a per capita basis is comparable to, and even less than handpump systems supplying the same service. The principal reason is that due to the limited pumping rate, only a few people can be served from a handpump. In contrast, a large number of people can be served from a PV pumping system. If well costs are high, PV pumps are particularly more cost-effective than handpumps.

From a RWS system implementation perspective, the above observation means that <u>PV pumping systems can be installed at a cost equal to or less than a handpump system.</u>

EXHIBIT 5-6 (Cont'd)
Least Water Cost Technologies for Various Village Sizes
Under Average Well Conditions*

Insolation: 6 kWh/m^2/day

Least Water Cost Technology	Village Size Range (no./village)	Water Cost ($/cubic meter)	Per Capita Capital Cost ($/person)
<------------------- 20 liters/person/day water consumption ------------------->			
Handpump	0 - 800	0.50	20
Photovoltaics	800 - 2,200	0.35 - 0.50	17 - 24
Diesel	> 2,200	0.19 - 0.35	6 - 9
<------------------- 40 liters/person/day water consumption ------------------->			
Handpump	0 - 75	1.35	105
Photovoltaics	75 - 800	0.50 - 1.35	40 - 105
Diesel	> 800	0.35 - 0.50	20 - 25

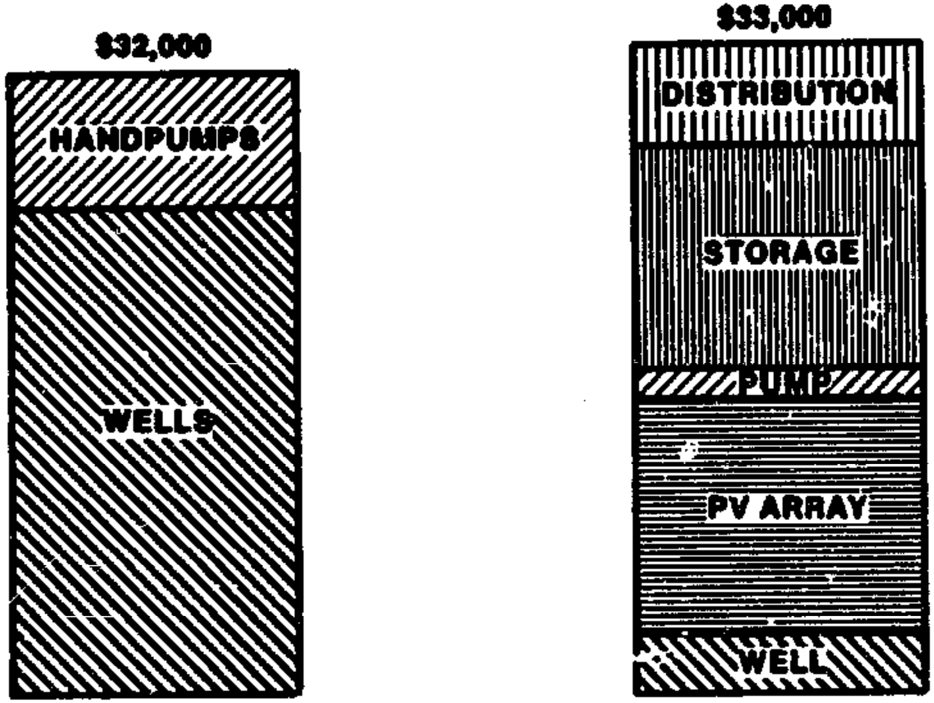
* Average well conditions: 20m water table depth and $2,500 well cost.

Exhibit 5-7

CAPITAL COST COMPARISON OF A HANDPUMP AND PV RWS PROJECT

Uganda Luwero Triangle Handpump RWS Project
UNICEF/Uganda Ministry of Water & Mineral Resources,
Water Development Department

Example: 2000 Persons/Village, 20 Liters/Capita/Day, 200 Persons/Water Point



CURRENT HANDPUMP RWS SYSTEM
AVERAGE CAPITAL COST
(10 HANDPUMPS)

EQUIVALENT PV RWS SYSTEM
ESTIMATED CAPITAL COST

For example, Exhibit 5-7 compares the initial capital cost of handpump and PV RWS systems in a 2,000 person village in the Luwero Triangle area in Uganda. The handpump system costs, water resource characteristics, number of persons served per waterpoint (handpump), and water demand are based on UNICEF experiences in the project area.[17] The PV system costs are based on insolation of 5 kWh/m^2/day in the worst month,[18] 20-meter water table depth, $2,500 well, same number of persons served per waterpoint as in the handpump case, and other cost and performance data as reported in Appendix A. The comparison clearly shows how a PV RWS system could have an initial capital cost similar to that of a handpump system. The initial capital cost of the handpump system is $16/person which UNICEF reports is among the lowest in Africa. The comparable PV system cost is $16.50/person, or only 3% higher than the handpump system cost.[19]

The exhibit also shows the system component cost breakdown. As indicated, the PV array cost is less than the cost of storage and distribution. If the community can be organized to volunteer their labor to assist in constructing the storage tank and laying the pipe distribution network, the PV RWS system cost could be less than the comparable handpump system cost.

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[17] Wolfe, P., "Signs of Self Sustaining Development: A Successful Water Supply Programme in Uganda," Development Business, No. 222, May 15, 1987.

[18] Photovoltaic Design Assistance Center, "Water Pumping: The Solar Alternative," SAND87-0804, April 1987, p. A-8, Figure A-7: Insolation Availability (Latitude Tilt, Summer).

[19] A comparable initial cost of $20/person was reported by David Kinley for a PV water supply system serving 2,000 persons in Baie de Henne, Haiti. (Kinley, D., "Sustainable Water Supplies in Developing Countries," Presentations of the Photovoltaics: Investing in Development Conference Proceedings, May 4-6, 1987, p. V-52.

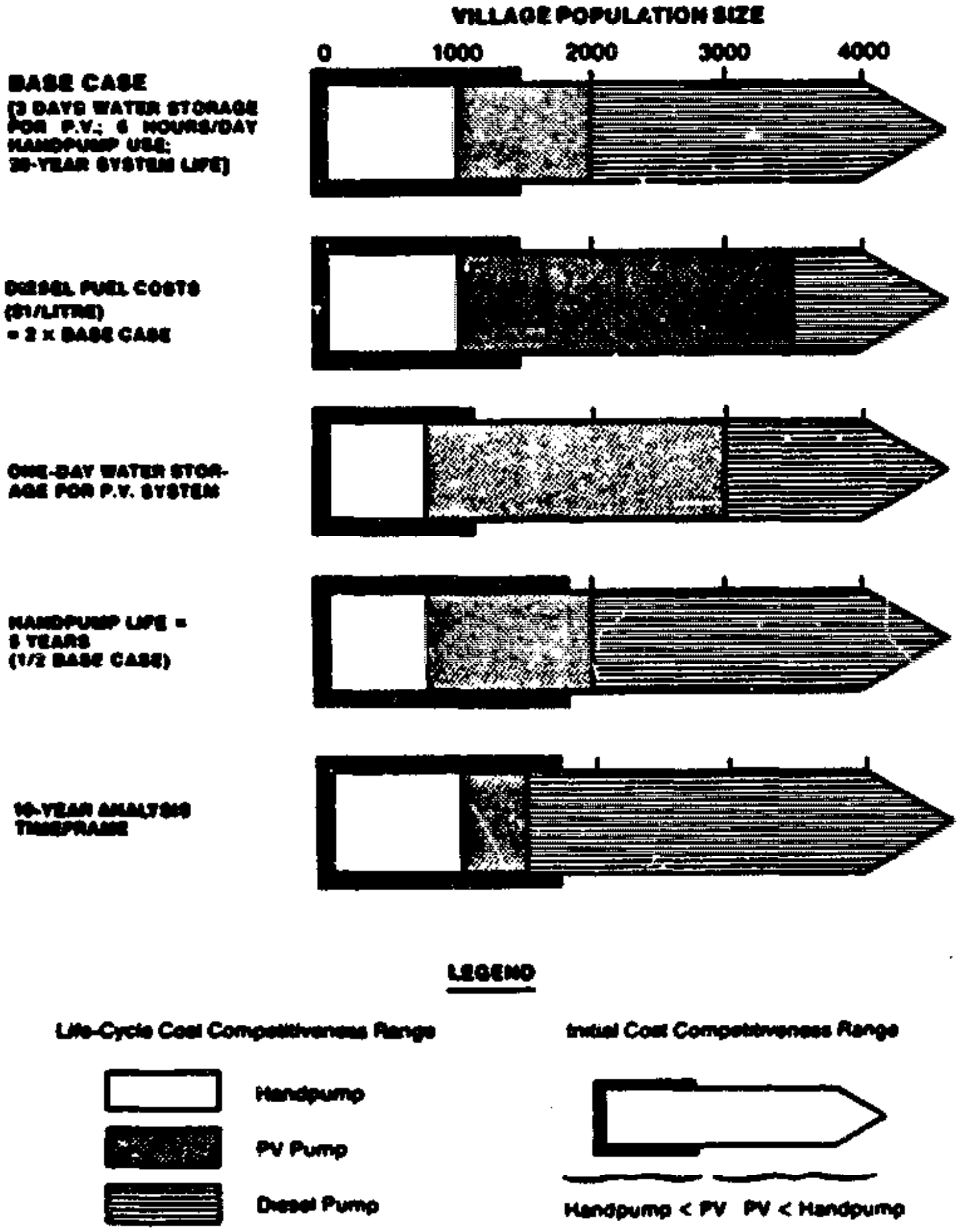
Exhibit 5-8

SENSITIVITY ANALYSIS

Life-Cycle and Per Capita Initial Cost Competitiveness

SCENARIO

Water Consumption Level - 20 LPCD
Insolation Level - 5kWh/M^2/Day
Well Cost - $2500
Water Depth - 20 M



5.5 Sensitivity Analyses for 20 LPCD Consumption

Exhibit 5-8 shows the sensitivity of PV competitiveness to a number of variables when water demand is 20 lpcd. The analyses are conducted under average conditions (i.e., insolation at 5 kWh/m^2/day and 20-m water depth and a well cost of $2,500).

The principal observation is that the village size at which water from PV becomes cheaper than that of handpumps does not vary significantly even though major changes are made to important variables. The two exceptions occur in cases in which well yield is limiting and a minimum of two wells is used. In these two instances, water from a PV system costs less than from a handpump when village size is about 1,600.

The cost-competitiveness point between PV and diesel is highly sensitive to the input assumptions. The reason for the sensitivity is that the water costs from PV and diesel systems are similar for larger village population sizes (see Appendix A). Accordingly, a slight difference in water costs can result in a major shift in cost-competitive village sizes. In such instances when PV and diesel costs are similar, PV may be preferred due to its greater reliability, unless there is a capital shortage. Therefore, when determining the relative competitiveness of PV to diesel, it is critical to gather accurate and representative data.

The exhibit also shows that in many cases, even on a per capita initial capital cost basis, PV is competitive with handpumps. For example, in the base case, PV initial capital cost is less than that of a handpump system when village population exceeds 1,500 persons.

Exhibit 5-8 (Cont'd)

SENSITIVITY ANALYSIS

Life-Cycle and Per Capita Initial Cost Competitiveness

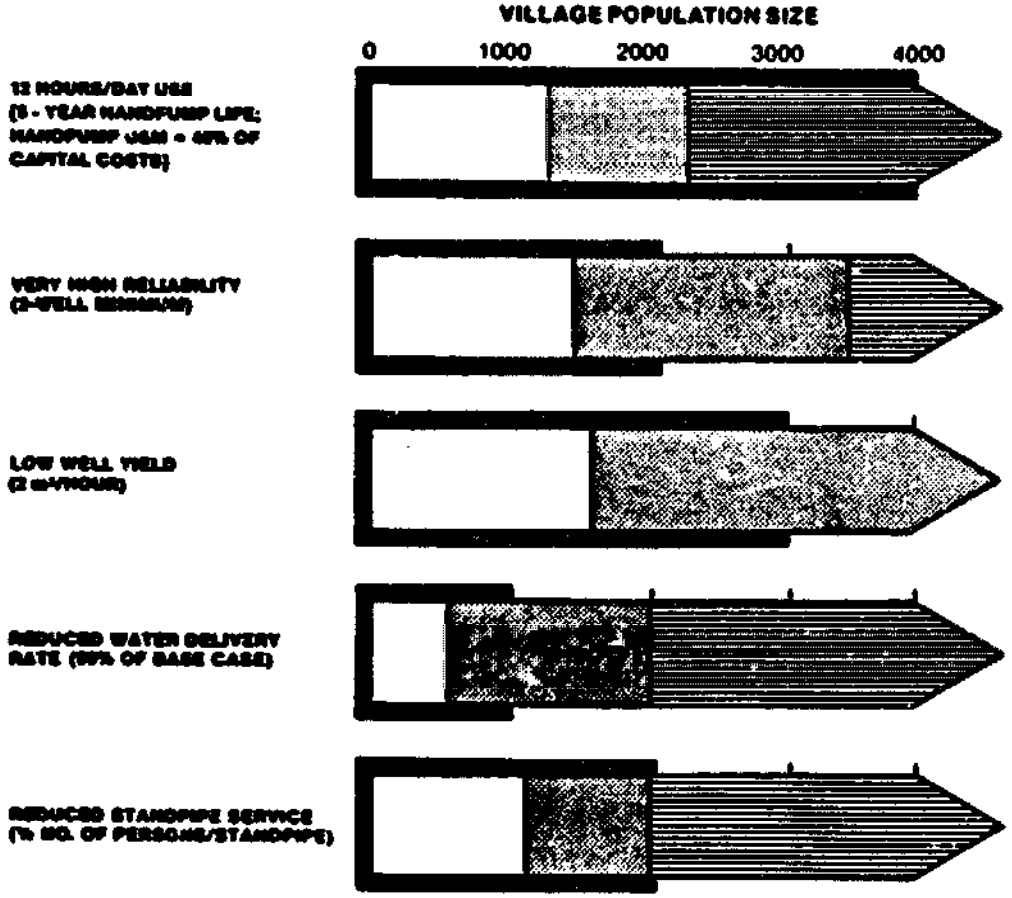


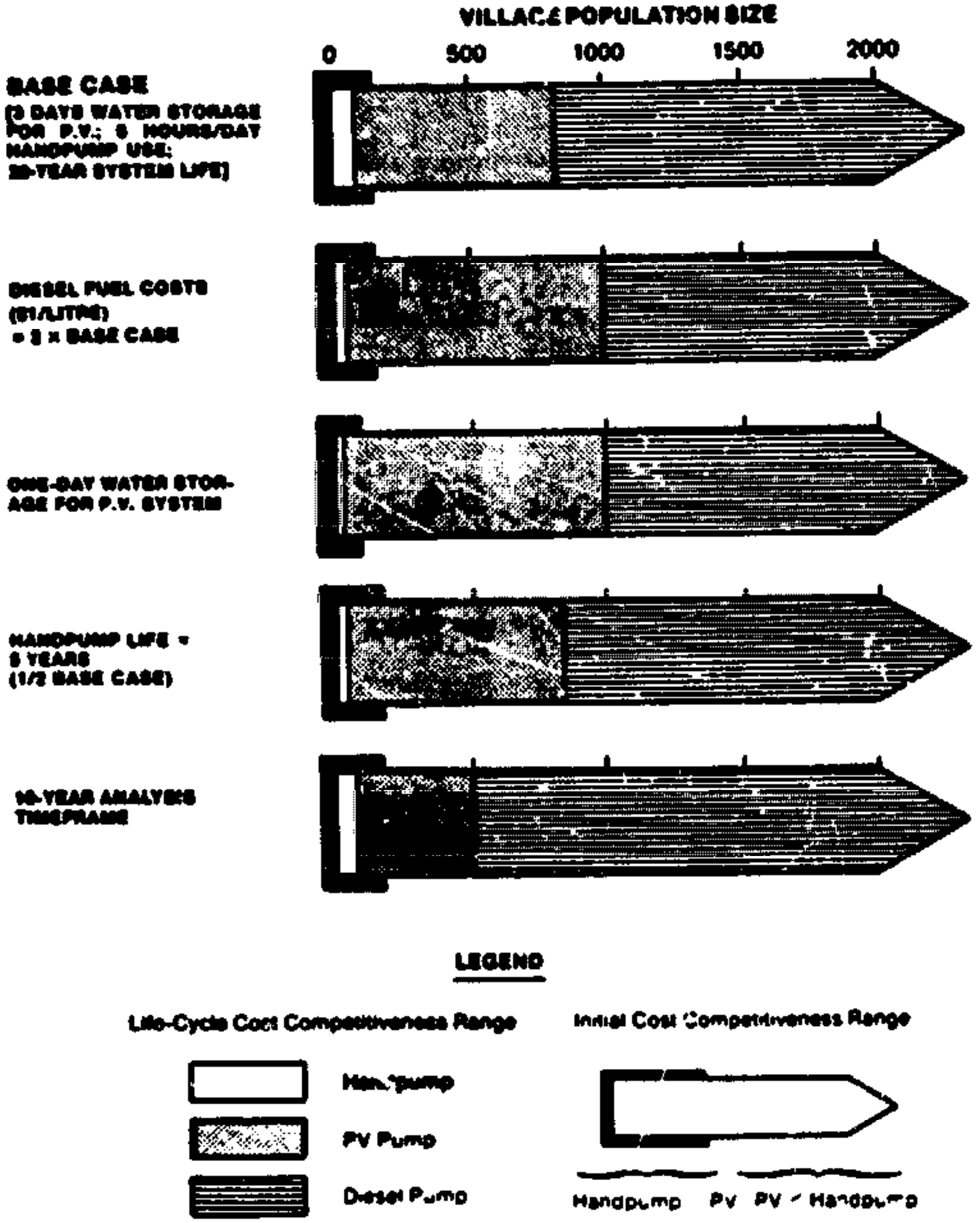
Exhibit 5-9

SENSITIVITY ANALYSIS

Life-Cycle and Per Capita Initial Cost Competitiveness

SCENARIO

Water Consumption Level - 40 LPCD
Insolation Level - 5 kWh/M^2/Day
Well Cost - $2500
Water Depth - 20 M



5.6 Sensitivity Analyses for 40 LPCD Consumption

Exhibit 5-9 shows sensitivity analysis results when water demand is 40 lpcd.

The principal observation is that the village size ranges for which PV is competitive with handpumps and diesels vary only slightly between scenarios. Typically, water supplied from a PV system is less costly than water from a handpump at a village size of 50-100 persons. The corresponding PV/diesel cost-competitiveness point is 800-1,200 persons. Also, even on a per capita capital cost basis, PV is the less costly option when the village population exceeds about 100 persons.

Exhibit 5-9 (Cont'd)

SENSITIVITY ANALYSIS

Life-Cycle and Per Capita Initial Cost Competitiveness

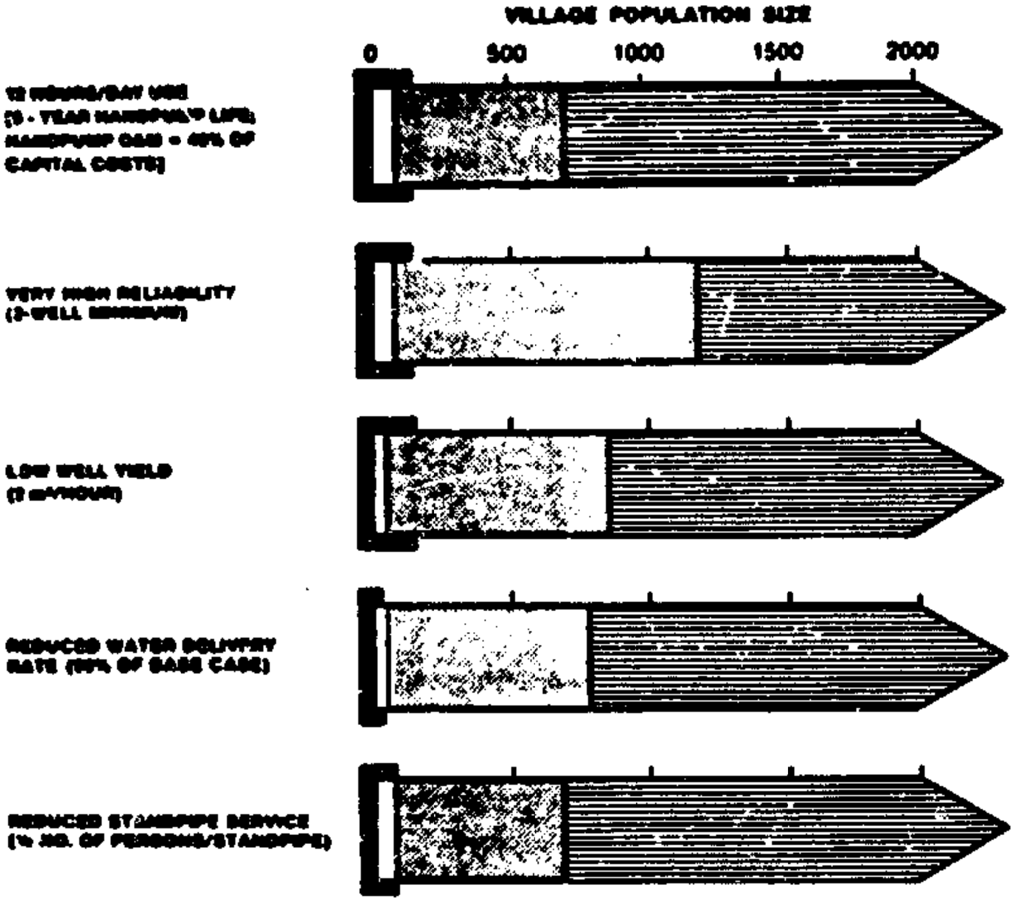


Exhibit 5-10

ESTIMATION OF POTENTIAL MARKET FOR PV WATER PUMPING SYSTEMS

NOTES-->	A	B	C	D	E	F
REGION	RURAL POPLTN. WITHOUT SAFE WATER ACCESS (MILLIONS)	ESTIMATED REGIONAL WELL COST ($)	ASSUMED POPULATION IN AREAS WATER TABLE >100M (MILL.)	WORST MONTH ISOLTN. KWH/M2/DAY	ASSUMED WATER USE RATE (LPCD)	PV COST COMPETITIVE VILLAGE SIZE (PERSONS)
ANDEAN COUNTRIES	13	2500	10	5	40	75-500
CENTRAL AMERICA & CARIBBEAN	32	2000	10	4	40	75-500
EQUATORIAL AFRICA	60	3000	41	6	30	500-2000
EASTERN & SOUTHERN AFRICA	64	2500	32	5	30	1000-2000
FAR EAST & THE PACIFIC	200	2500	80	5	40	75-500
INDIAN SUBCONTINENT	412	1500	124	6	40	200-500
LATIN AMERICA (N.E.C.) *	30	2500	10	4	40	75-500
MIDDLE EAST & NORTH AFRICA	110	2500	82	4	20	1200-2000
SAHEL	10	5000	8	6	30	200-2000
TOTAL	930		397			

NOTES-->	G	H	J	K	L
REGION	% POP. IN VILLAGES WHERE PV COMPETV.	POTENTIAL POPULATION SERVED BY PV SYSTEMS (MILLIONS)	POTENTIAL POPULATION SERVED BY HP/SURFACE (MILLIONS)	POTENTIAL POPULATION SERVED BY DIESELS (MILLIONS)	MAXIMUM EQUIVALENT PV NEEDED MWp
ANDEAN COUNTRIES	40	4	4	5	9
CENTRAL AMERICA & CARIBBEAN	14	1	23	8	4
EQUATORIAL AFRICA	35	14	36	10	29
EASTERN & SOUTHERN AFRICA	32	10	46	8	15
FAR EAST & THE PACIFIC	40	32	123	45	76
INDIAN SUBCONTINENT	30	37	293	82	89
LATIN AMERICA (N.E.C.)	14	1	19	9	4
MIDDLE EAST & NORTH AFRICA	38	31	54	25	31
SAHEL	82	7	1	1	7
TOTAL		137	599	193	264

Notes:

A. 1983 estimate, China is not included due to lack of data. Source: Report of the Secretary General to the UN to the Economic and Social Council of the UN General Assembly, "Progress in the Attainment of the International Drinking Water Supply and Sanitation Decade," A/40/108, March 1985.
B. Source: UNDP/World Bank Handpump Project and author estimates
C. Author estimates, based on knowledge of regional water table characteristics and on assumption that majority of rural persons are in areas where water table is shallow
D. From worst month insolation profile map developed by UNICEF (SPI Product Catalog, 1986).
E. Source: World Bank, Village Water Supply, 1984.
F. Estimated from analysis results shown in Exhibits 5-4 and 5-6 using regional characteristics given in columns B, D, and E.
G. Based on village population distributions in India reported in: Roche, Robert, The Impact of Water Quality and Water Quantity on Health in Rural Communities in Developing Countries, Ph.D. Dissertation, University of California at Berkeley, California, 1985. Indian data used in the absence of data from other countries or regions.
H. (Column G) * (Column C)/100
J. (Column A - Column C)* (fraction of population in villages smaller than village size lower limit in Column F). Village size distributions from Dr. Roche. Surface: Surface Water Sources.
K. (Column A)-(Column H)-(Column J)
L. 0.01*(30 m)*(Column E)/1000*(Column H)/[3.6*(PV pump eff)*(PV BOS eff)*(Column D)]

* *N.E.C. - Not elsewhere considered.*

5.7 Market Estimate for PV RWS Systems

A very large population can be cost-effectively served by PV water supply systems. Exhibit 5-10 presents a preliminary estimate of regional markets for PV water pumping systems and the number of persons served. The market is of the order of 250 MWp, which is several times the current worldwide PV production capacity. Additionally, rural populations are continuing to grow at a rate of 30 to 35 million persons per year. If PV retains the market share estimated in Exhibit 5-10, the annual demand for PV for this new population is nearly 10 MWp per year.

Exhibit 5-11 shows that the largest demand for PV is likely to be in Asia and the Pacific region, followed by Africa. Demand is expected to be relatively small in Latin America and the Caribbean. Exhibit 5-12 shows the breakdown of population served by handpumps, PV, and diesel. Handpumps are expected to mainly serve the shallow-well market. The handpump market segment includes rural populations served by surface water sources. A finer disaggregation of the shallow water table market segment could not be made due to lack of data. It is quite possible that PV or diesels could supply cost-competitive power for pumping from surface water sources, if gravity feed is infeasible.

The market estimate for diesels is based on the availability of reliable fuel supplies and maintenance services in rural areas. In many parts of the world, particularly in Africa, diesels have a poor operating record. If diesels are infeasible, PV pumping systems could likely replace them.[30]

Other analyses[31] report that considerable opportunities exist for PV RWS systems at 20-40 m water table depths. Zimbabwe is an example, where a typical village requires 12-25 m^3/day of water.[32] Water table depths in Zimbabwe range from 15-50 m. In a World Bank-funded project in Niger, 16,000 boreholes will be drilled and equipped with handpumps for supplying villages from a 20-40 m deep water table. These villages could be served economically and reliably with PV at a cheaper per capita cost, as well drilling costs are very high in Niger.[33] Water demand in Niger is about 20-30 lpcd. Also, handpumps in Niger have had a dismal reliability record; over 50 percent of the handpumps previously installed are inoperative. India will soon be implementing a five year $1.62 billion rural water supply

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[30] Note that the present analysis did not consider other pumping power sources such as wind power, which in suitable areas, could pump water more economically than PV or diesels. A wind technology competitiveness analysis was beyond the scope of this study.

[31] Leguerne, J.R. and Lascand. "An Analytical Approach to a PV Water Pumping System," and Vespierian B., "The Application of PV to Water Pumping and Irrigation in Africa." Proceedings, 3rd European Economic Community Photovoltaics Conference, D. Reidel, Boston, 1980.

[32] Ward, P.R.B., et al. "Solar Powered Ground Water Pumping for Medium Heads, Challenges in African Hydrology and Water Resources." Proceedings of the Harare Symposium, IAHS Publication No. 144, 1984.

[33] Meridian Corporation and IT Power, Inc. "Photovoltaics Project Identification Initiative," Interim Report to Sandia National Laboratories, October 1986.

Exhibit 5-11

REGIONAL PV PUMPING SYSTEMS POTENTIAL DEMAND DISTRIBUTION
Total Potential Demand - 264 MWp

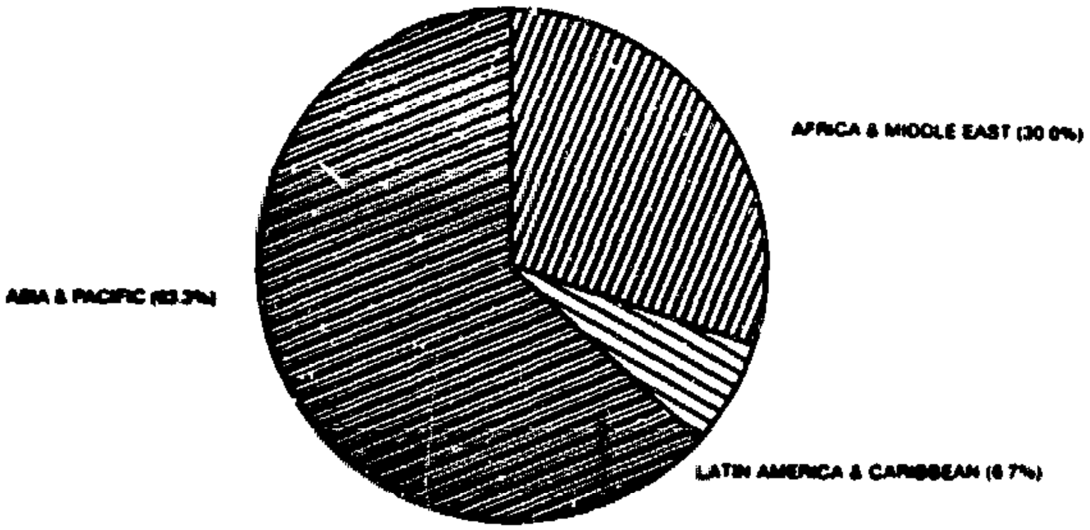
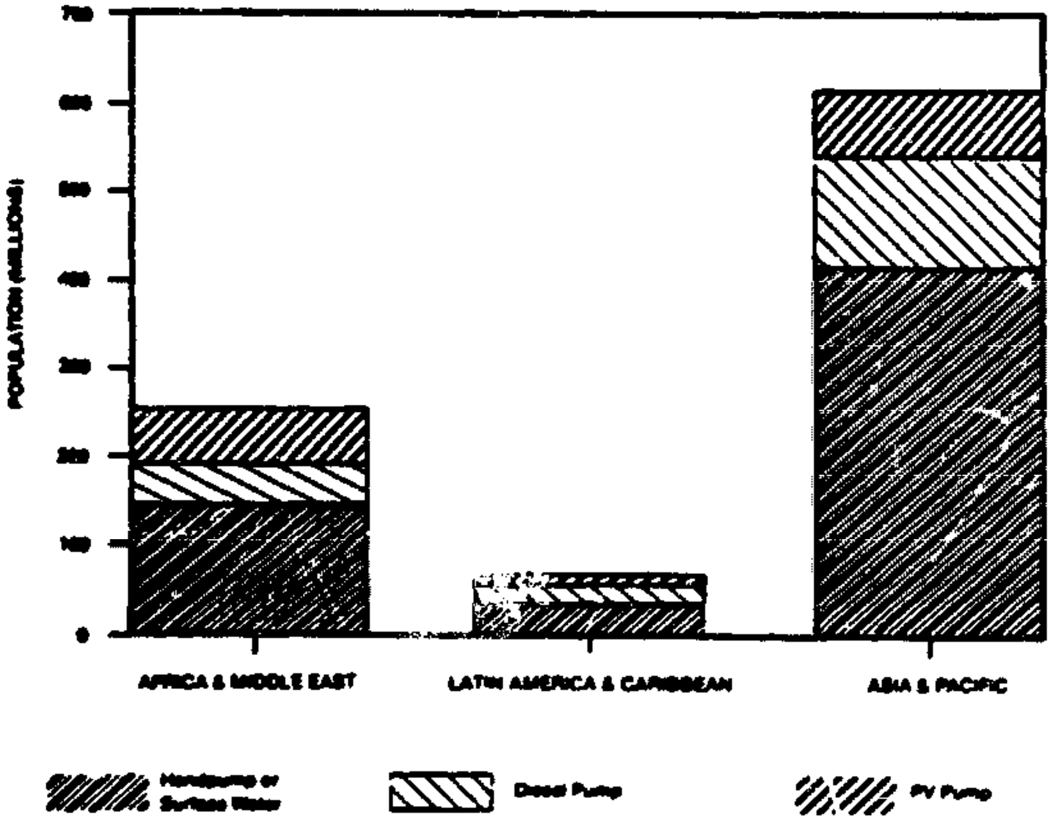


Exhibit 5-12

POTENTIAL POPULATION SERVED BY HANDPUMPS, PV & DIESEL
Total Rural Population Without Access to Safe Water - 928 Mill. (1983 Est.)



project that aims to provide water to 270,000 villages.[34] The average per capita cost is expected to be $20-50, which is within the cost-competitive range for PV as shown earlier.

In summary, the analyses clearly show that PV-based rural water supply systems are currently economical not only on a life-cycle cost basis, but also on an initial capital cost basis. The potential market for PV water supply systems that can serve villages in the 500 to 1,000 size range is immense, many times the current worldwide PV manufacturing capacity.

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[34] Zavala, A., Water and Urban Development Department, the World Bank, April 1987, personal communication.

Exhibit 5-13

PRELIMINARY ESTIMATE OF PV PUMPING SYSTEM SPECIFICATIONS

	A	A	B	C	D	E
REGION	INSOLATION KWH/M^2/DAY	ASSUMED WATER DEMAND (LPCD)	AVERAGE VILLAGE SIZE (# OF PERSONS)	AVERAGE PV POWER SYSTEM SIZE (Wp)	AVERAGE WATER DEMAND M^3/DAY PER VILLAGE	TOTAL NO. OF VILLAGES #
Andean Countries	5	40	500	1211	20	11000
Central America & Caribbean	4	40	300	908	12	333
Equatorial Africa	5	20	1300	1574	26	18462
East Africa	5	20	1500	1817	30	6667
Far East and Pacific	5	40	500	1211	20	64000
Indian Subcontinent	5	40	500	1211	20	74000
Latin America (N.E.C.)*	4	40	300	908	12	3333
Middle East	4	20	1800	2825	36	11667
Sahel	6	20	1500	15[illegible]	30	4667
Total/Average			706	1453	22	194128
Minimum			300	908	12	
Maximum			1800	2725	36	

Notes: A. From market potential estimation table (Exhibit 5-10).

- B. Average of village size range in Exhibit 5-10.
- C. Estimated as in column I in Exhibit 5-10.
- D. Village size times per capita demand.
- E. Potential population served by PV (column H in Exhibit 5-10)/village size.
- * N.E.C. - not elsewhere considered

5.8 PV Pumping System Specifications

Information in Exhibit 5-10 was used to obtain a preliminary estimate of PV pumping system specifications. The estimation procedure and the specifications are shown in Exhibit 5-13. The exhibit shows the size of the PV pumping systems, the daily water demand per village, and the number of villages categorized by region.

Typical system sizes range from 1 kWp to 2.7 kWp, supplying 12 to 36 m^3/day of water from a well at a water table depth of about 20 meters. The average system is 1.5 kWp and supplies 22 m^3/day.

This information should be used with extreme caution as it is based on many assumptions. For example, depending on the village size ranges as reported in Exhibit 5-10, the power requirements per system could range from 0.2 kWp to 3 kWp (see Exhibit 5-14). Uncertainties are due to a lack of accurate information on village size distribution and local or regional water table depths. However, the information in Exhibit 5-13 is useful in identifying typical system sizes needed for rural water supply. Further investigations are needed before system specifications can be defined more accurately.

EXHIBIT 5-14
Variability of PV Pumping System Specifications

PV PUMPING SYSTEM SIZE (Wp) RANGES
(BASED ON VILLAGE SIZE RANGES IN COLUMN F, EXHIBIT 5-10)

REGION	SMALL VILLAGE	LARGE VILLAGE
ANDEAN COUNTRIES	182	1938
CENTRAL AMERICA & CARIBBEAN	227	1514
EQUATORIAL AFRICA	606	2432
EAST AFRICA	1211	2422
FAR EAST AND PACIFIC	182	1938
INDIAN SUBCONTINENT	484	1938
LATIN AMERICA (N.E.C.)*	227	1514
MIDDLE EAST	1817	3028
SAHEL	252	2523
MINIMUM	182	1514
MAXIMUM	1817	3028

* N.E.C. - Not elsewhere considered

Exhibit 5-15

WATER COST VARIATION WITH PV ARRAY COST

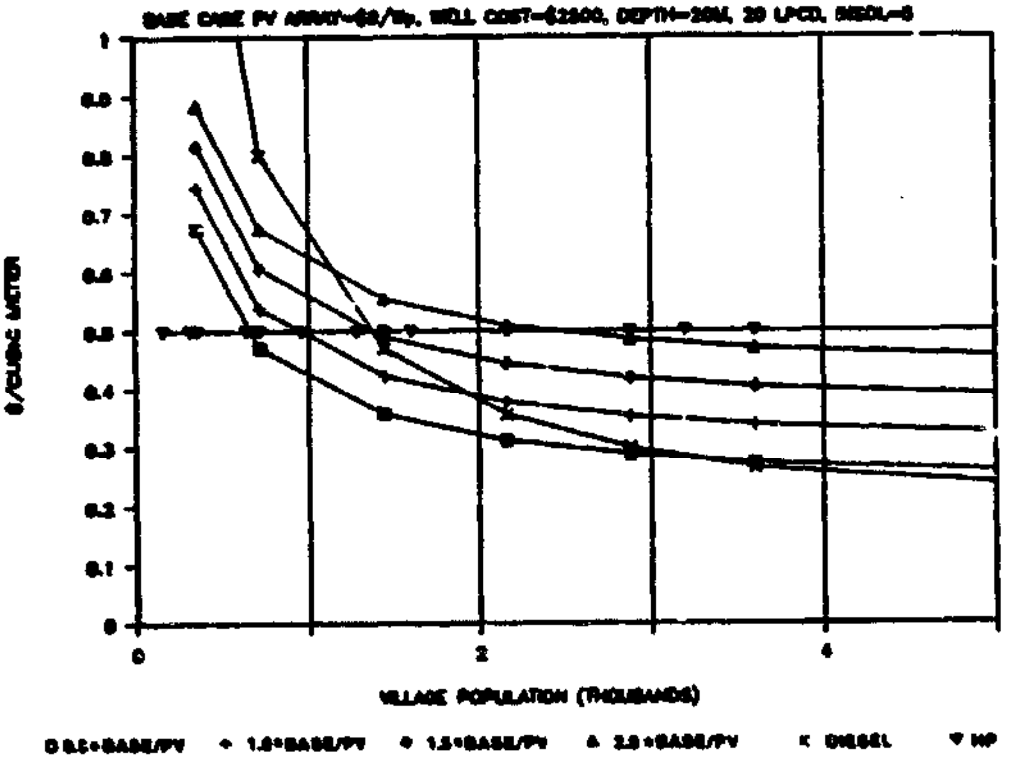
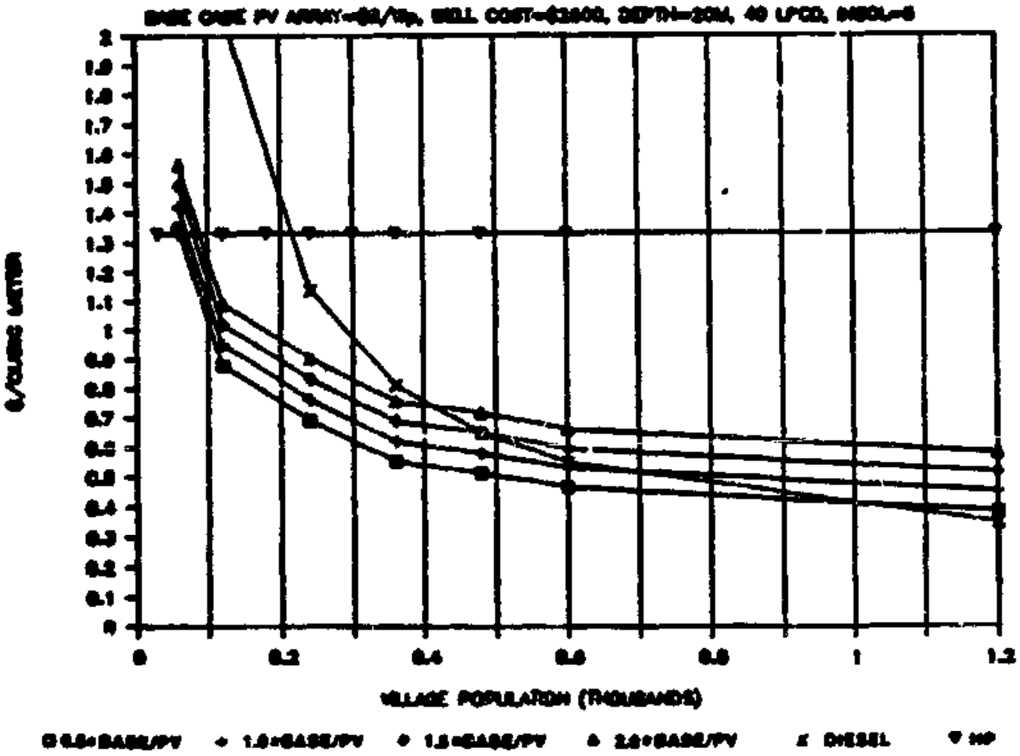


Exhibit 5-16

WATER COST VARIATION WITH PV ARRAY COST



5.9 Cost Competitiveness Sensitivity to PV Array Cost Variations

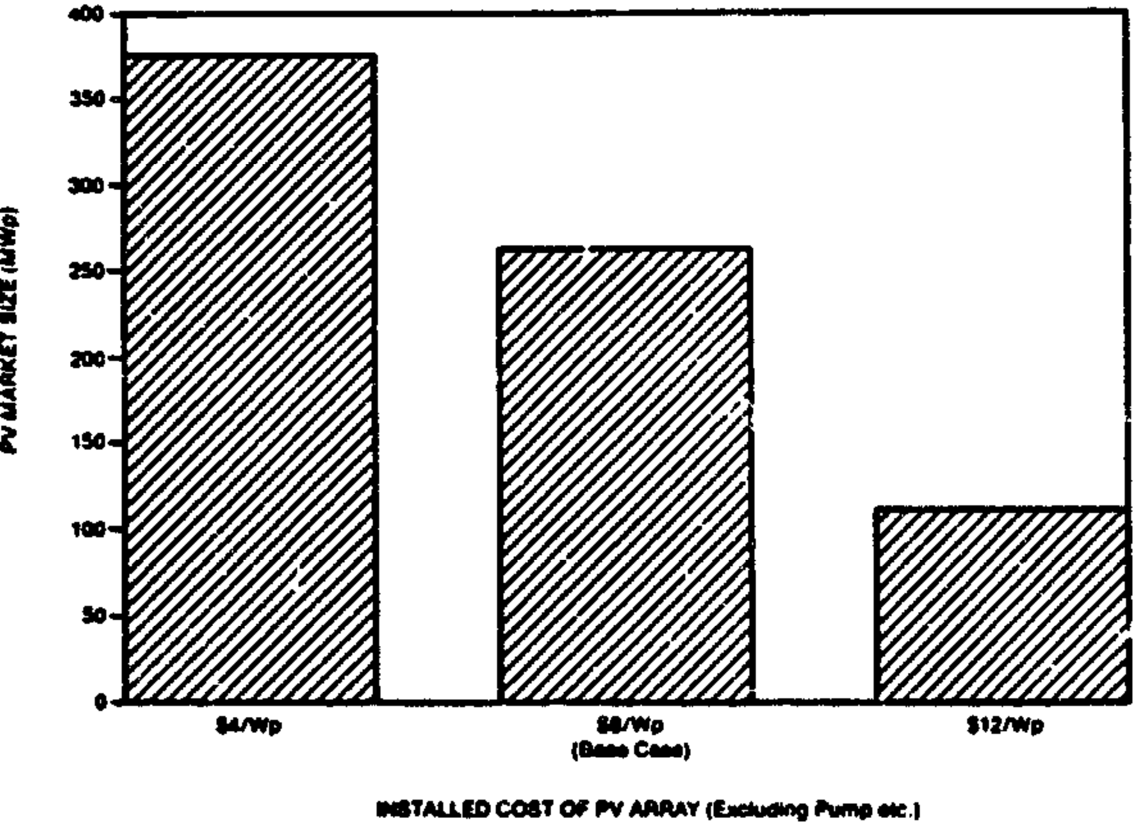
Exhibits 5-15 and 5-16 show the impact of installed PV <u>array</u> costs (excluding pump and other costs) on the cost competitiveness of PV-based RWS systems relative to handpumps and diesels, for 20 and 40 lpcd demand, respectively. The analysis is conducted using base case assumptions. Both exhibits demonstrate that the range of village sizes for which PV is the competitive power source is very sensitive to the cost of the PV array.

At 20 lpcd demand, if the installed PV array cost drops to $4/Wp (0.5 times base case cost), then the cost-competitive village size range is 700 to 3300 persons. If the cost of a PV array is more than $12/Wp, then PV is not a cost effective alternative unless well and/or diesel costs are high.

At 40 lpcd demand, PV becomes less costly compared to handpumps at about 50-75 persons per village. The PV/handpump cost competitive point does not vary significantly with changing array costs. In contrast, the PV/diesel competitiveness point is strongly influenced by PV array cost. For example, at $16/Wp, PV is the least cost technology for villages of less than 400 people. At $4/Wp, PV is the least cost technology for villages with less than 1000 people. Therefore, a fourfold increase in PV array cost results in a 2.5-fold increase in the competitive village size. In the 400 to 1,000 village size range, the cost of water from PV is similar to that from diesels. Accordingly, PV would be a preferred power source as PV has a lower recurrent cost and is more reliable than diesels, if there is no shortage of capital.

Exhibit 5-17

IMPACT OF PV ARRAY COST ON POTENTIAL PV DEMAND



5.10 Impact of PV Array Cost on PV Market Size

Using information in Exhibits 5-15 and 5-16 and similar graphs for other well cost/insolation combinations, the impact of PV array cost on PV market size was computed. The methodology described in Exhibit 5-10 was used in the market estimation. The impact of PV array costs on the market for PV is shown in Exhibit 5-17. As the exhibit shows, if array costs decrease to $4/Wp installed, the market for PV increases by about 42% to 376 MWp. Conversely if installed array cost is $12/Wp, the market declines by 57% to 113 MWp.

6.0 CONCLUSIONS

Three important conclusions emerge from the analyses:

1. Under average insolation and well conditions, at water demand levels of 20 lpcd, PV supplies the least cost water for villages ranging in size from 1,000 to 2,000 persons. If the water demand is 40 lpcd, PV is the least cost option for villages ranging in size from 80 to 800 persons. As well costs increase, PV becomes competitive at even smaller village sizes.

   In the 20 lpcd case, for villages of fewer than 1,000 persons, handpumps are the least-cost technology; for villages of more than 2,000 persons, diesel systems can supply water more cheaply. When water demand is 40 lpcd, handpumps are the least cost technology only when village size is less than 100 persons. The sensitivity analysis showed that the village size for which PV is competitive with handpumps is not significantly influenced by input data assumptions.

2. Contrary to conventional wisdom that claims PV is a capital-intensive technology, the analysis shows that the per capita initial capital cost of PV systems is similar to and even less than that of handpump systems which are traditionally considered a low-cost technology.

   In the 20 lpcd case, for villages of 1,000 to 2,000 persons, per capita initial cost is $19-24 for the PV system, when the well cost is $2,500. In comparison, handpumps have an initial capital cost of $20/capita.[25] In the 40 lpcd case, for villages of 80 to 800 persons and a well cost of $2,500, a PV system's initial cost is $50-125/ capita. The corresponding initial cost for a handpump system is $105/capita.

3. PV systems can provide water at a cost acceptable to rural families. In the competitive range when water demand is 20 lpcd, the cost of water from PV systems is equivalent to less than 2% of the annual income for a person in a poor developing country.[26] Saunders and Warford of the World Bank note that "a frequently used rule-of-thumb," is that a rural, near subsistence family "should never have to pay more than about 5% of their income for water."[27]

These inferences have two far-reaching implications for both rural water supply system planners and for PV pumping system manufacturers:

- PV water supply schemes are cost effective and affordable; they can be implemented at a cost comparable to a handpump-based system for moderate-size

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[25] The UNDP/World Bank estimates that rural water supply project costs range from $10-30/capita for handpump schemes to $30-60/capita for standpipe schemes. See: Arlosoroff, *op. cit.*, p. 2. Note that traditional standpipe schemes based on diesel power have much higher recurrent costs compared to PV.

[26] When a well costs $2,500 and insolation is 5 kWh/m^2/day, water cost is $0.40/m^3 for 20 lpcd water consumption level. Assuming a per capita annual income of $200, annual water expenses are 1.5% of per capita income.

[27] Saunders, R.J. and J.J. Warford, "Village Water Supply: Economics and Policy in the Developing World." The Johns Hopkins University Press, 1976, pp. 187-188.

villages. In addition to providing water at lower cost than handpumps, the scheme can also obtain other benefits such as a more convenient water source that can be expanded incrementally as the village grows, without the need for drilling additional wells.

- The potential market for PV pumping systems in the economically competitive range is very large. Therefore, investing in the development of PV pumping products specifically tailored to suit the application requirements will have a high payoff. The potential market is of the order of 250 MWp for typical PV pumping systems of 1-3 kWp each, for supplying 12-40 m^3/day of water from intermediate and deep water tables. These systems would serve villages with 300 to 2,000 persons.

PV provides a technically feasible and economic means for rural water supply authorities to provide water to moderate-sized villages. The previous alternatives were diesels or handpumps where grid-electric or gravity fed systems were infeasible. Planners should actively investigate the suitability of PV for their specific needs. Where necessary, assistance should be sought from international and bilateral donor organizations for assessing the feasibility of PV systems for specific applications and for procuring the systems.

A number of important institutional and organizational concerns must be addressed and resolved in the project design to ensure that a PV-based RWS system can be operated successfully in a rural setting. These concerns are also applicable to handpump and diesel RWS systems. These issues include the following:

- The expected demand for water must be accurately determined. An inadequate supply or inconvenient access to the water source will make the disenchanted community resort to using its old unsafe water sources. Conversely, an optimistic demand estimate will incur unnecessary costs.

- Users must be educated on responsible water use. Unlike handpumps, which are "self regulating" (i.e., water output depends on the effort of the water drawer), water is available on demand from a standpipe-based supply. Therefore, if a tap is left open, or a leaking faucet is not repaired in time, there would be inadequate water for others. Experiences from successful diesel and electric RWS systems would be useful in educating users on how to manage their water supply.

- Extent and type of community involvement in specifying requirements, installation, operation, and maintenance of the system must be established. Organizational capacity of the community must be assessed to identify the activities to be assigned to the community. An appropriate community organization must be established for operating and maintaining its water supply system.

- A responsive and reliable maintenance system must be established. In particular, the relative roles of the community and the public sector authority must be delineated. Appropriate training must be provided to community personnel on operation and maintenance of the system. It is also vital that a reliable and responsive system be established for supplying spare parts.

- The aquifer must be carefully tested to ensure that it is capable of delivering water at the expected pumping rate over the system's lifetime, without unacceptably high drawdown. This issue is more important to motorized pumping systems than for handpumps due to the higher pumping rates possible.

- The well must be properly designed, sited, and constructed to ensure that high quality water is obtained and potentially damaging sand pumping does not occur.

Diesel- and electric-powered RWS systems are faced with similar issues and therefore much can be learned from such experiences. A field survey of successful (and unsuccessful) electric- and diesel-powered RWS systems would yield information useful in designing a PV-powered RWS system.

Additionally, a number of field applications of PV-powered RWS systems should be monitored and/or field tests conducted in appropriate villages in various regions of the world. These case-study investigations will aid in convincing RWS planners in developing countries and in donor organizations that PV is an appropriate power source for RWS systems. Furthermore, these investigations will help identify and resolve unexpected problems that might emerge and aid in developing appropriate project design guides.

PV pumping system manufacturers must work closely with water supply planners to ensure that the technology is well matched to water resource characteristics and user water supply needs, while satisfying the ease of installation, reliability, maintainability, and other functional requirements of the user. Manufacturers need to convince potential users and decision-makers that PV should be the technology of choice for suitable water supply schemes.

Accessing the large potential market will require an extensive education and information dissemination effort directed at decisionmakers in developing countries and in international donor organizations. Decisionmakers must be convinced that PV can provide the service reliably and fit into the infrastructure being built to serve rural water supply systems.

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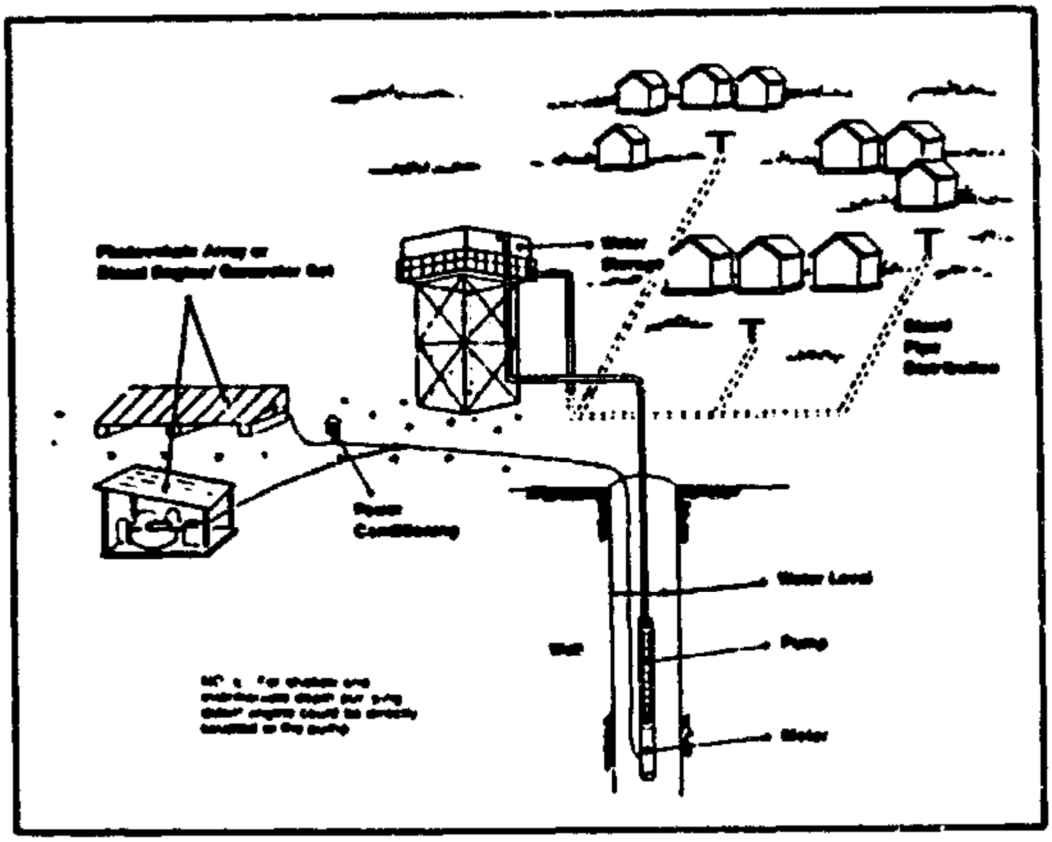
APPENDIX A

WATER SUPPLY TECHNOLOGY CHARACTERIZATION

Exhibit A-1

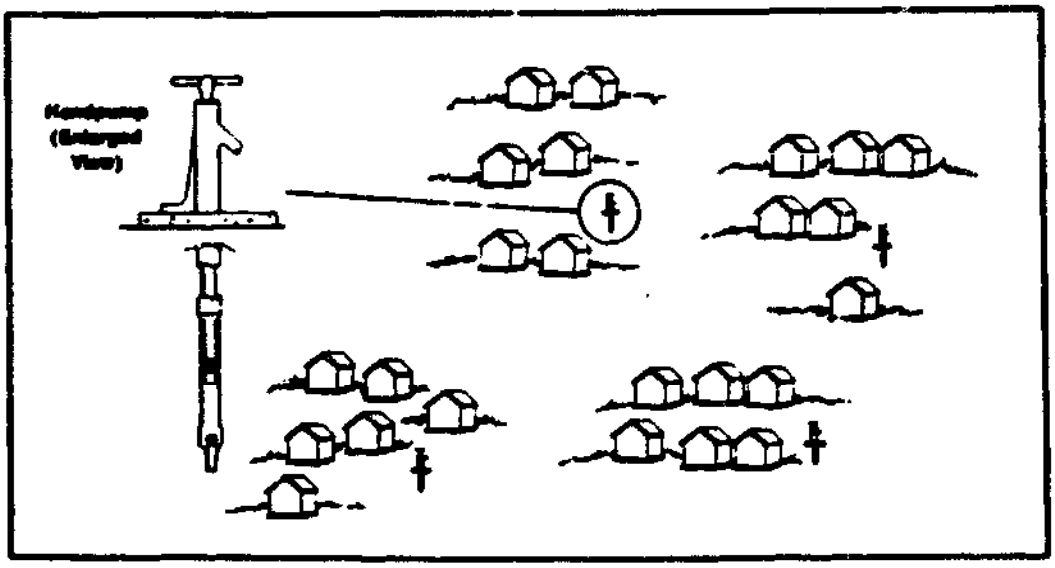
PUMPING SYSTEM CONFIGURATIONS

PV- or Diesel-Based Rural Water Supply System with Storage and Standpipe Distribution



HANDPUMP-BASED RURAL WATER SUPPLY SYSTEM

One Handpump Per Group Of Households



A. WATER SUPPLY TECHNOLOGY CHARACTERIZATION

A.1 Introduction

A rural water supply system using groundwater can be considered as the integration of four basic components: the well, the pumping system, storage, and distribution. Each component plays a critical role in the reliable delivery of safe water. Various technologies may be employed for each of these components.

Exhibit A-1 shows two basic rural water supply systems: one based on PV or diesel pumping technology, and one based on handpumps. In both cases, a well (or several wells in the case of handpumps), is installed to access the water source. The water pumping system is used to extract water from the well and dispense it to the user directly (handpumps) or deliver it to a storage tank and piped distribution system as with PV or diesel systems. Ground-based or elevated (shown) water storage systems store water and provide pressure to a piped delivery system such as a standpipe.

This Appendix describes applicable technologies and important characteristics that affect the costs of rural water supply. General cost and performance information is provided as background for the competitive assessment of handpump, PV, and diesel pumping technologies.

A.2 Wells

Groundwater extracted through wells is the basis of the majority of rural water supply programs. The cost of the well and its design and construction significantly influence the performance and cost of rural water supply systems. Wells must be designed to provide uncontaminated water free from abrasives that wear out pump components. Usually, wells are lined with a plastic or steel well casing extending to the aquifer.

Wells are normally constructed to the depth of the local water table plus an additional depth to account for pumping drawdown. Well yield is a crucial design parameter that must be considered relative to the maximum water pumping rate. Water extraction rate must not exceed the well yield, or the water table may fall below the suction of the pump. Many pumping system failures are directly attributable to well design and yield problems.

Well costs vary greatly from $500 per well in the alluvial soils of Bangladesh where there is a shallow aquifer, to $10,000 in West Africa. Exhibit A-2 shows sample well costs for selected regions.

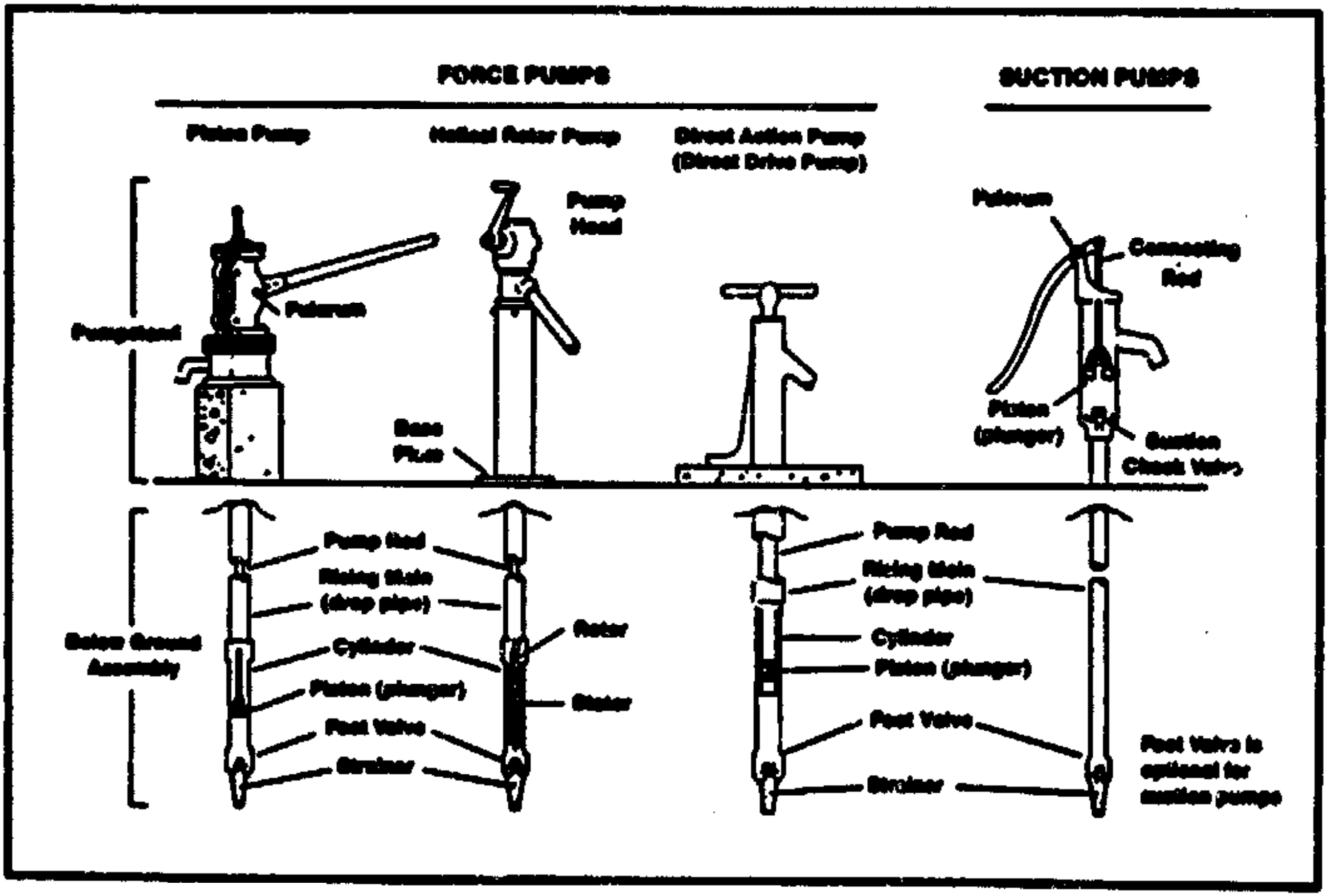
EXHIBIT A-2
Regional Breakdown of Typical Well Depth and Costs

Country	Well Costs ($)	Approximate Depth (Meters)
Bangladesh	500	<10
India	1,500	20-40
E. Africa	2,500	15-30
W. Africa	5,000 - 10,000	15-30
Latin America	2,500	10-20

Source: Dr. Robert Roche, World Bank, March 1987.

Exhibit A-3

HANDPUMP CONFIGURATIONS



Source: United Nations and World Bank. "UNDP Project Management Report Number 3, Laboratory Testing of Handpumps for Developing Countries: Final Technical Report." World Bank Technical Paper Number 19, Washington, D.C., 1984.

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The operation and maintenance (O&M) cost for wells is low. The UNDP/World Bank Handpump Project estimates that O&M costs are 1% of capital costs per year. The life of a well is estimated at 20 years.

A.3 Handpumps

Handpumps are the most common rural water pumping technology. They are initially inexpensive, generally simple to operate, and lend themselves to local repair. Because of these factors, a significant commitment has been made by the UNDP/World Bank to handpumps as the most appropriate technology for rural water supply. Field experience with handpumps, however, has been generally below expectations owing to high breakdown/wearout rates and the resulting poor reliability. This section presents an overview of handpump technology, its performance, and costs.

A.3.1 Pump Types

There are two basic types of handpump technologies, the suction pump and force pump. Exhibit A-3 shows typical configurations for each type of handpump.

Suction pumps are used for shallow-well water sources. The optimal operating depth to water table level is less than seven meters (at sea level). Suction pumps are comparatively easy to repair and maintain because the body of the pump including the piston or plunger is located above the ground.

The force pump is a standard technology used for deep-well pumping, and the depth at which it may be used is constrained only by the pump's durability and the strength of the operator. Maintenance and repairs performed on force pumps are more complex because the pumping elements (piston/plunger and cylinder) are located at the end of the rising main. The repairs may require lifting tackle to gain access to the pumping elements.

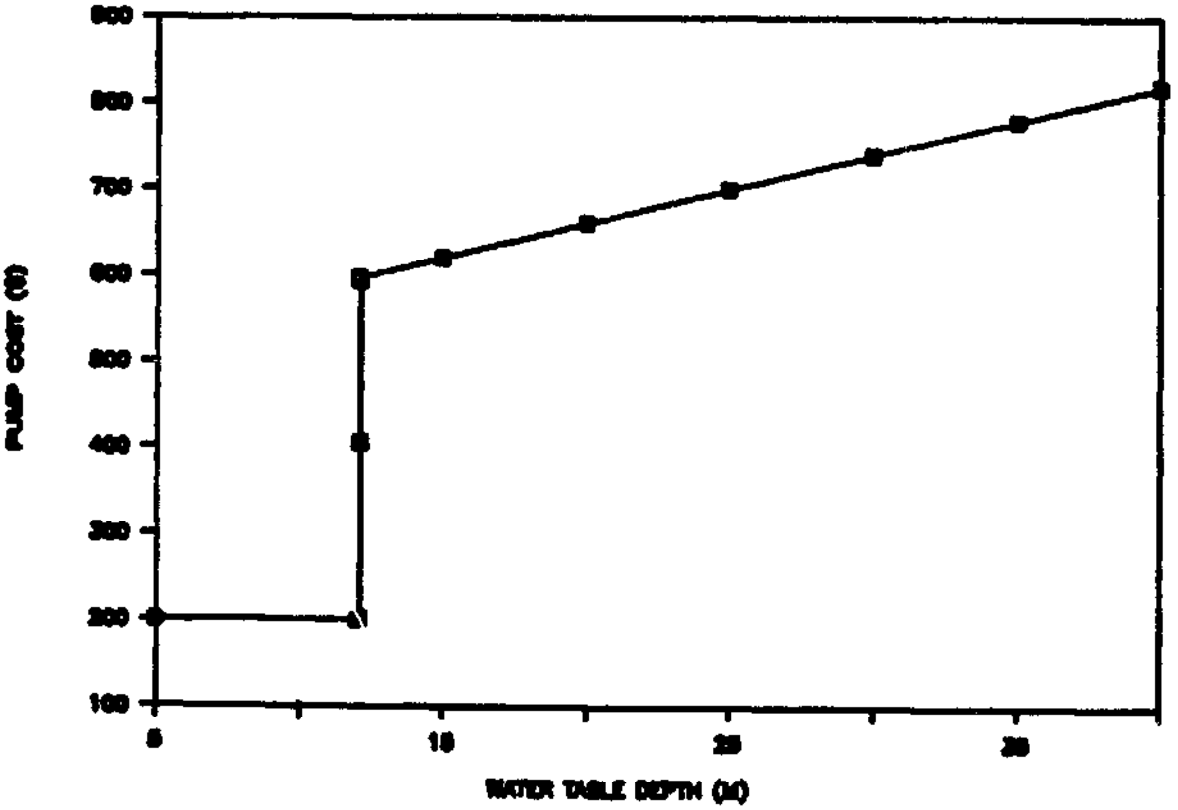
In 1980, the UNDP/World Bank began a major project to test and develop improved handpumps to serve the large potential market for rural water supply. A series of laboratory tests was performed to ascertain which pumps should be chosen for further field trials. Results from the laboratory tests were also relayed to manufacturers in order to promote the improvement of handpumps for village-level operation and maintenance.

The Project has introduced the concept of village-level operation and maintenance (VLOM) to enable pumps to be maintained by the community. The criteria for VLOM pumps include: simplified maintenance; inexpensive, easily replaced wearing parts; potential for local manufacture; standardization of pump design and spare parts; low capital and recurrent costs; and pump design matched to application in terms of lift and discharge rate. Currently, no single pump has been developed that meets all of these criteria. The pump that comes closest is a new generation handpump named the Afridev which is undergoing field testing.

The Afridev is currently regarded by the UNDP/World Bank staff as the most promising VLOM handpump for pumping lifts over 15 meters. The pump design makes extensive use of plastic parts, while the cylinder is lined with a stainless steel tube. The Afridev is regarded as a VLOM design, and is considered applicable for medium- and deep-well pumping for depths up to 45 meters.

Exhibit A-5

HAND PUMP COST



Handpump project experience in developing countries has not been well documented. While qualitative data are available from the field, quantitative data are not readily available. Field reports indicate that handpump maintenance is a major problem in sustaining reliable rural water supply, whether with deep- or shallow-well sources. Reports from the field suggest that downtime for routine and essential interventions is quite lengthy when a central maintenance system is used. Long downtime has been attributed to infrastructural and logistical problems rather than problems inherent to the handpump.

Laboratory tests of handpumps conducted in the UNDP/World Bank Handpump Project indicated Mean Time Between Failures (MTBF) to be about 1,500 hours. Field trials conducted by the UNDP/World Bank indicate that on the average there are 1.1 failures per year. Performance characteristics of several handpumps are shown in Exhibit A-4.

EXHIBIT A-4
Sample Handpump Characteristics

PUMP	APPLICABLE DEPTH (meters)	WATER DELIVERY RATE (l/min)	RELIABILITY (Failures/year)	MAINTENANCE COMPLEXITY
Tara	< 12	24 - 35	2	Medium
Afridev	12 - 40	10 - 24	1	Low
Mark II	12 - 40	8 - 18	1	Medium
Volanta	12 - 40	9 - 21	1	High

Source: Dr. Robert Roche, World Bank, February 1987.

A.3.2 Costs

For a shallow-well handpump, the average installed initial capital cost is approximately $200 per handpump. For an intermediate to deep-well handpump, initial capital costs are in the range of $500-$1,500.[1] The cost of a handpump can vary greatly across manufacturers.

The installed cost of handpumps used in this analysis is shown in Exhibit A-5. Operation and maintenance costs of handpumps are discussed later in this Appendix.

A.4 Photovoltaics

A.4.1 Types

Photovoltaics (PV) is the direct conversion of sunlight into electricity. Photovoltaic-powered water pumping systems utilize solar energy to drive a motor/pump set to pump

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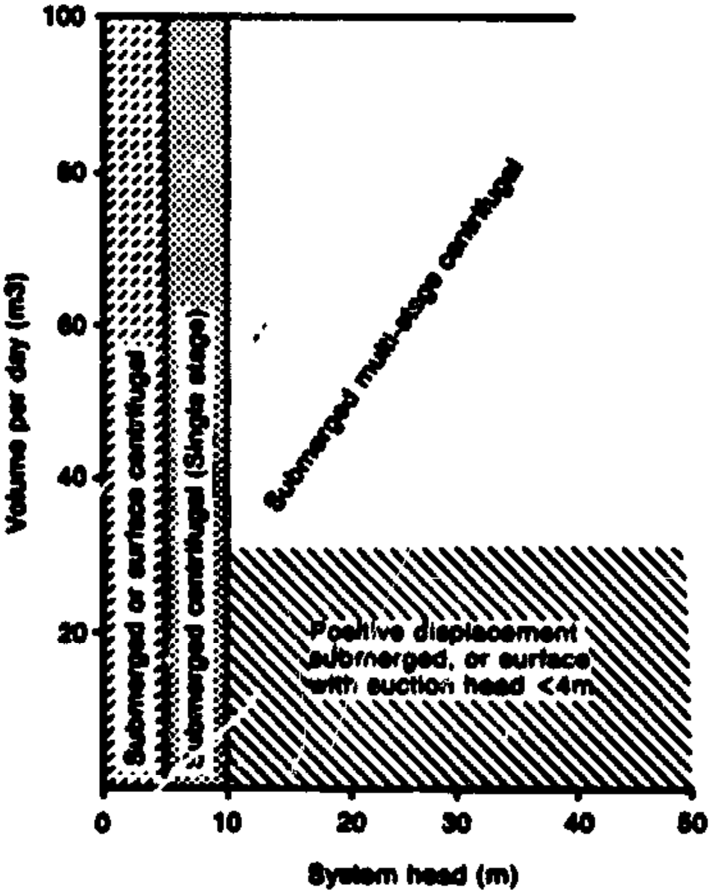
[1] Arlosoroff, op. cit., Chapter 6.

Exhibit A-6

PUMP TYPES SUITABLE FOR A RANGE OF PUMPING APPLICATIONS



Source: Kenna, Jeff; Gillet, Bill, Solar Water Pumping, A Handbook, Intermediate Technology Pub., London, 1985.

water.[3] There are many commercially available systems and more than 2,000 have been supplied worldwide.

Photovoltaic water pumping systems consist of a photovoltaic array, a motor, water pump, and optional power conditioning equipment and batteries. When sunlight strikes the PV array direct current (DC) electricity is produced. The DC electricity can be used to operate the pump. Larger systems often include power conditioning controls to improve efficiency. Power conditioning may include the conversion of DC to alternating current (AC) electricity. AC systems are generally used for intermediate- and deep-water table, high-water demand applications.

There are two basic types of water pumps: displacement (volumetric) pumps and rotodynamic pumps. The most common motorized pumps that fit into the displacement category are piston pumps (jackpumps), progressive cavity pumps, and diaphragm pumps. The most common motorized pumps that fit into the rotodynamic category are the jetpumps and centrifugal pumps. The criteria for deciding which pump is preferred for a particular pumping application are the depth of the water table (water head in meters) and the quantity of water needed (water volume in cubic meters). The preferred pump for various head/water volume combinations is shown in Exhibit A-6.

A centrifugal pump coupled to a DC motor can be directly operated off a PV array. The coupling requires that gear ratios, motor speed, voltage, and pump stage characteristics be carefully chosen for efficient operation. Mismatches between the PV array current/voltage (IV) characteristics and that of the motor/pump set could result in the very poor utilization of the PV array power. Electronic controls can be used to enhance the performance and are recommended even for centrifugal pumps. The PV pumping systems considered in this analysis assumes that electronic controls are employed.

Exhibits A-7 and A-8 show five principal configurations of commercially available solar pumps. These are grouped by application range as follows:

(A)(B) Shallow (up to 7 meters water depth)

Surface-mounted, single-stage centrifugal pump and DC motor sets are used for shallow water sources. Directly driven from the PV array through a controller, they represent a simple and reliable design. They are used for shallow water table applications up to a depth of about 7 meters (at sea level).

(C) Intermediate/Deep (to 20-40 meters depth), Less than 30 m^3 /day

Submerged reciprocating positive displacement pumps (jackpumps) are used for intermediate- or deep-water table depth applications where daily flows are limited to less than 30 m^3/day. PV jackpump systems can use DC electricity but require power conditioning to match the cycling nature of pump power requirements with the PV array output characteristics.

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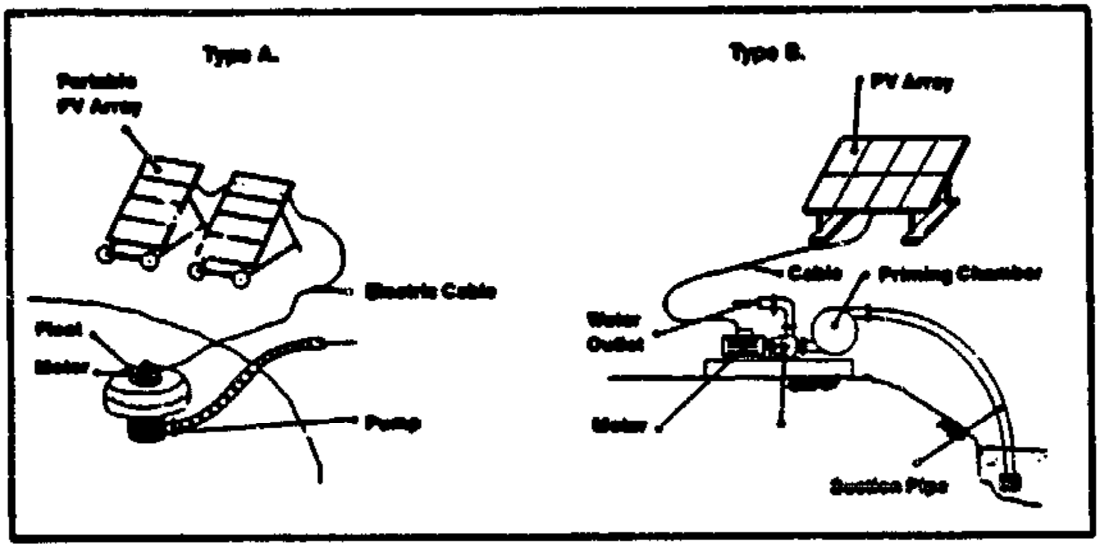
[3] For more details on PV water pumping, and an introduction to system design and bid request for quotation specification see: Photovoltaic Design Assistance Center, "Water Pumping: The Solar Alternative," SAND87-0804 (Albuquerque: Sandia National Laboratories, April 1987).

Exhibit A-7

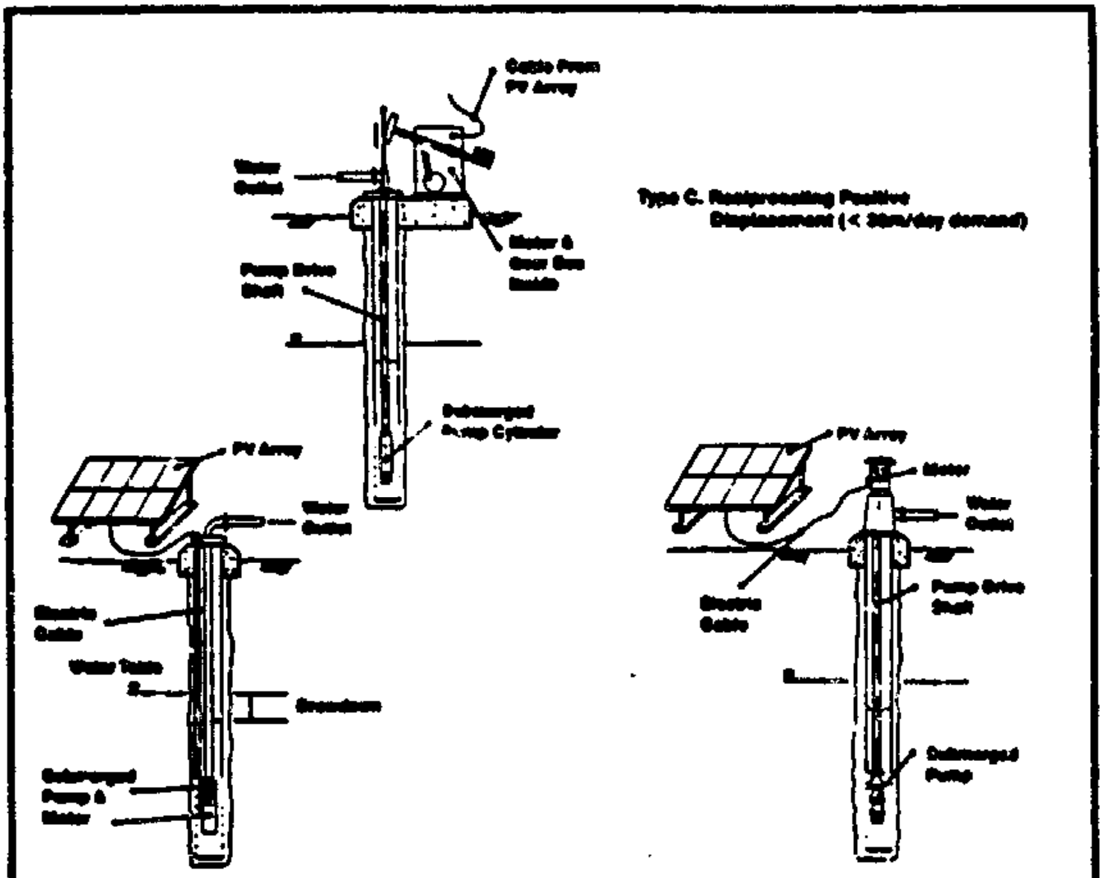
SHALLOW WELL APPLICATIONS (to 7 meters depth)



Source: IT Power Inc. Handbook of Solar Water Pumping. The World Bank.

Exhibit A-8

INTERMEDIATE/DEEP WELL APPLICATIONS (20-40 meters depth)



Type C. Reciprocating Positive
Displacement (< 30m³/day demand)

Type B. Submerged Motor/Multi-Stage
Centrifugal Pump Set (< 30m³/day)

Type E. Submerged Multistage Pump/
Surface Motor (< 30m³/day)

Source: IT Power Inc. Handbook of Solar Water Pumping. The World Bank

(D)(E) Intermediate/Deep (to 20-40 meters depth), More than 30 m^3 /day

Submerged motor/pump sets or submerged pump and surface motor systems are suitable for intermediate and deep water table depths where required flows are more than 30 m^3/day. Of the two types presented, there has been greater field experience with submerged centrifugal motor/pump sets. Submerged motor/pump sets are available as DC or AC systems. The trend with DC submersibles is to use a relatively new "brushless" motor design compared to a "brushed" DC motor which requires brush maintenance. Photovoltaic AC motor/pump systems are commercially available and field proven. They utilize conventional AC motor/pump sets that have been used for decades in many countries. AC systems require an inverter. The cost of a DC brushless submersible and an AC submersible with an inverter are currently similar although the manufacturer of the DC brushless motor advises that with increasing demand, the cost of DC brushless motors will decline and total system cost will be lower than AC submersible systems.[3]

Batteries can be used in a PV pumping system. Similar to electronic controls, battery storage enables the PV motor/pump set to operate at higher efficiencies thereby reducing the PV array size. If the well yield is low, batteries can allow the pump to operate at a lower pumping rate, over a longer period of time during the day, thereby preventing the pump from running dry. Batteries may reduce overall system cost by partly displacing array and water tank storage sizes. Batteries add complexity and cost, and there are losses associated with charging and discharging of the battery.

A.4.2 Performance Characteristics

The performance of a PV pumping system is a direct function of available sunlight intensity and the efficiency of the motor/pump set. With increased insolation and improved motor/pump set efficiencies, PV system performance increases, resulting in reduced delivered water costs.

Sunlight availability or insolation is measured in kilowatt-hours per square meter per day (kWh/m^2/day). It ranges from an average of 3 to 7 kWh/m^2/day worldwide. Insolation levels vary daily and seasonally depending on climate and location. A system is designed to account for the worst or lowest insolation month.

The efficiency of the operating motor/pump set changes over the day as the power output from the array changes with sunshine availability. The average daily operating efficiency of the motor/pump set ranges from 15% to 50% depending on the specific system. In this analysis, efficiencies of 25% and 35% are assumed for the motor/pump set for shallow and intermediate/deep water table applications, respectively.[4] These efficiency values assume the use of electronic controls or good PV array/motor/pump matches. When batteries are used, a motor/pump set efficiency of 45% is used.

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[3] Eckel, J., A.Y. McDonald Manufacturing Company, Personal Communication, March 1987.

[4] McNelis, B., "Photovoltaic Water Pumping," In: Presentations of the Photovoltaics: Investing in Development Conference, May 4-6, 1987, p.V-5.

A.4.3 Costs

PV array cost is often reported on a dollar per peak watt[8] basis ($/Wp), which is the system cost divided by the rated output of the array under peak sun conditions. Exhibit A-9 presents the PV array and motor/pump costs used in this analysis. These costs assume the purchase of PV pumping systems in lots of 10-15 or more. Exhibit A-10 is a graphic representation of PV pumping system installed cost as a function of array-rated power level.

EXHIBIT A-9
Installed Costs of PV Pump Systems

PV Array Power (Wp)	PV Array Costs ($/Wp)[a]	Motor/Pump Costs ($/Wp)
<200	8.00	7.00
200-500	7.75	4.25
500-1000	7.50	2.50
>1000	7.25[b]	b

a. Includes transportation to site, installation and array-related balance of systems (approximately 30% of FOB PV module cost).
b. Cost is similar to conventional AC submersible motor/pump sets. When AC is used, $ 0.75/Wp is added to PV array cost for a DC/AC inverter.

Sources: I.T. Power Inc., A.Y. McDonald Mfg. Co., Chronar TriSolar, Inc. (1987).

Operation and maintenance costs for the PV array are minimal and estimated at 1% of capital cost per year. Operation and maintenance costs for the motor/pump set depend to some extent on the motor/pump system. These costs are discussed in a later section.

A.5 Internal Combustion Engine Pumping Systems

A.5.1 Introduction

Since the invention of the internal combustion engine (ICE) at the turn of the 20th century, the ICE has become an almost universal power source in remote areas of both the developed and developing world. Internal combustion engines have predominantly been used for powering remote loads without access to utility electric power in the 5- to 500- horsepower range.

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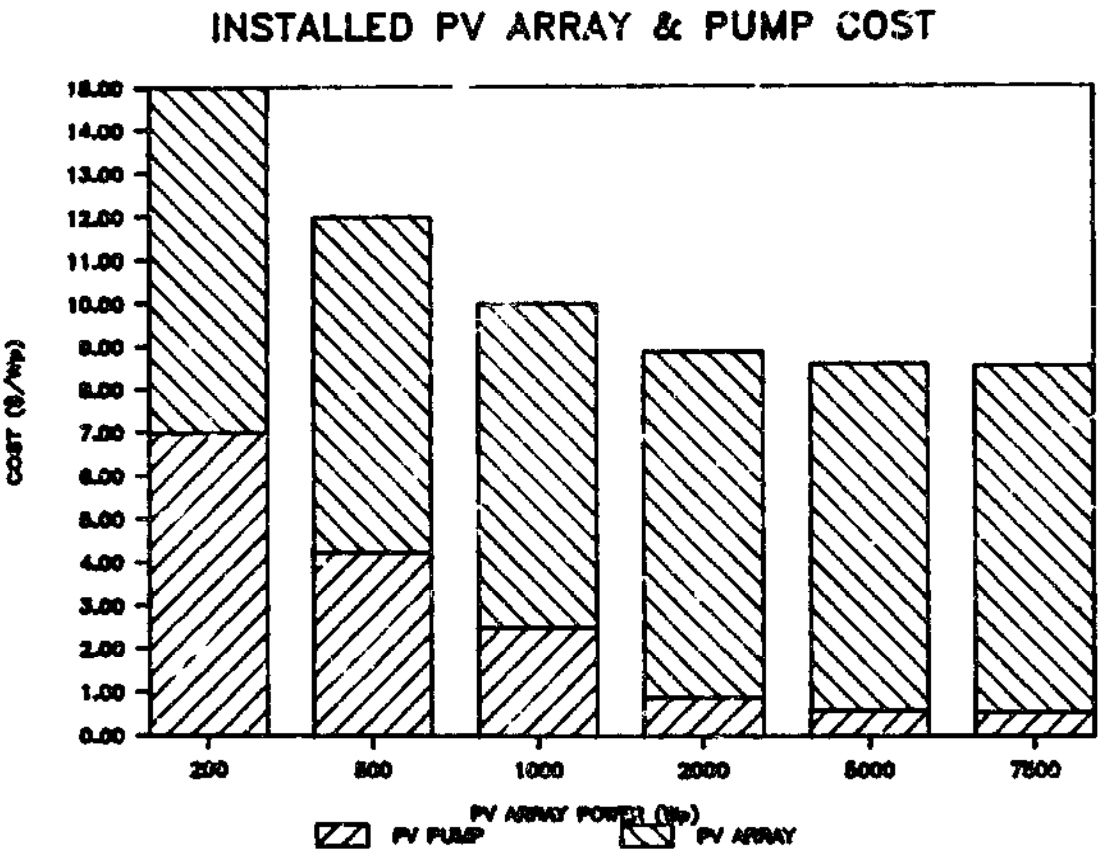
[8] Peak watts is a standard means of measuring power output of a PV array. It is defined as the power produced by the PV array under peak sunlight conditions of 1000 W/m^2, 25°C temperature, and a 1.5 air mass.

Exhibit A-10


INSTALLED PV ARRAY & PUMP COST
15.00
14.00
13.00
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
COST ($/Wp)
200
500
1000
2000
5000
7500
PV ARRAY POWER (Wp)
PV PUMP
PV ARRAY

The advantages of the ICE that have led to its widespread use for remote power over the past 50 years are twofold. First, the technical and economic characteristics of the ICE including its high power-to-weight ratio, compact size, instant start-up capability, and affordable cost have in many cases been superior to other options for power requirements for which human or animal labor is not viable. Second, the versatility of ICEs have led to their widespread use for diverse applications and to the extensive availability of engines, parts, and expertise throughout the developing world.

The two general types of internal combustion engines used around the world are the diesel engine and gas engine. Gas engines are preferred for smaller power applications in the 500 W to 3 kW range and where the usage pattern is not more than two to four hours a day. Diesel engines are used for almost all power demands exceeding 3 kW and are able to operate for much longer periods each day. The typical lifetime of a diesel engine (5 to 30 years) is considerably greater than the life of a gas engine (2 to 10 years). Gas engines tend to be small and lighter, and thus are used for mobile applications. Diesel engines, conversely, are larger and heavier and thus better suited to stationary power applications.

Given that typical water supply pumping applications involve more than 3 kW of power, require more than 4 hours per day of operation and longer engine life, and have stationary power needs at the well, diesel engines are preferred for water supply pumping. Gas engines are often used for irrigation pumping needs where their light weight and mobility are greatly valued.

A.5.2 Diesel Pump Configurations

There are three major diesel pumping design issues that need to be considered for meeting a particular water pumping requirement. First, a choice must be made whether to use a diesel directly driving the pump or a diesel generator set (gen-set) driving an electric motor and pump. Second, the most appropriate kind of pump for the application must be selected. Third, it will be necessary to decide whether the pump will be surface mounted or submersible. The major information needed to make these decisions is the depth of the water table (head in meters), the volume and rate of water demand (volume in cubic meters and flow in liters per minute), the capital and operating cost constraints, and the remoteness of the site.

A diagram of these different pumping configurations is found for PV pumping in Exhibits A-6 and A-7. The main change in the configurations when using diesel power is that the prime power source would be a diesel engine instead of a photovoltaic array.

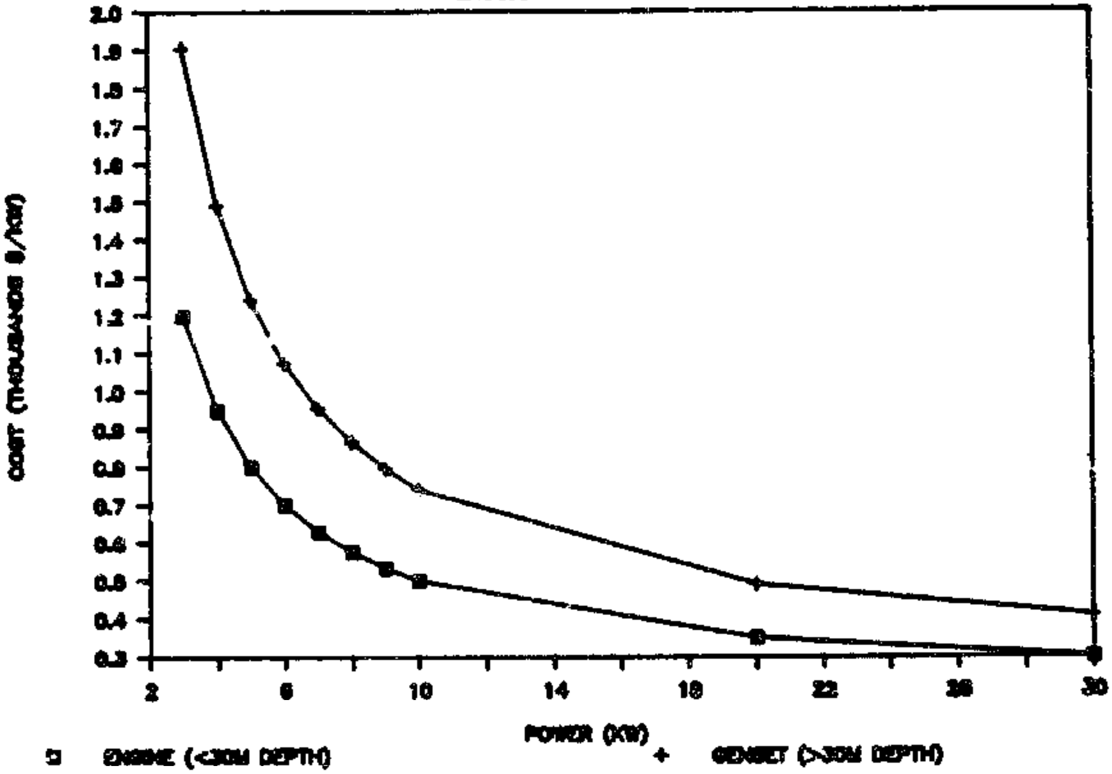
The decision to use a submersible versus a surface-mounted pump depends entirely on the depth of the water supply. A floating pump or surface-mounted pump is only used when the head is less than about 12 meters. A submersible pump is generally used with heads greater than 12 meters.

The choice between direct-drive and generator set diesel pumping systems for remote water supply is largely a function of the depth of the water table and the degree of flexibility and sophistication that is required and can be afforded. For heads below 30 meters, direct-drive diesel pumps are the cheapest and most reliable alternative. When the head exceeds 30 meters, a submersible motor/pump is recommended. At this point running wires down a deep well rather than a long shaft is preferable for installation and reliability purposes. In addition, the availability of the versatile electric power from the generator set can be used for other electric loads. At greater water depths, the increased cost and

Exhibit A-11

DIESEL ENGINE/GENERATOR COST

EXCLUDING PUMP COSTS



somewhat lower fuel-to-pumped water efficiency (due to the generator and motor losses) of a diesel gen-set is offset by its ease of installation and maintenance and its versatility.

A.5.3 Performance and Operating Characteristics

In the absence of viable alternatives, diesel pumps have for many years been the technology of choice for larger remote pumping needs. However, the recent emergence of new technologies has begun to highlight some of the disadvantages of diesel engines, particularly in remote areas. The three major problems with diesel engines for remote power pertain directly to their operating performance.

First, the complexity of installing and maintaining diesel engines is acutely felt in remote areas where spare parts and trained technicians are rarely available. Internal combustion engines require a systematic maintenance schedule to ensure reliable operation over the rated engine life. In rural areas where support services found in urban areas are not available, these maintenance schedules are rarely observed, leading to poor performance and shortened lives for most diesel pumps.

Second, the dependence of diesel engines on fuel that is rarely locally available and therefore has to be imported from other regions of the country or world introduces problems and costs in terms of operation and reliability. Delivering fuel to remote areas has proven costly and sometimes unreliable to a point that viable alternatives have been sought. In addition, since most countries have to import their fuel, the foreign exchange burden and the geopolitical dangers of dependency on foreign suppliers are increasingly being felt.

Third, diesel engines are generally oversized for the pumping loads they are supplying such that they operate at a lower efficiency, need more maintenance, and have a shorter life. Purchasers of diesels often buy extra capacity as a contingency for future needs or because no careful calculation of the load was made. In some applications, a diesel engine's capacity may exceed the peak load demand by a factor of as much as 4 or 5.

A.5.4 Capital and Operating Costs

Diesel pumping systems are characterized by fairly low capital costs and significantly high recurrent operating costs. This cost structure encourages the use of diesel pumps, because the initial cost is generally affordable and the operating costs can be deferred over an extended period of time.

The capital costs of a diesel engine are in the range of about $300 to $1,300 per kW of capacity. The costs of diesel generators are higher, ranging from about $400 to $2,000/kW (see Exhibit A-11).[6] There is a significant economy of scale for diesel gen-sets as the power requirements increase. Diesel engines and generator sets are generally not available below about 3 kW, but are manufactured in sizes exceeding 100 kW. Exhibit A-12 shows the cost of pumps as a function of power requirements.

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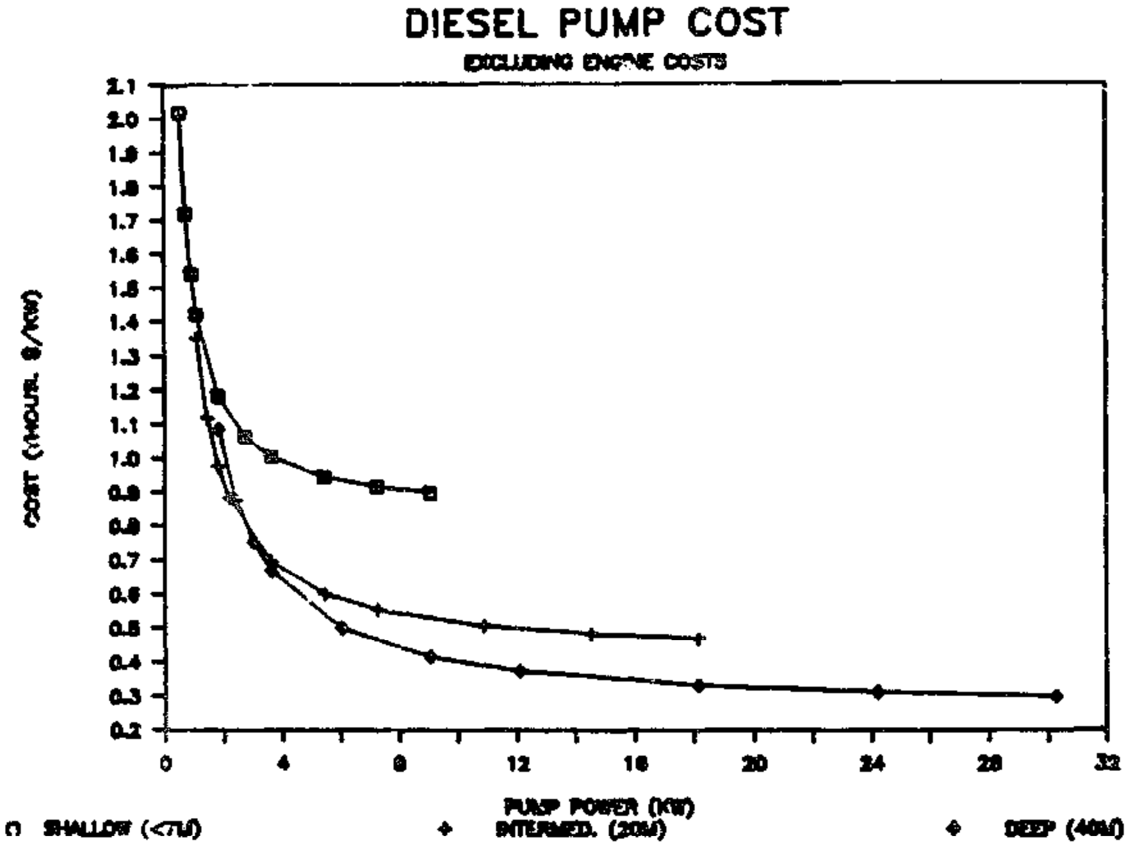
[6] Sources: Meridian Corporation, "Renewable Energy Technology Applications Identification for Egypt," US Agency for International Development Contract No: AID-263-0123-C-00-4067-00, Task 2.2, February 1986; Kenna, J., "Cost and Performance Data on Diesel Engine Generators and Pumps," SAND87-7109 (Albuquerque: Sandia National Laboratories, May 1987).

Exhibit A-12



Source: The UNDP/World Bank Handpump Project, 1987.

The operating cost of a diesel generator and pump has essentially four components: fuel cost, maintenance cost, operator cost, and repair cost. Fuel cost is a function of the size and duration of the load placed on the diesel. Maintenance cost is for routine tuneups, filter changes, etc., and for major engine overhauls that should be performed to ensure optimum efficiency and reliability. Repair cost is for repairing malfunctions. Operator cost is for diesel applications for which a part-time or full-time operator is present. A sample of these costs, broken down for diesel pumps in Kenya, is shown in Exhibit A-13. The total running costs for a diesel pump can be as high as 25-50% of initial capital costs.

EXHIBIT A-13
Diesel Pump Operating Costs

Location	Pump Rating (kW)	Fuel Cost ($/yr)	Maint. Cost ($/yr)	Repair Cost ($/yr)	Operator Cost ($/yr)	Total Running ($/yr)
Keramaini, Kenya	7	$250	$238	$100	$338	$926
Keramaini, Kenya	25	$1,276	$656	$100	$394	$2,426

Source: Kenna, J., Cost and Performance Data on Diesel Engine Generators and Pumps, 1987.

A.5.5 Shallow Water Table Depth Diesel Pumping

The preferred diesel pump configuration for shallow pumping applications with a 3 to 10 meter head is a direct-drive diesel engine with a surface-mounted centrifugal pump. The diesel engine commonly used in these types of rural pumping applications in developing countries involves a two-cycle engine with a large flywheel. The typical pump is a centrifugal pump that is mounted on and operates entirely from the surface.

This diesel pumping configuration has demonstrated a high level of reliability over more than a 30,000-hour life before requiring a major overhaul. The average operating efficiency in the field is about 7-10%. The capital costs for this system are relatively low. For example, a 4 kW unit would cost about $4,000 (1986 dollars). Annual operating costs, not including fuel, would be about $1,000 to $1,500. When properly maintained and operated, these systems have demonstrated 100% availability.

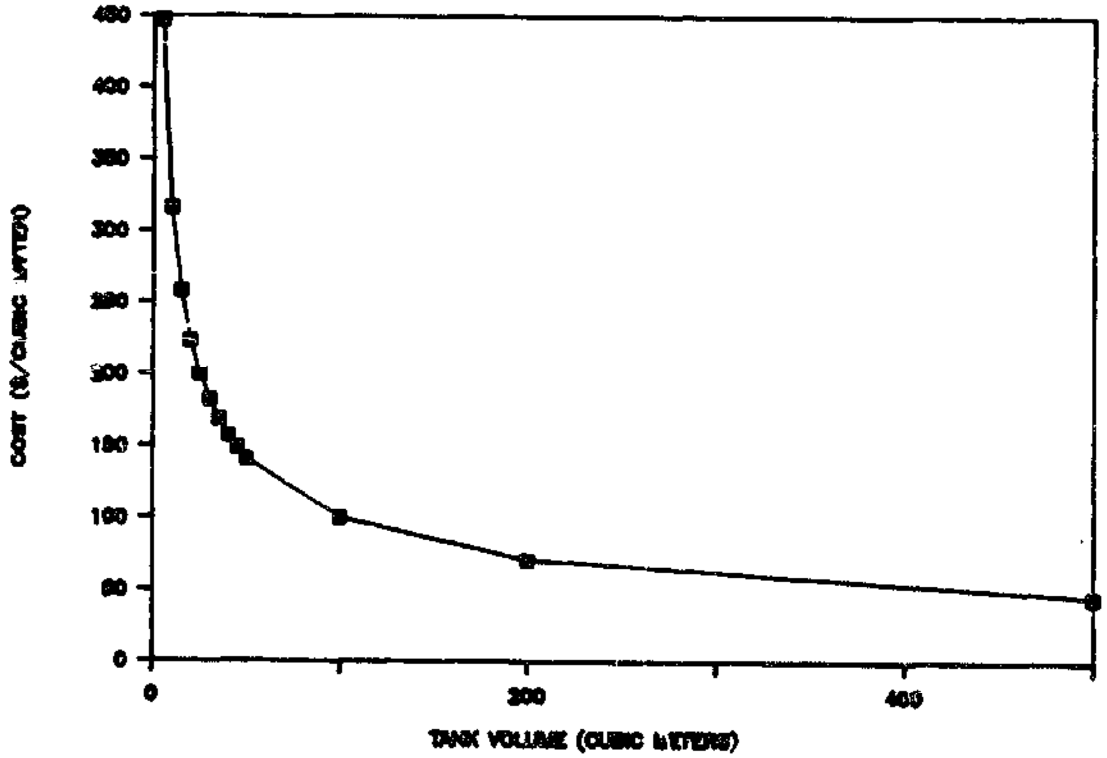
A.5.6 Intermediate/Deep Water Table Depth, Low-Flow Diesel Pumping

The preferred diesel pump configuration for intermediate/deep well depths of about 20 to 40 meters and low flows (less than 30 m^3/day) is a diesel engine directly driving a jackpump. The diesel engine commonly used in this configuration is a four-cycle engine. The pump commonly use in this application is a positive displacement pump using a derrick arm design and a submerged pump cylinder.

This diesel pumping design has demonstrated a high level of reliability over more than a 25,000-hour life before requiring a major overhaul. The average operating efficiency in the field is about 7-10%. The capital costs for this system would be about $6,500 (1986)

Exhibit A-14

STORAGE TANK COST



Source: The UNDP/World Bank Handpump Project.

for a 4.5 kW unit. Annual operating costs, not including fuel, would be about $1,500 to $2,500. When properly maintained and operated, these systems have demonstrated about 97% reliability.

A.5.7 Intermediate/Deep Water Table Depth, High-Flow Diesel Pumping

The preferred diesel pump configuration is a diesel engine driving an electric generator which in turn drives an electric motor and pump. The diesel engine commonly used in this configuration is a four-cycle engine with an AC generator. The typical pump for this application is a centrifugal submersible pump with an electric motor. The motor and pump are installed at the bottom of the well. Because the submerged pump only requires electric conductors between the diesel gen-set and the bottom of the well, the installation of the pump is easier than with the previous pump designs.

This diesel pumping design has demonstrated a high level of reliability over more than a 20,000-hour life before requiring a major overhaul. The average operating efficiency in the field is somewhat lower at about 6-8%, due to additional losses in the generator and motor. Capital costs for this system would be about $9,500 (1986) for a 6.0 kW unit. Annual operating costs, not including fuel, would be about $2,000 to $3,500. When properly maintained and operated, these systems have demonstrated about 95% reliability.

A.6 Storage

Energy storage in the form of water, battery, or fuel is usually incorporated in PV- and diesel-based rural water supply systems. Its primary function is to balance demand and supply. Storage is also used to protect against insolation variance in PV systems and fuel supply interruptions for diesel systems. Storage is not typically considered for handpump-based options as water is available upon demand. Consumers usually practice "home storage" when water has to be carried home, such as in a handpump- or standpipe-based RWS system. With a handpump-based system, if an equipment failure occurs water supply is interrupted until repairs are made. Overhead water storage tanks costs vary significantly depending on local conditions. Typically, costs range from about $500/m^3 for a 5 m^3 tank to $100/m^3 for a 100 m^3 tank (see Exhibit A-14).

Storage capacities considered for peak demands are typically between one-fourth and one-third of daily average water requirements. Capacity recommendations for diesel systems are one day of storage to provide for supply interruptions.[7] Storage requirements for PV-powered water pumping systems are typically one to three days to cover insolation variance and peak demand. According to Chapman at Sandia National Laboratories, a storage capacity of one day will provide an availability of approximately 97%.[8] A storage capacity of three days will provide 99% availability. For example, a 99% availability means that for about four days in a year, water output will be below the design level.

Battery storage systems consist of batteries connected in parallel with the PV array and motor/pump set. The battery acts as energy storage and a constant voltage source

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[7] Philippines Water Resources Council, "Rural Water Supply: Design Manual," 1979.

[8] Chapman, R. N., "Sizing Handbook for Stand-Alone Photovoltaic Storage Systems," SAND87-1087 (Albuquerque: Sandia National Laboratories, April 1987).

Exhibit A-15a

LAYOUT OF SIMPLE STANDPIPE DISTRIBUTION SYSTEM

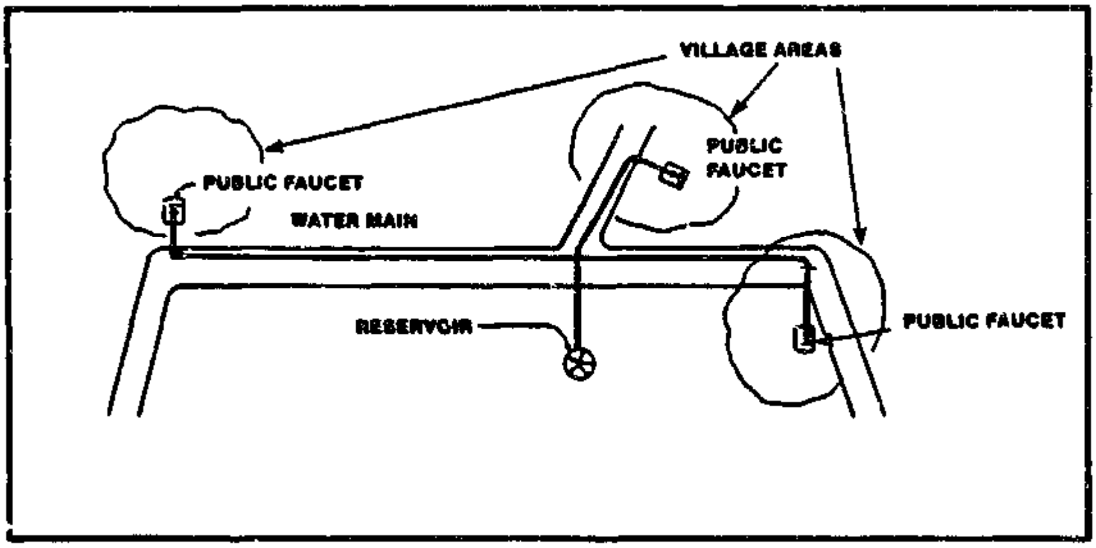
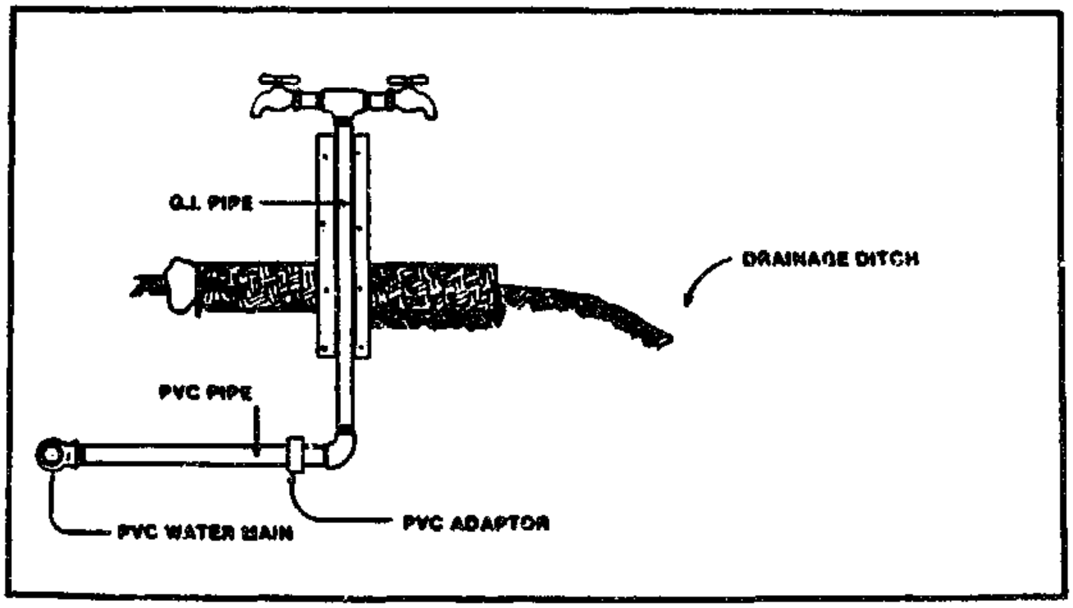


Exhibit A-15b

STANDPIPE DETAIL (2 taps/standpipe)



determined on a kWh basis and includes "reserve" capacity or that capacity below which the battery is not discharged. Battery life is a function of its discharge depth. For deep-cycle design batteries, a 5-year life is conservatively predicted for a daily depth of discharge limited to 50% of the total capacity.

A.7 Standpipes and Distribution Pipes

Standpipes are used for PV- or diesel-based water supply systems. Standpipes or public faucet water distribution systems supply water through main and submain piping to public water points. Exhibit A-15 shows a layout of a small standpipe-based rural water supply system. Standpipes are more convenient than handpump-based systems. Water points can be closer to residences and additional wells are unnecessary. Standpipe cost is estimated at $150 per standpipe, and includes the piping, fittings, and a concrete apron around the base of the standpipe for controlled drainage and general sanitation. Distribution piping costs are estimated at about $6 per meter installed. A cost breakdown for distribution piping and standpipes is shown in Exhibits A-16 and A-17, respectively.

A.8 O&M Cost Estimates

O&M costs are estimated for representative handpump, PV, and diesel water pumping system configurations. O&M costs include cost of parts, labor, and transportation. Cost estimates are provided for handpump, PV, and diesel systems for shallow and intermediate/deep-well applications. The cost estimates are used to calculate O&M cost as a percent of capital cost for use in the analysis.

The number of visits to the pump by maintenance personnel takes into consideration the routine maintenance needs as well as unscheduled maintenance requirements. The number of unscheduled maintenance visits per year is computed using reliability theory by estimating the expected number of failures per pump per year.

These types of maintenance personnel considered in the cost analytis are:

- Village Based (VB) - Maintenance is carried out by a designated member of the community.
- Area Maintenance (AM) - An area mechanic is contracted to provide maintenance services. The area mechanic can provide more sophisticated repair and maintenance services than VB maintenance.
- Central Maintenance (CM) - Pump maintenance is managed by an external agency with the village accepting certain responsibilities. The CM team travels from a base camp to the villages to provide the necessary services. These teams can supply more complex maintenance and repair services than either VB or AM.

Exhibits A-18 to A-20 show the O&M cost breakdown for the representative pumping systems. Exhibits A-21 through A-23 show the replacement parts schedule and costs for the centrifugal and jack pumps. Exhibit A-24 provides failure rate estimates for the handpump, PV, and diesel pumping systems.

EXHIBIT A-16
Water Distribution Piping Cost

MATERIALS	NUMBER	COST ($)
38 mm PVC Pipe	100 meters	362.00
Globe Values	2	55.54
38 mm Sockets	10	29.68
38 mm T-Joints	3	18.47
TOTAL MATERIAL COST		465.69
Labor at 30% of material costs		139.71
TOTAL COST/100 METERS		$595.40
Cost per meter of piping		$ 6.00

Source: National Water Resources Council, Republic of the Philippines, "Design Manual: Rural Water Supply," Volume 1, 1980. Costs were escalated 40% to reflect 1986 costs.

EXHIBIT A-17
Standpipe Estimated Cost

MATERIAL	NUMBER	COST ($)
25 mm GI Pipe	2 meters	3.64
25 mm bronze taps	2	22.98
25 mm socket	1	1.50
25 mm adapter socket	1	3.65
38 X 25 mm reducer	1	2.97
Concrete for 8' X 8' X 6' concrete slab and 3' X 12" X 6" concrete pillar	1	62.64
Reinforcing Mesh 8' X 8'		9.60
TOTAL MATERIAL COST		107.08
Labor at 30% of material		32.12
TOTAL COSTS		139.20
Assumed standpipe cost		$150.00

Source: National Water Resources Council, Republic of the Philippines, op. cit. Costs were escalated 40% to reflect 1986 costs.

Exhibit A-10 CPM SAMPLE CONFIGURATIONS
(5-Meter Depth Applications)

	Hand Pump		PV (Surf. Motor/Pump Set)			Diesel Engine		
Capital Cost	\$ 200[A]		\$ 625[B]			\$ 4600[C]		
Operation and Maintenance	AM*	VB*	CM*	AM	VB	CM	AM	VB
- Replacement Parts (\$/yr)	0	10[D]	0	30[E]	0	0	230[F]	50[F]
- Labor[G] (days/person/trip/yr)	0	25	0	1[H]	25	0	1[I]	365
- Labor Rates (\$/day)[J]	4	4	4	4	4	4	4	4
- Trips (#/year)	0	50[K]	0	1	50[K]	0	4	365[L]
- Distance (km/trip)[M]	50	.5	100	50	.5	100	50	.5
- Transport Cost (\$/km)[N]	.1	0	.35	.1	0	.35	.1	0
- Men/Crew[O]	1	1	3	2	1	3	2	1
Summary								
Parts (\$/yr)	0	10	0	30	0	0	230	50
Transport (\$/yr)[P]	0	0	0	5	0	0	20	0
Maintenance Labor (\$/yr)	0	15[Q]	0	8	15	0	32	365[S]
Attendant Labor (\$/yr, less maintenance associated costs)	NA	85	NA	NA	45	NA	NA	1095
Totals (\$/yr, less attendant) (% capital cost)	\$ 25 (13%)		\$ 58 (9%)			\$ 697 (15%)		
Totals (\$/yr, w/attendant)	\$ 110		\$ 103			\$1792		

* Area Maintenance (AM), Village Based (VB), Central Maintenance (CM).

Reference Notes - Exhibit A-18

A. Shallow-lift handpump capital and installation costs.

B. DC surface-mounted motor/pump set. Includes 1.25 factor for installation costs (Meridian Corporation, "Evaluation of International PV Projects," 1986).

C. Direct drive 4.0 kW diesel engine (Kenna, J., op. cit.)

D. Estimate for Tara handpump.

E. Annualized cost of replacement parts including motor brushes, motor (at six-year intervals), pump seals, and impellers (A.Y. McDonald Mfg. Co.).

F. Spare parts for diesel engine and centrifugal pump proportioned between AM and VB levels. (Kenna, op. cit.; Chronar TriSolar Inc.).

G. Labor consists of Village-Based attendant (VB), Area Mechanic (AM), and Central Maintenance (CM) as required. Village attendant at 0.5 days per week for handpump and photovoltaic systems.

H. Equivalent labor days for motor brushes and seal replacement at 3- and 6-year intervals, respectively.

I. Equivalent labor days for engine overhaul and pump maintenance at frequency of every four years (Kenna, op. cit.).

J. Labor rates based on estimates provided by Dr. Robert Roche of the World Bank.

K. One trip per week.

L. Represents a full-time operator, seven days per week (Kenna, op. cit.).

M. Example distances.

N. Example transport costs.

O. Minimum of two men per crew for AM and CM levels for PV and diesel systems.

P. Calculated as follows: Trips x Distance x Transport Costs.

Q. Estimates for Tara handpump, village-level maintenance (Dr. Robert Roche).

R. Calculated as follows: Men/Crew x Labor x Labor Rate x Trips, except where noted.

S. Twenty-five percent of attendant labor costs assumed directly maintenance-related for PV and diesel systems.

Exhibit A-19 O&M SAMPLE CONFIGURATIONS
(20-40 Meters Depth, < 30 m^3/day)

Capital Cost	Hand Pump $ 750^{A}		PV (Jack pump) $ 1,250^{B}			Diesel $ 9,500^{C}		
Operation and Maintenance	AM*	VB*	CM*	AM	VB	CM	AM	VB
- Replacement Parts	30^{D}	0	30^{E}	0	0	380^{F}	350^{F}	50^{F}
- Labor (days/person/trip/yr)	1^{G}	25	2	0	15	4^{H}	4^{H}	365
- Labor Rates ($/day)^{I}	4	4	4	4	4	4	4	4
- Trips (#/year)^{J}	3	50	1	0	50	2	2	365
- Distance (km/trip/pump)^{J}	50	.5	100	50	.5	100	50	.5
- Transport Cost ($/km)^{J}	.1	0	.35	.1	0	.35	.1	0
- Men/Crew^{J}	1	1	3	2	1	3	2	1
Summary								
Parts ($/yr)	30	0	30	0	0	380	350	50
Transport ($/yr)^{J}	15	0	35	0	0	70	10	0
Maintenance Labor ($/yr)^{J}	12	0	24	0	15	96	64	365
Attendant Labor ($/yr, less maintenance associated costs)		100	0	0	45	0	0	1095
Totals ($/yr, less attendant) (% capital cost)	$ 57 (8%)		$110 (9%)			$1385 (15%)		
Totals ($/yr, w/attendant)	$157		$155			$2608		

* Area Mechanic (AM), Village Based (VB), Central Maintenance (CM).

Reference Notes-Exhibit A-19

A. Average capital and installation costs of three hand pumps suitable for intermediate-depth applications.

B. Jack pump/motor set includes 1.25 factor for installation costs. (Meridian Corporation, "Evaluation of International PV Projects," 1986).

C. Direct drive 4.5 kW diesel engine (Kenna, op. cit.).

D. Estimates for selected handpumps based on data supplied by Dr. Robert Roche of the World Bank.

E. Annualized cost of replacement parts of jack pump over the life of the pump. Includes leathers, motor brushes, oil, bearings, belts, and one motor replacement. (Chronar TriSolar, Inc.)

F. Spare parts for diesel engine and jack pump proportioned between CM, AM, and VB levels (Kenna, op. cit.; Chronar TriSolar Inc.).

G. Estimates provided by Dr. Robert Roche, World Bank.

H. Consists of three days equivalent per year for diesel overhaul and one day equivalent for jackpump maintenance.

I. Labor rates based on estimates provided by Dr. Robert Roche, World Bank.

J. See Reference Notes - Exhibit A-18.

Exhibit A-20 O&M SAMPLE CONFIGURATIONS
(20 - 40 Meters Depth, > 30 m³/day)

	Handpump		PV (Multi-Stage Submersible)			Diesel Engine/Generator		
Capital Cost	$820[A]		$2600[B]			$12,500[C]		
Operation and Maintenance	AM*	VB*	CM*	AM	VB	CM	AM	VB
- Replacement Parts ($/year)	30[D]	0	0[E]	0	0	500	450	50
- Labor (days/person/trip/yr)[F]	1	25	1	0	15	4	4	365
- Labor Rates ($/day)[F]	4	4	4	4	4	4	4	4
- Trips (#/year)	3	50	1[G]	0	50	2	3	365
- Distance (km/trip/pump)[F]	50	.5	100	50	0	100	50	.5
- Transport Cost ($/km)[F]	.1	0	.35	.1	0	.35	.1	0
- Men/Crew[F]	1	1	3	2	1	3	2	1
Summary								
- Parts ($/year)	30	0	0	0	0	500	450	50
- Transport ($/year)	15	0	35	0	0	70	15	0
- Maintenance Labor ($/year)	4	0	12	0	15	96	96	365
- Attendant Labor ($/yr. less maintenance associated costs)	0	100	0	0	45	0	0	1095
Totals ($/yr. less attendant) (% capital cost)	$ 49 (6%)		$ 62 (Motor/pump repl. at 7.5 yrs) (2%)			$1642 (13%)		
Totals ($/yr. w/attendant)	$149		$107			$2737		

* Area Mechanic (AM), Village Based (VB), Central Maintenance (CM).

Reference Notes - Exhibit A-20

A. Estimates provided by Dr. Robert Roche, World Bank.

B. Multi-stage submersible dc or ac (with inverter) motor/pump sets (A.Y. McDonald, Grundfos). Includes 1.25 factor for installation costs (Evaluation of International PV Projects, Meridian Corp., 1986).

C. 6 kW diesel generator set (Kenna, op. cit.).

D. Average of World Bank estimates for Volanta and India Mark II handpumps, provided by Dr. Robert Roche, World Bank.

E. No anticipated scheduled maintenance requirements (Grundfos Pumps Corp., A.Y. McDonald Mfg. Co.). Pump/motor replacement at equivalent period of 7.5 years.

F. See Reference Notes for Exhibits A-18 and A-19.

G. Nominal one trip per year for inspection and repair support (i.e., failure rate estimates show one failure every two years. (See later Exhibits.)

EXHIBIT A-21
REPLACEMENT PARTS SCHEDULE AND COSTS FOR DC MOTOR/SINGLE STAGE CENTRIFUGAL PUMP - SURFACE MOUNT

Capital Cost: $625.00

Maintenance Item	Years 3	6	9	12	15	18
1. Motor Brushes ($)	30	30	30	30	30	30
2. Pump Seals/Impeller ($)		20		20		20
3. Motor Replacement ($)		280		280		280
4. Pump Replacement ($)				250		

Present Worth @ 10%
of Items 1-3 over
12-year life cycle = $ 220.00

Annualized O & M Cost = $ 32.00 (w/ motor/pump set life of 10 years considered normal)

Source: A.Y. McDonald Mfg. Co. for maintenance requirements and discounted cost.

EXHIBIT A-22
DC OR AC SUBMERSIBLE MOTOR/MULTI-STAGE CENTIFUGAL PUMP

Capital Cost: $2600.00

1. No scheduled maintenance requirements.
2. Insufficient field experience to determine life for DC brushless.
3. AC submersible includes inverter.
4. Nominal life of 7.5 years selected.

Sources: A.Y. McDonald Mfg. Co., Grundfos Pumps Corporation, Associates in Rural Development.

EXHIBIT A-23
REPLACEMENT PARTS SCHEDULE AND COSTS FOR JACKPUMP

Capital Cost: $1250.00

Maintenance Item	Years 2	4	6	8	10	12	14	16	18		
1. Leathers ($)			10	10	10	10	10	10	10	10	10
2. Motor Brushes ($)				25		25		25		25	
3. Oil ($)			10 per year								
4. Bearings ($)							60				
6. Belts ($)							20				
7. Motor Replacement ($)							145				

8. Pump Replacement 20 years

Present Worth @ 10%
of Items 1-7 = $ 170.00

Annualized O & M Costs = $ 30.00 (Includes $ 10.00 annual costs for oil)

Source: Chronar TriSolar, Inc. for maintenance requirements. Motor/pump costs calculated based on $2,100 system price less 152 watt array at $ 7.00/Wp.

Exhibit A-24

FAILURE RATE ESTIMATES

SYSTEM CONFIGURATIONS

HANDPUMPS

Components:	HANDPUMP
Failure Rate (#/hour):	667×10^{-6} (A)
MTBF (1/failure rate):	1,500 hours
Operating Hours/year:	2,190 hours
# Failures/year:	1.5

PV PUMPING SYSTEMS

Components:	PV ARRAY	CONTROLS/ INVERTER	MOTOR/PUMP SET
Failure Rate:	0 (B)	200×10^{-6} (C)	140×10^{-6} (C)
System Failure Rate:		340×10^{-6}	
MTBF:		2,940 hours	
Operating hours/year:		3,600 hours	
# Failures/year:		0.8	

DIESEL PUMPING SYSTEMS

Shallow Well Components:	DIESEL ENGINE	CENTRIFUGAL PUMP
Failure Rate:	1700×10^{-6} (C)	370×10^{-6} (C)
System Failure Rate:		2070×10^{-6}
MTBF:		483 hours
Operating hours/year:		1825 hours
# Failures/year:		3.8

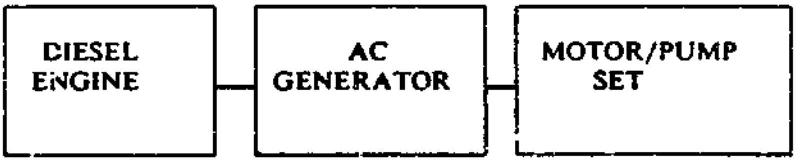
Exhibit A-24 (Cont'd)

FAILURE RATE ESTIMATES

SYSTEM CONFIGURATIONS

DIESEL SYSTEMS (Cont'd)

Deep Well Components:



Failure Rate:	1700×10^{-6} (C)	520×10^{-6} (C)	140×10^{-6} (C)
System Failure:		2346×10^{-6}	
MTBF:		424 hours	
Operating hours/year:		1,825 hours	
# Failures/year:		4.3	

Exhibit A-24 Reference Notes

A. UNDP/World Bank Handpump Project laboratory endurance tests. Average of pumps tested. Data supplied by Dr. Robert Roche, World Bank.

B. Module failure rates are on the order of 1 - 1.5 x 10^{-6} (Saunders, John, "The Concentrator Option," Photovoltaics International, June/July 1984). Calculated array failure rates are negligible (compared to other components) due in part to redundancy afforded by module parallel connections.

C. Failure rate data estimates based on: Bellinger, D. W., G. M. Pittler, R. E. Shelton, et al., "Reliability Prediction and Demonstration for Ground Electronic Equipment," Technical Report No. RADC-TR-68-280, Rome Air Development Center, Griffiss Air Force Base, New York, December, 1968; and Hughes Aircraft Company, "Nonelectric Reliability Notebook," Technical Report No. RADC-TR-75-22, Rome Air Development Center, Griffiss Air Force Base, New York, January 1975.

APPENDIX B

COMPARATIVE ANALYSIS PROGRAM DESCRIPTION

MERIDIAN CORPORATION
COMPARATIVE EVALUATION OF WATER SUPPLY SYSTEMS
HANDPUMPS VS. PV PUMPS VS. DIESEL PUMPS
FOR
RURAL WATER SUPPLY

COMPARATIVE ANALYSIS PROGRAM DESCRIPTION

The following is a description of the Lotus program developed and used in the analysis. The program uses a number of Lotus "@" functions such as @SUM, @VLOOKUP, @SQRT, @IF, @CHOOSE, etc. Please refer a Lotus manual for a description of these functions.

DESCRIPTION OF VARIABLE	VARIABLE NAME
Discount rate + 1	1PLUSDISCNT
Annualizing factor	ANNLFCTR
Arrival rate at water point (per hour)	ARVLRATE
Battery cost ($/kWh)	BATCOST
Allowable battery depth of discharge	BATDOD
Battery efficiency	BATEFF
Battery life (years)	BATLIFE
Battery size in PV-bat system (kWh)	BATSIZE
Battery cost in PV-bat system	BATTERYCOST
Base water storage cost	BCSTORE
Begin. of PV array cost lookup table	BEGPVLKUP
Civil works life (years)	CIVILIFE
Civil works O&M cost (%)	CIVILO&M
Water collection time cost ($/hour)	CLCTCOST
Begin. of component life lookup table	COMPRPLIFE2
Handpump delivery rate (l/min)	DELHP
Standpipe delivery rate (l/min)	DELSP
Water table depth (m)	DEPTH
Diesel engine size selected (kW)	DIESELSIZE
Discount rate (fraction)	DISCOUNT
No. of wells for 5 hr diesel operation	DSL5HRWELLNO
Diesel engine annual. cost ($/year)	DSLANCOST
Diesel attendant (hours/year)	DSLATTEND
Diesel system/capita annual. cost	DSLCAPITANCST
Diesel system/capita capital cost	DSLCAPITCAP
Diesel civil works annual. cost	DSLCIVILANCST
Diesel civil works O&M cost	DSLCVLO&MCST
Diesel fuel annual cost	DSLFUELANCST
Diesel engine fixed cost	DSLFXCST
Nominal diesel operating hours	DSLHRSNOM
Diesel engine nominal life (years)	DSLIFE
Diesel system water cost	DSLM3CST
No. wells when diesel operates longer hours	DSLMAXHRWELLNO
Diesel annual O&M cost	DSLO&MCST
Diesel pump cost	DSLPMPCOST
Diesel pump efficiency (fraction)	DSLPMPEFF
Diesel pump O&M cost (% capital cost)	DSLPMPO&M
Diesel pump annual O&M cost ($)	DSLPMPO&MCST
Diesel pump size (kW)	DSLPMPSIZE

Diesel pump annual cost	DSLPUMPANCST
Diesel water storage cost	DSLSTORCOST
Diesel water storage volume	DSLSTORVOL
Diesel total annual cost	DSLTTLANCST
Diesel total capital cost	DSLTTLCOST
Diesel daily use hours	DSLUSEHRS
Diesel engine actual useful life	DSLUSELIFE
Diesel pump variable cost (\$/m depth)	DSLVARM
Diesel pump variable cost (\$/m^3-hour)	DSLVARQ
Diesel well(s) cost	DSLWELLCOST
Diesel water storage days required	DSLWTRSTORE
End of PV cost lookup table	ENDPVLKUP
Diesel engine fixed cost (\$)	ENGFXCST
Diesel system engine capital cost	ENGINECOST
Diesel engine variable cost (\$/kw)	ENGVARCST
Family size	FSIZE
Fuel cost (\$/liter)	FUELCOST
Fuel to water efficiency	FUELTOWTREFF
Flow rate for selecting high-volume pump	HIFLOWPMP
No. of houses per hectare	HOUSES
Handpump annual cost	HPANCOST
Handpump O&M cost	HPANO&MCST
min. no. attend. hours/village	HPATTENDMIN
Handpump capital cost (\$/village)	HPCAPCOST
Handpump per capita capital cost (\$/person/yr)	HPCAPITCAPCST
Handpump water cost (\$/capita-yr)	HPCAPITWTRCOST
Handpump water collect time lookup table	HPCLCTBL
Handpump water collection time (min/trip)	HPCLCTIME
Fixed cost/handpump	HPFXDCST
Handpump life	HPLIFE
Handpump water cost (\$/m^3)	HPM3WTRCOST
Handpump O&M cost	HPO&M
Handpump total annual cost	HPTTLANCST
Handpump total capital cost	HPTTLCAPCOST
Handpump water collection time (min/l)	HPTTLTIME
Handpump variable cost (\$/m)	HPVARCST
Handpump annual well cost	HPWELLANCST
Handpump well capital cost	HPWELLCAPCOST
Handpump well O&M cost	HPWELLO&MANCST
Handpump water collection time	HPWTRCLCTIME
Max. handpump water delivery (loads/hour)	HPWTRLOAD
Handpump village daily water demand	HPWTRM3
Insolation (kWh/m^2/day on Plane of Array)	INSOL
Water demand (liters per capita-day)	LPCD
Max. allowable diesel operating hours	MAXDSLHRS
Max. diesel well water output (m^3/day)	MAXDSLWELLOP
Maximum persons served per handpump	MAXHPSERVE
Max. handpump village population	MAXHPVILLGE
Max. PV pump use hours (hours/day)	MAXPVPMPHRS
Max. PV well daily output (m^3/day)	MAXPVWELLOP
Max. persons/ stand pipe	MAXSPSERVE
Max. stand pipe village population	MAXSPVILLGE
Minimum diesel/PV pump cost (\$/pump)	MINPMPCST
Min. no. of wells required	MINWELLS

Pipe cost ($/m)	PIPECST
Length of pipe (m/village)	PIPELENGTH
Population	POPULATION
PV array annual cost	PVANCOST
PV system annual total cost	PVANTTLCOST
PV array size (Wp/pump)	PVARRAYSIZE
PV attendant hours/year	PVATTEND
PV-bat. annual array cost	PVBARRAYANCST
PV-bat. array capital cost	PVBARRAYCST
PV-bat. array size (Wp/pump)	PVBATARRAYSZ
PV-bat. daily energy demand (kWh/day)	PVBATENERGY
PV and battery O&M cost	PVBATO&M
PV-bat. pump use hours	PVBATPMPUSEHRS
PV-bat. pump size (W/pump)	PVBATPUMPSZ
PV-bat. battery cost	PVBATTRYCST
PV-bat. array size (Wp/well)	PVBATUNITARRAY
PV-bat. well cost	PVBATWELLCOST
PV-bat. no. of wells	PVBATWELLNO
PV-bat. annual per capita cost	PVBCAPITANCST
PV-bat. per capita capital cost	PVBCAPITCAP
PV-bat. civil works annual cost	PVBCVLANCST
PV-bat. civil works O&M cost	PVBCVLO&MCST
PV-bat. water cost ($\$/m^3$)	PVBM3CST
PV-bat. array & battery O&M cost	PVBO&MCST
PV balance of system efficiency	PVBOSEFF
PV-bat. pump annual cost	PVBPUMPANCST
PV-bat. pump capital cost	PVBPUMPCOST
PV-bat. pump O&M cost	PVBPUMPO&MCST
PV-bat. water storage cost	PVBSTORCOST
PV-bat. total annual cost	PVBTTLANCST
PV-bat. total capital cost	PVBTTLCOST
PV per capita capital cost	PVCAPCOST
PV per capita annual cost	PVCAPITANCST
PV civil works annual cost	PVCIVILANCOST
PV civil works O&M cost	PVCVLO&MANCST
PV array life	PVLIFE
PV pump & array cost lookup table ($/Wp)	PVLKUPTBL
PV cost multiplier	PVM
PV water cost ($\$/m^3$)	PVM3COST
PV array O&M cost ($/year)	PVO&MANCOST
PV per capita capital cost	PVPERCAPCOST
PV piping cost	PVPIPECOST
PV pump annual cost	PVPMPANCOST
PV pump O&M cost	PVPMPANO&MCST
PV pump efficiency (with battery)	PVPMPBATEFF
PV pump efficieny (without battery)	PVPMPEFF
High-flow PV pump life	PVPMPHILIFE
Low-flow PV pump life	PVPMPLOWLIFE
PV low-flow pump O&M (% capital cost)	PVPMPO&M
PV high-flow pump O&M (% capital cost)	PVPMPO&MHI
PV pump capital cost	PVPUMPCAPCST
PV pump size (W/well)	PVPUMPWATTS
PV array size range for costing pump & array	PVRANGE
PV water storage capital cost	PVSTORCAPCOST

PV water storage volume	PVSTORVOL
PV total capital cost	PVTTLCAPCOST
PV well cost	PVWELLCOST
PV no. of wells per village	PVWELLNO
PV water storage requirement (days)	PVWTRSTORE
Minimum water demand (liters/capita/day)	Q0
Water demand at cross-over point	QX
Replacement present value factor table	RPLTBL
Skilled labor wage rate ($/hour)	SKLDLBR
Standpipe water collect time lookup table	SPCLCTBL
Standpipe water collection time (min/trip)	SPCLCTIME
Cost per standpipe	SPCOST
No. of taps/standpipe	SPTAPS
Standpipe water gathering time (min/l)	SPTTLTIME
Standpipe water collect. time (hr/villg./yr)	SPWTRCLCTIME
Standpipe delivery rate (loads/hr)	SPWTRLOAD
Standpipe daily water demand (m^3/village)	SPWTRM3
Standpipe cost ($/village)	STNDPIPECOST
Analysis life	SYSLIFE
Water tank height + pumping losses	TANKHT
No. of taps per water point	TAPS
Time at q=lpcd on elastic demand curve	TELAST
Time at q=lpcd on inelastic demand curve	TINELAST
Load carried per trip (liters/trip)	TRIPLOAD
Time at cross over point (hr/m^3)	TXHRM3
Time at cross over point (min/l)	TXMINL
PV-bat. battery size (kWh/pump)	UNITBATSIZE
Water collection person's value of time ($/hr)	UNSLKWAGE
Standpipe use efficiency	USEFF
Water point use hours (hours/day)	USEHRS
Walking speed (km/hr)	WALK
Walking distance to water point (m)	WALKDIST
Walking time (min/trip)	WALKTIME
Fraction of family income spent on water	WATERINCM
Cost of a well	WELLCOST
Well type to be selected for analysis	WELLTYPE
Income producing work hours/family	WRKHRS
Select. water collect. time from demand curve	WTRCLCTIME
No. of water points	WTRPT
Maximum well yield (m^3/hour)	YIELD

INPUT DATA LISTING

Insolation (kWh/m^2/day - POA):	5 = INSOL
Water consumption (liters/cap/day):	20 = LPCD
Well type:	3 = WELLTYPE (1=\$500/5M, 2=\$1500/20M, 3=\$2500/20M, 4=\$5000/20M,5=\$5000/40M)
WATER DELIVERY RATES	
- Handpump, (l/min.)	@CHOOSE(WELLTYPE-1,20,15,15,15,12) = DELHP
- Stand pipe, (l/min.)	15 = DELSP
Income spent on water, (%)	3 = WATERINCM
Number of persons/family	8 = FSIZE
minimum water need, (LPCD)	10 = Q0
Work hours/family	20/8*FSIZE = WRKHRS
Housing density, houses/ha	25 = HOUSES
Walking speed, km/hour	3 = WALK
Maximum load/trip, l/trip	20 = TRIPLOAD
Water point use, hours	6 = USEHRS
No. Taps/standpipe	2 = TAPS
Standpipe use efficiency	1 = USEFF
Max. Well yield (m^3/hr)	50 = YIELD
Water table depth (m)	@CHOOSE(WELLTYPE-1,5,20,20,20,40) = DEPTH
Storage tank height (m)	10 = TANKHT
PV cost multiplier	1 = PVM
Minimum no. of wells	1 = MINWELLS

Capital costs - PV pump	up to Wp:	\$/Wp pump	\$/Wp array
	200	7.00	8.00*PVM
	500	4.25	7.75*PVM
	1000	2.50	7.50*PVM
	>1000		7.25*PVM

Note: for >1000 Wp, PV pump cost is based on diesel pump cost function adjusted for efficiency differences.

Capital costs:	Fixed	Var.(\$/m)	Var.(\$/m^3-hr)
Handpump	@IF(DEPTH<=7,200,500)	@IF(DEPTH<=7,0,8)	-
Diesel pump	275	25	75

Min. Pump cost (\$/pump):	@IF(DEPTH<=7,500,1000)
Diesel engine (\$/kW):	@IF(DEPTH<30,3000,5000)/KW + @IF(DEPTH<30,200,240), FOR kW>3
Storage cost (\$):	1000 *SQRT(VOLUME * DAYS OF STORAGE)
Piping cost (\$/m):	6 = PIPECST
Standpipe cost (\$):	150 = STNDPIPECST
Well cost (\$):	@CHOOSE(WELLTYPE-1,500,1500, 2500,5000,5000) WELLCOST

Battery cost ($/kWh): 200 = BATCOST
PV pump efficiency: @IF(DEPTH<12,0.25,0.35) = PVPMPEFF
PV pump eff w/ battery: 0.45 = PVPMPBATEFF
Battery efficiency: 0.8 = BATEFF
PV bos efficiency: 0.9 = PVBOSEFF
Diesel pump efficiency: 0.5 = DSLPMPEFF
Diesel fuel to water eff.: 0.02 = FUELTOWTREFF

Nominal diesel operation (hrs/day): 5 = DSLHRSNOM
Max diesel operating hrs (hrs/day): 12 = MAXDSLHRS
Maximum PV-bat. Pump hrs (hrs/day): 16 = MAXPVPMPHRS

Allowable battery DOD: 0.5 = BATDOD

Storage/system (days): 3 = PVSTORVOL
Storage/diesel (days): 1 = DSLSTORVOL

Max. PV well output (m^3/day): YIELD*MAXPVPMPHRS
Max. Diesel well output (m^3/day): YIELD*MAXDSLHRS

Handpump O&M (% of capital cost/year): @IF(DEPTH<7,@IF(USEHRS>6,40,20),
@IF(USEHRS>6,20,10)) = HPO&M

Civil works O&M (% capital cost/year): 1 = CIVILO&M
PV array & bat. O&M (% cap. Cost/yr): 1 = PVBATO&M
Diesel O&M (% capital cost/year): 15 = DSLO&M
PV motor/pump O&M (% cap. Cost/yr): 10 FLOWS < HIFLOWPMP = PVPMPO&M
PV motor/pump O&M (% cap. Cost/yr): 5 FLOWS > HIFLOWPMP = PVPMPO&MHI

Skilled attend. rate ($/hour): 0.5 = SKLDLBR
PV pump attendant (hours/pump/year): 2*52 = PVATTEND
Handpump, PV/standpipe attend.
(hours/water point/year): 0.5*365 = HPATTENDMIN
Diesel attendant (hours/pump/year): 2920 = DSLATTEND

Fuel cost ($/liter): 0.5 = FUELCOST

Handpump life (years): 10 = HPLIFE
Motor/pump life (years): 10, FOR FLOWS<HIFLOWPMP = PVPMPLOWLIFE
Motor/pump life (years): 7.5, FOR FLOWS>HIFLOWPMP = PVPMPHILIFE
Diesel life (years): @IF(DEPTH<7,10,10)
Civil works life (years): 20 = CIVILIFE
PV array life (years): 20 = PVLIFE
Battery life (years): 5 = BATLIFE

Discount rate: 0.1 = DISCOUNT
System life (years): 20 = SYSLIFE

Water collection wage rate ($/hour): 0.125 = UNSKLDLBR
Cost water collct. time? 0 (YES=1, NO=0)

Present value of replacements: 1+Σ(1PLUSDISCOUNT^(-N*YEAR)),
FOR N*YEAR<SYSLIFE
Capital equipment annualizing factor: DISCOUNT/(1-(1PLUSDISCNT^-SYSLIFE))

SELECTION OF MAXIMUM NUMBER OF PERSONS PER WATER POINT

This analysis is based on first calculating the time (T, minutes/liter) a person is willing to spend gathering L liters/capita/day of water using the water demand curves derived by the UNDP/World Bank Handpumps Project (as reported in: World Bank, "Rural Water Supply and Sanitation: Time for Change"). Two curves are used, in the inelastic demand region, the relationship between L and T is given by:

Water collection time/ inelastic demand curve =
T_i (min/l) = 1000*WRKHRS/((LPCD-Q0)*FSIZE)^2*60/1000
= TINELAST

In the elastic region, the relationship is:

Water collection time/elastic demand curve =
Te (min/l) = +WATERINCM/100*WRKHRS*1000/LPCD/7*60/1000
= TELAST

The time at the crossover point from inelastic to elastic demand is referred to as the "crossover point". The cross over point water demand, QX, and time, TX, is given by:

Water use at cross over point (liters/capita/day) = QX
= ((2*FSIZE*Q0*WATERINCM/100+1)+
@SQRT(4*FSIZE*Q0*WATERINCM/100+1))/ (2*(WATERINCM/100)*FSIZE)

TX (hrs/m^3) = 2000*WRKHRS*(WATERINCM/100)^2/
((2*FSIZE*Q0*WATERINCM/100+1)+ @SQRT(4*FSIZE
*Q0*WATERINCM/100+1)) = TXHRM3

TX (min/l) = TXHRM3*60/1000

The time corresponding to L = LPCD is given by:

Selected water collection time (min/l) = Td = @IF(LPCD>QX,TELAST,TINELAST)

The maximum number of persons served per water point is computed by selecting the number of persons (POP) served when water gathering time (Ts) is equal to the time a person is willing to spend (Td). Water collection time is composed of:

1. Walking time
2. Queuing time
3. Container filling time

Walking time depends on the distance walked and the walking speed. Walking distance depends on the population density and POP:

Walk distance (meters) = @SQRT(POP/FSIZE/HOUSES*10000)

Walk time (min/trip) = DIST/WALK/1000*60

Queuing time is computed using standard queuing models (See H. Wagner, "Principles of Operations Research," Second edition, Prentice Hall, Chapter 20). The handpump is modeled as a single server system with Poisson input and exponential service. The standpipe, which has two taps at each water point is modeled as a two server system with Poisson input and exponential service. The calculation equations are shown below:

Water delivery rate (loads/hour) = DELHP*60/TRIPLOAD, FOR HANDPUMP
= HPWTRLOAD
= DELSP*60/TRIPLOAD, FOR STANDPIPE = SPWTRLOAD

Arrival (trips/hr) = POP*LPCD/TRIPLOAD/USEHRS

Collct/HP (min/trip) = @IF(HPWTRLOAD>ARRVLRATE,1/(HPWTRLOAD-ARRVLRATE), @NA)*60 = HPCLCTTIME

Collct/SP (min/trip) = @IF(SPWTRLOAD*SPTAPS-ARRVLRATE>0, 60*(ARRVLRATE^2/(SPWTRLOAD* (4*SPWTRLOAD^2-ARRVLRATE^2))+1/SPWTRLOAD),@NA) = SPCLCTIME

Total water gathering time is given by:

Total time/HP (min/l) = (WALKTIME+HPCLCTIME)/TRIPLOAD

Total time/SP (min/l) = (WALKTIME+SPCLCTIME)/TRIPLOAD

An iterative procedure is used to select the population (POP) at which Ts equals Td:

Maximum number served per handpump = @MIN(YIELD*1000/LPCD*USEHRS, @VLOOKUP(WTRCLCTIME,HPCLCTBL,2)) = MAXHPSERVE

Maximum number served per standpipe = @VLOOKUP(WTRCLCTIME, SPCLCTBL,1)*USEFF = MAXSPSERVE

The following calculations compute the number of wells required per village, the system component sizes, and initial capital, annualized capital and O&M costs.

Handpump - maximum village population (#) = +MAXHPSERVE*WTRPT
Standpipe - maximum village population (#) = +MAXSPSERVE*WTRPT

Handpump daily water use (m^3) = +MAXHPVILLGE*LPCD/1000
Standpipe daily water use (m^3) = +MAXSPVILLGE*LPCD/1000

No. of wells needed with PV & no battery = @MAX(MINWELLS, @INT(+SPWTRM3/YIELD/INSOL+0.9))

No. of wells needed with diesel use = +DSLHRSNOM, hrs/day
= @MAX(MINWELLS, @INT(+SPWTRM3/ YIELD/DSLHRSNOM+0.9))

No. of wells needed if
Diesel used more hrs/day = @MAX(MINWELLS,
@IF(DSL5HRWELLNO=1,1,
@INT(SPWTRM3/MAXDSLWELLOP+0.9)))

Hrs/day use diesel = @IF(DSL5HRWELLNO = DSLMAXHRWELLNO,
DSLHRSNOM,+SPWTRM3/DSLMAXHRWELLNO/YIELD)

Diesel engine life years = @IF(DSLUSEHRS<5,DSLIFE,@INT(DSLIFE*5/DSLUSEHRS))

PV PUMPING SYSTEM COMPONENT SIZES (NO BATTERIES)

Pump size (watts) = 9.81*SPWTRM3*(DEPTH+TANKHT)/
3.6/PVPMPEFF/INSOL/PVWELLNO

Storage volume (m^3) = +SPWTRM3*PVWTRSTORE

PV array size (Wp) = +PVPUMPWATTS/PVBOSEFF

Piping length (m) = 90*WTRPT^0.4*(MAXSPVILLGE/FSIZE/HOUSES)^0.6

PV-BATTERY PUMPING SYSTEM CONFIGURATIONS

Number of wells required w/o battery = PVWELLNO

Number of wells required w/ battery = @MAX(MINWELLS,@IF(PVWELLNO=1,1,
@INT(SPWTRM3/MAXPVWELLOP+0.9)))

Energy required w/ battery (kWh/day) = 9.81*SPWTRM3*(DEPTH+TANKHT)
/3600/PVPMPBATEFF/BATEFF

Battery size (kWh) = +PVBATENERGY/BATDOD

Array size w/ bat. (kWp) = +PVBATENERGY/PVBOSEFF/INSOL

Pump use hrs/day (min=peak insol. hrs)
= @IF(+SPWTRM3/PVBATWELLNO/YIELD
<INSOL,INSOL,SPWTRM3/PVBATWELLNO/YIELD)

DIESEL PUMPING SYSTEM COMPONENT SIZES

Nominal pump size (kW) = 9.81*SPWTRM3*(DEPTH+TANKHT)
/3600/DSLPMPEFF/DSLUSEHRS/DSLMAXHRWELLNO

Storage volume (m^3) = +SPWTRM3*DSLWTRSTORE

Diesel engine (kW) = @MAX(@INT(DSLPMPSIZE/0.8+0.9),3)

COST ANALYSIS

CAPITAL COSTS OF HANDPUMP SYSTEM

```
Handpump costs ($)          = +WTRPT*(HPFXDCST+HPVARCST*DEPTH)

Well cost ($)               = +WTRPT*WELLCOST

Total cost ($)              = +HPCAPCOST+HPWELLCAPCOST

Handpump per capita capital cost ($) = +HPTTLCAPCOST/MAXHPVILLGE
```

PV SYSTEM COST (NO BATTERIES)

```
Pump cost ($)       = @IF(PVARRAYSIZE<1000,@MAX(PVWELLNO*@VLOOKUP
                          (PVARRAYSIZE,PVLKUPTBL,1)*PVARRAYSIZE,
                               PVWELLNO*MINPMPCST),PVWELLNO*
                                    DSLPMPEFF/PVPMPEFF*(DSLFXCST+
                                         DSLVARM*(DEPTH+TANKHT)+
                                               DSLVARQ*SPWTRM3/PVWELLNO/INSOL))

Storage cost ($)    = +BCSTORE*@SQRT(PVSTORVOL)

PV array cost ($) = @IF(PVARRAYSIZE<1000,PVWELLNO*
                          @VLOOKUP(PVARRAYSIZE,PVLKUPTBL,2)*PVARRAYSIZE,
                               PVWELLNO*(0.75+@VLOOKUP(PVARRAYSIZE,PVLKUPTBL,2))
                                    *PVARRAYSIZE)

Piping cost ($)     = +PIPECST*PIPELENGTH

Standpipe cost ($)       = +WTRPT*SPCOST

Well cost ($)       = +WELLCOST*PVWELLNO

Total PV system cost ($) = @SUM(PV SYSTEM COMPONENT COSTS)

PV pump per capita cost ($/person) = +PVTTLCAPCOST/MAXSPVILLGE
```

PV-BATTERY PUMPING SYSTEM COST

```
Pump cost ($)       = @IF(PVBATPUMPSZ<1000,@MAX(PVBATWELLNO*@VLOOKUP
                          (PVBATPUMPSZ,PVLKUPTBL,1)*PVBATPUMPSZ,
                            PVBATWELLNO*MINPMPCST),
                              DSLPMPEFF/PVPMPBATEFF*PVBATWELLNO*
                                (DSLFXCST+DSLVARM*(DEPTH+TANKHT)+
                                   DSLVARQ*WTRPT/PVBATWELLNO/PVBATPMPUSEHRS))

Storage cost ($)    = +PVSTORCAPCOST
```

PV array cost ($) = @IF(PVBATUNITARRAY<1000,PVBATWELLNO*
@VLOOKUP(PVBATUNITARRAY,PVLKUPTBL,2)*PVBATUNITARRAY,
PVBATWELLNO*(0.75+@VLOOKUP(PVBATUNITARRAY,
PVLKUPTBL,2))*PVBATUNITARRAY)

Piping cost ($) = +PIPECST*PIPELENGTH

Standpipe cost ($) = +WTRPT*SPCOST

Well cost ($) = +WELLCOST*PVBATWELLNO

Battery cost ($) = +UNITBATSIZE*BATCOST*PVBATWELLNO

Total PV system cost ($) = @SUM(PV-BAT SYSTEM COMPONENTS)

PV-bat pump per capita cost ($) = +PVBTTLCOST/MAXSPVILLGE

DIESEL PUMPING SYSTEM COSTS

Pump cost ($) = @MAX(MINPMPCST*DSLMAXHRWELLNO,
+DSLMAXHRWELLNO*(DSLFXCST+DSLVARM*(DEPTH+
TANKHT)+DSLVARQ*SPWTRM3/DSLUSEHRS/DSLMAXHRWELLNO))

Storage cost ($) = +BCSTORE*@SQRT(DSLSTORVOL)

Diesel cost ($) = +DSLMAXHRWELLNO*(ENGFXCST+ENGVARCST*DIESELSIZE)

Piping cost ($) = +PIPECST*PIPELENGTH

Standpipe cost ($) = +WTRPT*SPCOST

Well cost ($) = +WELLCOST*DSLMAXHRWELLNO

Total system cost ($) = @SUM(DIESEL SYSTEM COMPONENT COSTS)

Diesel per capita cost ($) = +DSLTTLCOST/MAXSPVILLGE

ANNUAL WATER COLLECTION COSTS USING HANDPUMPS AND STANDPIPES

Handpump water collection cost ($/year) = @IF(CLCTCOST=1,HPWTRM3*1000*
WTRCLCTIME/60*UNSLKWAGE*365,0)

Standpipe water collection cost ($/year)= @IF(CLCTCOST=1,SPWTRM3*1000*
WTRCLCTIME/60*UNSLKWAGE*365,0)

ANNUALIZED COSTS OF HANDPUMP SYSTEM

Handpump cost ($/year) = +HPCAPCOST*@VLOOKUP(HPLIFE,RPLTBL,1)*ANNLFCTR

Well cost ($/year) = +WELLCOST*WTRPT*ANNLFCTR*@VLOOKUP(CIVILIFE,RPLTBL,1)

Handpump O&M cost ($/year) = +HPCAPCOST*HPO&M/100+SKLDLBR*WTRPT*HPATTENDMIN

Well O&M cost ($/year) = +WTRPT*WELLCOST*CIVILO&M/100

Total cost ($/year) = @SUM(HANDPUMP SYSTEM ANNUALIZED COST COMPONENTS)

Handpump per capita cost ($/year) = (HPTTLANCST+HPWTRCLCTIME)/MAXHPVILLGE

Handpump water cost (\$/m^3) = (HPTTLANCST+HPWTRCLCTIME)/HPWTRM3/365

ANNUALIZED COSTS OF PV PUMP SYSTEM (NO BATTERIES)

PV array cost ($/year) = +PVCAPCOST*@VLOOKUP(PVLIFE,RPLTBL,1)*ANNLFCTR

Pump cost ($/year) = @IF(SPWTRM3/PVWELLNO<HIFLOWPMP,+PVPUMPCAPCST*@VLOOKUP(PVPMPLOWLIFE,RPLTBL,1)*ANNLFCTR,PVPUMPCAPCST*@VLOOKUP(PVPMPHILIFE,RPLTBL,1)*ANNLFCTR)

Civil work cost ($/year)= (PVWELLCOST+PVSTORCAPCOST+PVPIPECOST+STNDPIPECOST)*@VLOOKUP(CIVILIFE,RPLTBL,1)*ANNLFCTR

PV O&M cost ($/year) = +PVCAPCOST*PVBATO&M/100

Pump O&M cost ($/year) = @IF(SPWTRM3/PVWELLNO<HIFLOWPMP,+PVPUMPCAPCST*PVPMPO&M/100+PVATTEND*SKLDLBR*PVWELLNO,PVPUMPCAPCST*PVPMPO&MHI/100+PVATTEND*SKLDLBR*PVWELLNO)

Civil work O&M cost ($/year) = (PVSTORCAPCOST+PVPIPECOST+PVWELLCOST)*CIVILO&M/100+HPATTENDMIN*SKLDLBR*C541

Total cost ($/year) = @SUM(PV PUMP SYSTEM ANNUALIZED COST COMPONENTS)

Per capita cost ($/year) = (PVANTTLCOST+SPWTRCLCTIME)/MAXSPVILLGE

Per m^3 cost (\$/m^3) = (PVANTTLCOST+SPWTRCLCTIME)/SPWTRM3/365

ANNUALIZED COSTS OF PV-BATTERY PUMP SYSTEM

```
PV array cost ($/year) = +PVBARRAYCST*@VLOOKUP(PVLIFE,RPLTBL,1)*ANNLFCTR

Pump cost ($/year)     = @IF(WTRPT/PVBATWELLNO/PVBATPMPUSEHRS
                          <HIFLOWPMP/5,+PVBPUMPCOST
                              *@VLOOKUP(PVPMPLOWLIFE,RPLTBL,1)
                                  *ANNLFCTR,PVBPUMPCOST*@VLOOKUP
                                      (PVPMPHILIFE,RPLTBL,1)*ANNLFCTR)

Civil work cost ($/year) = (PVBATWELLCOST+PVBSTORCOST+PVPIPECOST
                              +STNDPIPECOST)*@VLOOKUP
                                  (CIVILIFE,RPLTBL,1)*ANNLFCTR

Battery cost ($/year)    = +BATTERYCOST*@VLOOKUP(BATLIFE,RPLTBL,1)*ANNLFCTR

PV, bat. O&M cost ($/year)= (PVBARRAYCST+BATTERYCOST)*PVBATO&M/100

Pump O&M cost ($/year)   = @IF(SPWTRM3/PVBATWELLNO/PVBATPMPUSEHRS<
                              HIFLOWPMP/5,+PVBPUMPCOST*PVPMPO&M/100
                                  +PVATTEND*SKLDLBR*PVBATWELLNO,
                                      PVBPUMPCOST*PVPMPO&MHI/100
                                          +PVATTEND*SKLDLBR*PVBATWELLNO)

Civil work O&M cost ($/year) = (PVBSTORCOST+PVPIPECOST+PVBATWELLCOST)*
                                  CIVILO&M/100+HPATTENDMIN*SKLDLBR*WTRPT

Total cost ($/year)           = @SUM(PV-BAT SYSTEM ANNUALIZED COST
                                  COMPONENTS)

Per capita cost ($/year)      = (PVBTTLANCST+SPWTRCLCTIME)/MAXHPVILLGE

Per m3 cost ($/m3)            = (PVBTTLANCST+SPWTRCLCTIME)/SPWTRM3/365
```

ANNUALIZED COSTS OF DIESEL PUMP SYSTEM

```
Diesel cost ($/year) = +ENGINECOST*@VLOOKUP(DSLUSELIFE,RPLTBL,1)*ANNLFCTR

Pump cost ($/year)   = @IF(SPWTRM3/DSLMAXHRWELLNO<HIFLOWPMP,
                        +DSLPMPCOST*@VLOOKUP(PVPMPLOWLIFE,RPLTBL,1)*
                            ANNLFCTR,DSLPMPCOST*@VLOOKUP(PVPMPHILIFE,RPLTBL,1)
                                *ANNLFCTR)

Civil work cost ($/year) = DSLSTORCOST+PVPIPECOST+STNDPIPECOST
                              +DSLWELLCOST)*@VLOOKUP(CIVILIFE,RPLTBL,1)
                                  *ANNLFCTR

Diesel O&M cost ($/year) = +DSLPMPO&M/100*ENGINECOST+SKLDLBR*DSLATTEND

Pump O&M cost ($/year)   = @IF(SPWTRM3/DSLMAXHRWELLNO<HIFLOWPMP,
                              +PVPMPO&M/100*DSLPMPCOST,
                                  PVPMPO&MHI/100*DSLPMPCOST)
```

Civil work O&M cost ($/year) = (DSLSTORCOST+PVPIPECOST+DSLWELLCOST)*
CIVILO&M/100

Fuel cost ($/year) = 9.81*SPWTRM3*(DEPTH+TANKHT)/
(3600*FUELTOWTREFF*10.5)*FUELCOST*365

Total cost ($/year) = @SUM(DIESEL PUMP SYSTEM ANNUALIZED COST COMPONENTS)

Per capita cost ($/year) = (DSLTTLANCST+SPWTRCLCTIME)/MAXSPVILLGE

Per m^3 cost ($/$m^3$) = (DSLTTLANCST+SPWTRCLCTIME)/SPWTRM3/365

SUMMARY STATISTICS

PER CAPITA CAPITAL COSTS

Handpump ($/person) = +HPTTLCAPCOST/MAXHPVILLGE

PV ($/person) = @MIN(PVBTTLCOST/MAXSPVILLGE,
PVTTLCAPCOST/MAXSPVILLGE)

Diesel ($/person) = +DSLTTLCOST/MAXSPVILLGE

COST OF WATER

Handpump ($/$m^3$) = +HPM3WTRCOST

PV ($/$m^3$) = @MIN(PVBM3CST,PVM3COST)

Diesel ($/$m^3$) = +DSLM3CST

SYSTEM TYPE

PV system selected = @IF(PVBM3CST<PVM3COST,"BATTERY","NO BATTERY")

No. of wells (PV) = @IF(PVBM3CST<PVM3COST,PVBATWELLNO,PVWELLNO)

No. of wells (diesel) = +DSLMAXHRWELLNO

APPENDIX C

SAMPLE ANALYSIS

```
            MERIDIAN CORPORATION

COMPARATIVE EVALUATION OF WATER SUPPLY SYSTEMS

    HAND PUMPS VS. PV PUMPS VS. DIESEL PUMPS

                    FOR

            RURAL WATER SUPPLY                                   APRIL 7, 1987
----------------------------------------------------------------------------------
INPUT DATA

INSOLATION                                    5 KWH/M2/DAY - POA
WATER CONSUMPTION              LPCD          20           LPCD
WELL TYPE                                     5 (1=$500/5M, 2=$1500/20M, 3=$2500/20M,
WATER DELIVERY RATES                             4=$5000/20M, 5=$5000/40M)
 - HAND PUMP                  L/MIN.         12
 - STAND PIPE                 L/MIN.         15
INCOME SPENT ON WATER              %          3
NUMBER OF PERSONS/FAMILY                      8
MINIMUM WATER NEED             LPCD          10
WORK HOURS/FAMILY             HOURS          20
HOUSING DENSITY           HOUSES/HA          25
WALKING SPEED               KM/HOUR           3
MAXIMUM LOAD/TRIP            L/TRIP          20
WATER  POINT USE              HOURS           6
NO. TAPS/SP                                   2
STANDPIPE USE EFFICIENCY                      1
MAX. WELL YIELD                  50 M3/HR
WATER TABLE DEPTH                40 M
STORAGE TANK HEIGHT              10 M           PV COST MULTIPLIER
MINIMUM NO. OF WELLS              1                       1
------------------------------------------------------------
CAPITAL COSTS - PV PUMP   UP TO Wp:   $/Wp PUMP  $/Wp ARRAY
                                200        7.00        8.00
                                500        4.25        7.75            FOR >1000 Wp, PUMP COST
                               1000        2.50        7.50            BASED ON DIESEL PUMP
                              >1000                    7.25    <------ COST ADJUSTED FOR
                                                                       EFFICIENCY DIFFERENCES
CAPITAL COSTS:                FIXED   VAR.($/M) VAR.($/M3-HR)
HANDPUMP                        500           8
DIESEL PUMP                     275          25            75
```

```
MIN  PUMP COST              1000 $
DIESEL ENGINE               5000 /KW      +          240 $/KW, KW>3
STORAGE COST                1000 *SQRT(VOLUME * DAYS OF STORAGE)
PIPING COST                    6 $/M
STANDPIPE COST               150 $ EACH
WELL COST                   5000 $
BATTERY COST                 200        $/KWH
------------------------------------------------------------
PV PUMP EFFICIENCY          0.35
PV PUMP EFF W/ BATTERY      0.45
BATTERY EFFICIENCY           0.8
PV BOS EFFICIENCY            0.9
DIESEL PUMP EFFICIENCY       0.5
DIESEL FUEL TO WATER EFF    0.08
------------------------------------------------------------
NOMINAL DIESEL OPERATION       5 HOURS/DAY
MAX DIESEL OPERATING HRS      12 HOURS/DAY
MAXIMUM PV-BAT. PUMP HRS      16 HOURS/DAY
ALLOWABLE BATTERY DOD        0.5
------------------------------------------------------------
STORAGE/PV SYSTEM              3 DAYS
STORAGE/DIESEL                 1 DAY
MAX. PV WELL OUTPUT          800 M3/DAY        (COMPUTED)
MAX. DIESEL WELL OUTPUT      600 M3/DAY        (COMPUTED)
------------------------------------------------------------
HANDPUMP O&M                  10 % CAPITAL COST/YEAR
CIVIL WORKS O&M                1 % CAPITAL COST/YEAR
PV ARRAY & BATTERY O&M         1 % CAPITAL COST/YEAR
DIESEL O&M                    15 % CAPITAL COST/YEAR
PV MOTOR/PUMP O&M             10 % CAP. COST/YR FLOWS <          30     M3/DAY
PV MOTOR/PUMP O&M              5 % CAP. COST/YR FLOWS >          30     M3/DAY
SKILLED ATTEND. RATE         0.5 $/HOUR
ATTENDANT COST (PV PUMP)     104 HOURS/PUMP/YEAR
ATTEND. COST (HP, PV/SP)     182 HOURS/WATER POINT/YEAR
DIESEL ATTENDANT            2920 HOURS/PUMP/YEAR
------------------------------------------------------------
FUEL COST                    0.5 $/LITER
------------------------------------------------------------
HANDPUMP LIFE                 10 YEARS
MOTOR/PUMP LIFE               10 YEARS FOR FLOWS <          30     M3/DAY
MOTOR/PUMP LIFE              7.5 YEARS FOR FLOWS >          30     M3/DAY
DIESEL LIFE                   10 YEARS
CIVIL WORKS LIFE              20 YEARS
PV ARRAY LIFE                 20 YEARS
```

```
BATTERY LIFE                    5 YEARS
DISCOUNT RATE                 0.1
SYSTEM LIFE                    20 YEARS
------------------------------------------------------------
WAGE RATE                   0.125 $/HOUR
COST WATER COLLCT. TIME?        0 (YES=1, NO=0)
------------------------------------------------------------

PRESENT VALUE OF REPLACEMENTS
        LIFE      FACTOR   1+DISCOUNT RATE      10-YEAR LIFE ANALYSIS REPLACEMENT FACTOR
          2        4.91         1.1                    3.54
          3        3.48                                2.74
          4        2.69                                2.15
          5        2.25                                1.62
          6        2.06                                1.56
        7.5        1.73                                1.49
         10        1.39                                   1
         12        1.32                                   1
         15        1.24                                   1
         20        1.00                                   1
CAPITAL EQUIPMENT ANNUALIZING FACTOR      0.1175

------------------------------------  ---------------------------------------------


            SELECTION OF MAXIMUM NUMBER OF PERSONS PER WATER POINT
            ======================================================

QUEUEING TIME IS MODELED AS A SINGLE SERVER MODEL WITH POISSON INPUT
AND EXPONENTIAL SERVICE FOR THE HANDPUMP CASE

QUEUEING TIME IS MODELED AS A MULTIPLE SERVER MODEL WITH POISSON INPUT
AND EXPONENTIAL SERVICE FOR THE STANDPIPE CASE
----------------------------------------------------------------------------------
CALCULATIONS

 1 ESTIMATE MAXIMUM PERSONS PER WATER DELIVERY POINT

1.1 CALCULATE WATER USE AT CROSS OVER POINT

QX                   LPCD            18.87
TX                   HRS/M3           3.98
                     MIN/L            0.24
1.2 SELECTION OF DEMAND FUNCTION
```

Ti	MIN/L	0.19
Te	MIN/L	0.26
WATER COLLECTION TIME	MIN/L	0.26

1.3 WATER DELIVERY RATE LOADS/HR 36 HP
45 SP

1.3

POP	WALK DIST (M)	WLK TME MIN/TRIP	ARRIVAL TRIPS/HR	COLLCT/HP MIN/TRIP	COLLCT/SP MIN/TRIP	TOTAL/HP MIN/L	TOTAL/SP MIN/L	POP
10	22.36	0.45	1.67	1.75	1.33	0.11	0.09	10
20	31.62	0.63	3.33	1.84	1.34	0.12	0.10	20
30	38.73	0.77	5.00	1.94	1.34	0.14	0.11	30
40	44.72	0.89	6.67	2.05	1.34	0.15	0.11	40
50	50.00	1.00	8.33	2.17	1.34	0.16	0.12	50
60	54.77	1.10	10.00	2.31	1.35	0.17	0.12	60
70	59.16	1.18	11.67	2.47	1.36	0.18	0.13	70
80	63.25	1.26	13.33	2.65	1.36	0.20	0.13	80
90	67.08	1.34	15.00	2.86	1.37	0.21	0.14	90
100	70.71	1.41	16.67	3.10	1.38	0.23	0.14	100
110	74.16	1.48	18.33	3.40	1.39	0.24	0.14	110
120	77.46	1.55	20.00	3.75	1.40	0.26	0.15	120
130	80.62	1.61	21.67	4.19	1.42	0.29	0.15	130
140	83.67	1.67	23.33	4.74	1.43	0.32	0.16	140
150	86.60	1.73	25.00	5.45	1.44	0.36	0.16	150
160	89.44	1.79	26.67	6.43	1.46	0.41	0.16	160
170	92.20	1.84	28.33	7.83	1.48	0.48	0.17	170
180	94.87	1.90	30.00	10.00	1.50	0.59	0.17	180
190	97.47	1.95	31.67	13.85	1.52	0.79	0.17	190
200	100.00	2.00	33.33	22.50	1.55	1.23	0.18	200
210	102.47	2.05	35.00	60.00	1.57	3.10	0.18	210
220	104.88	2.10	36.67	NA	1.60	NA	0.18	220
230	107.24	2.14	38.33	NA	1.63	NA	0.19	230
240	109.54	2.19	40.00	NA	1.66	NA	0.19	240
250	111.80	2.24	41.67	NA	1.70	NA	0.20	250
260	114.02	2.28	43.33	NA	1.74	NA	0.20	260
270	116.19	2.32	45.00	NA	1.78	NA	0.21	270
280	118.32	2.37	46.67	NA	1.82	NA	0.21	280
290	120.42	2.41	48.33	NA	1.87	NA	0.21	290
300	122.47	2.45	50.00	NA	1.93	NA	0.22	300
310	124.50	2.49	51.67	NA	1.99	NA	0.22	310
320	126.49	2.53	53.33	NA	2.05	NA	0.23	320
330	128.45	2.57	55.00	NA	2.13	NA	0.23	330

340	130.38	2.61	56.67	NA	2.21	NA	0.24	340
350	132.29	2.65	58.33	NA	2.30	NA	0.25	350
360	134.16	2.68	60.00	NA	2.40	NA	0.25	360
370	136.01	2.72	61.67	NA	2.51	NA	0.26	370
380	137.84	2.76	63.33	NA	2.64	NA	0.27	380
390	139.64	2.79	65.00	NA	2.79	NA	0.28	390
400	141.42	2.83	66.67	NA	2.95	NA	0.29	400
410	143.18	2.86	68.33	NA	3.15	NA	0.30	410
420	144.91	2.90	70.00	NA	3.38	NA	0.31	420
430	146.63	2.93	71.67	NA	3.64	NA	0.33	430
440	148.32	2.97	73.33	NA	3.97	NA	0.35	440
450	150.00	3.00	75.00	NA	4.36	NA	0.37	450
460	151.66	3.03	76.67	NA	4.86	NA	0.39	460
470	153.30	3.07	78.33	NA	5.50	NA	0.43	470
480	154.92	3.10	80.00	NA	6.35	NA	0.47	480
490	156.52	3.13	81.67	NA	7.55	NA	0.53	490
500	158.11	3.16	83.33	NA	9.35	NA	0.63	500
510	159.69	3.19	85.00	NA	12.34	NA	0.78	510
520	161.25	3.22	86.67	NA	18.24	NA	1.08	520
530	162.79	3.26	88.33	NA	36.34	NA	1.98	530
540	164.32	3.29	90.00	NA	NA	NA	NA	540
550	165.83	3.32	91.67	NA	NA	NA	NA	550
560	167.33	3.35	93.33	NA	NA	NA	NA	560
570	168.82	3.38	95.00	NA	NA	NA	NA	570
580	170.29	3.41	96.67	NA	NA	NA	NA	580
590	171.76	3.44	98.33	NA	NA	NA	NA	590
600	173.21	3.46	100.00	NA	NA	NA	NA	600
610	174.64	3.49	101.67	NA	NA	NA	NA	610
620	176.07	3.52	103.33	NA	NA	NA	NA	620
630	177.48	3.55	105.00	NA	NA	NA	NA	630
640	178.89	3.58	106.67	NA	NA	NA	NA	640
650	180.28	3.61	108.33	NA	NA	NA	NA	650
660	181.66	3.63	110.00	NA	NA	NA	NA	660
670	183.03	3.66	111.67	NA	NA	NA	NA	670
680	184.39	3.69	113.33	NA	NA	NA	NA	680
690	185.74	3.71	115.00	NA	NA	NA	NA	690
700	187.08	3.74	116.67	NA	NA	NA	NA	700
710	188.41	3.77	118.33	NA	NA	NA	NA	710
720	189.74	3.79	120.00	NA	NA	NA	NA	720
730	191.05	3.82	121.67	NA	NA	NA	NA	730
740	192.35	3.85	123.33	NA	NA	NA	NA	740
750	193.65	3.87	125.00	NA	NA	NA	NA	750
760	194.94	3.90	126.67	NA	NA	NA	NA	760
770	196.21	3.92	128.33	NA	NA	NA	NA	770

```
   780      197.48        3.95     130.00           NA          NA       NA        NA       780
   790      198.75        3.97     131.67           NA          NA       NA        NA       790
   800      200.00        4.00     133.33           NA          NA       NA        NA       800
   810      201.25        4.02     135.00           NA          NA       NA        NA       810
   820      202.48        4.05     136.67           NA          NA       NA        NA       820
   830      203.72        4.07     138.33           NA          NA       NA        NA       830
   840      204.94        4.10     140.00           NA          NA       NA        NA       840
   850      206.16        4.12     141.67           NA          NA       NA        NA       850
   860      207.36        4.15     143.33           NA          NA       NA        NA       860
   870      208.57        4.17     145.00           NA          NA       NA        NA       870
   880      209.76        4.20     146.67           NA          NA       NA        NA       880
   890      210.95        4.22     148.33           NA          NA       NA        NA       890
   900      212.13        4.24     150.00           NA          NA       NA        NA       900
   910      213.31        4.27     151.67           NA          NA       NA        NA       910
   920      214.48        4.29     153.33           NA          NA       NA        NA       920
   930      215.64        4.31     155.00           NA          NA       NA        NA       930
   940      216.79        4.34     156.67           NA          NA       NA        NA       940
   950      217.94        4.36     158.33           NA          NA       NA        NA       950
------------------------------------------------------------------------------------------------
WATER DEMAND                        LPCD          20.00
MAXIMUM NUMBER SERVED PER HAND PUMP              110.00
MAXIMUM NUMBER SERVED PER STAND PIPE             360.00
------------------------------------------------------------------------------------------------
           PER CAP.  POPULATION  POPULATION
        CONSUMPTION      SERVED      SERVED
        ------------------------------------
                 20         110         360
        ------------------------------------
```

MAXIMUM SIZE OF POPULATION SERVED

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	HANDPUMP MAXIMUM VILLAGE POPULATION #	STANDPIPE MAXIMUM VILLAGE POPULATION #	HANDPUMP DAILY WATER USE M3	STANDPIPE DAILY WATER USE M3	NO. OF WELLS NEEDED WITH PV & NO BATTERY	NO. OF WELLS NEEDED W/ DIESEL 5 HRS/DAY	NO. OF WELLS NEEDED IF DIESEL USED MORE HRS/DAY	DIESEL HRS/DAY USE DIESEL	ENGINE LIFE YEARS
20	1	110	360	2.20	7.20	1	1	1	5.00	10
	2	220	720	4.40	14.40	1	1	1	5.00	10
	4	440	1440	8.80	28.80	1	1	1	5.00	10
	6	660	2160	13.20	43.20	1	1	1	5.00	10
	8	880	2880	17.60	57.60	1	1	1	5.00	10
	10	1100	3600	22.00	72.00	1	1	1	5.00	10
	20	2200	7200	44.00	144.00	1	1	1	5.00	10

PV PUMPING SYSTEM COMPONENT SIZES (NO BATTERIES)

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	PUMP SIZE WATTS	STORAGE VOLUME M3	PV ARRAY SIZE Wp	PIPING LENGTH M
20	1	561	22	623	128
	2	1121	43	1246	256
	4	2242	86	2491	512
	6	3363	130	3737	768
	8	4485	173	4983	1024
	10	5606	216	6229	1281
	20	11211	432	12457	2561

PV-BATTERY PUMPING SYSTEM CONFIGURATIONS

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	DAILY WATER DEMAND M3	NUMBER OF WELLS REQUIRED W/O BATTERY	NUMBER OF WELLS REQUIRED W/ BATTERY	ENERGY REQUIRED W/ BATTERY KWH/DAY	BATTERY SIZE KWH	ARRAY SIZE W/ BAT. KWp	PUMP USE HRS/DAY (MIN-PEAK INSOL. HRS)
20	1	7	1	1	2.73	5.45	0.61	5.00
	2	14	1	1	5.45	10.90	1.21	5.00
	4	29	1	1	10.90	21.80	2.42	5.00
	6	43	1	1	16.35	32.70	3.63	5.00
	8	58	1	1	21.80	43.60	4.84	5.00
	10	72	1	1	27.25	54.50	6.06	5.00
	20	144	1	1	54.50	109.00	12.11	5.00

PV-BATTERY PUMPING SYSTEM COMPONENT SIZES

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	UNIT PUMP SIZE WATTS	STORAGE VOLUME M3	UNIT PV ARRAY SIZE Wp	PIPING LENGTH M	UNIT BATTERY SIZE KWH
20	1	545	22	606	128	5
	2	1090	43	1211	256	11
	4	2180	86	2422	512	22
	6	3270	130	3633	768	33
	8	4360	173	4844	1024	44
	10	5450	216	6056	1281	55
	20	10900	432	12111	2561	109

DIESEL PUMPING SYSTEM COMPONENT SIZES

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	NOMINAL PUMP SIZE KW	STORAGE VOLUME M3	DIESEL ENGINE KW	PIPING LENGTH M
20	1	0.39	7	3	128
	2	0.78	14	3	256
	4	1.57	29	3	512
	6	2.35	43	3	768
	8	3.14	58	4	1024
	10	3.92	72	5	1281
	20	7.85	144	10	2561

COST ANALYSIS

1. CAPITAL COSTS

CAPITAL COSTS OF HANDPUMP SYSTEM

NO. OF HANDPUMPS	HANDPUMP COSTS $	WELL COST $	TOTAL COST $
1	820	5000	5820
2	1640	10000	11640
4	3280	20000	23280
6	4920	30000	34920
8	6560	40000	46560
10	8200	50000	58200
20	16400	100000	116400

PER CAP. DEMAND LPCD	NO. OF HANDPUMPS	PER CAPITA CAPITAL COST $
20	1	53
	2	53
	4	53
	6	53
	8	53
	10	53
	20	53

PV SYSTEM COST (NO BATTERIES)

PER CAP. DEMAND LPCD	WATER POINTS #	PUMP COST $	STORAGE COST $	PV ARRAY COST $	PIPING COST $	STANDPIPE COST $	WELL COST $	TOTAL PV SYSTEM COST ($)
20	1	1557	4648	4671	768	150	5000	16794
	2	2487	6573	9966	1537	300	5000	25862
	4	2796	9295	19931	3073	600	5000	40696
	6	3104	11384	29897	4610	900	5000	54896
	8	3413	13145	39863	6147	1200	5000	68768
	10	3721	14697	49829	7683	1500	5000	82430
	20	5264	20785	99657	15367	3000	5000	149073

PER CAPITA PV PUMPING SYSTEM COST

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	PV PUMP PER CAPITA COST $
20	1	47
	2	36
	4	28
	6	25
	8	24
	10	23
	20	22

PV-BATTERY PUMPING SYSTEM COST

PER CAP. DEMAND LPCD	WATER POINTS #	PUMPS COST $	STORAGE COST $	PV ARRAY COST $	PIPING COST $	STANDPIPE COST $	WELL COST $	BATTERY COST $	TOTAL PV SYSTEM COST ($)
20	1	1363	4648	4542	768	150	5000	1090	17560
	2	1934	6573	9689	1537	300	5000	2180	27213
	4	2174	9295	19378	3073	600	5000	4360	43881
	6	2414	11384	29067	4610	900	5000	6540	59915
	8	2654	13145	38756	6147	1200	5000	8720	75622
	10	2894	14697	48444	7683	1500	5000	10900	91119
	20	4094	20785	96889	15367	3000	5000	21800	166935

PER CAPITA PV-BATTERY PUMPING SYSTEM COST

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	PV PUMP PER CAPITA COST $
20	1	49
	2	38
	4	30
	6	28
	8	26
	10	25
	20	23

DIESEL PUMPING SYSTEM COSTS

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	PUMP COST $	STORAGE COST $	DIESEL COST $	PIPING COST $	STANDPIPE COST $	WELL COST $	TOTAL SYSTEM COST ($)
20	1	1633	2683	5720	768	150	5000	15955
	2	1741	3795	5720	1537	300	5000	18092
	4	1957	5367	5720	3073	600	5000	21717
	6	2173	6573	5720	4610	900	5000	24976
	8	2389	7589	5960	6147	1200	5000	28285
	10	2605	8485	6200	7683	1500	5000	31474
	20	3685	12000	7400	15367	3000	5000	46452

PER CAPITA DIESEL PUMPING SYSTEM COST

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	DIESEL PER CAPITA COST $
20	1	44
	2	25
	4	15
	6	12
	8	10
	10	9
	20	6

ANNUALIZED COST COMPUTATIONS

ANNUALIZED COSTS OF HAND PUMP SYSTEM

PER CAP. DEMAND LPCD	WATER POINTS #	HANDPUMP COST $/YEAR	WELL COST $/YEAR	HAND PUMP O&M COST $/YEAR	WELL O&M COST $/YEAR	TOTAL COST $/YEAR
20	1	133	587	173	50	944
	2	267	1175	346	100	1887
	4	534	2349	692	200	3775
	6	801	3524	1038	300	5662
	8	1068	4698	1384	400	7550
	10	1335	5873	1730	500	9437
	20	2669	11746	3460	1000	18875

ANNUAL WATER COLLECTION COSTS USING HANDPUMPS AND STANDPIPES

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	HANDPUMP WATER COLLECTION COST $/YEAR	STANDPIPE WATER COLLECTION COST $/YEAR
20	1	0	0
	2	0	0
	4	0	0
	6	0	0
	8	0	0
	10	0	0
	20	0	0

TOTAL UNIT COSTS OF HAND PUMP SYSTEMS

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	PER CAPITA COST $/CAP-YEAR	PER M3 COST $/M3
20	1	8.58	1.18
	2	8.58	1.18
	4	8.58	1.18
	6	8.58	1.18
	8	8.58	1.18
	10	8.58	1.18
	20	8.58	1.18

ANNUALIZED COSTS OF PV PUMP SYSTEM (NO BATTERIES)

PER CAP. DEMAND LPCD	WATER POINTS #	PV ARRAY COST $/YEAR	PUMP COST $/YEAR	CIVIL WORK COST $/YEAR	PV O&M COST $/YEAR	PUMP O&M COST $/YEAR	CIVIL WORK O&M COST $/YEAR	TOTAL COST $/YEAR
20	1	549	253	1241	47	208	195	2493
	2	1171	405	1575	100	301	313	3864
	4	2341	455	2111	199	332	538	5975
	6	3512	630	2572	299	207	756	7976
	8	4682	693	2994	399	223	971	9962
	10	5853	756	3392	498	238	1184	11921
	20	11706	1069	5186	997	315	2232	21504

TOTAL UNIT COSTS OF PV PUMP SYSTEMS (NO BATTERIES)

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	PER CAPITA COST $/YEAR	PER M3 COST $/M3
20	1	6.92	0.95
	2	5.37	0.74
	4	4.15	0.57
	6	3.69	0.51
	8	3.46	0.47
	10	3.31	0.45
	20	2.99	0.41

ANNUALIZED COSTS OF PV-BATTERY PUMP SYSTEM

PER CAP. DEMAND LPCD	WATER POINTS #	PV ARRAY COST $/YEAR	PUMP COST $/YEAR	CIVIL WORK COST $/YEAR	BATTERY COST $/YEAR	PV, BAT. O&M COST $/YEAR	PUMP O&M COST $/YEAR	CIVIL WORK O&M COST $/YEAR	TOTAL COST $/YEAR
20	1	533	222	1241	288	56	188	195	2724
	2	1138	315	1575	575	119	245	313	4280
	4	2276	354	2111	1150	237	269	538	6935
	6	3414	490	2572	1725	356	173	756	9486
	8	4552	539	2994	2300	475	185	971	12016
	10	5690	588	3392	2875	593	197	1184	14520
	20	11381	831	5186	5751	1187	257	2232	26824

TOTAL UNIT COSTS OF PV-BATTERY PUMP SYSTEM

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	PER CAPITA COST $/YEAR	PER M3 COST $/M3
20	1	24.76	1.04
	2	19.46	0.81
	4	15.76	0.66
	6	14.37	0.60
	8	13.65	0.57
	10	13.20	0.55
	20	12.19	0.51

ANNUALIZED COSTS OF DIESEL PUMP SYSTEM

PER CAP. DEMAND LPCD	WATER POINTS #	DIESEL COST $/YEAR	PUMP COST $/YEAR	CIVIL WORK COST $/YEAR	DIESEL O&M COST $/YEAR	PUMP O&M COST $/YEAR	CIVIL WORK O&M COST $/YEAR	FUEL COST $/YEAR	TOTAL COST $/YEAR
20	1	931	266	1010	2318	163	85	213	4986
	2	931	283	1249	2318	174	103	426	5485
	4	931	318	1649	2318	196	134	853	6399
	6	931	441	2007	2318	109	162	1279	7246
	8	970	485	2342	2354	119	187	1705	8163
	10	1009	529	2663	2390	130	212	2131	9064
	20	1204	748	4154	2570	184	324	4263	13447

TOTAL UNIT COSTS OF DIESEL PUMP SYSTEMS

PER CAP. DEMAND LPCD	NO. OF WATER POINTS #	PER CAPITA COST $/YEAR	PER M3 COST $/M3
20	1	13.85	1.90
	2	7.62	1.04
	4	4.44	0.61
	6	3.35	0.46
	8	2.83	0.39
	10	2.52	0.34
	20	1.87	0.26

SUMMARY STATISTICS

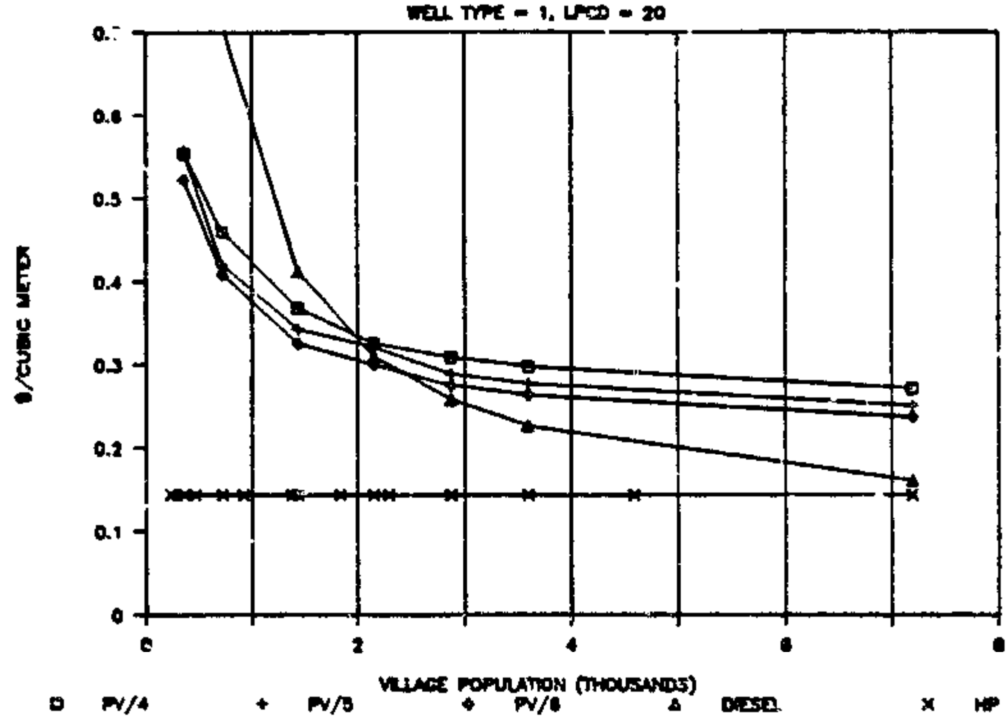
PER CAPITA DEMAND: 20 LITERS PER CAPITA-DAY
WELL COST: 5000 $ AT DEPTH: 40 METERS
INSOLATION: 5 KWH/M2/DAY

NO.OF WATER POINTS	POPULATION	PER CAPITA CAPITAL COSTS HANDPUMP $/PERSON	PV $/PERSON	DIESEL $/PERSON	COST OF WATER HANDPUMP $/M3	PV $/M3	DIESEL $/M3	PV SYSTEM SELECTED	NO. OF WELLS (PV)	NO. OF WELLS (DIESEL)
1	110	53			1.18					
2	220	53			1.18					
4	440	53			1.18					
6	660	53			1.18					
8	880	53			1.18					
10	1100	53			1.18					
20	2200	53			1.18					
1	360		47	44		0.95	1.90	NO BATTERY	1	1
2	720		36	25		0.74	1.04	NO BATTERY	1	1
4	1440		28	15		0.57	0.61	NO BATTERY	1	1
6	2160		25	12		0.51	0.46	NO BATTERY	1	1
8	2880		24	10		0.47	0.39	NO BATTERY	1	1
10	3600		23	9		0.45	0.34	NO BATTERY	1	1
20	7200		21	6		0.41	0.26	NO BATTERY	1	1

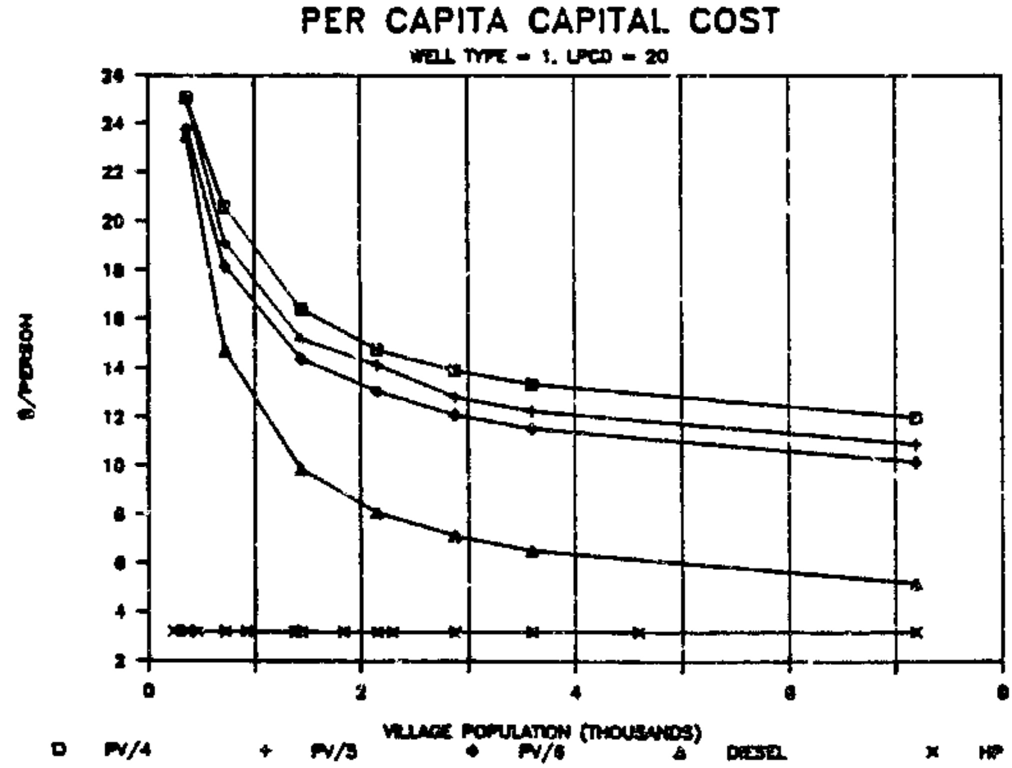
APPENDIX D

ANALYSIS GRAPHICAL OUTPUT

WELL COST: $500
DEPTH: 5 m
DEMAND: 20 lpcd

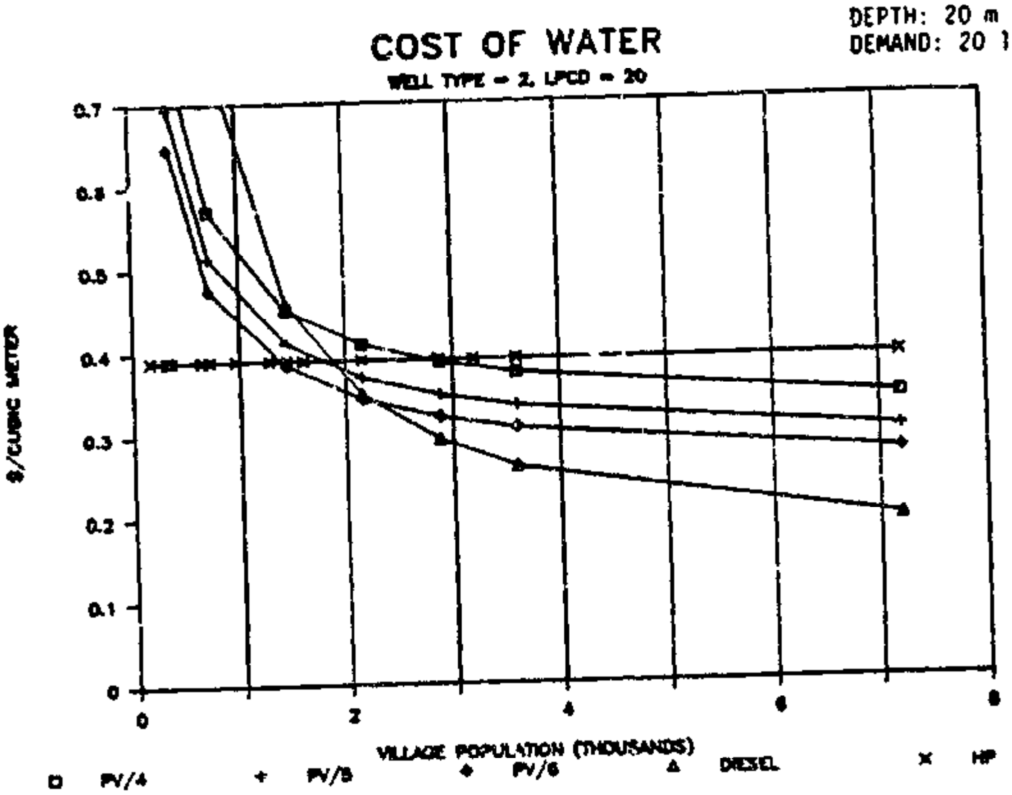

COST OF WATER

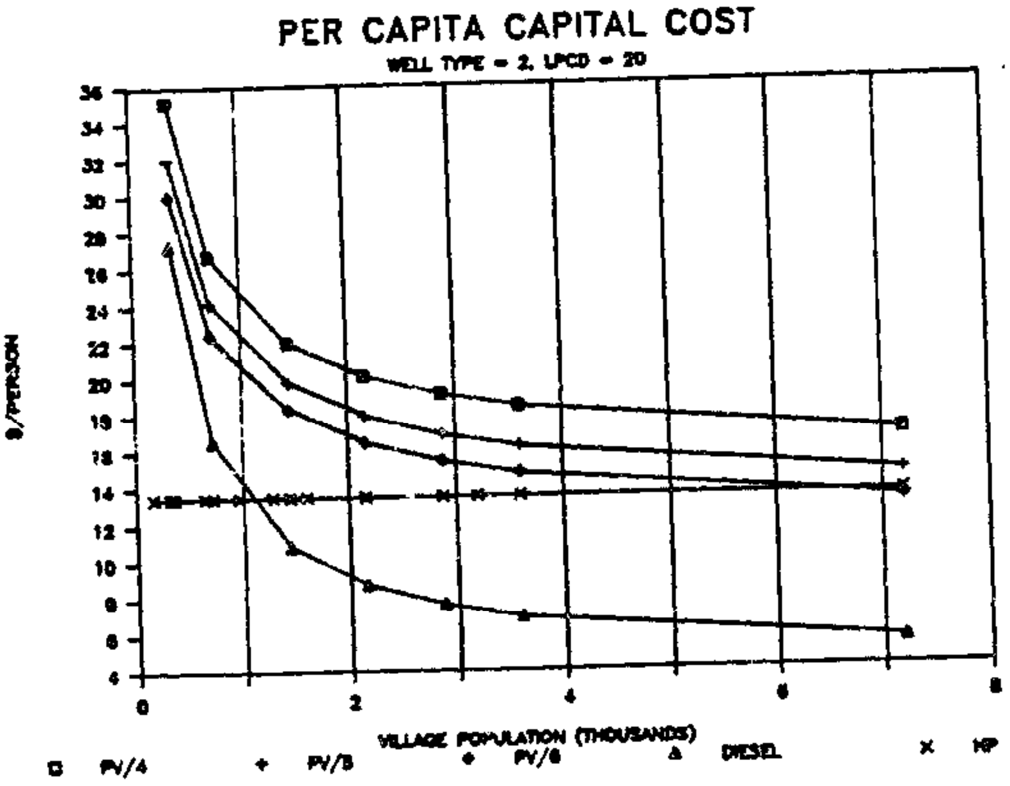
WELL TYPE = 1, LPCD = 20


PER CAPITA CAPITAL COST

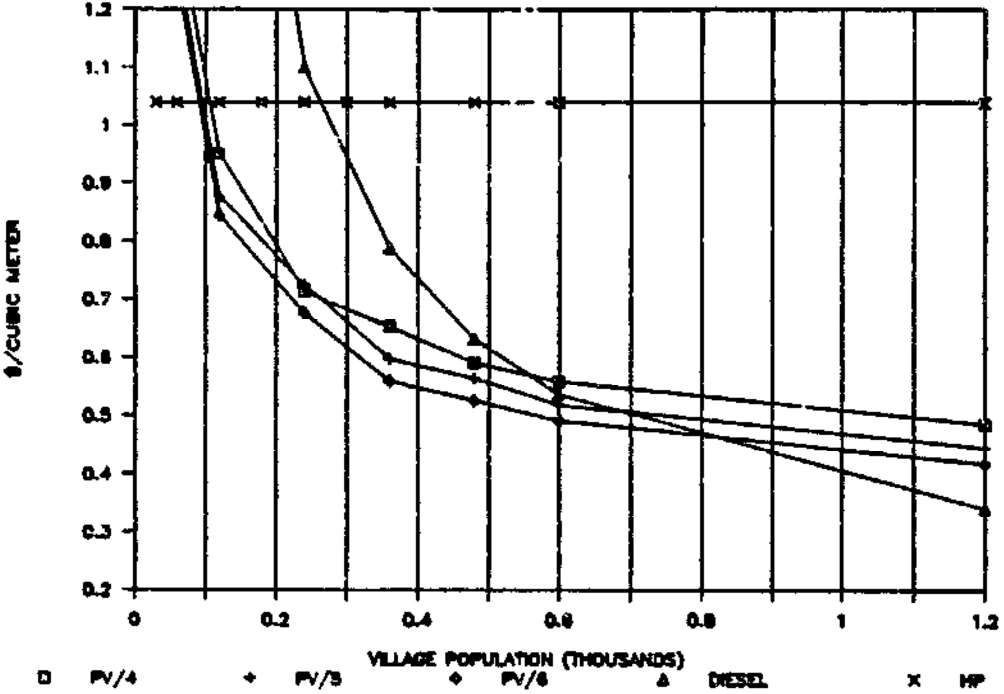
WELL TYPE = 1, LPCD = 20

WELL COST: $1,500
DEPTH: 20 m
DEMAND: 20 lpcd



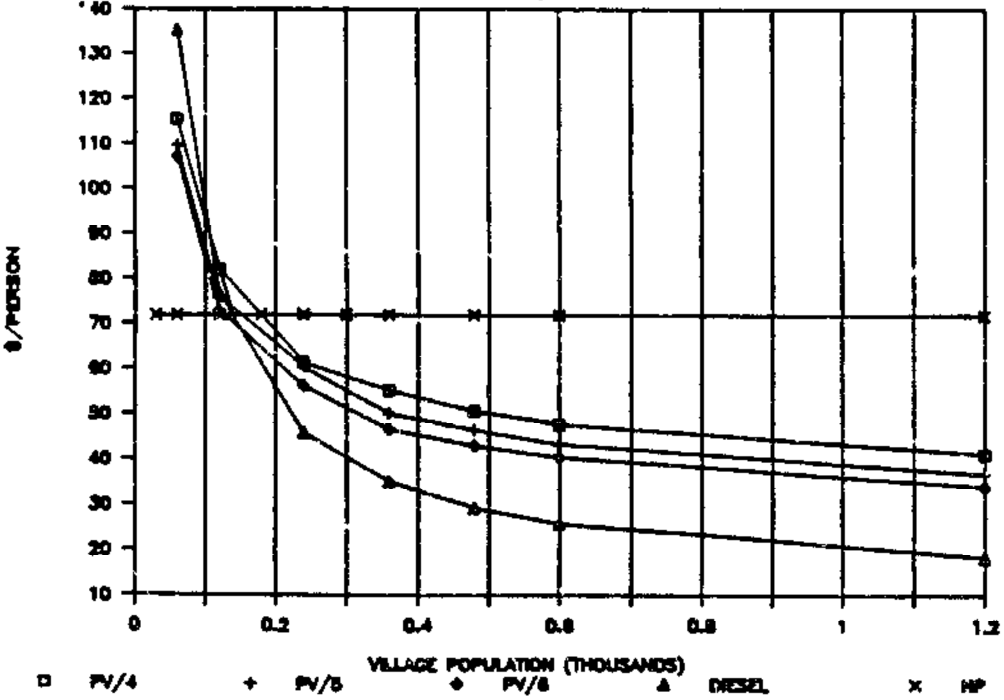


WELL COST: $1,500
DEPTH: 20 m
DEMAND: 40 lpcd



COST OF WATER

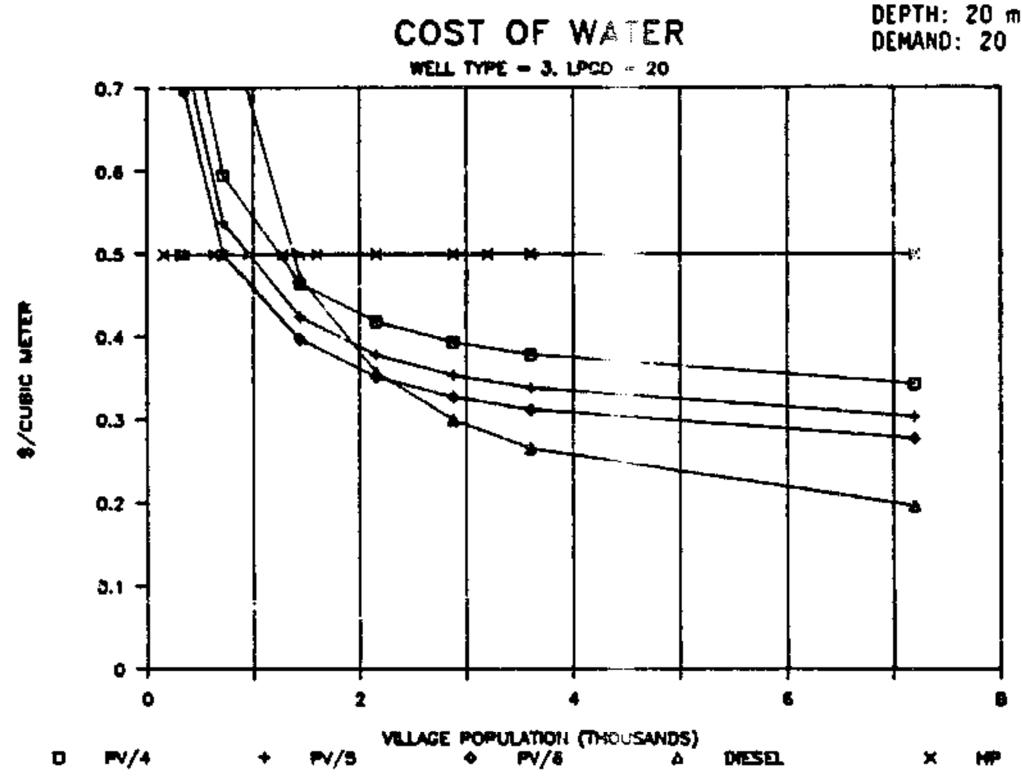
WELL TYPE = 2, LPCD = 40

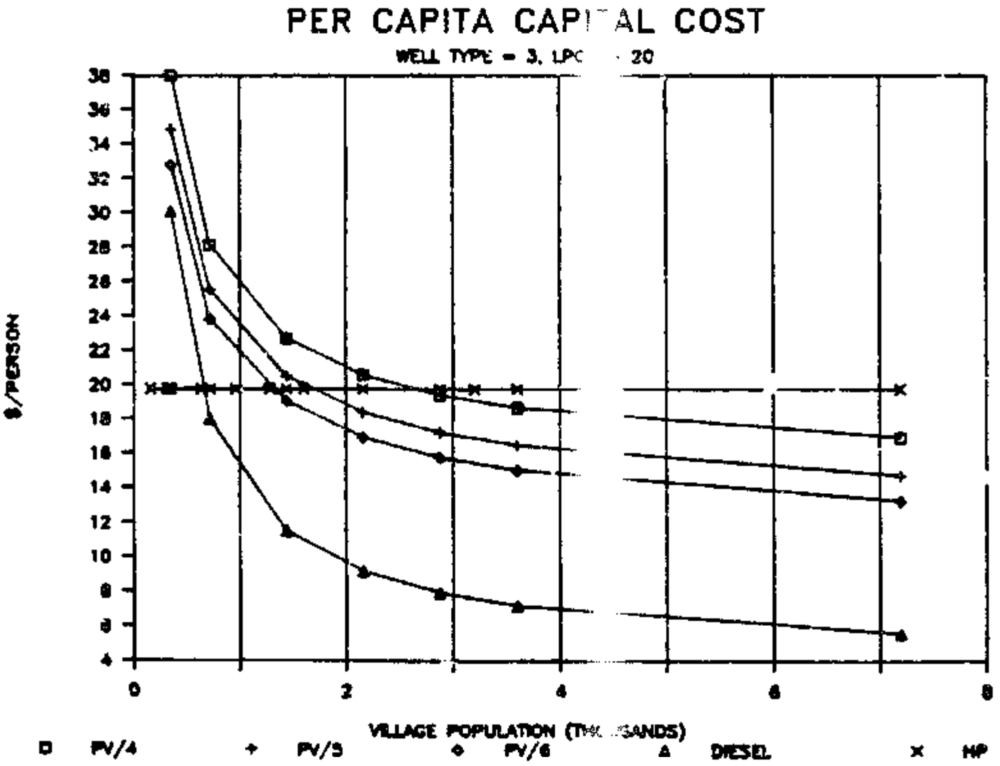


PER CAPITA CAPITAL COST

WELL TYPE = 2, LPCD = 40

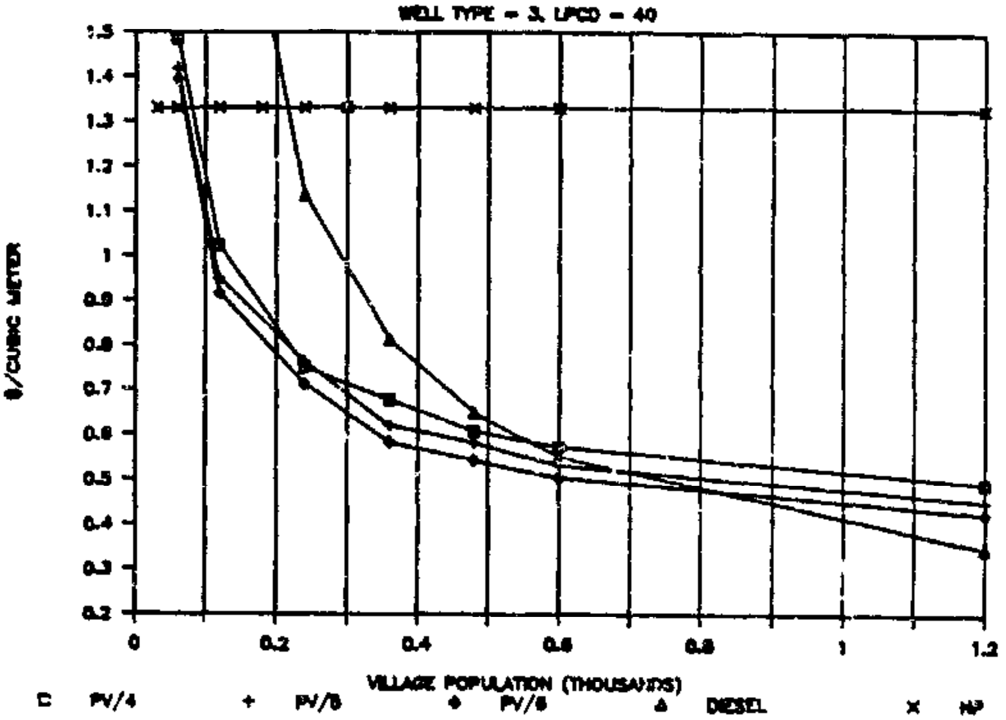
WELL COST: $2,500
DEPTH: 20 m
DEMAND: 20 lpcd



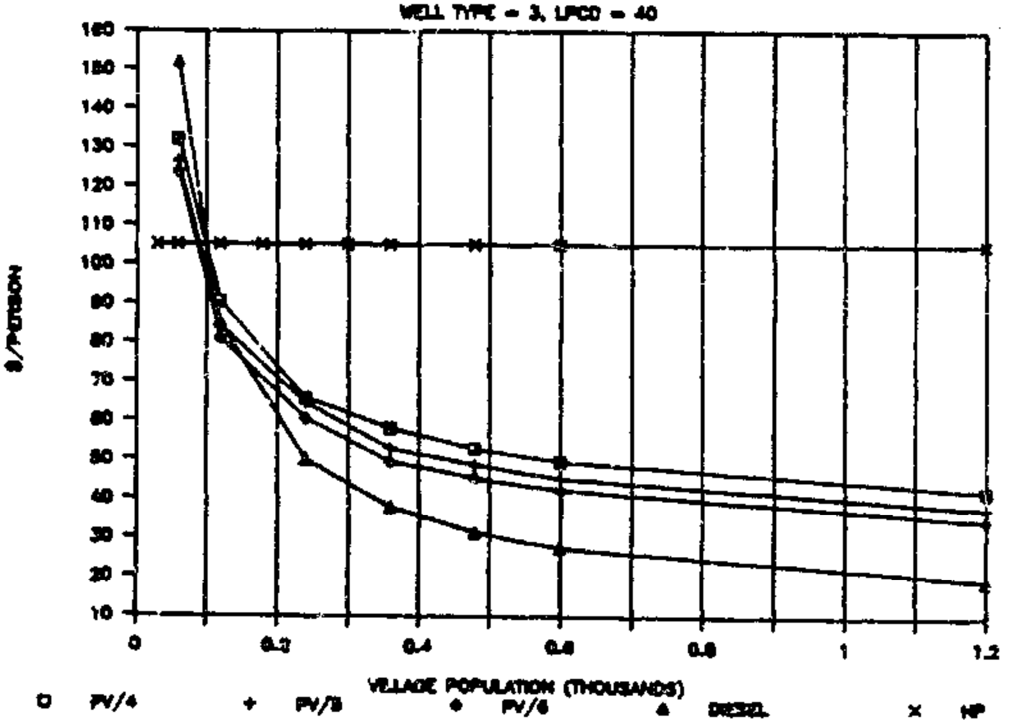


WELL COST: $2,500
DEPTH: 20 m
DEMAND: 40 lpcd

COST OF WATER



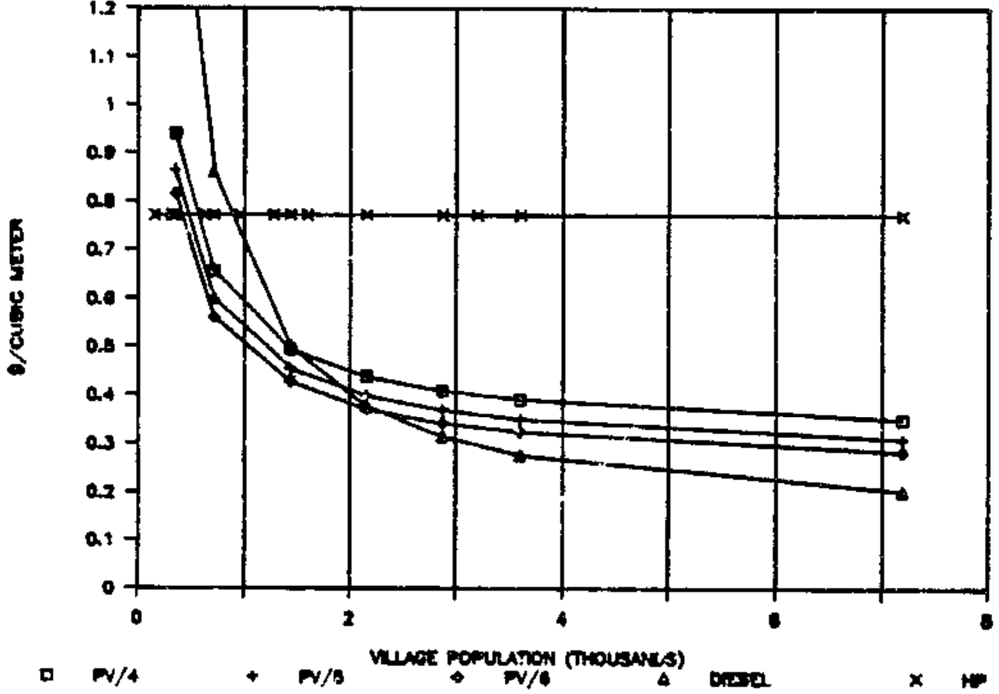
PER CAPITA CAPITAL COST



WELL COST: $5,000
DEPTH: 20 m
DEMAND: 20 lpcd

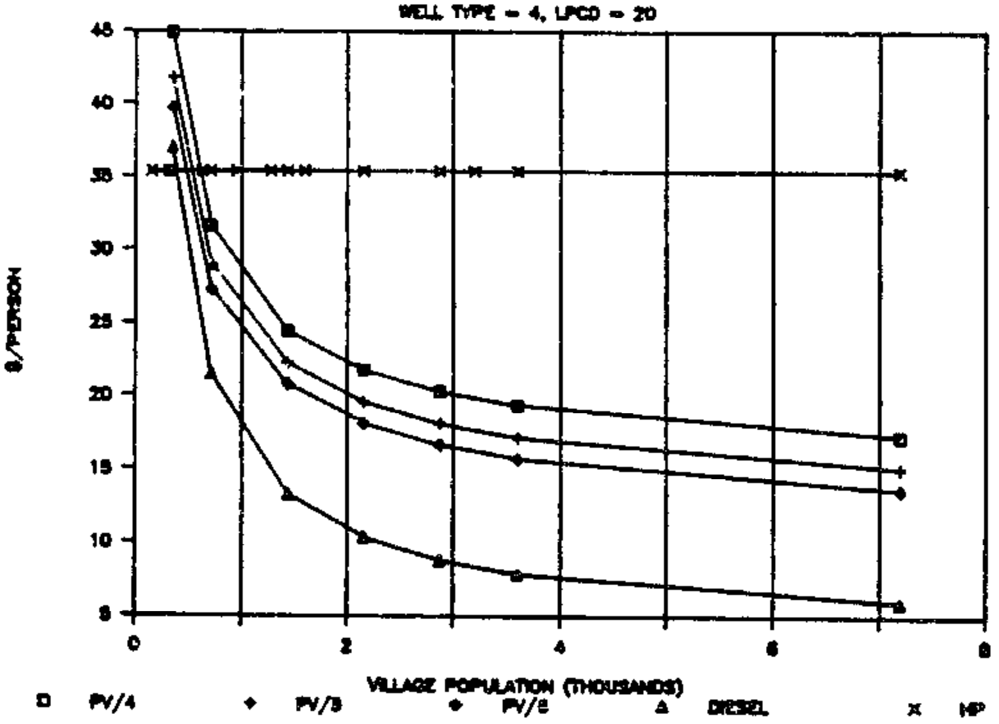
COST OF WATER

WELL TYPE = 4, LPCD = 20

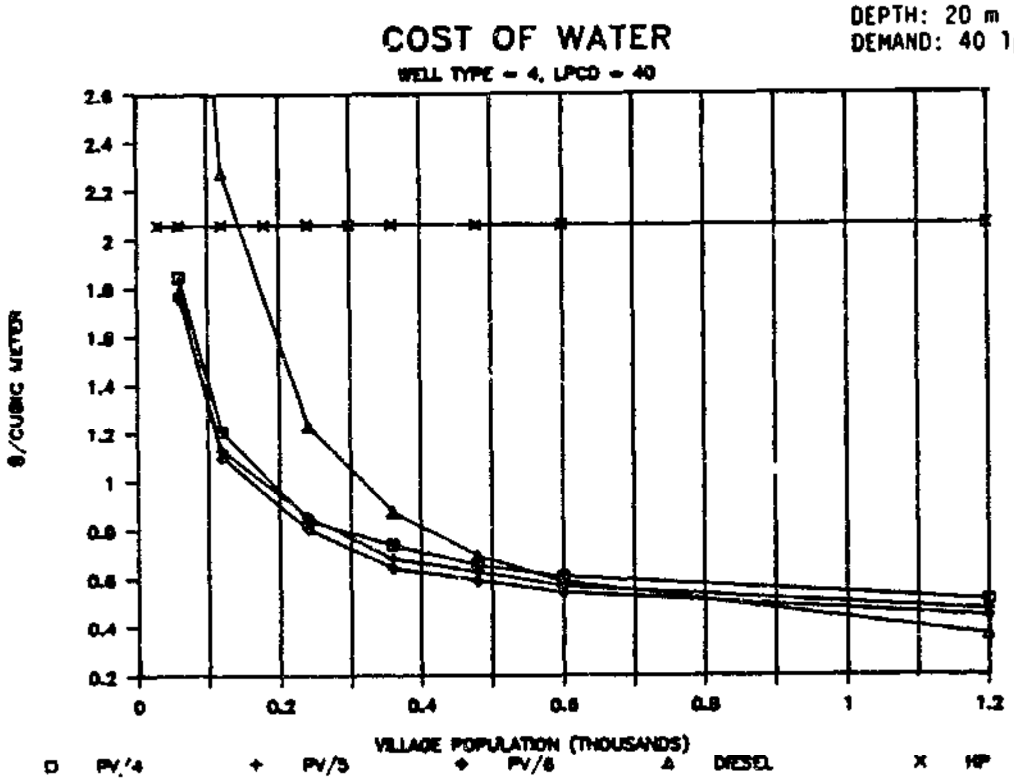


PER CAPITA CAPITAL COST

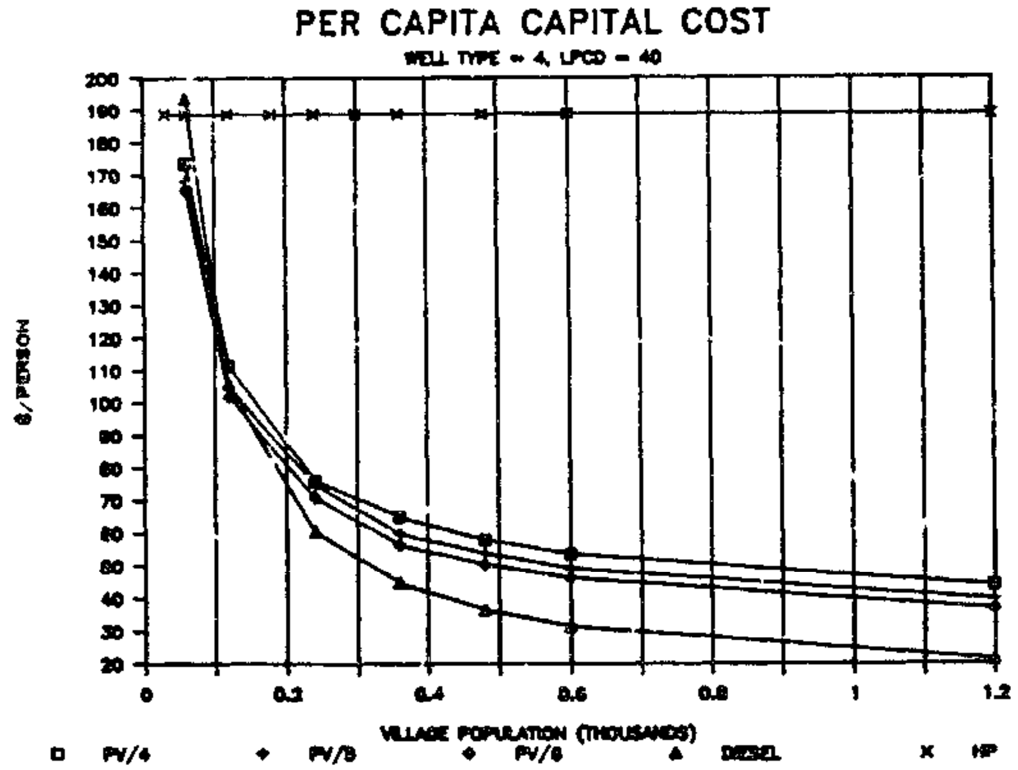
WELL TYPE = 4, LPCD = 20



WELL COST: $5,000
DEPTH: 20 m
DEMAND: 40 lpcd

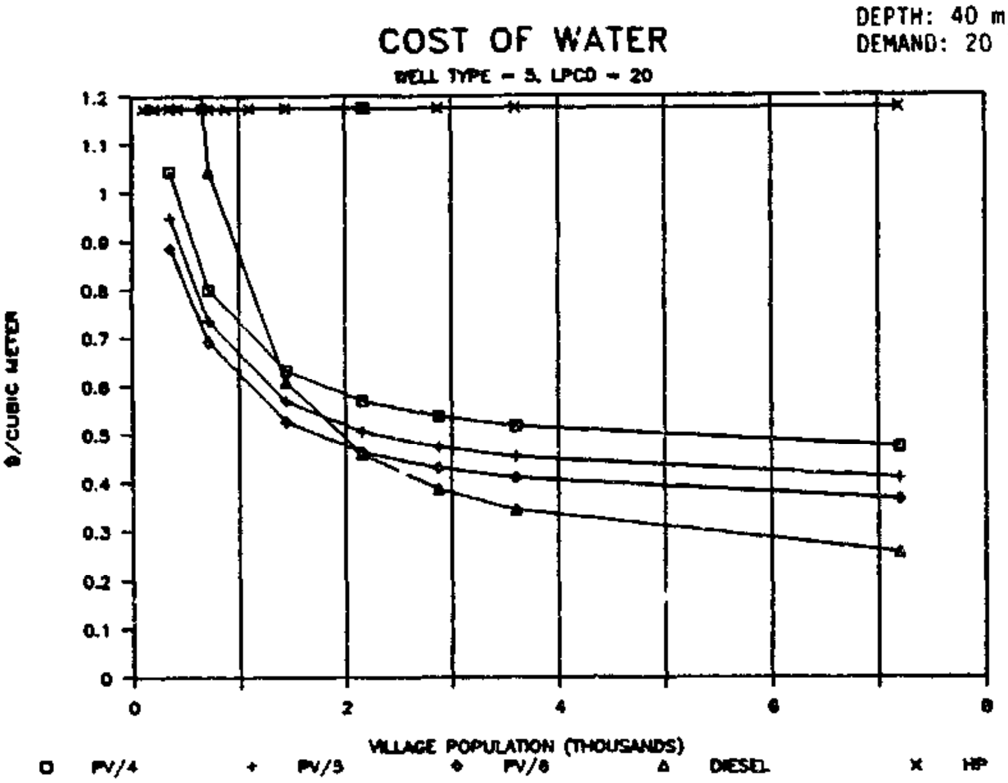

COST OF WATER

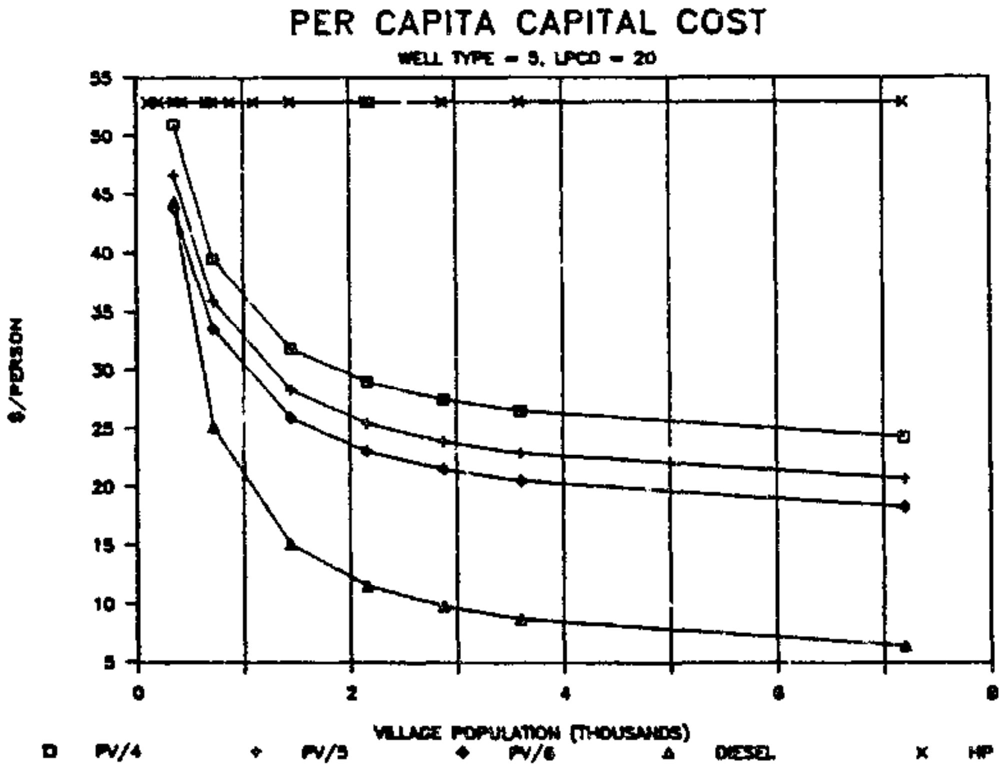
WELL TYPE = 4, LPCD = 40


PER CAPITA CAPITAL COST

WELL TYPE = 4, LPCD = 40

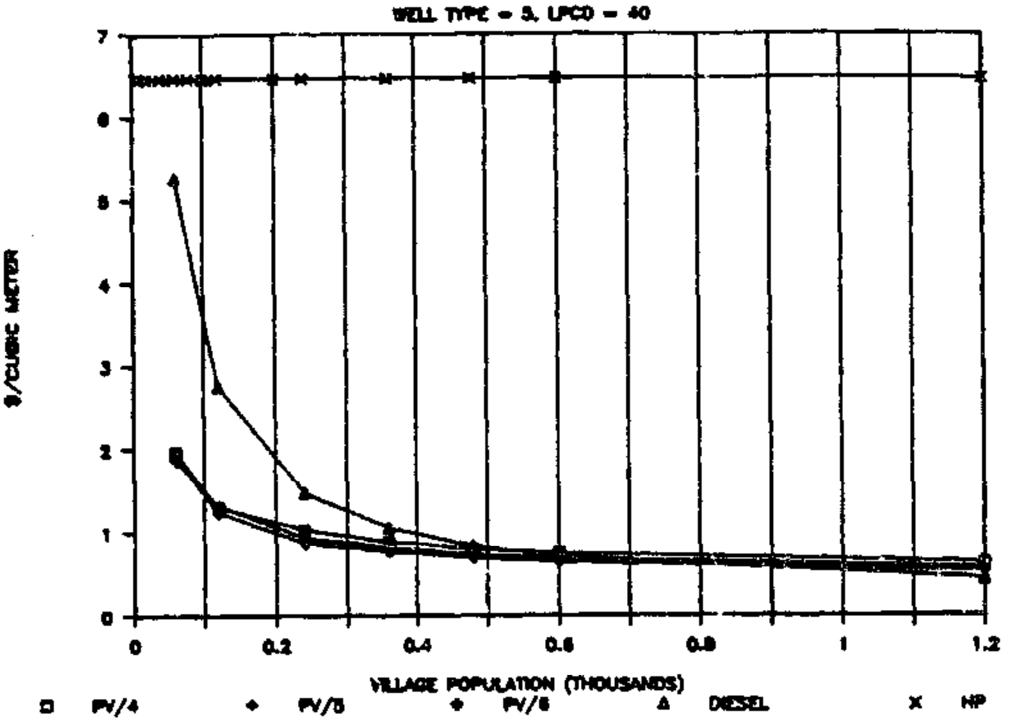
WELL COST: $5,000
DEPTH: 40 m
DEMAND: 20 lpcd



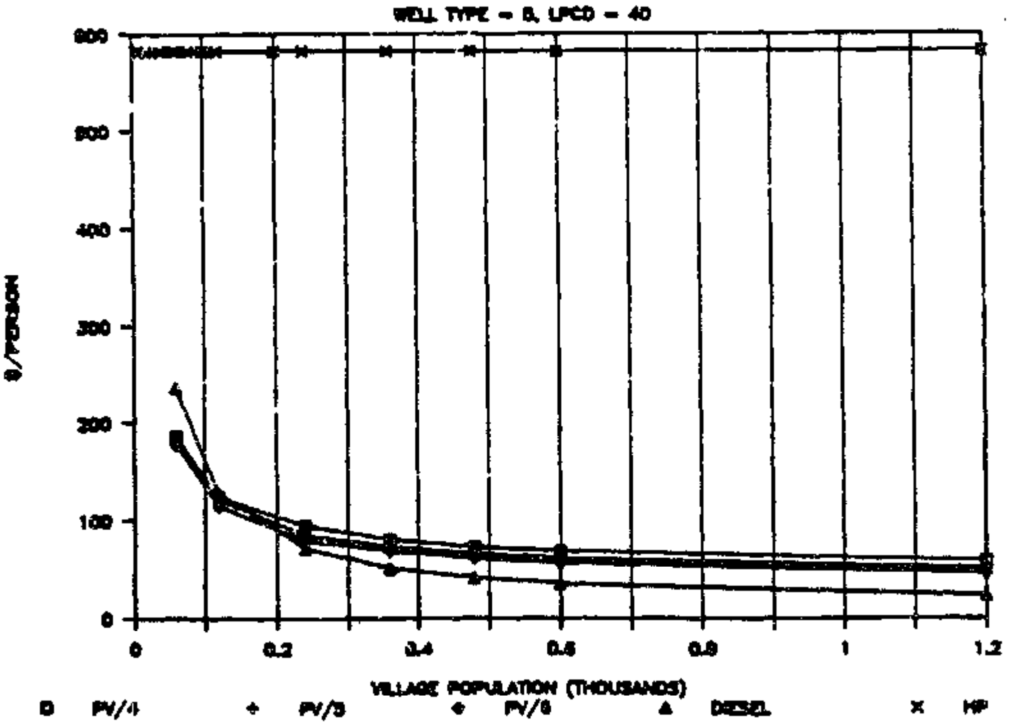


WELL COST: $5,000
DEPTH: 40 m
DEMAND: 40 lpcd

COST OF WATER



PER CAPITA CAPITAL COST



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Somerville, NJ 08876

Acurex Corporation
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Mountain View, CA 94039

AESI
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20442 Sun Valley Drive
Laguna Beach, CA 92651

Alabama Power Co.
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Birmingham, AL 35291

American Power Conversion Corp.
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89 Cambridge Street
Burlington, MA 01803-4115

Applied Solar Energy Corp.
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City of Industry, CA 91749

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Raju Yenamandra
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Billings, MT 59104

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ttn: A. Dickerson
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ttn: Angel Lopez
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ayaguez, Puerto Rico 00708

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ttn: Pandelis Zelissaropoulos
arketing Dept.
ox 177
rinceton, NJ 08542

hronar-TriSolar Corp.
ttn: Anand Rangarajan
0 De Angelo Drive
edford, MA 01730

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P. O. Box 1088
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Colorado Mountain College
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      Frank Goodman
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Palo Alto, CA 94303

Electric Research and Mgmnt.
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State College, PA 16804

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1055 Fort Cronkhite
Sausalito, CA 94965

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1015 Royal Lane
DFW Airport, TX 75261

Evans International
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3128 West Clarendon Avenue
Phoenix, AZ 85017

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Gardena, CA 90248

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Merritt Island, FL 32952

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Juno Beach, FL 33408

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Atlanta, GA 30302

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La Canada, CA 91011

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Clovis, CA 93612

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Washington, DC 20036

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Little Rock, AR 72219-8903

Jensen Brothers Manufacturing Co.
14th and Pacific
P. O. Box 477
Coffeyville, KS 67337

William Lamb Company
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10615 Chandler Blvd.
North Hollywood, CA 91601

March Manufacturing Co.
1819 Pickwick Avenue
Glenview, IL 60025

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Richmond, Indiana 47374

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A. Taylor
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New Boston, NH 03070

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Port Hueneme, CA 93043

Naval Weapons Center
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China Lake, CA 93555-6001

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Mukwonago, WI 53149

Onsite Energy
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Portland, OR 97204

Oxidizers, Inc.
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4990 Euclid Road
Virginia Beach, VA 23462

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Philadelphia Electric Company
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Scottsdale, AZ 85260

Photoelectric, Inc.
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Orange Park, FL 32703-2845

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Casanova, VA 22017

Remote Power Inc.
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Ft. Collins, CO 80524

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Specialty Concepts, Inc.
9025 Eton Ave., Suite D
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Charleston, SC 29409

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Rm. 509, SA-18
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Portland, OR 97232

U.S. Virgin Islands Energy Office
Institutional Conservation Program
Lagoon Complex, Bldg. 3, Room 233
St. Croix, U.S. Virgin Islands 00840

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6220 D. G. Schueler
6220 A. V. Poore
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6223 W. I. Bower
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